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Investigating energy expenditure in wheelchair athletes

Louise Croft

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

October 2011

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Abstract

The increased participation in elite wheelchair sport has provided the need to investigate the physiological requirements of wheelchair sporting competition and daily wheelchair propulsion. However, from a nutritional perspective, guidelines that have been established from the able-bodied population tend to be used by the practitioners working in disability sport and it is not known whether this information is directly transferable to the wheelchair athlete. Wheelchair sport is complex and athletes differ with respect to their sports classification based on factors relating to disability and functional capacity. Therefore, if nutritional guidance is required to optimise performance then information regarding energy expenditure (EE) in the wheelchair sports population becomes important for specific feedback. The aim of this thesis was to investigate EE in wheelchair athletes.

The results from Chapter 3 found resting energy expenditure (REE) in tetraplegic athletes to be lower than that calculated using predictive equations derived from an able-bodied cohort. However, paraplegic athletes showed comparable values to those which were predicted, suggesting these equations may be of use in paraplegic athletes. Chapter 4 extended this work and found similarities in the REE of the two aforementioned cohorts. This could have been due to the similarities that were found in their total-body fat free mass (FFM). The results from Chapter 5 showed EE reduced after both a short 36 minute exposure of wheelchair propulsion and after 3 weeks of wheelchair propulsion practice in novice wheelchair users. Temporal parameters improved after the practice period, suggesting there is an association between EE and propulsion technique. Chapter 6 extended these findings with results confirming that experienced wheelchair users expended significantly less energy during wheelchair propulsion than novice individuals who had up to 3 weeks practice. It is clear that EE of daily wheelchair ambulation should not be a generic value and different levels of experience must be considered so that the nutritional needs can be tailored accordingly.

Chapters 7 and 8 examined the physiological demands of elite competitive wheelchair basketball players in relation to the International Wheelchair Basketball Federation (IWBF) classification categories and identified differences in the physiological demands and physiological fitness of wheelchair basketball and tennis players. These results found that IWBF Class 3 – 4.5 (high point) players expended more energy per hour during competition than those with a lower classification (IWBF Class 1 – 2.5). However, when actual playing time was considered the low classification group showed a similar EE to the higher classification group. Furthermore, wheelchair basketball players had a higher EE per hour than wheelchair tennis players during elite competition. However, the wheelchair tennis players spent a significantly longer duration on court resulting in similar EE during a typical competition within each sport. This suggests nutritional advice should be tailored both to the duration of competitive play (where EE may be similar between sports (basketball vs. tennis)); and to training (where athletes with a higher functional capacity may have higher EE). This thesis revealed several important physiological considerations to appreciate when investigating the EE of wheelchair sportsmen and women. Findings would suggest that type of disability, wheelchair propulsion experience and sport classification are all important considerations for the accurate assessment of EE in this cohort of athletes.

Key Words: Paralympic athletes, wheelchair propulsion, energy cost, physiology, fat free mass, sports performance.
Acknowledgements

Throughout my PhD there have been many challenges and completion of this thesis would not have been possible without the help of many important individuals. I owe so much gratitude to my supervisor, Dr Vicky Tolfrey. Through her calm and positive approach, she allowed me to complete this research and provided many opportunities to work with Paralympic sports teams. I have learnt so much and have grown as a sports physiologist and as an academic in the last three years. I am tremendously grateful to Vicky for this opportunity. I am also very grateful to Dr Keith Tolfrey for the consistent support and feedback he provided over the three years. His thoughtful advice helped the completion of this thesis. I owe an enormous amount of thanks to John Lenton who helped with the data collection, assisted in analysis and provided helpful advice throughout. The input of Dr Barry Mason and Christof Leicht must be acknowledged for the support they provided during data collection and writing.

I was fortunate during my studies to have met several European experts in spinal cord injury rehabilitation and sport. My discussions with Professor Lucas van der Woude, Professor Thomas Janssen and Dr Claudio Perrett have helped shape this thesis and I am very grateful for their generous advice. I am also grateful to Jeanette Crosland who initiated many of the ideas behind this research and Dr Katherine Brooke-Wavell for her valued input to the earlier part of my work. I am indebted to ParalympicsGB, the School of Sport, Exercise and Health Sciences at Loughborough, and the Peter Harrison Centre for Disability Sport, who supported and financially contributed to this PhD. Mhairi Keil and Dr Rachel Duckham must be thanked for their assistance and expertise during data collection. Thanks also go to Bob Budge, John and Marta for their technical assistance and the help of Suzanne Dybrus, Katie Griggs and Alicia Lauckner was paramount for data collection. The staff at Bromakin wheelchairs have all been extremely generous with the provision of wheelchairs for data collection and appreciation goes to them.

I am forever grateful to my friends who have helped calm me down and provide help with my PhD but, equally as important, have provided a lot of fun times and great company over these 3 years. Jules, Steve, Tom, Mel, Tracey and Charlotte, thank you! Finally, a huge thank you goes to the athletes, coaches and support staff from the Great Britain wheelchair basketball and rugby squads, alongside the individual Paralympic athletes who have sacrificed their time to participate in my studies; I wish you the best of luck for London 2012.
Dedication

This thesis is dedicated to my Mum and Dad whose tireless support and encouragement has helped me through the three years. Their advice is used every day in the way I approach work and life. Thank you for everything.
Preface

Part of the research presented throughout the current thesis has been peer reviewed through the following publications and communications:

Publications

Chapter 8: Appendix I


Conference communications

Chapter 4:

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## List of Abbreviations

Frequently used terms throughout the thesis are abbreviated below. All abbreviations were defined in full the first time they were used in the text.

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<td>95% CI</td>
<td>95% confidence intervals</td>
</tr>
<tr>
<td>AB</td>
<td>Able-bodied</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>APT</td>
<td>Actual playing time</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine triphosphate</td>
</tr>
<tr>
<td>B-APT</td>
<td>Basketball actual playing time</td>
</tr>
<tr>
<td>[BLa]</td>
<td>Blood lactate</td>
</tr>
<tr>
<td>b·min⁻¹</td>
<td>Beats per minute</td>
</tr>
<tr>
<td>BMR</td>
<td>Basal metabolic rate</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CON</td>
<td>Control</td>
</tr>
<tr>
<td>DIT</td>
<td>Diet induced thermogenesis</td>
</tr>
<tr>
<td>DXA</td>
<td>Dual X-ray absorptiometry</td>
</tr>
<tr>
<td>EE</td>
<td>Energy expenditure</td>
</tr>
<tr>
<td>ES</td>
<td>Effect size</td>
</tr>
<tr>
<td>EXP</td>
<td>Experimental</td>
</tr>
<tr>
<td>Fdrag</td>
<td>Drag force</td>
</tr>
<tr>
<td>FEF</td>
<td>Fractional effective force</td>
</tr>
<tr>
<td>FFM</td>
<td>Fat free mass</td>
</tr>
<tr>
<td>Fres</td>
<td>Resultant force</td>
</tr>
<tr>
<td>Ftan</td>
<td>Tangential force</td>
</tr>
<tr>
<td>GE</td>
<td>Gross mechanical efficiency</td>
</tr>
<tr>
<td>HR</td>
<td>Heart rate</td>
</tr>
<tr>
<td>h·wk⁻¹</td>
<td>Hours per week</td>
</tr>
<tr>
<td>IWBF</td>
<td>International Wheelchair Basketball Federation</td>
</tr>
<tr>
<td>IWRF</td>
<td>International Wheelchair Rugby Federation</td>
</tr>
<tr>
<td>IWTF</td>
<td>International Wheelchair Tennis Federation</td>
</tr>
<tr>
<td>Kcal·h⁻¹</td>
<td>Kilocalories an hour</td>
</tr>
<tr>
<td>L·min⁻¹</td>
<td>Litres per minute</td>
</tr>
<tr>
<td>LT</td>
<td>Lactate threshold</td>
</tr>
<tr>
<td>LTP</td>
<td>Lactate turn point</td>
</tr>
<tr>
<td>m</td>
<td>Minutes</td>
</tr>
<tr>
<td>mmol·L⁻¹</td>
<td>Millimoles per litre</td>
</tr>
<tr>
<td>m·s⁻¹</td>
<td>Metres per second</td>
</tr>
<tr>
<td>N</td>
<td>Newtons</td>
</tr>
<tr>
<td>O₂</td>
<td>Oxygen</td>
</tr>
<tr>
<td>P₀</td>
<td>Power output</td>
</tr>
<tr>
<td>PRAC</td>
<td>Practice</td>
</tr>
<tr>
<td>REE</td>
<td>Resting energy expenditure</td>
</tr>
<tr>
<td>RER</td>
<td>Respiratory exchange ratio ((\bar{V}CO_2/\bar{VO}_2))</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>RPE</td>
<td>Rating of perceived exertion</td>
</tr>
<tr>
<td>s</td>
<td>Seconds</td>
</tr>
<tr>
<td>SCI</td>
<td>Spinal cord injury</td>
</tr>
<tr>
<td>VO₂</td>
<td>Oxygen uptake</td>
</tr>
<tr>
<td>VCO₂</td>
<td>Carbon dioxide production</td>
</tr>
<tr>
<td>VT</td>
<td>Ventilatory threshold</td>
</tr>
<tr>
<td>W</td>
<td>Watts</td>
</tr>
<tr>
<td>WBP</td>
<td>Wheelchair basketball play</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organisation</td>
</tr>
<tr>
<td>WTP</td>
<td>Wheelchair tennis play</td>
</tr>
</tbody>
</table>
Chapter 1

1.0 Introduction

The Great Britain Paralympic athletes were highly successful at the Beijing 2008 Paralympic Games, the team returning with 102 medals and being placed second in the medals table. This world-class performance may be attributed to the increased training, professionalism and commitment to the demands of their sport by the athletes, along with increased knowledge and sports science practice. That said, many of these athletes are still using nutritional advice and training methods based on what is known about their able-bodied counterparts. Through investigating the energy expenditure (EE) of daily living and sporting competition within this cohort, specific nutritional advice can then be given. The total daily EE of an individual includes basal metabolism (60–75%) and the thermic effect of food (10%) alongside the energy produced through physical activity (15-30%) (McArdle et al., 2001). Examining the various components of total EE will allow a greater understanding of the health status and metabolic requirements of an individual. This is of particular importance in sports performers, as these individuals need to account for energy used during competition and regular training on top of that necessary for a normal daily routine (Westerterp, 1998). Consequently, sports practitioners and health care professionals can advise individuals about optimal combinations of fuel selection and training regimes in order to maintain energy balance in relation to an individual’s lifestyle.

In the able-bodied literature, in terms of resting energy expenditure (REE), prediction equations and general recommendations are given in relation to age, sex and body mass (Schofield, 1985) and the energy cost of specific activities is provided in terms of body mass (McArdle et al., 2001; Ainsworth et al., 2011). When considering the wheelchair user population, in addition to the other key variables that can determine EE, disability must also be accounted for. Using able-bodied values may overestimate the EE of wheelchair users due to the latter’s reduced active muscle mass and the type of activity completed (Davis et al., 1981; Maynard et al., 1997). Yet, the contribution of sports training to the EE of wheelchair users could provide us with different values to those found in a sedentary setting because of the potential for an increase in the athlete’s fat-free mass (FFM; the sum of lean mass and bone mineral content). It is therefore essential to establish whether able-bodied EE guidelines and recommendations used by the general and athletic...
populations are applicable to wheelchair athletes. A greater understanding of these athletes’ EE will help increase the knowledge of the practitioners who work with them.

Whilst specific advice according to sport is necessary, understanding the general health aspects of accurate EE calculation is also an important factor to consider, especially in the disabled population. Paffenbarger et al. (1986) suggested that physical activity EE of 2000-2500 kcal (or more) a week can reduce the risk of mortality in a male, able-bodied population (45-84 years). However it is questionable whether or not these recommendations are applicable to disabled populations. This is in light of the evidence that individuals with a chronic spinal cord injury (SCI) have lower levels of physical activity compared to able-bodied populations (Dearwater et al., 1985; Jacobs and Nash, 2004). Accordingly, sports participation is promoted in specialist SCI units in the UK so physical activity can be re-introduced to offset the potential negative effects of sedentary behaviour.

The focus of the present PhD is on athletes with a disability who are not necessarily the target group for inactivity and low fitness levels. However, this thesis will provide an understanding of total EE in an athletic cohort and serve as a foundation to build on health-related topics. The objective is to give athletes and practitioners information for training practices directly for their own use, and also provide data relating to disabled sports and wheelchair propulsion which can be used to guide individuals across the rehabilitation - elite sports continuum. To develop the topic of EE in wheelchair athletes this thesis was divided into three main themes (i) resting; (ii) daily propulsion; and (iii) sports competition EE.

1.1 Aims and objectives of the thesis

The aim of the thesis was to examine the EE of wheelchair athletes. In order to achieve this the following objectives were formulated:

1) To investigate the relationship between body composition and REE in athletes with a disability and to compare measured values of REE to predicted equations for the able-bodied population.

2) To explore the effect of wheelchair propulsion practice and experience on the EE of wheelchair propulsion during daily ambulatory speeds.
3) To analyse the physiological variables and the EE of wheelchair sports competition, with comparisons between sports and between disability classifications.

1.2 Organisation of the thesis

The literature review (Chapter 2) will explore the basic principles of EE in humans and then introduce wheelchair sports and the individuals who take part in these sports. The review will then explore the physiology of specific disabilities and how these contribute to changes in body composition and EE. The physiological capacities wheelchair athletes can reach will add to the understanding of differences between individuals who take part in disability sports. The literature review will then consider the research that has investigated EE in resting conditions and daily activities of wheelchair users and finish by examining EE during wheelchair sports and what is needed to further this topic of interest. Three themes will then be established for the development of the experimental chapters. These are (a) REE in elite disabled athletes; (b) EE during daily wheelchair propulsion, exploring the effects of manual wheelchair experience; and (c) EE during wheelchair sports competition.

Investigating the REE of wheelchair athletes (Chapters 3 and 4) will establish whether able-bodied predictive equations are of use in this population group. Exploring FFM and its relationship with REE will provide a clearer picture regarding the contribution of active metabolic mass to EE in this sporting population group. This relationship has been established in both the healthy able-bodied and rehabilitation settings (Monroe et al., 1998; Heymsfield et al., 2002; Buchholz et al., 2003a; Johnstone et al., 2005). Considering the differences in FFM and REE between two separate wheelchair sports teams will ascertain if any distinctions exist in REE due to nature of the different physiology between the two groups.

Another aspect of the wheelchair athlete’s metabolism is related to the wheelchair itself. Exploring the EE of wheelchair propulsion (Chapters 5 and 6) helps provide information regarding daily activity in wheelchair users, an important consideration for the athletes who use a wheelchair for daily living. Investigating the effect of experience on the EE of wheelchair propulsion will provide further explanation of the EE patterns shown during the process of learning this skill. This is an important consideration as single values
of EE during wheelchair activities may not be applicable to both novice individuals and habitual wheelchair users.

Focusing on the EE of wheelchair sports competition (Chapters 7 and 8) will help establish physiological values for these sports to help coaches and practitioners understand more about the demands of specific Paralympic sport. Aside from the comparison between sports, one of the biggest influences on the physiology of wheelchair athletes is classification. Detailed information regarding the EE of separate disability classification groups within sport can help provide more specific and individualised feedback for further nutritional and training advice.

A general discussion and practical implications (Chapter 9) will help provide information that practitioners and athletes can use. Future directions will lead on from the conclusion about the important findings of this thesis and how it has contributed to the understanding of EE in wheelchair athletes. The disabled participants recruited for these studies all represent the Paralympic community with the majority involved in wheelchair sports. Subsequently, the primary disabilities include SCI and amputation, with the former as the main disability focus for this thesis. Furthermore, whilst recruitment centred on male participants, the comparison of wheelchair sports (Chapter 8) involved four females across the sports of wheelchair basketball and tennis.
Chapter Two

2.0 Literature Review

2.1 Metabolism and EE

Measuring the EE of humans helps in the provision of nutritional requirements needed for health and survival. Metabolic equations to predict EE in the able-bodied population are continually being developed to provide the recommended calorie intake per day based on an individual’s physiology (WHO, 2001).

2.1.1 Metabolism

Energy use can be measured from heat produced by the metabolism of carbohydrate, fat, protein and alcohol. For every litre of oxygen (O\textsubscript{2}) consumed, there is a known amount of heat released within the body depending on the nutrient being oxidised (Jequier et al., 1987). Glucose and glycogen are predominant sources of energy from carbohydrate and both can be used in equations to estimate EE. However, for the purposes of continuity, glucose will be studied in this thesis. Palmitate is the most abundant fatty acid in the diet and plasma (Jeukendrup and Wallis, 2005). These sources of energy have very different compositions and, therefore, different amounts of O\textsubscript{2} are required to oxidise one mole of each nutrient to carbon dioxide (CO\textsubscript{2}) and water (H\textsubscript{2}O) as shown below:

\[
\text{Glucose oxidation} - C\textsubscript{6}H\textsubscript{12}O\textsubscript{6} + 6O\textsubscript{2} \rightarrow 6 \text{CO}_{2} + 6 \text{H}_{2}\text{O} \\
\text{Fat oxidation (Palmitate)} - C\textsubscript{16}H\textsubscript{32}O\textsubscript{2} + 23 O\textsubscript{2} \rightarrow 16 \text{CO}_{2} + 16 \text{H}_{2}\text{O}
\]

The energy obtained from a nutrient released by oxidation is, in part, lost as heat. The rest of the energy obtained is formed as the energy transfer compound, adenosine triphosphate (ATP) (Ferrannini, 1988). Heat produced by the oxidation of molecules is measured in calories. The calorie (often reported as kilocalories (kcal)) is a measure of the quantity of heat needed to raise the temperature of 1 kg (1 litre) of H\textsubscript{2}O by 1 degree centigrade (°C). The amount of energy that is available within the phosphate bond of an ATP molecule is 12.5 kcal·mol\textsuperscript{-1} (Ferrannini, 1988).

Table 2.1 shows that more ATP is produced from oxidation of one mole of palmitate than of glucose, as more hydrogen atoms are available in lipids for cleavage and oxidation for energy (McArdle et al., 2001). However, the relative O\textsubscript{2} that is needed to
produce the ATP from 1 mole of palmitate is higher than that of glucose. Therefore, glucose oxidation is the most efficient way of using O₂ to produce energy (Ferrannini, 1988).

2.1.2 Indirect calorimetry

Metabolic rate can be calculated through both direct and indirect calorimetry. Direct calorimetry measures the absolute heat dissipated by the human body. However, the response is delayed as it is measuring the actual heat loss of the body (Jequier et al., 1987). Indirect calorimetry is the measurement of the estimated heat released by oxidative processes, using equations based on O₂ consumption (\(\dot{V}O_{2}\)), CO₂ production (\(\dot{V}CO_{2}\)), and urinary nitrogen excretion during the measured time of metabolism. Expired gas must be obtained for an estimation of O₂ and CO₂, and the changes in the O₂ and CO₂ in the exhaled air along with the volume of expired gas and the ambient conditions are used to calculate the energy metabolism of that individual. The contribution of protein to the calculation of EE is considered negligible (McArdle et al., 2001), so often only the non-protein calculations are implemented. Ferrannini (1988) suggested that although protein measurement was an important consideration, if protein oxidation was misjudged by 50% there would only be a 1.2% error in the estimation of energy production.

Although there are various equations to calculate substrate oxidation, the modified equation of Frayn (1983) has been widely used for the calculation of carbohydrate and fat oxidation values from O₂ and CO₂ (in L):

\[
\text{Carbohydrate (g): } (4.55 \times \dot{V}CO_{2}) - (3.21 \times \dot{V}O_{2})
\]

\[
\text{Fat (g): } (1.67 \times \dot{V}O_{2}) - (1.67 \times \dot{V}CO_{2})
\]

A gram of carbohydrate is assumed to produce 4 kcal, and a gram of fat is assumed to produce 9 kcal (Atwater, 1889). These calculations have been derived from the heat of combustion of the individual nutrient (WHO, 1985) and therefore, calculated amounts of carbohydrate and fat can be used for the estimation of kcal produced.
Table 2.1. Energy balance for glucose and palmitate (taken directly from Ferrannini, 1988).

<table>
<thead>
<tr>
<th>Oxidised fuel</th>
<th>$\Delta G^1$</th>
<th>$O_2$ used</th>
<th>$CO_2$ produced</th>
<th>RQ$^2$</th>
<th>Net ATP yield</th>
<th>Caloric cost of ATP</th>
<th>$O_2$ cost of ATP</th>
<th>Caloric equivalent of $O_2$</th>
<th>ATP equivalent of $O_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>673 (kcal･mol$^{-1}$)</td>
<td>6 (mol)</td>
<td>134 (L)</td>
<td>1.00</td>
<td>36 (mol)</td>
<td>18.3 (L)</td>
<td>18.7 (kcal･mol$^{-1}$)</td>
<td>3.72 (kcal･L$^{-1}$)</td>
<td>5.02 (mol/mol$^{-1}$)</td>
</tr>
<tr>
<td>Palmitate</td>
<td>2398 (kcal･mol$^{-1}$)</td>
<td>23 (mol)</td>
<td>515 (L)</td>
<td>0.70</td>
<td>131 (mol)</td>
<td>66.4 (L)</td>
<td>18.3 (kcal･mol$^{-1}$)</td>
<td>3.93 (kcal･L$^{-1}$)</td>
<td>4.66 (mol/mol$^{-1}$)</td>
</tr>
</tbody>
</table>

1 $\Delta G =$ energy liberated as heat

2 RQ = Respiratory quotient (the ratio of $CO_2$ production to $O_2$ consumption).

3 mol = moles
Indirect calorimetry requires certain assumptions to be met in order to obtain accurate measurements. Expired gas measured from the mouth is assumed to be representing what is happening in the body. Oxygen consumption measured from expired gas immediately follows whole body O$_2$ consumption as there is no O$_2$ reserve within the body (Ferrannini, 1988). However, at a cellular level, CO$_2$ is produced and enters a bicarbonate pool (Ferrannini, 1988). If hyper or hypo-ventilation occurs, the O$_2$ and CO$_2$ values in expired gas will not be a true reflection of the metabolism in the body and may cause error in EE estimation. An increase in lactate from anaerobic glycolysis during exercise leads to its hydrogen being buffered by bicarbonate. Bicarbonate is then converted to H$_2$O and CO$_2$. This excess CO$_2$ is reflected in expired gas (Beaver et al., 1986). On the other hand, a decrease in lactate causes a reduction in hydrogen ions, and CO$_2$ is used to then replenish bicarbonate. This could cause an under-estimation of the body’s CO$_2$ from the expired gas (Ferrannini 1988). To minimise these errors, measurement of expired gas is obtained during rest or steady state metabolism, where O$_2$ metabolism is sufficient to meet the energy demand of the exercising muscle (Brown et al., 2006).

2.1.3 Total EE

Total EE during a 24 hour period consists of EE at rest, the energy used to digest a meal (diet-induced thermogenesis; DIT), and the energy used during physical activity. Basal metabolic rate (BMR) is the energy used to maintain essential bodily functions, reflecting the body’s heat production at rest. It represents the rate of EE of an individual who is awake, physically and mentally rested, post-absorptive and thermo-neutral. Of the different components of total EE, BMR accounts for 45 - 70% of total EE, depending on age and lifestyle (WHO, 2001).

Diet-induced thermogenesis increases energy metabolism. Factors such as body size, macronutrient and energy composition of the meal as well as the time elapsed since the previous meal, affects the DIT (McArdle et al., 2001; Westerterp et al., 2004). For example, protein has a high thermic effect due to the digestion of this nutrient within the body (Westerterp et al., 2007). This means that fewer calories become available from protein ingestion compared to fat and carbohydrate. Diet-induced thermogenesis can account for 10% of total EE and a high protein and carbohydrate diet induces a greater thermic response in healthy individuals compared to a diet high in fat (Westerterp, 2007).
Physical activity in the able-bodied population accounts for between 15% - 30% total daily EE. It is the component that has the greatest effect on the EE of an individual during a 24 hour period (McArdle et al., 2001; Westerterp, 2007). It is the element which varies the most when compared to REE and DIT (Westerterp, 2007). As this component varies inter and intra-individually, the correct assessment of the demands of activities becomes paramount to be able to assess an individual’s active EE. As this knowledge has been driven through an able-bodied focus, consideration of the influence disability has on physical activity in relation to total EE becomes an important topic.

2.2 Introduction to wheelchair sports

Wheelchair sport has grown from its rehabilitation origins at Stoke Mandeville Hospital in England over 50 years ago to the present Paralympic games (Tweedy and Diaper, 2010). Within the Paralympics there are twenty summer sports. However, it is beyond the scope of the thesis to discuss all these sports and the associated disabilities. Instead, the aim is to introduce the wheelchair sports of basketball, rugby and tennis and to provide a brief background to these three sports in the following section.

A wheelchair basketball team comprises five players and seven substitutes. A game is made up of four, 10-minute periods of play, typically lasting 75 minutes at international standard (Pérez et al., 2007). As with the running game, the players must dribble the ball and score a basket within 24 seconds of team possession (IWBF, 2010). Classification in wheelchair basketball (points 1.0 – 4.5) is sport specific and players are classed on their functional ability. A classification of 1.0 relates to an athlete with least functional ability and classification 4.5 the greatest functional capacity. At any one time on the court, a value of 14 points from the classification of five players cannot be exceeded (IWBF, 2010). Athletes who qualify to play wheelchair basketball have a range of disabilities and any individual who is unable to play able-bodied basketball due to their physiology or biomechanics is eligible. The range of disabilities found in a team of wheelchair basketball makes this cohort heterogeneous (ranging from club foot and lower limb amputation to SCI). Therefore, when studying the physiology of a wheelchair basketball team, there will be a large range of functional ability and disabilities to consider.

Wheelchair rugby, on the other hand, is mainly played by a homogenous group of individuals who have an SCI with a cervical lesion level of C6 - C8 and who have limited or no function in at least three limbs. Wheelchair rugby is played on an indoor court (28 x
15 m), with a white ball identical to a volleyball and both men and women play on the same team according to the International Wheelchair Rugby Federation (IWRF). Players have to score a goal in between two markers at one end of the court. They must defend the ‘goal’ at the other end of the court. The game consists of four 8-min quarters (IWRF, 2009) and typically lasts just under 70 minutes (Sarro et al., 2010). Classification is in accordance with an individual’s functional ability in relation to the sport, alongside their physiological capacities such as balance, muscle tone and flexibility (IWRF, 2009).

Wheelchair tennis is played by a range of individuals who are eligible to play in one of two categories. The open classification includes individuals with disabilities such as paraplegia, amputation, spina bifida, post-polio, brittle bones and club foot. (IWTF, 2011a). The ‘Quad’ classification includes individuals with an SCI, lesion level of C6 – C8, or by an individual who has a substantial loss of function in one or both of their upper limbs. Often, the racquet is strapped to the hand during game play to help stabilise it (IWTF, 2011b). The game of wheelchair tennis is played to the same rules of the International Tennis Federation with the exception of the ball being allowed to bounce twice. The length of a wheelchair tennis match varies considerably with match lengths ranging from 1-3 hours (Diaper and Goosey-Tolfrey, 2009).

As previously mentioned, wheelchair sports encourage people with a variety of disabilities to participate. The focus of the next section will be to describe some of the eligible physical impairments of the three aforementioned wheelchair sports. The term SCI is used in this following section to describe the consequence of a traumatic event resulting in paralysis. It is also used as a term to include post-polio and spina bifida in the later sections of this work. These two latter disabilities are described separately in this following section.

2.2.1 Amputation

Amputation is performed to remove a limb due to pain or disease. Lower limb amputations are performed on individuals with limb ischaemia (dysvascular amputation), diabetic feet, venous ulceration or after a major trauma (Harker, 2006). Complications associated with wound healing from an amputation are infection, pain, wound breakdown, bone erosion, haematoma and stump oedema (Harker, 2006). For the newly amputated individual, prostheses are often required and the stump-to-prosthesis interface is an important issue in an amputee’s health and wellbeing. The soft tissue of the stump may
become irritated or develop ulcers due to the stress it is put under from the load of the rest of the body (Dou et al., 2006). An uncomfortable or even painful interface may result in a reduction in physical activity and movement until the stump has healed. Depending on the level of amputation, the limb amputated and the number of limbs removed, an individual may use a wheelchair as their form of ambulation.

2.2.2 Spinal cord injury

Traumatic SCI results in varying types of motor, sensory and autonomic damage (Jacobs and Nash, 2004). A loss of motor and/or sensory function in the cervical area of the spine leads to impairment in all four limbs and the trunk (tetraplegia). A loss of motor and/or sensory function in the thoracic, lumbar or sacral area of the spine results in impairment of the lower limbs and/or the trunk (paraplegia) (Jacobs and Nash, 2004). The spinal cord is part of the central nervous system and is protected by the spinal column. The spinal column consists of eight cervical, twelve thoracic, five lumbar, five sacral and one coccygeal vertebrae (Tweedy and Diaper, 2010). Sensory neurons enter and motor neurons leave the spinal cord via segmental nerves which are numbered according to where they lie in the vertebral column (Maynard et al., 1997). The central nervous system consists of the brain and the spinal cord while the peripheral nervous system includes nerves that connect with organs outside of the brain. The somatic nervous system controls the voluntary contraction of skeletal muscle and this control originates from the spinal cord, brain stem and cerebral cortex. The autonomic nervous system controls the involuntary actions of smooth muscle, cardiac muscle and glands with SCI potentially affecting both of these nervous systems (Maynard et al., 1997; Totora and Graboski, 2003).

When the spinal cord is damaged, excitatory impulses are prevented from travelling past the level of the lesion. Within the sympathetic nervous system (Figure 2.1), excitatory impulses are unable to reach the distal end of the spinal cord (Hopman et al., 1994; Maynard et al., 1997). Therefore, skeletal muscles controlled by sections of the central nervous system below the level of the damaged spinal cord become paralysed. However, the parasympathetic nervous system has preganglionic neurons located in the brain stem (Figure 2.2). Consequently, all SCI individuals have intact parasympathetic nerves affecting the heart, lungs, intestine and liver. The parasympathetic nervous system affecting the pelvis however has splanchnic nerves located in the spinal cord region of (sacral) S2 – S5, and an individual with a lesion level above S2 may have limited
parasympathetic nervous control of the bladder, genitals and uterus (Figure 2.2). The physiological consequences of a complete SCI versus an incomplete SCI may differ considerably. An incomplete lesion results when some of the connection between the brain and the area below the lesion level stays intact. Some individuals who have an incomplete SCI may use some of the muscles below the level of injury and thus have a varied physiological response to certain stimuli (Tweedy and Diaper, 2010).

2.2.3 Post-polio (Poliomyelitis)

Post-polio (poliomyelitis) is a virus that often affects children. This virus gains access to its human host through the mouth or pharynx where it then moves to the bloodstream (Neumann, 2004). There is a great variety of physiological consequences to polio. However, in its most aggressive form, this disease attacks motor-neurons in the spinal cord and the brainstem, which can lead to permanent paralysis or weakness of the muscles (Laffont et al., 2010). Depending on the affected area of the spinal cord, an individual may acquire permanent tetraplegia or paraplegia (Neumann, 2004).

2.2.4 Spina bifida

Spina bifida (bifida is latin for the phrase ‘left in two parts’) is a congenital defect which occurs when a section of the vertebral arch within the spinal column either partly fuses or does not fuse at all. The incomplete spinal cord results in paralysis of the lower limbs in affected individuals (Foster, 2009). Myelomeningocele is the most common form of spina bifida, accounting for 94% of cases causing neural damage due to the protrusion of the spinal cord through the un-fused spinal column. This often leads to paralysis in the lumbosacral segment of the spinal cord (Foster, 2009). Neurological damage in the lumbar region of the spine can cause denervation to the bladder (see Figure 2.1). In certain circumstances this can lead to a blockage of urine caused by neurogenic bladder, a diseased bladder due to nerve damage of the spinal cord as a result of spina bifida (Foster, 2009).
Figure 2.1. Sympathetic nervous division. Taken from Tortora and Grabowski, (2003).
Figure 2.2. Parasympathetic nervous division. Taken from Tortora and Grabowski, (2003).
2.3 Physiological changes with SCI and amputation

2.3.1 Spinal cord injury and body composition

Spinal cord injury results in changes in body composition due to muscle atrophy below the level of lesion alongside bone demineralisation and joint deterioration (Wilmet et al., 1995; Jacobs and Nash, 2004). When comparing individuals with an SCI to able-bodied controls matched for age, a lower FFM or lean mass is shown in the former group (Monroe et al., 1998; Spungen et al., 2000; 2003; Jones et al., 2003; Maggioni et al., 2003; Dionyssiotis et al., 2008). Actual values of FFM have shown to vary considerably, from 51.6 kg in both tetraplegic and paraplegic individuals to 64.1 kg in an able-bodied group (Monroe et al., 1998). Buchholz et al. (2003a) also demonstrated a lower FFM value of 64.1 kg in paraplegic individuals compared to 77.2 kg in an able-bodied cohort. Other authors have noted a lower value of lean muscle mass in SCI when individuals with an SCI were compared to the able-bodied population (Spungen et al., 2000; Jones et al., 2003; Spungen et al., 2003; Dionyssiotis et al., 2008). Within the SCI rehabilitation setting, tetraplegic individuals have a lower total lean body mass when compared to paraplegic individuals (Spungen et al., 2003).

Results from analysis of segmental body composition suggest that lean mass in the upper body increases by up to 15% during the first year after onset of an SCI due to intensive rehabilitation (Wilmet et al., 1995). Although the absolute lean mass in the upper limbs of sedentary paraplegic individuals is similar to the able-bodied population (Spungen et al., 2000; 2003; Dionyssiotis et al., 2008), FFM in the upper body of an elite sporting population with a disability is actually greater than that of an able-bodied cohort (Sutton et al., 2009). Figure 2.3 shows an example of body composition from dual energy X-ray absorptiometry (DXA) scans in two wheelchair athletes, one of whom is ambulant and one who has an SCI. There are clear differences shown in body composition in the lower limbs of the two athletes in Figure 2.3. Table 2.2 highlights the larger amount of FFM in the lower limbs and total body in the ambulant athlete, and the larger fat mass in the lower limbs of the athlete with an SCI. However, the values presented here also highlight the similarities in upper limb body composition in the two wheelchair athletes, emphasising the impact specific sports training has on the upper body.
Figure 2.3. Dual energy X-ray absorptiometry (DXA) scans of an ambulant male wheelchair athlete (left) and a male wheelchair athlete with an SCI (right).

Table 2.2. A comparison of DXA-determined body composition between an ambulant male wheelchair athlete and a male wheelchair athlete with an SCI.

<table>
<thead>
<tr>
<th></th>
<th>Ambulant wheelchair athlete</th>
<th>Wheelchair athlete with an SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FFM (kg)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper limbs</td>
<td>12.8</td>
<td>11.4</td>
</tr>
<tr>
<td>Lower limbs</td>
<td>21.1</td>
<td>7.0</td>
</tr>
<tr>
<td>Total</td>
<td>72.7</td>
<td>45.8</td>
</tr>
<tr>
<td><strong>Fat mass (kg)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper limbs</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Lower limbs</td>
<td>3.2</td>
<td>4.9</td>
</tr>
<tr>
<td>Total</td>
<td>17.7</td>
<td>18.1</td>
</tr>
</tbody>
</table>
Monitoring body composition is an important aspect from both a wheelchair sports setting and a health perspective. Excess body mass may lead to increased rolling resistance of the wheelchair and athlete interface which may be detrimental to performance (Reilly and Crosland, 2010). Exploring seasonal changes in body composition or gaining a snapshot at a particular part of the season can be an integral part of any athlete’s preparation for competition, as it can be used to inform whether training or nutritional interventions have been successful (Carling et al., 2009). From a health perspective, as FFM has been shown to be an important determinant of REE in individuals with an SCI (Buchholz et al., 2003a) the assessment of FFM should be of interest in future work. In light of this, there are various methods for the assessment of body composition. Traditionally, underwater weighing has been used as the most accurate estimate of body composition. This has been achieved through the calculation of known densities of fat mass and FFM alongside the measurement of whole-body density (Hawes and Martin, 2004). Aside from the obvious limitations of measuring individuals with a disability by underwater weighing, it is emerging that the use of DXA, which is becoming more readily available to researchers, is also becoming the criterion method of body composition measurement in the able-bodied population (Hawes and Martin, 2004). However, the DXA scan produces low levels of ionising radiation and for this reason unnecessary exposure must be eliminated alongside rigorous ethical approval. Individuals with a disability may be more exposed to X-rays if these are required for routine hospital check-ups, so measuring body composition through DXA to aid metabolic research may not always be straightforward. In light of this, skin-fold thickness assessment, a common and practical estimation of body composition is often used. This technique involves the measurement of subcutaneous fat which is used to represent total body fat. Skin-fold assessment is suggested to be useful for monitoring wheelchair athletes if sum of skin-folds are used rather than predicted body fat percentage from equations that have been calculated from the able-bodied population (Reilly and Crosland, 2010).

2.3.2 Spinal cord injury and the physiological responses to exercise

The autonomic nervous system has a large effect on the outcome of an individual’s physiological responses to exercise when considering central limitations to exercise. The celiac ganglion is part of the sympathetic ganglia which lie anterior to the spinal column close to the abdominal arteries (with innervation from T6 – T8 in the spinal column, Figure 2.1). The celiac ganglia innervate the adrenal gland and other splanchnic organs. The
adrenal gland is of particular importance during exercise, as the adrenal medulla releases catecholamines which are responsible for an increased rate and contraction of the heart (Esler et al., 1990; McArdle et al., 2001). If an individual has an SCI with a lesion level above T6, the release of nor-epinephrine (Steinberg et al., 2000; Teasell et al., 2000) and epinephrine (Schmid et al., 1998a) has been shown to be blunted at rest and both nor-epinephrine and epinephrine reached lower levels during exercise when compared to controls and individuals with lower spinal cord lesion levels (Schmid et al., 1998a; Steinberg et al., 2000). Individuals with a lesion level above T6 may also show reduced sympathetic innervation to the heart (Hopman et al., 1994) and will rely on the withdrawal of vagal tone to increase heart rate (HR) (Hopman et al., 1994; Schmid et al., 1998a).

Cardiac output is mediated by stroke volume and HR. Stroke volume has been shown to be lower in the SCI population, primarily as a result of a reduced venous return in the lower limbs due to an inactive muscle pump in that region (Hopman et al., 1994). Individuals who have innervation to the splanchnic region and release catecholamines will have improved sympathetic stimulation to the heart, but will still have a decreased venous return due to the inactive muscle pump of the lower limbs. Peripheral muscle fatigue, as with able-bodied persons, will be one of the main contributors to the limit of an individual’s exercise capacity during upper-body exercise (Hopman et al., 1994).

The release of catecholamines may affect EE due to the influence both epinephrine and nor-epinephrine have on carbohydrate metabolism. Epinephrine increases the action of glycogen phosphorylase, which cleaves a glucose molecule from glycogen to provide blood glucose for body tissue (Totora and Grabowski, 2003). A reduction of catecholamines at rest and during exercise (Schmid et al., 1998a; Teasell et al., 2000) could have implications for the absolute EE which individuals with a lesion level above T6 may show. In the wheelchair sports setting, subcutaneous adipose tissue lipolysis was shown to be lower in individuals with an SCI compared to able-bodied controls during exercise (Stalknecht et al., 2001). Skrinar et al. (1982) also reported relatively low glycogen utilization in wheelchair athletes during exercise. As Price (2010) suggested, during exercise SCI individuals may demonstrate lower levels of substrate utilisation compared to that of able-bodied individuals, and this could have an effect on the energy expended during sports competition.
For this thesis, within the sport of wheelchair basketball, individuals with post-polio had paralysis in the lower limbs. The majority of individuals with spina bifida also have a defect in the lumbar region of the spine (Foster, 2009) and, therefore, the sympathetic nervous system will not be affected at the thoracic level and normal regulation of the heart and catecholamine release will persist. As shown in Figure 2.1, the denervation of the lumbar region will affect the bladder, colon, genitals and uterus. Consequently, individuals with post-polio and spina bifida who regularly take part in exercise and elite competition will potentially be subjected to the same limitations to exercise as low lesion level paraplegics.

2.3.3 Amputation and the physiological response to exercise

Reduced movement and changes to an individual’s biomechanics due to an amputation has obvious detriments to sport and physical activity. The limitations to exercise that an individual with a lower limb amputation may be subject to will be focused mainly on the lack of a lower extremity muscular pump. Consequently this may limit venous return, and therefore cardiac output, during wheelchair exercise. Harker (2006) stated that stump wounds occur mainly in the unhealthy population. Therefore, if an individual is healthy, the limitations to exercise will not be related to an unhealed stump. Research that has had an interest in the EE of individuals with a lower limb amputation focuses on the increase in EE during ambulation due to extra upper-extremity weight bearing if crutches are used, or increased EE of the remaining muscle to move the prosthesis (Waters and Mulroy, 1999). This must be considered as part of an amputee’s total daily EE. However, this is not the focus of the thesis, and individuals with an amputation will be considered in regards to the energy expended during wheelchair sport.

2.4 Physiology of exercise in wheelchair users

2.4.1 Maximal cardiovascular capacity

Various physiological aspects need to be considered in relation to the small muscle mass of the upper body during wheelchair exercise. To estimate EE during sub-maximal exercise, the energy demand of the exercising muscle must be met by sufficient O2 metabolism (Brown et al., 2006). When this is achieved, it is termed steady state exercise. Wheelchair propulsion has been shown to elicit a high metabolic and cardiovascular stress when compared to lower-body exercise at a given workload (Glaser et al., 1979), so a
higher $O_2$ demand on the upper body is shown during sub-maximal exercise. This must be considered when estimating the EE of an individual during wheelchair propulsion if comparisons were to be made with other exercise modalities.

Maximal $O_2$ uptake during exercise is defined as a plateau in $O_2$ uptake even though exercise intensity increases (McArdle et al., 2001). However, during exercise where a small muscle mass is being used to move the whole body, peripheral fatigue may often occur before cardiovascular fatigue. The definition of maximal $O_2$ uptake is then termed $\dot{V}O_{2peak}$ (Goosey-Tolfrey and Price, 2010). This may occur in upper-body exercise, and especially during wheelchair propulsion due to the likelihood of fatigue occurring in the small muscle mass responsible for propelling the whole body forwards (Hopman et al., 1994). It is worthy of note that the $\dot{V}O_{2peak}$ reduces during upper-body exercise when compared to leg exercise (Colivicchi et al., 2002).

Due to the extensive research area of $\dot{V}O_{2peak}$ in wheelchair users and wheelchair athletes, for the purposes of this review, a selection of studies are presented in Tables 2.3 and 2.4. Both tables show the $\dot{V}O_{2peak}$ and peak HR (HR$_{peak}$) of wheelchair users and individuals completing upper-body exercise to highlight comparisons between selected population groups. A larger physiological capacity has been shown in the able-bodied athletic population compared to their sedentary counterparts (McArdle et al., 2001) and in trained wheelchair athletes when compared to sedentary wheelchair users (Zwiren and Bar-Or, 1975; Huonoker et al., 1998). Table 2.3 highlights a greater $\dot{V}O_{2peak}$ in paraplegic compared to tetraplegic individuals (Coutts et al., 1983; Dreisinger et al., 1984; Coutts and Stogryn, 1987; Burkett et al., 1990; Janssen et al., 2002; Hopman et al., 2004). Janssen et al. (2002) reported the aerobic capacity of 166 SCI male individuals and produced guidelines to suggest that tetraplegics with a $\dot{V}O_{2peak}$ of $> 1.19$ L·min$^{-1}$ and paraplegics with a $\dot{V}O_{2peak}$ of $> 2.31$ L·min$^{-1}$ had excellent physical capacity. This highlights the greater capacity of the paraplegic individuals with a value nearly twice that of the tetraplegic individuals. Coutts et al. (1983) suggested the increase in functional muscle mass as SCI lesion level decreases leads to an increased $O_2$ delivery and/or utilisation. A greater functional muscle mass in the upper body of trained wheelchair athletes when compared to un-trained able-bodied individuals (Sutton et al., 2009) may also be responsible for the higher $\dot{V}O_{2peak}$ seen in the former group (Huonoker et al., 1998).
When comparing sedentary paraplegic individuals to paraplegic athletes, it seems the athletes can reach a higher HR during peak exercise (Zwiren and Bar-Or, 1975; Huonker et al., 1998). Paraplegic athletes have also demonstrated a similar HR_{peak} when compared to sedentary able-bodied individuals (Huonker et al., 1998), suggesting an uncompromised HR_{peak} in the former group. Table 2.3 shows paraplegic individuals have a greater HR_{peak} than tetraplegic individuals (Coutts et al., 1983; Coutts and Stogryn, 1987; Burkett et al., 1990). This can be explained by the reduction in venous return alongside a lack of sympathetic innervation to the heart which is apparent in tetraplegic individuals with a lesion level above C8 (See Figure 2.1 illustrating the innervation to the heart through the cardiac plexus at spinal level T1). Individuals with no sympathetic innervation to the heart rely fully on the withdrawal of the parasympathetic nervous system to increase the HR (Hopman et al., 1994) up to the intrinsic rate of the sinoatrial node of 100 b∙min^{-1} (Brubaker and Kitzman, 2011). This peak value has been shown in tetraplegics completing maximal exertion tests (Coutts et al., 1983; Coutts and Stogryn, 1987; Schmid et al., 1998a).

A comparison of the \( \text{VO}_{2\text{peak}} \) between wheelchair sports is displayed in Table 2.4. It is clearly evident that wheelchair basketball players have a greater aerobic capacity than that of wheelchair tennis players. \( \text{VO}_{2\text{peak}} \) has been shown to be a central measure of an athlete’s physiological capacity and was the focus of wheelchair basketball team training leading up to a major championship (Goosey-Tolfrey, 2005). Both of these sports however, are intermittent in nature and anaerobic capacity may be an important feature of a team sports player’s success (Vanlandewijck et al., 1995; Bernardi et al., 2010). This point will be discussed in the next section. The wheelchair rugby players demonstrate a lower \( \text{VO}_{2\text{peak}} \) as well as a lower HR_{peak} when compared to the other two wheelchair sports, which is in agreement with the data from Table 2.3 showing lower values in un-trained tetraplegic compared to untrained paraplegic individuals.
Table 2.3. A selection of studies reporting mean (±SD) \( \dot{V}O_2 \text{peak} \) and \( HR_{\text{peak}} \) of paraplegic and tetraplegic individuals during upper-body exercise. *all male unless otherwise stated.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Trained status</th>
<th>n*</th>
<th>Age (years)</th>
<th>Modality</th>
<th>( \dot{V}O_2 \text{peak} ) (L/min(^{-1}))</th>
<th>( HR_{\text{peak}} ) (b/min(^{-1}))</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetraplegics</td>
<td>Untrained</td>
<td>8</td>
<td>29</td>
<td>WERG</td>
<td>0.99</td>
<td>109</td>
<td>Coutts et al. (1983)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td></td>
<td>13 (2 female)</td>
<td>29</td>
<td>WERG</td>
<td>2.00</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Tetraplegics</td>
<td>Untrained</td>
<td>12</td>
<td>---</td>
<td>WERG</td>
<td>0.87</td>
<td>121</td>
<td>Dreisinger et al. (1984)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td></td>
<td>18</td>
<td>---</td>
<td>WERG</td>
<td>1.56</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>Tetraplegics</td>
<td>Untrained</td>
<td>25</td>
<td>34</td>
<td>WERG</td>
<td>1.03</td>
<td>110</td>
<td>Schmid et al. (1998b)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td></td>
<td>30</td>
<td>35</td>
<td>WERG</td>
<td>2.08</td>
<td>177</td>
<td></td>
</tr>
<tr>
<td>Tetraplegics</td>
<td></td>
<td>4  (2 female)</td>
<td>27</td>
<td>WERG</td>
<td>0.55</td>
<td>134</td>
<td>Burkett et al. (1990)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td>Untrained</td>
<td>7</td>
<td>31</td>
<td>WERG</td>
<td>1.57</td>
<td>182</td>
<td></td>
</tr>
<tr>
<td>Paraplegics</td>
<td>Trained</td>
<td>4</td>
<td>33</td>
<td>WERG</td>
<td>2.12</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Tetraplegics</td>
<td>Mixed</td>
<td>50</td>
<td>35</td>
<td>WERG</td>
<td>0.90</td>
<td>---</td>
<td>Janssen et al. (2002)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td>Mixed</td>
<td>96</td>
<td>34</td>
<td>WERG</td>
<td>1.80</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Tetraplegics</td>
<td>Trained</td>
<td>2</td>
<td>25</td>
<td>WERG</td>
<td>1.02</td>
<td>102</td>
<td>Coutts and Stogryn (1987)</td>
</tr>
<tr>
<td>Paraplegics</td>
<td></td>
<td>1 (female)</td>
<td>22</td>
<td>ACE</td>
<td>1.42</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>Paraplegics</td>
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<td>3</td>
<td>28</td>
<td>WERG</td>
<td>3.18</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Tetraplegic</td>
<td>Trained</td>
<td>6</td>
<td>26</td>
<td>ACE</td>
<td>0.86</td>
<td>129</td>
<td>Hopman et al. (2004)</td>
</tr>
<tr>
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<td></td>
<td>6</td>
<td>33</td>
<td>ACE</td>
<td>1.68</td>
<td>179</td>
<td></td>
</tr>
</tbody>
</table>

Key: ACE - Arm crank ergometry; WERG - Wheelchair ergometry; --- not reported.
Table 2.4. A selection of studies reporting mean (±SD) \( \dot{V}O_{2peak} \) and HR\textsubscript{peak} of wheelchair basketball players and a review of the literature for mean (±SD) \( \dot{V}O_{2peak} \) and HR\textsubscript{peak} of wheelchair tennis and rugby players \( ^a \) all male unless otherwise stated.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Impairment</th>
<th>n( ^a )</th>
<th>Mean age (years)</th>
<th>Modality</th>
<th>( \dot{V}O_{2peak} ) (L( \cdot )min(^{-1} ))</th>
<th>HR\textsubscript{peak} (b( \cdot )min(^{-1} ))</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCBB</td>
<td>Mixed</td>
<td>52</td>
<td>30</td>
<td>MDT</td>
<td>2.29</td>
<td>--</td>
<td>Vanlandewijck et al. (1995)</td>
</tr>
<tr>
<td>WCBB</td>
<td>Mixed</td>
<td>12</td>
<td>32</td>
<td>WERG</td>
<td>2.83</td>
<td>185</td>
<td>Goosey-Tolfrey (2005)</td>
</tr>
<tr>
<td>WCBB</td>
<td>Mixed</td>
<td>5</td>
<td>34</td>
<td>WERG</td>
<td>2.94</td>
<td>180</td>
<td>Pérez et al. (2007)</td>
</tr>
<tr>
<td>WCBB</td>
<td>Mixed</td>
<td>13</td>
<td>31</td>
<td>ACE</td>
<td>2.70</td>
<td>189</td>
<td>Bemardi et al. (2010)</td>
</tr>
<tr>
<td>WCBB</td>
<td>Mixed</td>
<td>17</td>
<td>25</td>
<td>MDT</td>
<td>1.92</td>
<td>186</td>
<td>de Lira et al. (2010)</td>
</tr>
<tr>
<td>WCT</td>
<td>Tetraplegia</td>
<td>4</td>
<td>30</td>
<td>ACE</td>
<td>1.03</td>
<td>133</td>
<td>Goosey-Tolfrey et al. (2006)</td>
</tr>
<tr>
<td>WCT</td>
<td>Mixed</td>
<td>6</td>
<td>40</td>
<td>ACE</td>
<td>2.10</td>
<td>144</td>
<td>Roy et al. (2006)</td>
</tr>
<tr>
<td>WCT</td>
<td>Paraplegic</td>
<td>4</td>
<td>39</td>
<td>ACE</td>
<td>2.27</td>
<td>177</td>
<td>Bemardi et al. (2010)</td>
</tr>
<tr>
<td>WCR</td>
<td>Tetraplegia</td>
<td>4</td>
<td>29</td>
<td>ACE</td>
<td>0.89</td>
<td>136</td>
<td>Goosey-Tolfrey et al. (2006)</td>
</tr>
<tr>
<td>WCR</td>
<td>Tetraplegia</td>
<td>8</td>
<td>29</td>
<td>MDT</td>
<td>1.77</td>
<td>136</td>
<td>Leicht et al. (2011)</td>
</tr>
<tr>
<td>WCR</td>
<td>Tetraplegia</td>
<td>30</td>
<td>31</td>
<td>MDT</td>
<td>1.90</td>
<td>--</td>
<td>Morgulec-Adamowicz et al. (2011)</td>
</tr>
</tbody>
</table>

Key: WCBB – Wheelchair basketball; WCT – Wheelchair tennis; WCR – Wheelchair rugby; ACE - Arm crank ergometry; MDT – Wheelchair propulsion on a motor driven treadmill; WERG - Wheelchair ergometry; -- not available.
A point worthy of note is that consideration must be taken when comparing values obtained from arm crank ergometry and wheelchair propulsion. It has been acknowledged that gross mechanical efficiency (GE) is greater during arm crank ergometry due to the constant force application during this movement (Price and Campbell, 1999). Although wheelchair ergometry has a discontinuous force application, thus resulting in a less efficient movement, it is a greater replication of wheelchair sports performance. Wheelchair ergometry or wheelchair propulsion on a motorised treadmill therefore provides a useful measurement tool for applicable testing to the field. Nevertheless, a large majority of the studies that investigate wheelchair sport have used arm crank ergometry as a form of physiological assessment. These studies are considered and compared to data presented in this thesis because of the individuals and sports these studies represent.

2.4.2 Physiological parameters of wheelchair users during sub-maximal exercise

As expected, trained wheelchair athletes appear to show higher aerobic capacities when compared to both sedentary wheelchair users and sedentary able-bodied individuals (Zwiren and Bar-Or, 1975; Hooker and Wells, 1992; Huonker et al., 1998). This however, only explains a small part of an athlete’s overall physiological capacity, and reference to other sub-maximal physiological parameters such as ventilatory threshold and blood lactate reference points should be made. Ventilatory threshold occurs at a workload where a greater increase in V\textsubscript{CO\textsubscript{2}} production in respect to O\textsubscript{2} consumption is shown (Bernardi et al., 2010). It has also been described as occurring when a rapid rise in blood lactate is seen, which can be observed at higher intensities than the LT (Bourdon et al. 2000).

Values of 1.35 - 2.46 L\textsuperscript{-1} \text{VO}_2 have been shown at ventilatory threshold in paraplegic athletes (Coutts and MacKenzie, 1995; Vinet et al., 1997; Bloxham et al., 2001; Bernardi et al., 2010 de Lira et al., 2010) and relative values have been shown to correspond to 57% - 74% of \text{VO}_2\text{peak} (Vinet et al., 1997; Bloxham et al., 2001; Bernardi et al., 2010; de Lira et al., 2010). The relative values are lower than those reported for able-bodied athletes during running (e.g. ventilatory threshold occurred at 65-85% of \text{VO}_2\text{peak}; Suriano and Bishop, 2010). When the same exercise modality is compared (e.g. arm crank ergometry), paraplegic athletes display a higher relative exercise intensity at anaerobic threshold than able-bodied individuals (Schneider et al., 1999). The higher relative values may be due to greater training in arm exercise in these athletes.
From the previous literature it seems that wheelchair athletes have a superior physiological capacity when compared to untrained able-bodied and disabled individuals during upper body exercise. It will be of great advantage to link the physiological variables that define wheelchair athletes in their particular sport to the EE of those sports. The importance of descriptive physiology in this area is to establish the capacity wheelchair athletes are achieving in relation to their sport and to their disability. However, the addition of EE can provide data for the practitioner to help the individual athlete achieve energy balance for optimal performance. It can also provide data on typical EE of wheelchair sports, an important information tool when trying to encourage sedentary individuals to become more active.

2.5 Resting energy expenditure

2.5.1 Resting energy expenditure in the able-bodied population

The energy intake requirements for the general, able-bodied population are recommended according to sex, body mass and physical activity level (WHO, 2001). Thus, physically active individuals will require a higher energy intake when compared to the sedentary population for weight maintenance. To illustrate this point, it has been recommended that a 70 kg male athlete who trains for > 90 min·day⁻¹ consumes 3500 kcal·day⁻¹ (Economos et al., 1993), which is higher than that for the inactive general population (2450 - 2550 kcal·day⁻¹) and those engaged in moderate work (3200 - 3300 kcal·day⁻¹) (WHO, 2001). By obtaining accurate EE, advice may be given regarding energy intake and nutrition necessary to maintain energy balance.

During waking hours, BMR is the minimum amount of energy needed for chemical reactions in the body to take place to maintain functions vital to the health of the individual (McArdle et al., 2001). This baseline measurement has conditions that need to be met for the correct calculation of a true basal state. Measurement is completed after a 12 hour fast in the post-absorptive state. The individual must not complete physical activity or smoke for up to 24 hours preceding the measurement. The individual must be rested in the supine position in a quiet, thermoneutral environment for at least 30 minutes. The terms BMR and REE have been used interchangeably within the literature (Ravussin and Bogardus, 1989; Zurlo et al., 1990). Although the measurement criteria for REE measurement is similar to BMR (Compher et al., 2006), usually BMR is measured after an overnight stay in the clinic or laboratory where the research is being completed (Figueroa-Colon, 1996).
importance of REE came to light when the World Health Organisation (WHO, 1985) published a document providing information on using EE to estimate energy requirements (Henry, 2005). The percentage of total EE that REE accounts for is up to 75% (McArdle et al., 2001), the largest portion of daily EE (Ravussin et al., 1982), and is therefore an important component of an individual’s daily energy cost.

The average value of REE in the able-bodied male population has been reported extensively in the literature with various metabolic equations devised for individual prediction from large databases using body mass as a predictor variable (see Table 2.5). However, there is literature to suggest similar REEs may be obtained through application of equations from different studies in individuals with varying body masses. In the general male population values of REE have been reported as 74.0 kcal∙h⁻¹ (mean body mass; 87.5 kg Mifflin et al., 1990) and 75.7 kcal∙h⁻¹ (mean body mass; 78.0 kg, Westerterp and Goran, 1997). Although some research (Clark and Hoffer, 1991; Ramirez-Zea, 2005) has reported a slight over-estimation from Schofield’s equations (Schofield, 1985), there is no other as widely accepted model for estimating REE. All of the World Health Organisation (WHO) (2001), the Department of Health (1991) and authors investigating disabled individuals (Buchholz et al., 2003a) have used the Schofield prediction equations, which use regression analysis on over 7393 able-bodied individuals collected from sources that the author deemed scientifically sound. Schofield (1985) based the prediction of REE in MJ/24 h on age, sex and body mass. When taking body mass into account, the different equations in Table 2.5 predict similar REE for a typical male able-bodied individual, and these equations have helped inform clinical and athletic populations regarding important metabolic information.

2.5.2 Resting energy expenditure in the disabled population

Measured REE in individuals with a disability is lower than values derived from validated prediction equations in able-bodied samples (Cox et al., 1985; Mollinger et al. 1985; Sedlock and Laventure, 1990). Also, REE has been shown to be lower as level of SCI increases (Mollinger et al., 1985). Lower values have also been reported for the SCI population when compared to able-bodied individuals (Monroe et al. 1998; Buchholz et al., 2003a; Jeon et al. 2003; Bertoli et al., 2006; Liusuwan et al., 2007). Although regression equations provide an estimation of REE and can be easily accessed by the wider public (Table 2.5), the differences shown between actual measurements and predictive equations
Table 2.6) suggest actual measurement of REE is an important consideration for metabolic analysis in populations with a disability.

Due to paralysis and loss of limbs, a reduced metabolically active mass is available in individuals with a disability when compared to the able-bodied population (Buchholz et al., 2003a; Maggioni et al. 2003). However, as section 2.3.1 discussed, SCI athletes have been shown to have a more favourable body composition to that of sedentary individuals with an SCI (Olle et al., 1993) and even a similar upper-body FFM when compared with the untrained able-bodied population (Sutton et al., 2009). Furthermore, the REE of elite disabled athletes has shown a close comparison with predicted equations when each disability group was considered separately (Thompson et al., 1995). When disability groups were pooled however, able-bodied predictive equations overestimated REE in athletes (Abel et al., 2003; 2008). It seems that there is clear evidence to support the lower REE values of SCI individuals during rehabilitation. However, the REE of the disabled athlete population is an area that needs further investigation. The REE may be greater in the athletic disabled population compared to a rehabilitation cohort due to the potential increase in FFM, the largest predictor of EE at rest (Johnstone et al., 2005).

2.5.3 Resting energy expenditure and FFM in the able-bodied athletic population

Within the general male able-bodied population it seems as though there is a range of fat percentage from 12-24% (Westerterp and Goran, 1997; McArdle et al., 2001; Jackson et al., 2002). However, fat percentage in a range of male able-bodied athletes was reported at 11% (Stewart and Hannan, 2010) and other studies have shown 6 – 18% in team sports, 5 – 11% in cycling, 6 – 12% in swimming, and as low as 5 – 12% in running (Wilmore and Costill, 1999). Fat-free mass has shown to range from 63 – 66 kg (Gallagher et al., 1998; Jackson et al., 2002; Bosy-Westphal et al., 2003) in the general able-bodied male population but when taking sports training into account, lean mass alone has been shown to increase to values ranging from 60 – 72 kg, in a variety of sports including judo, water polo karate, weight lifting, swimmers, runners and skiers (Šprynarová and Pařízková, 1971; Andreoli et al., 2001). The difference in FFM due to trained status has been shown by Whalley et al. (2004) who reported a higher FFM in endurance trained individuals (63 kg) when compared to untrained individuals (58 kg).
Table 2.5. Resting energy expenditure prediction equations and corresponding estimated value.

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n</th>
<th>Equation</th>
<th>Estimated REE (kcal·h⁻¹)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harris-Benedict equation</td>
<td>Males &amp; females; range of ages</td>
<td>169</td>
<td>88.362 + 4.799 (height) + 13.397 (weight) - 5.677 (age)</td>
<td>71.7</td>
</tr>
<tr>
<td>(Roza et al., 1984)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schofield et al. (1985)</td>
<td>Male &amp; female adults &amp; children; range of ages</td>
<td>7,393</td>
<td>Adults 18 – 30 years 0.063<em>weight+2.896 / (24</em>238.86)</td>
<td>72.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adults 30 – 60 years 0.048<em>weight+3.653 / (24</em>238.86)</td>
<td>69.8</td>
</tr>
<tr>
<td>WHO (1985)</td>
<td>Male &amp; female adults &amp; children; range of ages</td>
<td>11,000</td>
<td>Adults 18 – 30 years 15.3*weight+679 / (24)</td>
<td>72.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Adults 30 – 60 years 11.6*weight+879 / (24)</td>
<td>70.5</td>
</tr>
<tr>
<td>Owen et al. (1987)</td>
<td>Lean &amp; obese males; range of ages</td>
<td>60</td>
<td>879+10.2*weight ( /24)</td>
<td>66.4</td>
</tr>
<tr>
<td>Mifflin et al. (1990)</td>
<td>Male &amp; female adults and children; range of ages</td>
<td>498</td>
<td>Males 10<em>weight+6.25</em>height-5*age+5</td>
<td>69.6</td>
</tr>
<tr>
<td>Muller et al. (2004)</td>
<td>Male &amp; female adults and children; range of ages</td>
<td>2,528</td>
<td>0.047<em>weight (kg)+ 1.009</em>sex- 0.01452*age (yrs) + 3.21 (*238.86)</td>
<td>70.4</td>
</tr>
</tbody>
</table>

**Key:** ¹Estimated REE for a 70 kg man, 180 cm and aged 30 yrs.
Table 2.6. Measured and predicted REE of athletic and non-athletic disabled individuals. a male unless otherwise stated.

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n²</th>
<th>Protocol</th>
<th>REE (kcal∙h⁻¹)</th>
<th>Predicted REE/comparison with control group (kcal∙h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elite wheelchair athletes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Track athletes (Paraplegic)</td>
<td>6</td>
<td>Measured on 3 consecutive mornings</td>
<td>68.7</td>
<td>Predicted (Harris and Benedict, 1919) 69.0</td>
</tr>
<tr>
<td></td>
<td>Track athletes (Tetraplegic)</td>
<td>2</td>
<td></td>
<td>64.4</td>
<td>69.5</td>
</tr>
<tr>
<td></td>
<td>Weight lifters (Paraplegic)</td>
<td>3</td>
<td></td>
<td>79.0</td>
<td>78.4</td>
</tr>
<tr>
<td></td>
<td>Hand-bikers (SCI)</td>
<td>17(3 female)</td>
<td>BMR measured after an overnight fast for 30 minutes with a metabolic cart</td>
<td>65.4</td>
<td>Predicted (WHO, 1998) 74.2</td>
</tr>
<tr>
<td></td>
<td>WC racers (SCI)</td>
<td>10 (3 female)</td>
<td></td>
<td>60.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WC Rugby (Tetraplegic)</td>
<td>12</td>
<td>REE measured after an overnight fast for 30 minutes measured with the K4b²</td>
<td>63.5</td>
<td>Predicted (WHO, 1998) 73.9</td>
</tr>
<tr>
<td></td>
<td>WC Tennis (Paraplegic)</td>
<td>14</td>
<td></td>
<td>66.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WC Basketball (Paraplegic)</td>
<td>10</td>
<td></td>
<td>62.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non-athletic population</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedlock &amp; Laventure (1990)</td>
<td>Paraplegics</td>
<td>4</td>
<td>REE measured for 1 hour by indirect calorimetry (ventilated hood)</td>
<td>63.7</td>
<td>Predicted (Cunningham, 1980) 71.6</td>
</tr>
<tr>
<td>Monroe et al. (1998)</td>
<td>SCI individuals</td>
<td>10</td>
<td>REE measured with the ventilated hood for 21 minutes</td>
<td>72.9</td>
<td>Control 91.7</td>
</tr>
<tr>
<td></td>
<td>AB controls</td>
<td>59</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buchholz et al. (2003a)</td>
<td>Paraplegics</td>
<td>26 (11 female)</td>
<td>REE measured after a 12 hour fast for 60 minutes with open circuit indirect calorimetry (ventilated canopy)</td>
<td>61.1</td>
<td>Control 69.6</td>
</tr>
<tr>
<td></td>
<td>AB controls</td>
<td>34 (10 female)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jeon et al. (2003)</td>
<td>Paraplegics</td>
<td>7</td>
<td>REE measured for 30 minutes by indirect calorimetry (ventilated hood)</td>
<td>60.5</td>
<td>Control 77.0</td>
</tr>
<tr>
<td></td>
<td>AB controls</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: AB – Able-bodied; WC - Wheelchair
### Table 2.6. continued

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n(^a)</th>
<th>Protocol</th>
<th>REE (kcal-h(^{-1}))</th>
<th>Predicted REE/comparison with control group (kcal-h(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young individuals (11–21 years)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liusuwan et al. (2007)</td>
<td>SCI individuals</td>
<td>33 (mixed sex)</td>
<td>REE measured for 30 minutes by indirect calorimetry (metabolic cart)</td>
<td>51.2</td>
<td>Control</td>
</tr>
<tr>
<td></td>
<td>Spina bifida</td>
<td>66</td>
<td></td>
<td>54.1</td>
<td>60.6</td>
</tr>
<tr>
<td></td>
<td>AB controls</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rehabilitation (^b)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mollinger et al. (1985)</td>
<td>High Tetraplegia</td>
<td>14</td>
<td>BMR measured from a meteorologic balloon on three consecutive mornings</td>
<td>50.3</td>
<td>Predicted(Harris and Benedict, 1919) 70.7</td>
</tr>
<tr>
<td></td>
<td>Low Tetraplegia</td>
<td>13</td>
<td></td>
<td>55.4</td>
<td>69.2</td>
</tr>
<tr>
<td></td>
<td>High Paraplegia</td>
<td>16</td>
<td></td>
<td>62.6</td>
<td>73.5</td>
</tr>
<tr>
<td></td>
<td>Low Paraplegia</td>
<td>5</td>
<td></td>
<td>65.4</td>
<td>74.6</td>
</tr>
</tbody>
</table>

**Key:** AB – Able-bodied \(^b\) High tetraplegia, individuals with a lesion level of C6 or higher. Low tetraplegia, individuals with a lesion between C6 – T1. High paraplegia, individuals with a lesion between T1 – T10. Low paraplegia, individuals with a lesion of T10 or lower.
A positive relationship between FFM and REE has been demonstrated in the able-bodied population (Cunningham, 1991; Weinsier et al., 1992; Arciero et al., 1993; Heymsfield et al., 2002; Johnstone et al., 2005). So, as able-bodied athletes have shown the potential to gain a greater FFM than the general population, a higher REE can then be expected. This higher REE has been found in healthy males, with REE increasing from 66 to 72 kcal·h\(^{-1}\) after a 24-week strength training programme alongside an increase in FFM of 3% (Lemmer et al., 2001). Resting energy expenditure also increased in healthy elderly individuals after endurance training (Goran and Poehlman, 1992). Poehlman et al. (1988) reported a higher REE in exercise-trained individuals (77.4 kcal·h\(^{-1}\)) when compared to non-exercise trained individuals (70.2 kcal·h\(^{-1}\)). Although FFM was not significantly higher in the trained group (67.0 kg) compared to the untrained group (64.6 kg) in the study this marginally higher FFM may have caused the higher value in REE (Poehlman et al., 1988). The REE and FFM has been shown in other studies to not be significantly different after an exercise training regime in able-bodied individuals (Bingham et al., 1989; Broeder et al., 1992). Broeder et al. (1992) did however, find a non-significant increase in FFM in conjunction with an increase in REE in weight-trained individuals. So it seems higher FFM is related to a rise in REE in the able-bodied population.

2.5.4 Resting energy expenditure and FFM in the disabled athletic population

The positive relationship between FFM and REE in the able-bodied population has also been found in the disabled population (Sedlock and Laventure, 1990; Monroe et al., 1998; Buchholz et al., 2003a). Furthermore, when FFM or lean mass is accounted for, REE values are similar between SCI and able-bodied groups (Buchholz et al., 2003a; Liusuwan et al., 2007). Fat-free mass values in the SCI population are lower than those shown in the able-bodied population (Monroe et al., 1998; Buchholz et al., 2003a; Maggioni et al., 2003; please refer to section 2.3.1).

In athletic cohorts, there is very little data to suggest the FFM of elite disabled athletes differs from that of sedentary disabled individuals. Olle et al. (1993) demonstrated a similar FFM value between the two groups. These authors did however report a lower % of fat mass in the athletes. From the limited data on elite disabled populations it has been reported that paraplegic athletes have a higher % body fat (22%) than healthy able-bodied males who have between 8 – 11% body fat (Bulbulian et al., 1987). Inukai et al. (2006) reported that wheelchair basketball players had 24.7%, wheelchair track and field athletes
21%, and wheelchair tennis players 27% fat, which are higher values to those established in able-bodied athletes (Wilmore and Costill, 1999; Stewart and Hannan, 2010). These limited data suggest disabled athletes carry more fat than both the able-bodied elite athletes and the general able-bodied population.

As mentioned above, data on the relationship between FFM and REE in the general SCI population concludes that these individuals have lower FFM and lower REE than the able-bodied population but the relationship between the two is similar. However, to date the relationship between REE and FFM has not been examined in the elite SCI population and warrants attention.

2.6 Energy expenditure during daily living

Quantifying daily EE in disabled, athletic individuals is important to better understand the nutritional requirements for this population. Many widely used databases have reported values of EE for walking and other daily activities in humans with limited information regarding wheelchair activities (Passmore and Durnin, 1955; McArdle et al., 2001; Ainsworth et al., 2011). The American Heart Foundation have recommended individuals expend an extra 150 – 200 kcal through moderate intensity exercise on most days of the week to reduce the risk of cardiovascular disease (Hayes et al., 2005). Paffenbarger et al. (1986) suggested that a higher physical activity EE of 2000-2500 kcal (or more) a week can reduce the risk of mortality in a male, able-bodied population (45-84 years). It remains a challenge however, to provide generic values of the required EE on a daily basis for a variety of populations that may differ in dietary patterns, activity levels and body composition. Investigating the metabolic cost of different activities will allow a greater understanding of suitable EE and will help individuals to understand how much activity is needed to balance their daily energy intake.

In recent years there has been a rise in non-communicable diseases which may be associated with changes in lifestyle, physical inactivity, diet and smoking (Amuna and Zotor, 2008). Individuals who use a wheelchair may be more susceptible to these diseases as, although smoking prevalence in individuals with SCI has been shown to be similar to the able-bodied population (Bauman and Spungen, 2008), inactivity levels are known to be higher in the former group (Jacobs and Nash, 2004). With this in mind, there is a drive to find ways to help reduce obesity, with literature focusing on energy balance in rehabilitation patients (Cox et al., 1985; Mollinger et al., 1985), sedentary individuals in a
controlled respiratory chamber (Monroe et al., 1998), and in free-living populations (Yamasaki et al., 1992; Buchholz et al., 2003b; Hayes et al., 2005; Collins et al., 2010). Alongside the EE of these individuals, direct measures of physical activity of the sedentary SCI population have been calculated through validated self-report techniques (Ginnis et al., 2005; 2008), activity monitors (Dearwater et al., 1985), HR monitoring (Janssen et al., 1994) and wheelchair data loggers (Tolerico et al., 2007).

2.6.1 Energy expenditure during daily activities in wheelchair users

Studies that have measured the daily EE of wheelchair users report sedentary or moderately active wheelchair users expend less energy than their able-bodied counterparts (Yamasaki et al., 1992; Monroe et al., 1998) or complete less activity than is recommended by the WHO (Buchholz et al., 2003b). However, during ‘active’ days, wheelchair dependent individuals who complete over 3 hours of sport each week displayed a daily EE that did not differ to that of an able-bodied control group (Yamasaki et al., 1992). This suggests that active wheelchair users may benefit from the nutritional recommendations of the able-bodied population if they expend a similar amount of energy. The importance of energy balance or even energy manipulation in very active and elite trained athletes is vital for optimal, individual sports performance. However, when investigating elite trained athletes, it becomes harder to provide generic EE recommendations. Training programmes and diet become individualised and varying disabilities bring about potential differences in REE. We can therefore start to appreciate the need to quantify wheelchair propulsion activities.

The 24-hour EE of SCI individuals has been reported in the range of 1863-2656 kcal-day\(^{-1}\) (Yamasaki et al., 1992; Monroe et al., 1998; Buchholz et al., 2003b). In a comparison study SCI individuals displayed lower daily EE by 21\% when compared to able-bodied controls (Monroe et al., 1998). Although daily 24-hour EE is useful to understand, athletes have variable training structures and daily routines, dependent on competition and ‘down time’. Therefore, measuring EE during fixed daily propulsion speeds in elite wheelchair athletes may help provide data on the energy they use during everyday propulsion. Using exact speeds when measuring EE allows athletes to be able to replicate the chosen speeds with knowledge of the metabolic cost. The EE of wheelchair activity has been quantified at particular given speeds, to help understand the metabolic demands of wheelchair propulsion. Researchers have found that the O\(_2\) cost of pushing at
speeds between 1.2 – 1.3 m∙s\(^{-1}\) in an ultra-light wheelchair is 0.13 – 0.14 ml·kg·m\(^{-1}\) (Beekman et al., 1999) and in a normal manual wheelchair is 0.22 ml·kg·m\(^{-1}\) (Mukherjee et al., 2002) These studies however, did not report absolute EE and so cannot be directly related to the nutrition an athlete would take in during these activities.

Hayes et al. (2005) provided information regarding daily living tasks in the wheelchair user population and Collins et al. (2010) produced a comprehensive database describing the EE of various wheelchair activities in a larger cohort of SCI individuals (see Table 2.7). Despite the latter research providing an insight into EE during propulsion over various floor surface conditions, pushing was completed at ‘normal speeds’ which were not recorded and therefore unknown. This work can be developed by collecting data during wheelchair propulsion at a selection of daily speeds encountered by wheelchair users. Energy expenditure will change with increasing intensity of a task and so quantifying this intensity is an important component of investigating calorie expenditure in wheelchair propulsion.

2.6.2. Daily speeds in wheelchair propulsion

There seems to be very limited data confirming the actual daily speeds of wheelchair users during their normal routines. In this context, both Dearwater et al. (1985) and Janssen et al. (1994) reported the activity levels of sedentary wheelchair users through motion sensors but did not calculate the wheelchair propulsion speeds. Other studies quantifying the O\(_2\) cost and EE of daily wheelchair propulsion have employed experimental designs that ask participants to push at ‘normal speeds’ (Beekman et al. 1999; Mukerjee et al. 2002; Collins et al. 2010). Clearly, if we want to estimate EE during daily propulsion speeds, we must first know exactly what these speeds are which is difficult to ascertain from the aforementioned studies. Table 2.7 shows a selection of studies that have looked at EE over a selection of daily pushing speeds.

Tolerico and colleagues (2007) examined the speeds and distances covered over a period of 2 to 3 weeks in a large cohort of wheelchair users (n = 52) with a custom-made data logger. The data logger measured the rotation of the wheel with the use of 3 reed switches which record a date and time stamp at each wheel rotation. The results of this study found daily speeds to range between 0.72 – 0.93 m∙s\(^{-1}\). This study confirmed the chosen speeds in earlier work of Hildebrant et al. (1970) who examined the energy cost of wheelchair propulsion at 0.28 – 1.1 m∙s\(^{-1}\). The authors concluded that the daily propulsion
Table 2.7. Energy expenditure of daily wheelchair propulsion in experienced wheelchair users.  

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Protocol (Speed m–s&lt;sup&gt;–1&lt;/sup&gt;)</th>
<th>EE value ( kcal–h&lt;sup&gt;–1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hildebrandt et al. (1970)</td>
<td>Wheelchair users with post-polio, SCI &amp; osteogenesis imperfecta</td>
<td>10 (4 female)</td>
<td>0.28 m·s&lt;sup&gt;–1&lt;/sup&gt; 0.56 m·s&lt;sup&gt;–1&lt;/sup&gt; 0.83 m·s&lt;sup&gt;–1&lt;/sup&gt; 1.10 m·s&lt;sup&gt;–1&lt;/sup&gt;</td>
<td>Net energy was calculated with no report of the REE value 48 66 96 108</td>
</tr>
<tr>
<td>Hayes et al. (2005)</td>
<td>Tetraplegic &amp; paraplegic wheelchair users</td>
<td>13 (1 female)</td>
<td>Pushing on tile at unknown speed</td>
<td></td>
</tr>
<tr>
<td>Collins et al. (2010)</td>
<td>Tetraplegic &amp; paraplegic wheelchair users</td>
<td>35 (mixed sex)</td>
<td>EE values during a variety of wheelchair activities (no speeds given)</td>
<td>Tile Tetraplegic (n=8): 157 High Paraplegic (n=20): 182 Low Paraplegic (n=7): 158 Outside Tetraplegic (n=3): 174 High Paraplegic (n=14): 204 Low Paraplegic (n=4): 239</td>
</tr>
</tbody>
</table>

**Key:** <sup>b</sup> High paraplegia, individuals with a lesion between T1 – T10. Low paraplegia, individuals with a lesion of T10 or lower.
of wheelchair users is not strenuous enough to elicit any training effect so extra physical activity is needed.

Interestingly the speeds recorded by Tolerico et al. (2007) are lower than those that have typically been used in laboratory studies where speeds of 1.34 – 2.20 m∙s\(^{-1}\) have been reported (Boninger et al., 1997; van der Woude et al., 1999; Hiremath, 2009; Rice et al., 2010). Furthermore, they were also found to be lower than the ‘normal’ pace around a sports hall which was described in a study conducted by Washburn and Copay (1999), where descriptors of ‘slow’, ‘normal’ and ‘fast’ pushing corresponded to 1.36 m∙s\(^{-1}\), 1.89 m∙s\(^{-1}\) and 2.47 m∙s\(^{-1}\) respectively.

Tolerico et al. (2007) provided information on the average speeds participants encountered over a 2 – 3 week period. It is likely that there would be occasions that individuals reach higher speeds during the day. Health programmes and measurement of physiological parameters during wheelchair propulsion can progress if actual propulsion speeds – including the full range and peak speeds achieved are known. Although Tolerico et al. (2007) provide a good estimate of average wheelchair propulsion speed over a large period of time, there is information lacking about the range of and maximum speeds wheelchair users complete every day. There was also no record of the trained status of the individuals in the study by Tolerico et al. (2007). Different fitness levels and trained status could influence average and maximum speeds and amount of activity done between individuals who use a wheelchair.

2.6.3. Energy expenditure of wheelchair propulsion in different populations

There has been a large focus in the literature on the metabolic cost of wheelchair propulsion in the laboratory focusing on individuals going through rehabilitation after an SCI (Dallmeijer et al., 1999a; de Groot et al., 2005; de Groot et al., 2007) and in novice able-bodied individuals learning the skill of wheelchair propulsion (Dallmeijer et al., 1999b; van der Woude et al., 1999; de Groot et al., 2002a; de Groot et al., 2008; van den Berg et al., 2010). As shown in Table 2.8 and Table 2.9 this research has predominantly focused on the \(\text{VO}_2\) and GE of wheelchair propulsion rather than the absolute EE of this skill. Using the working definition of GE as the ratio of external work accomplished (power output; \(P_o\)) over metabolic power needed to do that work (Stainsby et al., 1980), it has been shown that wheelchair propulsion is an inefficient mode of exercise. Typically GE values rarely reach over 12% in daily wheelchair use (van der Woude, et al., 1986;
Table 2.8. Mean $\dot{V}O_2$ at fixed speeds for novice able-bodied individuals during wheelchair propulsion.\(^a\) male unless otherwise stated.

<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n(^a)</th>
<th>Protocol</th>
<th>Speed</th>
<th>$\dot{V}O_2$ (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>van der Woude et al. (1989b)</td>
<td>AB participants</td>
<td>10(sex not specified)</td>
<td>Speed at 0 (^\circ) incline</td>
<td>0.96 m/s(^{-1})</td>
<td>0.75</td>
</tr>
<tr>
<td>de Groot et al. (2008)</td>
<td>AB participants pre and post 7-week low intensity wheelchair propulsion practice</td>
<td>14</td>
<td>Exercise blocks were completed before &amp; after practice at 20% &amp; 40% maximum $P_O$</td>
<td>1.39 m/s(^{-1})</td>
<td>20% 40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pre = 0.86 1.17 Post = 0.68 0.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>van den Berg et al. (2010)</td>
<td>AB participants pre and post 7-week low intensity wheelchair propulsion practice</td>
<td>9</td>
<td>Before training at 11 W 15 W After training at 23 W 30 W</td>
<td>1.39 m/s(^{-1})</td>
<td>0.69 0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: AB = Able-bodied.
<table>
<thead>
<tr>
<th>Author</th>
<th>Participants</th>
<th>n</th>
<th>Protocol</th>
<th>Speed</th>
<th>VO₂ (L·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>van der Woude et al. (1988)</td>
<td>Wheelchair athletes with mixed disability</td>
<td>8</td>
<td>Speed at a 1° gradient</td>
<td>1.39 m·s⁻¹</td>
<td>1.03</td>
</tr>
<tr>
<td>van der Woude et al. (1989a)</td>
<td>Wheelchair athletes with mixed disability</td>
<td>6</td>
<td>Speed at a 2° gradient</td>
<td>0.55 ms⁻¹</td>
<td>0.72</td>
</tr>
<tr>
<td>van der Woude et al. (1989a)</td>
<td>Wheelchair athletes with mixed disability</td>
<td>6</td>
<td>Speed at a 2° gradient</td>
<td>0.83 ms⁻¹</td>
<td>0.95</td>
</tr>
<tr>
<td>van der Woude et al. (1989a)</td>
<td>Wheelchair athletes with mixed disability</td>
<td>6</td>
<td>Speed at a 2° gradient</td>
<td>1.11 ms⁻¹</td>
<td>1.15</td>
</tr>
<tr>
<td>Beekman et al. (1999)</td>
<td>Paraplegic wheelchair users Lesion T2 – T8</td>
<td>24 (1 female)</td>
<td>Slow</td>
<td>1.2 m·s⁻¹</td>
<td>0.76</td>
</tr>
<tr>
<td>Beekman et al. (1999)</td>
<td>Paraplegic wheelchair users Lesion T10–L1</td>
<td>22 (2 female)</td>
<td>Speed</td>
<td>0.72 m·s⁻¹</td>
<td>0.71</td>
</tr>
<tr>
<td>Beekman et al. (1999)</td>
<td>Paraplegic wheelchair users Lesion T2 – T8</td>
<td>24 (1 female)</td>
<td>Freely chosen speed</td>
<td>0.95 ms⁻¹</td>
<td>0.64</td>
</tr>
<tr>
<td>Beekman et al. (1999)</td>
<td>Paraplegic wheelchair users Lesion T10–L1</td>
<td>22 (2 female)</td>
<td>Slow</td>
<td>0.41 m·s⁻¹</td>
<td>0.44</td>
</tr>
<tr>
<td>Beekman et al. (1999)</td>
<td>Paraplegic wheelchair users Lesion T2 – T8</td>
<td>24 (1 female)</td>
<td>Fast</td>
<td>1.20 m·s⁻¹</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Key:**
- range 0.68 – 1.13 m·s⁻¹

Table 2.9. Mean VO₂ at fixed speeds during wheelchair propulsion for experienced wheelchair users, unless otherwise stated.
Veeger et al., 1992a; Vanlandewijk et al., 1994a). Consequently, the importance of learning wheelchair propulsion and the pattern of \( O_2 \) utilisation as individuals become accustomed to the skill may assist our understanding of EE during this critical time-frame.

The energy cost of wheelchair propulsion has been shown to be influenced by the properties of the wheelchair and its user (van der Woude et al., 1989a; Beekman et al., 1999; van der Woude et al., 2009). To highlight this, Beekman et al. (1999) reported a higher \( O_2 \) cost per distance travelled pushing a standard wheelchair when compared to an ultra-light weight wheelchair. Seat height of the wheelchair has also had an effect on the \( \text{VO}_2 \) values of wheelchair propulsion with low values being shown at 110 – 130° elbow angle (van der Woude et al., 2009). The push strategy of the user influences the \( O_2 \) cost of wheelchair ambulation with ‘freely chosen frequency’ resulting in the lowest \( O_2 \) cost of propulsion (van der Woude et al., 1989b; Goosey et al., 2000). The process of learning the skill of wheelchair propulsion is a topical area in the current literature, and reductions in \( \text{VO}_2 \) and improvements in GE in both novice able-bodied individuals and individuals with an SCI have been noted (de Groot et al., 2002a; 2005; 2007; 2008; van den Berg et al., 2010). These studies clearly show that many confounding factors can influence the \( O_2 \) cost of wheelchair propulsion. Therefore, where possible, establishing homogenous cohorts and consideration to the wheelchair-user interface and selected propulsion speeds is paramount in providing accurate data for these groups.

### 2.7 Energy expenditure and \( O_2 \) cost during wheelchair sports

Databases exist in the literature providing detailed outlines of the demands and metabolic cost of particular able-bodied sports (Seliger, 1968; Reilly, 1990a; Reilly, 1990b; McLaren, 1990; McArdle et al., 2001). From a disability perspective, these generic databases do not exist. Yet specific, smaller individual studies have examined the EE or \( O_2 \) cost during wheelchair basketball training (Burke et al., 1985; Bernardi et al., 1988; Abel et al., 2008; Bernardi et al., 2010), disabled fencing and table tennis (Bernardi et al., 1988; 2010), 5 km time trial (Lakomy et al., 1987; Bernardi et al., 2010), 10km time trial (Campbell et al., 2002), wheelchair tennis training (Roy et al., 2006; Abel et al., 2008; Bernardi et al., 2010) and wheelchair rugby training (Abel et al., 2008). EE during actual wheelchair sporting competition has been studied but with low sample sizes (\( n = 4 \))
Chapter 2

Literature Review

(Bernardi et al., 1988); n = 6 (Roy et al., 2006)). The following sections will provide an overview of these disability sport specific studies.

2.7.1 Wheelchair basketball

Previous wheelchair basketball research has reported average game play HRs of 128 to 155 b·min\(^{-1}\) male players (Burke et al., 1985; Bernardi et al., 1988; Coutts, 1988; Bloxham et al., 2001, Pérez et al., 2007; Bernardi et al., 2010) which is lower than the recorded average of 165 b·min\(^{-1}\) for able-bodied male basketball players (Drinkwater et al., 2008). Average game \(\dot{V}O_2\) consumption has been recorded for male wheelchair basketball competition and simulated competition between 1.3 and 2.3 L·min\(^{-1}\) (Bernardi et al., 1988; Bernardi et al., 2010). Moreover, the EE of wheelchair basketball training in various male paraplegic players is limited and ranges from 246 to 516 kcal·h\(^{-1}\) (Burke et al., 1985; Usita et al., 2003; Abel et al., 2008). These values are much lower than the EE of able-bodied basketball competition which is estimated at 636 kcal·h\(^{-1}\) for a 71 kg man (McArdle et al., 2001). Further investigation into the EE of wheelchair basketball competition is needed before conclusions can be drawn as to whether the noted difference could be due to: a) the nature of the competitive environment vs. the training environment or b) the physiological differences between wheelchair and able-bodied athletes.

2.7.2 Wheelchair rugby

Abel et al. (2008) reported the EE of wheelchair rugby training to be 250 kcal·h\(^{-1}\), a much smaller value to that approximated during a game in able-bodied rugby league players of 1100 kcal·h\(^{-1}\) (Coutts et al., 2003). The large difference seen between able-bodied rugby and wheelchair rugby could be due to the lower FFM shown in the tetraplegic wheelchair rugby players (Price, 2010) and the obvious movement differences between the running and wheelchair game play.

2.7.3 Wheelchair tennis

Studies investigating the physiology of wheelchair tennis have found typical average HR’s during a game in both male and female players to be between 121-128 b·min\(^{-1}\) (Coutts, 1988; Roy et al., 2006; Barfield et al., 2009). Higher values of 140 – 160 b·min\(^{-1}\) have been shown in trained able-bodied tennis players (König et al., 2001; Fernandez-Fernandez et al., 2009). The EE of a tennis match in male able-bodied players was reported as 526 kcal·h\(^{-1}\) (Fernandez-Fernandez et al., 2009) which is higher than the
EE during wheelchair tennis competition (301 kcal·h⁻¹) or training (324 kcal·h⁻¹) (Roy et al., 2006; Abel et al., 2008 respectively).

2.7.4 Endurance performance

The \( \text{VO}_2 \) of endurance performance has been studied in tetraplegic and paraplegic wheelchair athletes (Lakomy et al., 1987; Campbell et al., 2002). An average of 1.03 and 1.12 L·min⁻¹ was reported in tetraplegic athletes completing a 5km and 10km wheelchair propulsion time trial respectively (Lakomy et al., 1987; Campbell et al., 2002). This corresponded to 90% and 88% \( \text{VO}_2\text{peak} \). Paraplegic athletes consumed more \( \text{O}_2 \) (1.50 and 1.60 L·min⁻¹) than their tetraplegic counterparts during both the 5km trial (Lakomy et al., 1987) and a 10km trial (Campbell et al., 2002) respectively. However, when normalised to their \( \text{VO}_2\text{peak} \), the intensity they were working at was lower than the tetraplegic athletes (at 76% respectively) suggesting a higher physiological capacity in the paraplegic athletes. Data obtained from able-bodied endurance runners is hard to compare with the different activity of wheelchair propulsion. However, in a comparison of upper-body exercise at 76% of their \( \text{VO}_2\text{peak} \), able-bodied individuals would use 1.88 L·min⁻¹ during a continuous and increasing arm crank ergometry protocol (Price et al., 2011). This value of \( \text{VO}_2 \) is higher than that of paraplegic athletes during a 10km trial (Campbell et al., 2002), suggesting even non-specifically trained able-bodied individuals consume a greater \( \text{VO}_2 \) during upper-body exercise than paraplegic athletes. Again, this could be due to a potential for a greater functional mass in the able-bodied individuals being utilised, but may also have been related to a difference in protocol between studies of which the limitations are highlighted in section 2.4.1.

2.7.5 Classification of wheelchair sport

The EE and physiological responses of able-bodied athletes have been shown to be dependent on the playing position (Duthie et al., 2003; Stolen et al., 2005; Drinkwater et al., 2008) and demands of the sport (McArdle et al., 2001). Whilst these considerations are necessary also for the disabled sporting populations, another important factor to consider is the impact that specific disability and level of impairment will have on sports performance (Price, 2010). As described previously in section 2.2, within disability sport athletes are classified according to their sport-specific functional capacity (Tweedy and Diaper, 2010). Classification systems are used to reduce the impact of a disability on competition outcomes and each sport has a separate classification system (Tweedy and Diaper, 2010).
Disability classification and the physiology of each classification is a useful tool for monitoring the capabilities of individuals within a team and for a team as a whole. Values for EE between classification groups during a match will aid nutrition advice for players alongside other parameters of daily EE. However, to date this data is not available.

Studies investigating classification in wheelchair sport have established physiological differences between classification groups, supporting the functional classification systems of each sport or athletic competition (Vanlandewijck et al., 1994b; 1995; van der Woude et al., 1998; 2002; de Lira et al., 2010). In wheelchair basketball, significant correlations have been found between the IWBF classification and \( \bar{VO}_2 \)peak, \( VO_2 \) at ventilatory threshold, \( P_O \) and sport-specific performance on court (Vanlandewijck et al., 1994b; 1995; de Lira et al., 2010). This basketball classification system (IWBF, 2009) provides a platform to provide grouping into classes based on wheelchair basketball players’ ability to complete basketball movements, including wheelchair propulsion, dribbling, shooting, passing, rebounding and reaction time (IWBF, 2009). It also ensures that a basketball team will win on the basis of athletic ability and skill rather than an unbalanced advantage or disadvantage purely based on disability (IWBF, 2009). For wheelchair tennis two classifications exist; Quad and open, as described in section 2.2. To date, no research has compared the physiology of wheelchair tennis players in relation to their classification, and the research that has reported the physiology of wheelchair tennis players involves individuals from the open class (Roy et al., 2006; Abel et al., 2008; Barfield et al., 2009; Bernardi et al., 2010).

Interestingly, when comparing physiological parameters between wheelchair athletes, other classification categories have been used. The most common of these has grouped SCI athletes according to the level of lesion or completeness (Coutts et al., 1983; Lakomy et al., 1987; Wells and Hooiker, 1990; Veeger et al., 1991; Hooker et al., 1993; Campbell et al., 1997; Schmid et al., 1998a; 1998b; van der Woude et al., 1998; 2002; Haisma et al., 2006). With the large heterogeneity within and between experimental groups with respect to lesion level, a limited statistical power in many of the aforementioned studies has been evident. It seems the physiology of wheelchair athletes depends on sport and classification within that sport. Developing the concept of categories will assist our understanding of EE with respect to different wheelchair sports and between disability classification. Knowledge of the EE would help provide a greater insight into the nutritional advice during training and competition in wheelchair athletes.
2.8 Summary

Having reviewed the literature that was relevant towards understanding EE in wheelchair users during daily and sports-specific situations, it is clear that further investigation is needed. In this review the following points have been highlighted:

1. There is a paucity of data regarding the REE of elite wheelchair athletes. Resting energy cost is a fundamental aspect of an individual’s daily EE and literature has shown how REE may be influenced by disability when compared to able-bodied control groups or predicted values. In relation to this, there is a need to explore the FFM of elite wheelchair athletes as clearly, disability alters body composition and the relationship between FFM and REE remains an unexplored area of research in this cohort.

2. It appears that the majority of studies investigating the wheelchair propulsion of both novice and experienced users typically used the measurement of O₂ uptake for the calculation of GE. This calculation has been fundamental to these studies to show how improvements in propulsion technique following practice and years of experience may be associated with physiological adaptations. However, of this work, only a small number of studies have explored the EE of manual wheelchair propulsion. To be able to inform individuals of the direct nutritional consequences of wheelchair propulsion during rehabilitation and during everyday life, direct values of EE are needed.

3. Many studies have either a) investigated the physiological consequences of various disability athletic groups without accounting for the sport or training that they do or b) focused on the physiology of the sports (e.g. wheelchair basketball) without accounting for the nature of the individual disabilities involved. That said, to be able to provide specific physiological feedback and absolute values of EE, data from homogenous groups of wheelchair athletes is needed. Classification within wheelchair sport which is designed to make sports competition equitable provides us with a system which is based around an individual’s functional capacity. It is essential that we use and develop our physiological knowledge from a disability classification perspective to further our understanding of the nutritional requirements during competition and training.
4. Finally, relatively few studies exploring wheelchair sports performance have used a wheelchair ergometer or motor-driven treadmill to profile the athlete in the laboratory when comparisons are made to game play. Alternative methodologies such as arm crank ergometry have been employed which could be considered as being methodologically flawed, as there are clear GE differences between this exercise modality and wheelchair locomotion. It is important that the choice of experimental design for testing wheelchair athletes can be transferred to the performance setting of wheelchair sports propulsion.
Chapter 3

Resting energy expenditure in elite athletes with a disability

3.1 Abstract

Purpose: This study examined REE in athletes with a disability in relation to predicted REE values taken from prediction equations verified in able-bodied individuals. Methods: Fourteen tetraplegic and 16 paraplegic individuals alongside six athletes with a disability but without a spinal cord injury (non-SCI) took part in this study. Following a 12-hour fast, REE was determined over a continuous 35-min period using the Cosmed K4b² portable spirometric system (Cosmed, Rome, Italy). Results: There was no significant difference in REE between participants in the tetraplegic, paraplegic and non-SCI groups (mean (±SD) 63.4(14.3), 70.0(13.4) and 77.7(7.5) kcal·h⁻¹ respectively; p = 0.09). However, further analysis reported a mean difference of 14 kcal·h⁻¹ (95% CI 1 to 27 kcal·h⁻¹) between the tetraplegic group and the non-SCI group which provided a moderate effect size (ES) of 0.47. In terms of predicted values, there was a significant difference in measured REE in participants with tetraplegia (63.4(14.3) kcal·h⁻¹) compared to predicted values based on equations from an able-bodied cohort (73.2(8.3) kcal·h⁻¹) (p = 0.01, ES = 0.64). A moderate ES was shown between measured and predicted values for the non-SCI group (p = 0.26; ES = 0.49) but no difference and a small ES for the paraplegic group (p = 0.31; ES = 0.26). Conclusions: These data provide an evaluation of REE in a large cohort of athletes with a disability. The findings suggest that the REE of non-SCI participants is higher than tetraplegics, implying energy intake would need to be greater for weight-maintenance in the former group. However, the results do not support a similar disparity when comparing tetraplegic and paraplegic athletes. To further our understanding, the relationship between metabolically active tissue and REE must be explored.
3.2 Introduction

The energy intake requirements for the general, able-bodied population are recommended according to sex, body mass and physical activity level (WHO, 2001). Resting energy expenditure accounts for the largest portion of daily EE (Ravussin et al., 1982) with other portions including physical activity and DIT (Himms-Hagen, 1976). Due to paralysis and loss of limb function, a reduced metabolically active mass is available in participants with SCI when compared to the able-bodied population (Buchholz et al., 2003a; Maggioni et al., 2003) which may lead to a lower REE.

Direct comparisons have shown that participants with tetraplegia and paraplegia have lower REE than the able-bodied population (Monroe et al., 1998; Buchholz et al., 2003a; Jeon et al., 2003; Liusuwan et al., 2007). Furthermore, measured REE in groups with a disability was lower than values derived from validated prediction equations in able-bodied samples (Mollinger et al., 1985; Sedlock and Laventure, 1990). Able-bodied prediction equations are compared in these studies due to the lack of coherent data available for accurate prediction equations to be made for groups of people with specific disabilities. However, there is a great variety of able-bodied prediction equations used in the literature. Although some research (Clark and Hoffer, 1991; Ramirez-Zea, 2005) has reported a slight over-estimation of REE from Schofield’s equations (Schofield, 1985), there is no other as widely accepted model. Investigations by the WHO (2001), the Department of Health (1991) and authors looking at individuals with a disability (Buchholz et al., 2003a) have used the Schofield able-bodied prediction equations, which use regression analysis to estimate the REE in over 7549 individuals collected for sources that the author deemed scientifically sound.

When considering the relationship between REE and FFM in SCI due to paralysis, individuals have a reduced metabolically active tissue mass (Monroe et al., 1998; Buchholz et al., 2003a; Jeon et al., 2003; Liusuwan, et al., 2007). Tetraplegic participants have a lower total lean body mass when compared to paraplegic participants within the rehabilitation setting (Spungen et al., 2003) which could explain the differences in REE shown between these two cohorts as described by Cox et al. (1985) who found that rehabilitating tetraplegic individuals expended significantly less energy than paraplegic individuals.
Due to sports training, athletes with a disability have the potential to maximise the active muscle mass that is available to them. The studies of Abel et al. (2003; 2008) have reported REE in SCI athletes who participate in wheelchair sports. Again, a lower REE was evident in the SCI athletes (63.4(12.2) kcal\cdot h^{-1}) compared to estimates using able-bodied prediction equations based on sex, body mass and age (74.2 kcal\cdot h^{-1}) (Abel et al., 2003). Abel et al. (2008) reported similar findings to their previous work when comparing the athletes with a disability with able-bodied prediction equations. However, interestingly, the authors found similar REE values between wheelchair rugby players with tetraplegia (63.5(12.9) kcal\cdot h^{-1}), wheelchair tennis players with paraplegia (66.8 (12.8) kcal\cdot h^{-1}) and wheelchair basketball players (62.7(15.0) kcal\cdot h^{-1}) with paraplegia. The literature has focused on the REE in athletes with an SCI although athletes with other disabilities are involved in wheelchair sports teams. Both amputation and club foot are amongst these other disabilities which are the focus of this chapter alongside athletes with an SCI. The athletes with an amputation and club foot may differ in REE values when compared to athletes with an SCI if they typically have more active muscle mass and therefore a potentially greater REE although this has not been shown empirically.

Obtaining individual or disability group specific REE is critical to ensure accurate, specific nutrition advice is provided for different athletic groups. General able-bodied EE values or prediction equations derived from able-bodied samples will be misleading if used to recommend nutritional intake in populations with a disability. There is sparse data on the REE of elite athletes with a disability which may differ from the REE of sedentary or moderately active individuals with a disability, as an athlete’s metabolically active tissue may increase due to training. Although Abel et al. (2003) reported the REE in athletes; these athletes were grouped according to sport rather than disability. Abel et al. (2008) measured REE in athletes with a disability according to SCI level. These athletes were reported to train, on average, 6 hours a week for their sport, which, when the authors calculated the energy cost of this training, fell slightly short of the recommendation of Paffenbarger et al. (1986) to expend around 2000 – 3500 kcal per week to maintain or increase health benefits.

Therefore, the aim of this study was to provide direct estimates of SCI and non-SCI REE in athletes regularly competing in elite level competition. Direct measurements will be compared across disability groups including SCI, amputation and club foot. Values will
be compared to prediction equations for REE derived from able-bodied samples with body mass and age as the primary determinants. This work will extend that of Abel et al. (2008) by including athletes who do not have a spinal cord injury (non-SCI).

3.3 Methods

3.3.1 Participants

Thirty six male, trained athletes with a disability, aged between 19 and 52 years, volunteered to take part in this study that was approved by the University Ethical Advisory Committee. Individuals were grouped according to disability, including a tetraplegic group (n = 14), paraplegic group (n = 16) and a non-SCI group including individuals with a lower limb amputation (n = 5) and club foot (1). All participants had the experimental procedures explained to them both in writing and verbally before providing their written informed consent, and each participant completed a health and disability questionnaire. All participants were considered trained (average training per week > 13.8 hours). The participants trained for and competed in a variety of sports including wheelchair rugby, wheelchair tennis, wheelchair basketball, archery, amputee marathon running, sledge ice hockey, hand cycling and power lifting. Participant characteristics are shown in Table 3.1.

3.3.2 Body mass and length

Body mass was measured in minimal clothing, to the nearest 0.1 kg, using a wheelchair double beam scale (300 series, Marsden, London, UK). The same scales were used for the ambulant participants using a standardised chair. Body length was measured to the nearest 0.1 cm with a Luftkin measuring tape with participants in the supine position. For participants who were unable to lie straight, body length was taken from the sum of body segments.
Table 3.1. Participant characteristics with respect to the disability classification of tetraplegia, paraplegia and non-spinal cord injured (non-SCI). Values are means (±SD).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Tetraplegic n = 14</th>
<th>Paraplegic n = 16</th>
<th>Non-SCI n = 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.5 (4.8)</td>
<td>31.9 (8.3)</td>
<td>27.2 (7.7)</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>72.6 (13.8)</td>
<td>72.7 (10.6)</td>
<td>68.3 (10.1)</td>
</tr>
<tr>
<td>Body length (m)</td>
<td>1.79 (0.09)</td>
<td>1.72 (0.10)</td>
<td>1.65 (0.25)</td>
</tr>
<tr>
<td>Onset of disability (yrs)</td>
<td>11.0 (4.9)</td>
<td>19.5 (8.4)*</td>
<td>17.2 (11.16)</td>
</tr>
<tr>
<td>Wheelchair sports experience (yrs)</td>
<td>9.5 (5.0)</td>
<td>12.5 (4.6)</td>
<td>7.6 (5.6)</td>
</tr>
<tr>
<td>Training (h·wk⁻¹)</td>
<td>14.0 (3.3)</td>
<td>14.4 (5.3)</td>
<td>13.8 (3.4)</td>
</tr>
<tr>
<td>Participants with complete/incomplete lesions</td>
<td>11/3</td>
<td>13/3</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Key: *Difference between paraplegic and tetraplegic participants (p = 0.02, effect size ES = 0.54, 95% CI, 2 to 15 years).

3.3.3 Resting energy expenditure

A Cosmed K4b² portable spirometric system (Cosmed, Rome, Italy) (Figure 3.1) was used to determine \( \dot{V}O_2 \), \( \dot{V}CO_2 \) and ventilation (VE) on a breath-by-breath basis during supine rest. A bi-directional flowmeter was used to measure expired gas volume. The flowmeter was attached to a facemask (Hans Rudolf, USA) with a dead space volume of 60-70 mL, which was checked for leaks prior to each test. Gas calibration, flow meter calibration and room air calibration were performed according to the manufacturer’s specifications before each test. Ventilatory variables were collected on a breath-by-breath basis and interpolated into 1 second intervals. \( \dot{V}O_2 \) consumption and \( \dot{V}CO_2 \) production values from 5 to 35 minutes were used for data analyses. Individual \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) values that were >1 standard deviation of the mean were removed.
Participants arrived in the laboratory after a 12-hour fast, but ad libitum water intake, and were asked to avoid vigorous exercise 24-hours prior to testing (Compher, 2006). They rested in a supine position for a 35-minute period in a quiet, thermo-neutral environment (range 18.1 – 23.2 ºC) and were asked not to fall asleep during data collection. The first five minutes of data collection were excluded from the analysis.

3.3.4 Calculation of REE

Five minute rolling averages were established for ventilatory variables, and the lowest five minute rolling average of $\dot{V}O_2$ along with the corresponding $\dot{V}CO_2$ value were used to calculate REE. The equation by Frayn (1983) was used to estimate carbohydrate and fat oxidation in grams per minute (g·min⁻¹) using the values of $\dot{V}O_2$ and $\dot{V}CO_2$ in litres per minute (L·min⁻¹):

Carbohydrate: $\((4.55 \times \dot{V}CO_2) - (3.21 \times \dot{V}O_2)\)$

Fat: $\((1.67 \times \dot{V}O_2) - (1.67 \times \dot{V}CO_2)\)$

The Atwater factors (Atwater, 1889) were used to convert the grams of carbohydrate and fat used into EE (grams of carbohydrate x 4; grams of fat x 9) and establish kilocalories used in one minute. This value was reported in kilocalories per hour (kcal·h⁻¹) for comparison with previous literature. Schofield’s (1985) prediction equations based on age, body mass and sex were used to predict REE:
3.3.5 Pilot work

Data was collected to look at the variation in O$_2$ consumption and CO$_2$ production between the Cosmed K4b$^2$ and the Douglas Bag technique. There was a consistently higher value of VO$_2$ and VCO$_2$ when expired gas is collected with the K4b$^2$ (difference range 0.02 – 0.12 L·min$^{-1}$). These data suggest that assumptions made about the similarity of absolute values of REE measured with the K4b$^2$ and the Douglas bag may need to be interpreted with caution. However, this should not affect the comparisons of REE between the different groups studied in this thesis.

3.3.6 Statistical analyses

Data were reported as mean (±SD). The statistical package for social sciences (SPSS; version 16.0 Chicago, Illinois, USA) was used for data analyses. Normal distribution was verified using the Shapiro-Wilk test ($p \geq 0.53$) and Levene’s test confirmed the variances were homogeneous between groups ($p \geq 0.19$). Between group differences in the characteristics displayed in Table 3.1 and the measured REE (Table 3.2) were examined using separate one-way between-group analysis of variance (ANOVA). Differences between the measured and predicted (method) REE (Table 3.2) across the three disability groups were analysed using a 3 x 2 (group x method) mixed measures ANOVA. The significance level was set at $p \leq 0.05$ for all analyses. Effect sizes (ES) and 95% confidence intervals of the differences (95% CI) are provided where appropriate in addition to alpha (p) values. The ES of the difference between groups and between actual and predicted REE was calculated as $\frac{t^2}{(t^2 + df)}$, with 95% CI of the difference between the means where $t =$ the t value from the SPSS output and $df =$ degrees of freedom (population – 2). A low (0.1), medium (0.3) and large (0.5) ES was reported according to Cohen (1992).

3.4 Results

Table 3.1 displays the characteristics and physical values of the participants. There were no differences in age, body mass, body length, years playing disability sport and
weekly training times. The paraplegic athletes, however, had a disability for longer than the tetraplegic athletes (p = 0.02). Correlational analysis revealed no relationship between age and REE ($R^2 = -0.1$, $p = 0.55$) thus the inclusion of the age range of participants was justified. There was also no relationship found when correlating predicted and actual REE in participants with complete lesions and also in participants with incomplete lesions ($R^2 = 0.28$ and $R^2 = 0.16$ respectively). The measured and predicted REE are shown in Table 3.2. A trend for differences in measured REE between groups was evident ($p = 0.09$), but the combined ES was low ($ES = 0.37$). The mean difference of 14 kcal·h$^{-1}$ (95% CI 1 to 27 kcal·h$^{-1}$) between the tetraplegics and non-SCI was the largest, providing an ES of 0.47 with only small effects for the other between-group comparisons ($ES \leq 0.28$; 95% CI -4 to 20 kcal·h$^{-1}$).

**Table 3.2.** Measured and predicted REE in tetraplegic, paraplegic and non-SCI participants. Values are means (±SD).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tetraplegic</th>
<th>Paraplegic</th>
<th>Non-SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured REE (kcal·h$^{-1}$)</td>
<td>63.4 (14.3)$^\dagger$</td>
<td>70.0 (13.4)</td>
<td>77.7 (7.5)</td>
</tr>
<tr>
<td>Predicted REE (kcal·h$^{-1}$)</td>
<td>73.2 (8.3)</td>
<td>72.3 (5.1)</td>
<td>70.6 (5.8)</td>
</tr>
<tr>
<td>Effect size</td>
<td>0.62</td>
<td>0.22</td>
<td>0.51</td>
</tr>
<tr>
<td>95% CI of the difference</td>
<td>-17 to -3</td>
<td>-8 to 3</td>
<td>-7 to 21</td>
</tr>
</tbody>
</table>

**Key:** $^1$ Schofield’s (1985) equation was used to predict REE using body mass and age.

$^\dagger$ Within group paired difference between REE and predicted REE in tetraplegic participants; $p = 0.01$.

The (3 x 2) group by method interaction ($p = 0.02$) suggested that differences between the measured and predicted REE were dependent on disability group. Follow-up pair-wise
comparisons revealed moderate to large ES for the tetraplegics and non-SCI groups whereas the difference for the paraplegic athletes was small (Table 3.2).

3.5 Discussion

The main finding from this study is that the three groups of non-SCI, tetraplegic and paraplegic athletes did not have significantly different measured REE values. However, the moderate ES between the REE of the non-SCI and the tetraplegic participants suggests the 14 kcal·h⁻¹ difference between the groups is an important finding. The moderate ES for the tetraplegic and non-SCI athletes when comparing the measured and predicted REE in each group separately suggest that using the equation provided by Schofield (1985) may result in invalid estimations for these two groups of elite wheelchair athletes. In the rehabilitation setting, Mollinger et al. (1985) reported a significantly lower REE in individuals with tetraplegia with a lesion level of C6 and below (55.4 kcal·h⁻¹) compared to individuals with paraplegia with a lesion level of T10 and below (65.4 kcal·h⁻¹). It has been suggested that the lower REE in tetraplegic individuals compared to paraplegic individuals is due to physiological differences between the disability groups (Mollinger et al., 1985; Cox et al., 1985). Active tissue mass is denervated below the level of a spinal cord lesion in an individual depending on the type of disability and the sensory and motor input to tissue (Maynard et al., 1997). Therefore, individuals with tetraplegia may not be able to recruit as much active tissue as individuals with paraplegia, leading to the former group having a lower metabolic rate. That said, a more recent study reported that the REE of 32 tetraplegic individuals (58.8 kcal·h⁻¹) was similar to 34 paraplegic individuals (59.7 kcal·h⁻¹) (Collins et al., 2010). These authors however, reported a large variation in time since injury and did not report activity levels, precluding an examination of the data relative to training status. Our findings support those of Abel et al. (2008) who found no difference in REE between wheelchair rugby players with tetraplegia and wheelchair tennis and basketball players with paraplegia. The difference shown in the REE values between rehabilitation groups may be reduced in SCI participants who are post-rehabilitation (Collins et al., 2010), although this cannot be confirmed.

A difference in REE between individuals with an SCI and able-bodied control groups of between 8 – 9 kcal·h⁻¹ has been shown previously (Buchholz et al., 2003a; Liusuwan et al., 2007). Mollinger et al. (1985) also reported a significant 10 kcal·h⁻¹ difference in REE between individuals with tetraplegia and individuals with low lesion...
level paraplegia (lesion below T10) in the rehabilitation setting. A lack of statistical power in the small non-SCI sample in the current study contributed to the ES and explains the large 95% CIs. It is important to note, however, that if the mean difference between the tetraplegic and non-SCI groups of ~14 kcal·h⁻¹ is extrapolated over longer time periods, it could have an impact on nutritional requirements for these athletes.

No study, to the authors’ knowledge, has compared directly the REE of athletes with an SCI to athletes with a disability without an SCI. However, previous research has found that non-athletic tetraplegic and paraplegic individuals have a lower REE than able-bodied matched controls, due to a lower FFM or lean body mass (Monroe et al., 1998; Buchholz et al., 2003a; Jeon et al., 2003; Liusuwan et al., 2007). Therefore, the lower REE in the tetraplegics compared to non-SCI in the present study could be a consequence of higher FFM in the latter group. This may warrant further study to confirm.

In agreement with the concept that participants with an SCI have a lower REE than their able-bodied counterparts, the predicted REE was 10.2 kcal·h⁻¹ (95% CI: -17 to -3 kcal) higher than measured REE for the tetraplegic athletes in our study. Many studies are in agreement that widely used prediction equations over-estimate REE in sedentary SCI participants and those undergoing rehabilitation for SCI (Mollinger et al., 1985; Sedlock and Laventure, 1990). Moreover, this appears to extend to wheelchair athletes (Abel et al., 2003; 2008). In contrast, the results of the current study suggest that Schofield’s prediction equation for REE might provide a reasonable prediction for paraplegic athletes compared to a direct measurement. These participants were highly trained, with potentially larger metabolically active tissue mass than sedentary individuals with a disability, which could account for the group similarity in measured and predicted REE. This notion is strengthened by the non-SCI participants having a non-significantly higher measured REE than predicted REE, suggesting the need for actual measurement. This is especially important when considering both individuals with a disability and individuals from athletic populations. It should be noted however, that the slight increase in estimated \( \dot{V}O_2 \) and \( \dot{V}CO_2 \) with the K4b² when compared to the Douglas bag technique may have caused this increase in EE. Although prediction equations have been acquired from many pieces of equipment, values might need to be interpreted with caution when comparing REE measured with the K4b² and the Douglas bag technique.
To increase our understanding of REE in athletes with a disability, accurate quantification of metabolically active tissue in these groups is warranted, in conjunction with direct measurements of REE. Reduced FFM is evident in sedentary paraplegics compared to able-bodied controls (Spungen, et al., 2000; Buchholz et al., 2003a; Maggioni et al., 2003). Moreover, lean tissue appears to be lower in trained populations with a disability compared to able-bodied sedentary controls (Mojtahedi, et al., 2008). Future directions should explore the relationship between REE values and metabolically active tissue in specific disability groups.

3.6 Conclusions

This study examined the REE of a large cohort of athletes with a disability, consisting of tetraplegics, paraplegics and a small mixed non-SCI group. The findings suggest that the REE of non-SCI participants is higher than tetraplegics, implying energy intake would need to be greater for weight-maintenance in the former group. However, the results do not support a similar disparity when comparing tetraplegic and paraplegic athletes. The results also suggest the use of able-bodied predictive equations would lead to an over estimation of REE in tetraplegic athletes but may provide a reasonable prediction for paraplegic athletes.
Resting energy expenditure in relation to fat free mass in elite wheelchair athletes.

4.1 Abstract

**Purpose:** Sedentary tetraplegic individuals have lower REE than sedentary paraplegic individuals, but similar values have been shown in sports trained individuals irrespective of SCI classification. The explanation of these findings may lie with variations in FFM. The aim of the study was to examine the relationship between REE and FFM in highly trained SCI athletes. **Methods:** Twenty-four wheelchair athletes were assigned to two groups (13 tetraplegics and 11 paraplegics). Resting respiratory gas exchange was measured using the Cosmed K4b² portable spirometric system (Cosmed, Rome, Italy) and REE was estimated from VO₂ consumption and VCO₂ production. Fat free mass was estimated using dual energy X-ray absorptiometry. Values for FFM in the arms (left and right), the trunk, the upper body (trunk + arms) and the lower limbs were obtained from lean mass and bone mineral content in each participant. **Results:** Absolute REE (63.4 (14.9) vs. 71.8 (15.0) kcal·h⁻¹), total-body FFM (53.1 (9.0) vs. 52.1 (7.0) kg) and upper-body FFM (33.6 (5.6) vs. 35.9 (4.6) kg) were not significantly different between tetraplegic and paraplegic individuals respectively. The REE, adjusted for upper-body FFM (with analysis of covariance), was similar between groups (p = 0.42). Differences were shown in REE between groups when adjusted for total-body (62.7 (10.9) vs. 72.5 (10.9) kcal·h⁻¹) and lower-body FFM (59.2 (14.0) vs. 76.8 (14.2) kcal·h⁻¹) in the tetraplegic and paraplegic participants respectively; p < 0.05. **Conclusions:** REE adjusted for upper-body FFM did not differ between groups. The comparable upper-body FFM values may be a consequence of elite sports training specific to this study’s cohort.
Chapter 4                                      Resting energy expenditure in relation to fat free mass

4.2 Introduction

Comparisons of REE, whether objectively measured or estimated from predictive equations, are lower for SCI than able-bodied individuals (Mollinger et al., 1985; Sedlock and Laventure, 1990; Monroe et al., 1998; Buchholz et al., 2003a; Jeon et al., 2003; Liusuwan et al., 2007). When considering the level of SCI, REE is lower in tetraplegics than paraplegics within the rehabilitation setting (Cox et al., 1985; Mollinger et al., 1985). Conversely, measured REE was similar in a large cohort of tetraplegic and paraplegic males (Collins et al., 2010) and similar in tetraplegic and paraplegic athletes (Abel et al., 2008). The fact that similarities in REE have been noted in active/trained wheelchair athletes of differing levels of SCI raises important questions regarding the physiology of specific disabilities in relation to trained status, classification and functional capacity.

Variations or indeed similarities in REE between individuals with different disabilities may be explained by FFM, which itself could be determined by severity of disability or cardio-respiratory fitness levels. This is due to the positive relationship between FFM and REE which is apparent in able-bodied populations (Cunningham, 1991; Weinsier et al., 1992; Arciero et al., 1993; Heymsfield et al., 2002; Johnstone et al., 2005). A positive relationship has also been identified in populations with a disability (Sedlock and Laventure, 1990; Monroe et al., 1998; Buchholz et al., 2003a), with FFM accounting for 70% of the variation in REE in healthy paraplegics (Buchholz et al., 2003a). When REE values were scaled to account for differences in total FFM, they were similar between SCI and able-bodied groups (65.3(5.0) vs. 66.2(5.0) kcal·h·1 respectively) (Buchholz et al., 2003a). Similarities are also evident when expressed relative to lean mass (Liusuwan et al., 2007).

From the majority of both able-bodied and SCI literature, the consensus is that there is a positive relationship between FFM and REE (Sedlock and Laventure, 1990; Cunningham, 1991; Weinsier et al., 1992; Arciero et al., 1993; Monroe et al., 1998; Heymsfield et al., 2002; Buchholz et al., 2003a; Johnstone et al., 2005). An explanation for similarities in REE in the trained SCI population could be due to the level of sports training of these groups. Abel et al. (2003; 2008) showed comparable REE values in highly trained tetraplegic and paraplegic participants and suggested that the similarity may be due to a greater fitness in the tetraplegics leading to a similar musculature in the active tissue shown in both groups. The authors did not however, quantify these results by determining the
metabolically active tissue within trained athletes with a disability. By scaling REE to FFM we can further develop our understanding of REE between tetraplegic and paraplegic athletes.

To extend our understanding of the relationship between FFM and REE within a population with a disability, it is important to examine potential differences in FFM between populations with and without a disability. Studies have shown lower lean mass or lower FFM in sedentary SCI compared with able-bodied controls (Monroe et al., 1998; Spungen et al., 2000; 2003; Buchholz et al., 2003a; Jones et al., 2003; Maggioni et al., 2003; Dionyssiotis et al., 2008). Taking lesion level into account, limited but empirical evidence has shown that tetraplegic participants have a lower total lean body mass when compared to paraplegic participants within the rehabilitation setting (Spungen et al., 2003).

When training status is considered, larger FFM values are shown in trained compared to sedentary able-bodied participants (Whalley et al., 2004). However, in a population with a disability, whilst a higher percentage body fat was shown between sedentary participants compared to those who are active, they demonstrated similar FFM values (Olle et al., 1993). This suggests that, while being active compared to being sedentary may reduce body fat in individuals with a disability (Olle et al., 1993), a higher level of training may be required to show improvements in FFM as shown in the able-bodied population (Whalley et al., 2004). What is still not clear is how a similar standard of training affects FFM in athletes who have different levels of SCI. This is important to consider due to the similarity found in the REE between tetraplegic and paraplegic athletes who are trained to an elite level (Abel et al., 2008). Therefore, the aim of this study was to compare standardised fasting REE between tetraplegic and paraplegic elite athletes relative to FFM as derived from dual energy X-ray absorptiometry (DXA). The research hypothesis was that REE and FFM would be similar in tetraplegic and paraplegic athletes who have comparable training schedules.

4.3 Methods

4.3.1 Participants

Twenty-four trained SCI athletes (13 tetraplegic and 11 paraplegic individuals) aged 22 to 45 years volunteered to take part in this study that was approved by the University Ethical Advisory Committee. All participants had procedures explained to them
in writing and verbally before informed consent was given, and a health questionnaire and disability questionnaire were completed. Individual disabilities included SCI (C6 – T12), spina bifida and post-polio. All participants were eligible for Paralympic sport and trained to an elite level (≤ 20 hours a week) regularly for wheelchair rugby and wheelchair basketball. Participant characteristics are shown in Table 4.1.

4.3.2 Measurements

4.3.2.i Body mass and body length

Body mass was measured in minimal clothing, to the nearest 0.1 kg, using a wheelchair double beam scale (300 series, Marsden, London, UK). Body length was measured in the supine position to the nearest 0.1 cm (Luftkin tape). For participants who were unable to lie straight, body length was taken from the sum of body segments.

4.3.2.ii Resting energy expenditure

Measurement and calculation of REE was obtained according to the methods in the previous chapter (Chapter 3, section 3.3.3 and 3.3.4).

Table 4.1. Participant characteristics with respect to the disability classification of tetraplegia and paraplegia. Values are means (±SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tetraplegics(^1)</th>
<th>Paraplegics(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 13</td>
<td>n = 11</td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>30.8 (4.8)</td>
<td>31.3 (5.9)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>71.5 (13.7)</td>
<td>73.6 (11.5)</td>
</tr>
<tr>
<td>Body length (m)</td>
<td>1.79 (0.1)</td>
<td>1.73 (0.1)</td>
</tr>
<tr>
<td>Body fat percentage (%)</td>
<td>24.6 (6.9)</td>
<td>28.6 (6.5)</td>
</tr>
<tr>
<td>Onset of disability (yrs)</td>
<td>10.4 (4.7)*</td>
<td>20.3 (9.2)</td>
</tr>
<tr>
<td>Wheelchair sports experience (yrs)</td>
<td>8.8 (4.5)</td>
<td>12.7 (5.4)</td>
</tr>
<tr>
<td>Training (h·wk(^{-1}))</td>
<td>13.9 (3.4)</td>
<td>16.5 (4.4)</td>
</tr>
<tr>
<td>Participants with complete/incomplete lesions</td>
<td>11/2</td>
<td>11/0</td>
</tr>
</tbody>
</table>

Key: *denotes a between-group difference (p = 0.01)

\(^1\) All participants in this chapter were used in Chapter 3 and their data reanalysed.
4.3.3 Body composition measurement

Dual energy x-ray absorptiometry (Lunar Prodigy Advance, GE Medical Systems Lunar, Belgium) was used to estimate body composition. Participants were in a postprandial, euhydrated state, and were asked if they had any metal implants that may affect the scan. They lay as still as possible in a supine position for the duration of the 10 minute scan. The beam quantified the body compartments in one measurement (Lohman, 1996) and all scans were conducted and analysed by a trained technician. The three compartments measured were bone mineral content, fat mass and lean mass. The FFM was estimated from the lean mass and the bone mineral content in each participant and segmental values were given for FFM in the arms (left and right), the trunk, the upper-body (trunk + arms) and the lower limbs. A value of total-body FFM was derived from the summation of segmental values, and total-body percentage fat mass was obtained from the fat mass divided by the total-body mass.

4.3.4 Statistical analyses

Data were reported as mean (±SD). The SPSS version 16.0 (Chicago, IL, USA) was used for data analyses. Normal distribution was verified using the Shapiro-Wilk test (p ≥ 0.05) and Levene’s test was used to check if variances were homogeneous between groups (p ≥ 0.05). Independent Student’s t-tests were used to locate differences in participant characteristics, REE and FFM between disability groups. Studies report that dividing REE by FFM through ratio scaling is not a suitable expression of the relationship between these two variables as the regression line does not have a zero intercept (Ravussin and Bogardus, 1989; Heshka et al., 1990; Weinsier et al., 1992; Gallagher et al., 1998; Wang et al., 2000). With this in mind analysis of covariance, with FFM as the between group covariate, was used to report any differences in adjusted REE values. Analysis found that tetraplegic participants had a larger lower-body FFM than paraplegic participants, so further examination of the results was conducted to see if this finding was related to time since injury. Therefore, the relationship between years since disability and lower-body FFM was examined with regression analysis. Statistical significance was assumed at p ≤ 0.05; ES and 95% CI were also provided to complement the more traditional statistics as previously described in Chapter 3 section 3.3.5. Using GPower 3.1.2, and the work of Mollinger et al. (1985), calculations showed 10 participants would be needed in each group to detect a similar change in REE, with an alpha of 0.05, power of 80%.
4.4 Results

4.4.1 Participant characteristics

There was no difference between groups in age, body mass, body length, body fat percentage, years playing current sport and hours of training per week (Table 4.1). However, participants in the paraplegic group had acquired their disability significantly earlier than the tetraplegic participants (p = 0.01).

4.4.2 Absolute REE and FFM

Absolute REE as shown in Table 4.2 was not significantly different between the two groups (p = 0.18). The paraplegic participants were closer to their predicted values from equations for the able-bodied population as compared to the tetraplegic participants who showed a significantly lower REE than predicted (p = 0.04) (see Table 4.2). The values for upper-body FFM (33.6 (5.6) vs. 35.9 (4.6) kg, p = 0.29) and trunk-FFM (25.9 (4.4) vs. 25.9 (3.8) kg, p = 0.98) were also not different between tetraplegic and paraplegic participants respectively (Figure 4.1). In contrast, arm FFM was lower in tetraplegic (7.7 (1.3) kg) compared to paraplegic (10.0 (1.2) kg) (p < 0.01) participants. This difference was reversed when examining lower-body FFM, (tetraplegics; 15.0 (3.0) kg and paraplegics; 11.3 (3.3) kg; p = 0.01). Consequently, total-body FFM was similar in tetraplegic (53.1 (9.0) kg) and paraplegic (52.1 (7.0) kg; p = 0.76) participants. Lower-body FFM was calculated as 30% of total-body FFM. Another worthy note was FFM in individuals with incomplete lesions were within the range for all tetraplegic participants and were thus included in the analysis.
### Table 4.2: Absolute REE (kcal h⁻¹) and covariate adjusted REE in tetraplegic and paraplegic participants. Values are means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>Tetraplegic</th>
<th>Paraplegic</th>
<th>ES</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute REE</td>
<td>63.4 (14.9)</td>
<td>71.8 (15.0)</td>
<td>-2.10 to -4.3</td>
<td>-13.8 to 5.9</td>
</tr>
<tr>
<td>Predicted REE</td>
<td>72.6 (15.0)</td>
<td>69.4 (11.4)</td>
<td>-17.0 to 3.2</td>
<td>-18.0 to 1.4</td>
</tr>
<tr>
<td>REE adjusted for Body mass</td>
<td>65.4 (11.9)</td>
<td>71.0 (11.9)</td>
<td>0.29</td>
<td>0.23</td>
</tr>
<tr>
<td>REE adjusted for Upper-body FFM</td>
<td>64.0 (11.9)</td>
<td>70.1 (11.9)</td>
<td>0.17</td>
<td>0.36</td>
</tr>
<tr>
<td>REE adjusted for Trunk FFM</td>
<td>63.4 (11.4)</td>
<td>71.7 (11.4)</td>
<td>0.28</td>
<td>0.23</td>
</tr>
<tr>
<td>REE adjusted for Arm FFM</td>
<td>63.4 (11.4)</td>
<td>71.7 (11.4)</td>
<td>0.28</td>
<td>0.36</td>
</tr>
<tr>
<td>REE adjusted for Total-body FFM</td>
<td>59.2 (14.0)*</td>
<td>76.8 (14.2)</td>
<td>0.25</td>
<td>0.42</td>
</tr>
<tr>
<td>REE adjusted for Lower-body FFM</td>
<td>59.2 (14.0)*</td>
<td>76.8 (14.2)</td>
<td>0.25</td>
<td>0.42</td>
</tr>
</tbody>
</table>

**Key:**
- *Denotes a significant difference (p < 0.05) in adjusted REE between tetraplegic and paraplegic participants.
- †Denotes a significant difference between measured and predicted REE values.

1 Predicted values from Schofield (1985).
4.4.3 \textit{REE corrected for body mass and FFM}

Analysis of covariance suggested that there was no difference in REE between tetraplegic and paraplegic participants when upper-body FFM was included as a covariate (Table 4.2, \( p = 0.42 \)). There was no difference in REE when arm FFM and trunk FFM were used as covariates (\( p > 0.09 \)). When total and lower-body FFM were used as covariates, tetraplegic participants had lower REE values than paraplegic participants (\( p = 0.04 \) and \( p = 0.01 \) respectively; Table 4.2). Regression analysis was used to confirm a significant, negative relationship between years since onset of disability and lower-body FFM (\( r^2 = 0.38; \ p = 0.001 \)).

4.5 Discussion

The results of the current study support the hypothesis to show that there was no significant difference between tetraplegic and paraplegic wheelchair athletes in absolute REE or absolute upper-body FFM, and no difference when REE was adjusted for upper-
body FFM. The tetraplegic participants had a larger lower-body FFM, and consequently this led to a lower REE when adjusted for this FFM segment. A lower REE was also shown in the tetraplegic athletes when adjusted for total FFM, which may have also been a consequence of larger lower-body FFM.

4.5.1 Characteristics of elite wheelchair athletes.

It was noted that the training (of up to 20 hours per week) in both tetraplegic and paraplegic athletes consisted of comparable drills including short sprints, chair agility drills and general pushing. These observations complemented the recent pilot work of Sporner et al. (2009), who found similarities between wheelchair basketball players (paraplegic) and wheelchair rugby players (tetraplegic), in the distance covered (2680 vs. 2365 m respectively) and time spent on court (30.3 vs 30.0 minutes respectively) during match play. The amount of training and the involvement by all participants at an international competitive level highlights the elite trained status of this cohort. The mean percentage body fat of the current participants (26.4 (6.9)%) suggests that the tetraplegics and paraplegics in this study compare well to other cohorts of trained male wheelchair athletes (Inukai et al., 2006; Miyahara et al., 2008; Mojtahedi et al., 2008). Yet participants in the present study displayed higher total lean mass (49.4 kg) in comparison with published data from other trained male wheelchair athletes (41.7 – 45.1 kg) whose training averaged 8.7-15 h-wk\textsuperscript{-1} (Miyahara et al., 2008; Mojtahedi et al., 2008). With this in mind, the current study found no difference in trunk, upper-body and total-body FFM between the two groups of elite athletes when grouped according to disability (tetraplegia vs. paraplegia).

4.5.2 Absolute REE and FFM.

The REE of the paraplegic participants in the current study (71.8 kcal\textsuperscript{-1}h\textsuperscript{-1}) is higher than non-athletic paraplegic participants with reported REE of 59.0 – 65.4 kcal\textsuperscript{-1}h\textsuperscript{-1} (Mollinger et al., 1985; Buchholz et al., 2003a; Buchholz et al., 2003b; Collins et al., 2010) and also higher than athletic paraplegics with reported values of 60.3 – 66.8 kcal\textsuperscript{-1}h\textsuperscript{-1} (Abel et al., 2003; Abel et al., 2008). The athletes in the studies by Abel et al. (2003; 2008), however, took part in ≤ 8.9 hours training a week, a significantly lower amount of training when compared to the cohort in the current study. The absolute values of REE between tetraplegics and paraplegics of 63.4 and 71.8 kcal\textsuperscript{-1}h\textsuperscript{-1} in the current study were not statistically different, which is in agreement with the similarities shown in REE of post-rehabilitation or athletically trained paraplegic and tetraplegic individuals (Abel et al., 2008;
Collins et al., 2010). Conversely, this 8.4 kcal·h\(^{-1}\) difference in REE between groups in the current study could be meaningful if extrapolated over a 24 hour period. It is evident that, within a rehabilitation setting, REE in tetraplegic individuals is lower than that in paraplegic individuals (Cox et al., 1985), and Mollinger et al. (1985) reported REE values of 55.4 vs 64.0 kcal·h\(^{-1}\) for tetraplegic (with lesion C6-C8) and paraplegic individuals (with a lesion of T10 or below) respectively during rehabilitation. This difference between groups is similar to the non-significant 8.4 kcal difference reported in the current study between tetraplegic and paraplegic individuals. To help try and explain this finding, it is important to explore the possible influence of segmental FFM on the value of REE.

The differences found in REE between disability groups (Cox et al., 1985; Mollinger et al., 1985) could be due to tetraplegic participants having greater denervation to metabolic tissue when compared to participants with paraplegia (Maynard et al., 1997), leading to muscle atrophy below the spinal cord lesion level (Jacobs and Nash, 2004). Strengthening this concept, reduced function in the elbow, wrist and finger extensors has been shown in tetraplegia compared to individuals with paraplegia who have full upper-limb nervous function (Maynard et al., 1997). Spungen et al. (2003) reported lower FFM in sedentary tetraplegics when compared to sedentary paraplegics and, within the different body compartments, reported lower arm FFM values in the tetraplegic participants. The elite tetraplegics in the current study were shown to have significantly lower FFM in the arms when compared to the paraplegic participants, which supports the notion of muscle atrophy following an SCI found within a clinical setting (Jacobs and Nash, 2004).

4.5.3 Resting energy expenditure adjusted for FFM.

When REE was adjusted for total-body FFM, the REE values became statistically different (tetraplegic; 62.7 (10.9) kcal·h\(^{-1}\) and paraplegic; 72.5 (10.9) kcal·h\(^{-1}\)). However, when individual FFM segments in the upper-body were analysed, adjusted REE was similar between groups. Total-body FFM is important to consider as this whole value will determine the overall REE of an individual. Nevertheless, upper-body FFM is an imperative variable to consider in the sports setting due to the ability to increase this mass through sports training. When REE in the current study was adjusted for trunk and arm FFM, REE values show a greater similarity between groups due to the slightly higher arm FFM in the paraplegic participants and the slightly lower REE in the tetraplegic participants. This is in agreement with previous literature that shows REE is similar between paraplegic and able-bodied...
individuals when FFM is adjusted for (Buchholz et al., 2003a; Jones et al., 2003). This would suggest the higher FFM in the arms of the paraplegic group may be the cause of their non-significantly higher REE.

However, the total-body FFM values were similar between groups, suggesting total-body FFM may not be responsible for the 8.4 kcal variance shown in REE. The higher FFM in the lower body of the tetraplegic individuals is also not easily explained. As the REE was slightly lower in the tetraplegic group, the difference in REE between groups increased after adjustment of this FFM variable. It could also be speculated that the change in the adjusted REE value, which occurred when using total-body FFM, could be due to lower-body FFM influencing the measured outcome. This cohort of trained tetraplegic and paraplegic athletes allows us to explore REE in relation to unique body compositions, arguably different to that of the rehabilitation population in which both paraplegic and tetraplegic individuals may have been injured for a similar amount of time (Cox et al., 1985; Mollinger et al., 1985).

4.5.4 Years since onset of disability.

Tetraplegic participants in the current study have a significantly shorter time since onset of disability when compared to paraplegic participants. A greater atrophy in the lower limbs of the paraplegic individuals when compared to the tetraplegics could be explained by duration of time effect. Lean tissue mass had a significant negative correlation with duration of injury in a study comparing able-bodied and SCI monozygotic twins (Spungen et al., 2000), which is also in agreement with the moderate but significant negative relationship shown in the current study between years since onset of disability and lower-body FFM ($r = 0.62; p = 0.001$). Inukai et al. (2006) reported higher whole body fat mass in paraplegic athletes who had a disability longer than 15 years when compared to paraplegic athletes who had their disability less than 15 years and a reduction in total-body FFM in another study was shown to be related to duration of injury in SCI individuals (Spungen et al., 2003). Due to the nature of recruitment of elite tetraplegic athletes, who in this study play wheelchair rugby, and of paraplegic athletes, the majority of whom play wheelchair basketball, this may not be an isolated finding. Some paraplegic participants within a wheelchair basketball squad have a congenital disability, so the wasting of muscle (or FFM) will have been taking place since birth. Within a wheelchair rugby squad, the majority of the players have tetraplegia, with young men being the most likely to have an SCI resulting in this level of spinal cord injury (Gall et al., 2008). What appeared as a potential confounding variable
(difference in time since onset of disability) may be a unique characteristic of the difference between wheelchair basketball players and wheelchair rugby players. To further the research in this area, it may be useful to understand the pattern of REE in tetraplegic and paraplegic individuals who have the same time since onset of disability. However, this may mean the study of sub-elite wheelchair athletes, whereas the primary focus of this study was elite athletes.

4.5.5 Elite training and body composition.

Although time since injury may have a large effect on segmental FFM and therefore on REE, the elite training these participants take part in could also influence the physiology of individuals with tetraplegia and paraplegia. Inukai et al. (2006) reported that paraplegic participants who trained > 7 h·wk⁻¹ have significantly less fat mass in the upper extremities, trunk and total-body but not the legs when compared to paraplegics who trained < 7 h·wk⁻¹. Sutton et al. (2009) found a greater lean mass in the upper body of elite female wheelchair basketball players when compared to a matched able-bodied group who did not take part in competitive sport. The able-bodied group however had a greater lower-body lean mass. These findings suggest that upper-body FFM could be changed with training, but muscle wastage due to time since injury is more likely to influence values of body composition in the lower body. Elite sports training of up to 20 h·wk⁻¹ could optimise an individual’s potential FFM, and the nature of both wheelchair basketball and rugby training could be causing similar FFM values in certain segments of the body in these athletes. In agreement with this concept, the results of this study show similarities in REE corrected for all FFM segments of the upper-body.

4.5.6 Spinal cord injury and body composition.

Skeletal muscle has a low metabolic activity when compared to the organs in the trunk (Wang et al., 2000). However, muscle mass is large and has been shown to be one of the major contributors to REE (Illner et al., 2000) along with the brain and the liver (Gallagher et al., 1998). No changes in mass are reported in the liver after an SCI (Sugarman, 1985), and the contribution of heart mass to total REE is small (Gallagher et al., 1998). With this in mind, the concept of skeletal muscle contributing to the differences in metabolism in different disability groups is strong. An important point to note is that completeness of lesion level would potentially have a greater effect on FFM than time since injury. Individuals with an incomplete lesion level show a higher percentage of FFM per
body mass than individuals with complete lesions (Buchholz et al., 2003a). However, as there were only 2 tetraplegic individuals out of 13 who had incomplete lesions, this would not likely have had a significant effect on the FFM between the two groups.

4.5.7 Limitations

The results show a non-significant yet meaningful difference in absolute REE between tetraplegic and paraplegic athletes. Although power analysis suggested 10 participants in each group was adequate for significance to be found, the finding of no significant difference in REE may be due to a large variation in participants. A potential lack of true rested state must also be acknowledged, as these elite athletes, although fasted, may have elevated REE due to unrecorded sports participation the day prior to testing. As described previously, a greater lower-body FFM was shown in the tetraplegic, when compared to the paraplegic athletes. Although this may have been due to the time since disability, as discussed earlier, it must be noted that 4 out of 11 participants in the paraplegic group had a congenital disability leading to potentially different body composition of the lower limbs.

4.6 Conclusions

The body composition and large amount of sports training of this unique cohort suggests the results of the current study are applicable to the elite wheelchair sport setting. The absolute REE results of the current study are in disagreement with previous reports that REE is significantly lower in tetraplegic when compared to paraplegic individuals (Cox et al., 1985; Mollinger et al., 1985). In this respect it is hard to generalise the outcome of the current study to the non-athlete rehabilitation setting. It is important to account for the various segments of FFM when comparing REE between groups so we can understand how each segment is affecting the overall REE of an individual. However, it is imperative to consider absolute values of both FFM and REE for practitioners to be able to give advice to athletes. The greater lower-body FFM in the tetraplegic group may lead to differences in REE when correcting for this FFM segment. However, lower-body FFM as a percentage of total-body FFM is smaller than that of upper-body FFM. With this in mind, it can be suggested that the REE of elite athletes with tetraplegia and paraplegia is similar when adjusted for upper-body FFM. The comparable upper-body FFM values may be a consequence of elite sports training specific to this study’s cohort.
Chapter 5

Energy expenditure of wheelchair propulsion in novice individuals after 3 weeks practice

5.1 Abstract

**Purpose:** To firstly investigate the effect of 3 weeks practice on EE during wheelchair propulsion in novices and secondly, to examine any effects of practice on temporal and force application parameters. **Methods:** Twenty-two male, able-bodied participants were pair-matched according to push frequency between two groups: practice (PRAC; n=11) and control (CON; n=11). Pre- and post-test measures consisted of three 4-minute stages at 1.1, 1.5 and 1.9 m·s⁻¹ at a 0% gradient on a motor driven treadmill. During the final minute of each stage, VO₂ and push frequency were recorded, and HR was monitored continuously throughout the test. The PRAC group took part in wheelchair propulsion three times a week for 3 weeks. Each practice session consisted of two 4-minute stages at fixed P₀ of 10 and 18 watts (W) at a speed of 1.1 m·s⁻¹. Before the main protocol, a 4-minute exercise stage was completed using a 0.614m SMARTWheel which collected kinetic measures from each participant. Energy expenditure was estimated from the VO₂ measurement at each speed. **Results:** For the EE data across all speeds, there was a significant main effect of time (p < 0.05) but no main effect of group or interaction between time and group. Trends in the data suggested that EE decreased as a result of practice with relative reductions of 10%, 13% and 9%. In comparison, the CON group showed smaller reductions of 5% 8% and 6% at 1.1, 1.5 and 1.9 m·s⁻¹ respectively. In terms of push frequency, there was a significant main effect of time showing a reduction in push frequency between pre- and post-test across all three speeds (p ≤ 0.001). The effects of practice on temporal and force application parameters at 1.1 m·s⁻¹ show mean work per cycle, stroke time and recovery time all increased significantly from pre- to post-test (p < 0.001). Comparable to push frequency findings, both groups reported similar responses over the 3-wk practice regardless of intervention. **Conclusions:** Energy expenditure, HR, VO₂ and push frequency all reduced, and GE, cycle time, recovery time and work per cycle increased, from pre- to post-test. These changes appear to be related not only to 3 weeks practice but also after 36 minutes of propulsion by the CON group during the pre-test protocol.
5.2 Introduction

Previous research has demonstrated that the O$_2$ cost of wheelchair propulsion is directly related to hand-rim velocity (Veeger et al., 1992a), can be influenced by the properties of the wheelchair-user interface (van der Woude et al., 1989a; Beekman et al., 1999; van der Woude et al., 2009), through various periods of learning (de Groot et al., 2002a; 2005; 2007; 2008) and chosen push strategy (van der Woude et al., 1989b; Goosey et al., 2000; Lenton 2008a; 2008b; 2009). Despite the interest in this topic, wheelchair propulsion remains a relatively inefficient mode of ambulation with GE values rarely exceeding 10% during daily wheelchair use (van der Woude et al., 1986; Vanlendewijck et al., 1994). Stainsby et al. (1980) defined GE as the ratio of external work accomplished (power output) over metabolic power needed to do that work. Therefore, when $P_O$ is maintained and GE increases, as research has suggested following wheelchair practice (Dallmeijer et al., 1999b; van der Woude et al., 1999; de Groot et al., 2002a; 2005; 2008), a reduction in EE would be anticipated. In light of this, the development of an efficient propulsion technique is warranted to reduce the strain on muscles (de Groot et al., 2007). In addition, an understanding of what happens during the early stages of skill acquisition in terms of EE for this exercise modality is of interest to practitioners to help inform them of the most appropriate nutritional advice to offer.

A reduction in the EE of wheelchair locomotion following 7 weeks low intensity training has been reported in able-bodied participants (van den Berg et al., 2010). The physiological and biomechanical variables associated with this reduction remain unclear, but improvements in propulsion technique and co-ordination may be responsible, as suggested by de Groot et al. (2002a). Interestingly, research has found no change in the forces applied to the hand-rim following practice (de Groot et al., 2002a; Goosey-Tolfrey et al., 2011). This is in contrast to earlier research suggesting force application and push characteristics may help provide an insight into the pattern of metabolic cost during practice, with lower GE being the consequence of ineffective propulsion force (Veeger et al., 1992a). Individuals producing forces considered ineffective for the forward movement of the wheelchair are required to produce larger forces to generate an effective torque (Boninger et al., 1997), suggesting a potentially greater physiological cost is needed to produce these forces. However, Bregman et al. (2009) actually reported a greater strain on the shoulder and less muscular efficiency when measuring forward force during wheelchair propulsion. In a study investigating both novice and experienced wheelchair users, Veeger
et al. (1992b) found no difference in force application to the hand-rim between these two cohorts. Effective force application was shown not to change after 8 minutes of propulsion in novice individuals (de Groot et al., 2003) or after 3 weeks practice in novice individuals (de Groot et al., 2002a). Therefore, further research is warranted to explore the adaptations during the course of practice alongside other propulsion-related variables.

To further investigate the improvements in GE and therefore the potential reduction in EE following practice, temporal parameters exhibited during the propulsive cycle may be of interest. In contrast to most other activities, wheelchair propulsion provides individuals the opportunity to self-select an arm frequency and propulsion technique which suits them and the task requirements (Lenton et al., 2008a). It has become evident, following 3 weeks practice, that there is a reduction in push frequency and an increase in cycle/push time (de Groot et al., 2002a; Goosey-Tolfrey et al., 2011). Since these adaptations are shown alongside improvements in GE, there is a potential link between these parameters (de Groot et al., 2002a; de Groot et al., 2008).

Therefore, the purpose of the study was, firstly, to investigate the effect of 3 weeks practice on EE during wheelchair propulsion and, secondly, to examine the effects of 3 weeks practice on temporal and force application parameters. The research hypotheses were: i) Three weeks practice significantly reduces EE and other physiological variables during wheelchair propulsion, and ii) Practice significantly reduces push frequency, increasing the cycle/push time.

5.3 Methods

5.3.1 Participants

Twenty-two able-bodied male participants with no prior wheelchair propulsion experience gave written informed consent prior to participation. Approval for the study was obtained from Loughborough University’s Ethical Committee. Body mass was recorded to the nearest 0.1 kg using double beam wheelchair scales (300 series, Marsden, London, UK). Body length was recorded using a Leicester height measure (SECA Ltd). Body composition was measured using the skin-fold technique with Harpenden skin calipers (FitnessAssist, Wrexham, UK). Measurements were taken on the right hand side of the body (Marfell-Jones et al., 2006), and the four sites measured were the triceps, biceps, sub-scapular and iliac crest.
5.3.2 Design

Participants were pair matched according to push frequency between two groups: practice (PRAC; n=11) and control (CON; n=11). Participant characteristics are shown in Table 5.1. All participants were tested in the same wheelchair (Invacare Top End Crossfire Titanium; Bromakin, UK), configured with 0.592 m diameter wheels, 4° camber, solid tyres and a total mass of 12.5kg. All testing took part on a motor driven treadmill (HP Cosmos Saturn, Nussdorf-Traunstein, Germany). The PRAC group took part in wheelchair propulsion three times a week for 3 weeks. Before (pre-) and after (post-) the 3 week practice period, participants attended the laboratory between 08:00 – 09:00 hours after a 12-hour fast to perform a sub-maximal exercise test. Data obtained included sub-maximal EE, GE and propulsion technique parameters. The CON group participated in both pre- and post-tests but received no wheelchair propulsion practice in between. The participants were asked not to change their normal daily activity patterns during this experimental period.

5.3.3 Test protocol

The sub-maximal exercise test consisted of four 4-min stages at 0.7, 1.1, 1.5 and 1.9 m·s⁻¹ (0% gradient) with a 5-minute rest period between stages. Speeds used were in accordance with previous literature (van der Woude et al., 1988; 1999; Washburn and Copay 1999; de Groot et al., 2002a). A pilot study was also completed, which recorded the speeds of daily propulsion. Using wheelchair data loggers described in Tolerico et al. (2007), the data revealed that speeds ranged from 1.0 – 2.1 m·s⁻¹, further supporting the selected speeds for the current investigation. The data obtained during the 0.7 m·s⁻¹ stage was not used in subsequent analysis due to high respiratory exchange ratio (RER) values measured in individuals. A further four exercise stages were completed for separate analysis (as part of Chapter 6) and these results were not included in the current study. This resulted in an extra 16 minutes of propulsion equalling 36 minutes in total for the pre-test. During the pre- and post-tests, push frequency and ratings of perceived exertion (RPE) were recorded in the final minute of each stage. Each participant received detailed instructions about the use of the 15-point Borg scale (Borg, 1970) and given an example of how to score their RPE. Expired gas was collected using the Douglas bag technique. Oxygen uptake and \( \dot{V}CO_2 \) concentrations in expired gas were measured using a paramagnetic oxygen analyser and infrared CO₂ analyser (Series 1400, Servomex Ltd., Sussex, UK), which was calibrated with known gas concentrations. A dry gas meter
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Energy expenditure of wheelchair propulsion after 3 weeks practice

(Harvard Apparatus, Kent, UK) was used to determine the volume of the expired gas samples, which were corrected to standard temperature and pressure (dry). Heart rate was recorded continuously (PE4000 Polar Sport Tester, Kempele, Finland) using radio telemetry.

On completion of the post-test sub-maximal stages, all participants had a 20-minute recovery period. Following this, participants performed a $\dot{V}O_2$\textsubscript{peak} test. This test to volitional exhaustion involved an incremental gradient protocol starting at 1% gradient, with increments every minute at a constant speed which ranged from 1.3 - 1.7 m·s\textsuperscript{-1}. All participants satisfied the criteria for a valid $\dot{V}O_2$\textsubscript{peak} of a peak RER $\geq$ 1.10 and an RPE score of 19 or 20 (Borg, 1970). However, 4 PRAC and 3 CON participants did not reach the HR$\text{peak} \geq 95\%$ of the age-predicted maximum (200 b·min\textsuperscript{-1} minus age in years) (Goosey-Tolfrey and Price, 2010). This is most likely as a result of exercise termination due to peripheral fatigue rather than maximal cardiovascular values (Bar-Or and Zwiren, 1975).

5.3.4 Practice

The practice period completed by PRAC consisted of two 4-minute exercise stages at a fixed $P_0$ of 10 and 18 W and propulsion speed of 1.1 m·s\textsuperscript{-1}. This was to ensure all participants received the same volume of exercise. Practice was conducted at the same time of day on three separate days of the week for a 3-week period.

5.3.5 Energy expenditure

The equation by Frayn (1983) was used to estimate carbohydrate and fat oxidation in g·min\textsuperscript{-1} using the values of $\dot{V}O_2$ and $\dot{V}CO_2$ in L·min\textsuperscript{-1}:

\begin{align*}
\text{Carbohydrate:} & \quad (4.55 \times \dot{V}CO_2) - (3.21 \times \dot{V}O_2) \\
\text{Fat:} & \quad (1.67 \times \dot{V}O_2) - (1.67 \times \dot{V}CO_2)
\end{align*}

The Atwater factors (Atwater, 1889) were used to convert oxidised carbohydrate and fat into EE (kcal·h\textsuperscript{-1}) as described in Chapter 3, section 3.3.4. The original $\dot{V}O_2$ and $\dot{V}CO_2$ were used when the RER was between 0.7 and 1.05 (de Groot et al., 2007). However, when the RER was out of this range, regression analysis was performed between EE and HR of preceding and subsequent stages to predict the EE for the given stage.
5.3.6 Gross mechanical efficiency

Gross efficiency was calculated for each of the sub-maximal exercise blocks according to the following equation:

\[ \text{GE} \% = \left( \frac{\text{external work}}{\text{EE}} \right) \times 100 \quad \text{(Stainsby et al., 1980)}. \]

5.3.7 Kinetic measurements

Prior to the sub-maximal testing protocol, a separate 4-minute exercise stage at 1.1 m·s\(^{-1}\) (0% gradient) was completed using a 0.614 m SMART\(^\text{Wheel}\) (Three Rivers Holdings LLC, Phoenix, AZ). The wheel was positioned on the right side of the chair to collect force application data. This data was collected via a wireless transmitter and filtered with a frequency of 20 Hz to enable hand-rim forces and moments around the wheel axis to be measured. From the data, torque (M), velocity (v) and components of force (Fx (horizontally forwards), Fy (vertically down) and Fz (horizontally inwards)) were used to calculate forces. The total force (F\(_{\text{res}}\)) was calculated according to Veeger et al. (1992c):

\[ F_{\text{res}} \, (N) = \sqrt{F_x^2 + F_y^2 + F_z^2} \]

The tangential force (F\(_{\text{tan}}\)), described as the force contributing to the effective movement of the wheel, was calculated according to Veeger et al. (1992c):

\[ F_{\text{tan}} \, (N) = \frac{M}{r_r} \]

where \(r_r\) is the radius of the hand-rim (0.276 m).

The fractional effective force (FEF) can be determined:

\[ \text{FEF} \% = \left( \frac{F_{\text{tan}}}{F_{\text{res}}} \right) \times 100 \]

All forces and moments were expressed as mean values per stroke and were then averaged over the total number of strokes produced during the final minute of data collection. The push time was defined as the time a positive torque was exerted by the wheelchair user. Recovery time was defined as the period between pushes, and cycle time was the total time
of both the push and recovery. Work per cycle was calculated as work done divided by cycle time.

5.3.8 Calculation of fixed $P_O$

To obtain the fixed $P_O$, a drag test was performed for each individual. The drag test consisted of the wheelchair being pulled with a cord from a force transducer (Figure 5.1) at a treadmill speed of 1.1 m·s$^{-1}$ at fixed incremental gradients. The force transducer (KAP-E – Angewandte System Technik, Germany; Software –ADA2, Vrije Universiteit; Amsterdam) measured drag force ($F_{drag}$), which was used in the equation from van der Woude et al. (2001):

$$P_O(W) = F_{drag} \times v$$

Where $v = $ velocity of the treadmill. This equation allowed each individual’s $P_O$ to be calculated. To ensure the same $P_O$ for all participants the following calculation was used:

$$\frac{(\text{individual } P_O / v) - (\text{standard } P_O / v)}{9.81}$$

This required additional mass (kg) to be added on a pulley system (Figure 5.2), so all participants were pushing at the same $P_O$. They did not receive any verbal instructions on wheelchair propulsion during this period.

![Figure 5.1](image_url) Illustration of the wheelchair during the drag test for the calculation of drag force.
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5.3.9 Statistical analyses

Data were reported as mean (±SD). The SPSS (version 18; Chicago, Illinois, USA) was used for all statistical analyses. Independent t-tests were used to establish if there were any significant differences between groups for characteristics. Separate 2 x 2 (time x group) mixed measures ANOVA were used to establish if there was any significant differences between PRAC and CON over the 3 week period in EE, GE, HR, \( \dot{V}O_2 \), RPE, push frequency and force application parameters. These analyses were completed separately for the three speeds. The significance level was set at \( p \leq 0.05 \). Push frequency and HR at 1.9 m.s\(^{-1}\) were log transformed due to skew, kurtosis and non-parametric distribution prior to performing statistical analysis. Means (±SD) are reported from the original data.

5.4 Results
5.4.1 Characteristics

There was 100% adherence to the intervention from all participants. No significant differences were found between groups for age, body length and body mass (Table 5.1). No significant differences were found in post-test levels of \( \dot{V}O_2 \)\(_{\text{peak}} \) or \( HR \)\(_{\text{peak}} \) between the two groups (Table 5.1).
5.4.2 Energy expenditure

Energy expenditure at the three speeds for both groups is plotted in Figure 5.3. For all speeds there was a significant main effect of time (p < 0.05) but no main effect of group or interaction between time and group. Trends in the data suggested that EE decreased between pre- and post-tests following practice. Relative reductions were greater in the PRAC group (10%, 13% and 9%) when compared to the CON group (5% 8% and 6%) for EE at 1.1, 1.5 and 1.9 m·s⁻¹ respectively. The PRAC group showed a trend in the data towards larger reductions to that of CON despite a non-significant main effect of group over the three speeds (p > 0.05).

5.4.3 Gross mechanical efficiency

The GE at the three speeds for both groups is shown in Table 5.2. No significant main effect of group or significant interaction between time and group was shown at any propulsion speed. A non-significant main effect of time was shown in GE between pre- and post-tests (p ≤ 0.13). Following practice, GE improved relatively by 11%, 13% and 9% at 1.1, 1.5 and 1.9 m·s⁻¹ respectively. The control group also improved GE by 2% at each speed.

### Table 5.1. Participant characteristics for PRAC (n=11) and CON (n=11). Values are means (±SD).

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yrs)</th>
<th>Body length (m)</th>
<th>Body mass (kg)</th>
<th>VO₂peak (L·min⁻¹)</th>
<th>HRpeak (b·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRAC</td>
<td>20.6(2.9)</td>
<td>1.83(0.71)</td>
<td>75.4(8.9)</td>
<td>2.50(0.45)</td>
<td>173(13)</td>
</tr>
<tr>
<td>CON</td>
<td>21.7(3.1)</td>
<td>1.85(0.67)</td>
<td>81.8(15.1)</td>
<td>2.54(0.54)</td>
<td>172(18)</td>
</tr>
</tbody>
</table>
Figure 5.3. Mean (±SD) EE for pre-test and post-test in the PRAC and CON at
1.1 m·s⁻¹, 1.5 m·s⁻¹ and 1.9 m·s⁻¹. * Significant difference (p < 0.01) and # (p <
0.05) between pre-test and post-test (main effect of time).

5.4.4 Physiological variables and perceptions of effort

Heart rate across the three speeds decreased from pre- to post-test (Table 5.2); however there was no significant main effect of group and no interaction between time and group. The same patterns were shown for VO₂, with a significant main effect of time showing a reduction in VO₂ between the pre- and post-tests (Table 5.2). There was a significant main effect of group at 1.5 m·s⁻¹ (although the PRAC and CON groups had different values at pre-test, the difference was not significant, p = 0.28). The reduction in VO₂ followed the same pattern in both groups as evidenced by a non-significant (p > 0.31) group by time interaction over the three speeds. There was a main effect of time (p < 0.02) for RPE with a reduction from pre- to post-test at all three speeds. Although there was no significant main effect for group, there was a significant interaction between time and group at 1.5 and 1.9 m·s⁻¹ (p = 0.01 and 0.04 respectively) and a trend towards a significant interaction at 1.1 m·s⁻¹ (p = 0.08) showing that, with practice, RPE decreases to a greater extent than in the CON group over the three speeds.
5.4.5 Hand-rim forces and timing parameters

There was a significant main effect of time showing a reduction in push frequency between pre- and post-tests at all three speeds (p ≤ 0.001) (Figure 5.4). There was no significant main effect of group at any of the speeds and no significant interaction between time and group, suggesting both groups responded in a similar way. The effects of practice on hand-rim forces and the timing variables at 1.1 m·s⁻¹ are shown in Figure 5.5. Mean FEF, work per cycle, push time and recovery time all increased significantly from pre- to post-test (p < 0.001). Both PRAC and CON demonstrated identical trends regardless of intervention over the 3-week period.

Table 5.2. Gross efficiency, HR, RPE and $\dot{V}$O₂ for PRAC and CON at the 3 speeds and results of the 2x2 (time x group) mixed design ANOVA. Values are means (±SD).

<table>
<thead>
<tr>
<th>Speed (m·s⁻¹)</th>
<th>PRAC</th>
<th>CON</th>
<th>ANOVA p values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test</td>
<td>Post-test</td>
<td>Pre-test</td>
</tr>
<tr>
<td>1.1</td>
<td>3.75 (0.39)</td>
<td>4.15 (0.69)</td>
<td>3.99 (0.56)</td>
</tr>
<tr>
<td>1.5</td>
<td>4.09 (0.55)</td>
<td>4.61 (0.70)</td>
<td>4.25 (0.67)</td>
</tr>
<tr>
<td>1.9</td>
<td>4.08 (0.90)</td>
<td>4.45 (1.13)</td>
<td>4.16 (0.57)</td>
</tr>
<tr>
<td>1.1</td>
<td>85 (12)</td>
<td>75 (10)</td>
<td>85 (12)</td>
</tr>
<tr>
<td>1.5</td>
<td>91 (15)</td>
<td>81 (10)</td>
<td>97 (13)</td>
</tr>
<tr>
<td>1.9</td>
<td>105 (23)</td>
<td>94 (14)</td>
<td>107 (17)</td>
</tr>
<tr>
<td>1.1</td>
<td>10 (1)</td>
<td>8 (2)</td>
<td>9 (2)</td>
</tr>
<tr>
<td>1.5</td>
<td>12 (1)</td>
<td>10 (1)</td>
<td>11 (2)</td>
</tr>
<tr>
<td>1.9</td>
<td>13 (1)</td>
<td>11 (2)</td>
<td>12 (2)</td>
</tr>
<tr>
<td>1.1</td>
<td>0.62 (0.06)</td>
<td>0.56 (0.09)</td>
<td>0.65 (0.14)</td>
</tr>
<tr>
<td>1.5</td>
<td>0.75 (0.06)</td>
<td>0.68 (0.09)</td>
<td>0.86 (0.21)</td>
</tr>
<tr>
<td>1.9</td>
<td>0.99 (0.15)</td>
<td>0.88 (0.17)</td>
<td>1.05 (0.20)</td>
</tr>
</tbody>
</table>
Chapter 5  Energy expenditure of wheelchair propulsion after 3 weeks practice

Figure 5.4. Mean (±SD) push frequency for both PRAC and CON from pre- to post-test at 1.1 m·s\(^{-1}\), 1.5 m·s\(^{-1}\) and 1.9 m·s\(^{-1}\). * Significant difference (p <0.01) between pre- and post-test at all speeds.

5.5 Discussion

This study investigated the effects of three weeks’ wheelchair propulsion practice on the physiological, kinetic and temporal responses in novice able-bodied participants. The main findings report reductions in EE, \(\dot{V}O_2\) and HR following a 3-week period regardless of intervention (PRAC or CON). Improvements are also shown in temporal parameters. This supported the hypothesis that three weeks of wheelchair propulsion practice would lead to an improvement in both physiological and technique parameters. However, it does not support the hypothesis that improvements would be significantly greater in the PRAC group in comparison to the CON group.
Figure 5.5. Mean (±SD) for (a) resultant force (F<sub>res</sub>), (b) tangential force (F<sub>tan</sub>), (c) fractional effective force (FEF), (d) work per cycle, (e) push time and (f) recovery time during wheelchair propulsion at 1.1 m·s<sup>-1</sup> for PRAC and CON for pre-test and post-test trials. *Significant difference from pre- to post-test (p < 0.01).

Note. This data was collected using the 0.614 m SMART<sup>Wheel</sup>. 
5.5.1 Energy expenditure and GE

To the author’s knowledge this study was the first to document a reduction in EE following practice over a 3-week period. Practice is an interesting phenomenon for able-bodied participants without any experience in wheelchair propulsion, as several adaptations can occur during the initial phases of learning (de Groot et al., 2003; Dallmeijer et al., 1999b; van der Woude et al., 1999). The hypothesis that ‘three weeks’ practice significantly reduces EE in comparison to no practice’ was rejected, as a reduction of 5-6% was also observed in the CON group. These participants performed only 36 minutes of wheelchair propulsion during the pre-test session yet, as shown, this short propulsion exposure seemed to have impacted upon the post-test performance. In comparison, the PRAC group performed 108 minutes of wheelchair propulsion, including the pre-test, which resulted in a greater reduction in EE (9-13%) although statistically insignificant. Research has demonstrated that wheelchair propulsion skills can be learned following only 8 minutes of practice (de Groot et al., 2003) and so the validity of experimental designs that include a control group is somewhat questionable. It must be noted that the inter-individual variation in EE could have contributed, together with sample size, to the lack of significance between groups. However, as three weeks of practice demonstrated a greater reduction in EE than no practice, it is suggested that further investigation should explore the duration and type of practice to greater understand optimal reduction in EE. The aforementioned improvements for both PRAC and CON is not a unique finding, as improvements in GE have also been noted after a short period of practice in novice wheelchair users and between pre- and post-test results for control groups (Dallmeijer et al., 1999b; van der Woude et al., 1999).

Absolute EE has been shown to reduce after wheelchair propulsion practice at the same relative \( P_0 \) and at a speed of 1.39 m\( \cdot \)s\(^{-1} \) (van den Berg et al., 2010). The results of the current study add to this data and suggest that novice individuals show a reduction in EE at the faster speed of 1.9 m\( \cdot \)s\(^{-1} \). If EE reduces and other physiological measures improve at fast daily speeds, individuals may be able to exercise regularly at higher intensities after practice. Greater fitness gains and higher activity levels could then be achieved. However, it is still important to be cautious in the early stages of rehabilitation as practice programmes may adopt a lower push frequency technique to reduce the chance of overuse injury and optimise correct wheelchair propulsion (Boninger et al., 2002).
5.5.2 Physiological variables and perceptions of effort

Heart rate and \( \dot{\text{VO}}_2 \) showed similar trends to that of EE with a reduction between pre- and post-tests. Once more, there were no differences shown between groups. The results are in agreement with data showing decreases in HR and \( \dot{\text{VO}}_2 \) after 7 weeks of wheelchair propulsion training in novice able-bodied participants (de Groot et al., 2008; van den Berg et al., 2010). Interestingly, both studies described their 7-week practice intervention as low intensity ‘training’ (working at 30% HR reserve). Yet since this is lower than the minimal recommended exercise intensity of \( \geq 40\% \) HR reserve (ACSM, 2006), these studies show physiological adaptations were more likely to be achieved through changes in propulsion technique rather than through improvements in physical fitness. As the current study was also not designed to induce training effects, this adds to the literature providing practitioners with an appreciation of the physiological effect which learning wheelchair propulsion has without the influence of training.

A different response was shown in the subjective measures of effort during daily propulsion (RPE) after practice when compared to CON. Interestingly, the interaction effect between time and group suggested an effect of practice on RPE, with greater relative reductions of up to 18% when compared to a maximum of a 5% reduction for the CON group. The importance of understanding how an individual subjectively rates exercise intensity is a key issue in the rehabilitation setting where individuals practice wheelchair skills. This is also important for the general wheelchair user population, where adherence to physical activity may improve as it becomes subjectively easier to do. Our findings suggest that RPE reduces to a greater extent after 3 weeks of practice, so if RPE is used as a tool to monitor exercise intensity then the practitioner must be aware of these patterns over time.

The measurement of RPE in a population with a disability may be of greater value than the HR to monitor exercise intensity, as spinal cord injury can cause a disruption to the autonomic nervous system (Maynard et al., 1997). Subjective signs of exercise intensity may be more sensitive to practice than physiological markers, and adherence to physical activity may improve if it is subjectively easier to do. To obtain health benefits from exercise, wheelchair users must remain physically active during and after rehabilitation programs (Dallmeijer et al., 1999c) and, therefore, RPE offers a useful tool for individuals to use in their own environment to self-regulate exercise intensity (Grange et al., 2002; Goosey-Tolfrey et al., 2010).
5.5.3 Hand-rim force application and timing parameters

The FEF for both groups reduced from pre- to post-test which was most likely due to the reduced ratio between $F_{tan}$ and $F_{res}$, thus indicating that there was an increase in force application but not in the forward direction. An improvement in $F_{tan}$ may not, therefore, be necessary for the significant reduction in EE. This is in disagreement with Veeger et al. (1992a) who suggested that a decreased GE and increased EE is due to ineffective force production. In line with their findings, Dallmeijer et al. (1999b) reported an increase in GE and an improvement in FEF in a group following a 7-week wheelchair training programme and in a control group, although this latter improvement was not significant. However, the present study’s force application results are not isolated. De Groot et al. (2002b) found that, although FEF can improve with visual feedback practice over a 3-week period with this improvement, no expected improvement in GE was reported. In line with this, de Groot et al. (2002a) and Goosey-Tolfrey et al. (2011) found an increase in GE with no change in force parameters after three weeks of practice. In direct contrast to Dallmeijer et al. (1999b), Bregman et al. (2009) actually found greater strain on the shoulder and less efficiency of the muscle when measuring $F_{tan}$ during wheelchair propulsion. From these findings it seems an improved direction of force on the hand-rim is not related to a reduction in EE. Consequently, other parameters of propulsion technique may have a greater influence on the metabolic cost of this skill.

From pre- to post-test, results show a reduction in push frequency in PRAC and CON. Alongside this, mean work per cycle, stroke time and recovery time increased in both groups. The findings are in agreement with Goosey-Tolfrey et al. (2011), who reported an increase in cycle time alongside an improvement in GE after a 3-week practice period in novice wheelchair users. In the able-bodied literature, Lay et al. (2002) reported significant reductions in $\dot{V}O_2$ and increased recovery duration during strokes after practice in rowing. The suggestion was that decreased muscle activation could be, in part, responsible for a lower metabolic cost. A reduced cycle frequency and longer recovery between pushes may reduce arm acceleration and deceleration (de Groot et al., 2003). The result of a reduced arm de/acceleration has been linked to decreased muscular activity which, in turn, leads to less energy consumption (Vanlandewijck et al., 1994a).
5.6 Conclusions

The first hypothesis of the current study was accepted as three weeks of practice resulted in reductions in EE, HR, VO\textsubscript{2} and RPE. Moreover, the second hypothesis was also accepted as there was a significant reduction in push frequency and an increase in recovery and cycle time after the 3-week practice period. However, it was interesting to note that improvements were not only a consequence of 3 weeks of practice, but also due to just 36 minutes of wheelchair activity. The increased recovery and cycle time, rather than effectiveness of the force application, may be linked with a decrease in EE. The reduction in EE after only a short period of exposure to wheelchair propulsion confirms that the metabolic cost is influenced through learning and improved propulsion technique. To take this a step further, an exploration of the effects of experience and practice on the EE of wheelchair propulsion will be the main focus of the next chapter. Progression of this research looks to offer a greater insight into the pattern of EE in the rehabilitation setting as well as during habitual daily life in wheelchair users.
6.1 Abstract

**Purpose:** To investigate the effects of experience on EE during wheelchair propulsion at fixed P₀’s. **Methods:** Thirty-one participants were assigned to a group in accordance to their wheelchair propulsion experience: 1) novice able-bodied individuals (NOV; n = 11), 2) able-bodied individuals habituated to three weeks practice (PRAC; n = 11) and 3) experienced paraplegic daily-wheelchair users (EXP; n = 9). The PRAC group took part in three weeks of wheelchair propulsion practice, consisting of two 4-minute stages on a motor-driven treadmill at fixed P₀’s of 10 and 18 W at a speed of 1.1 m·s⁻¹, prior to testing. The sub-maximal exercise testing session consisted of three 4-min stages at 10, 18 and 26 W at a 0% gradient with a 5-minute rest period between stages. During the final minute of each stage, VO₂ and push frequency were recorded and HR was recorded continuously. Energy expenditure was estimated from VO₂ values. **Results:** Energy expenditure analysis revealed a significant main effect of P₀ and group (p < 0.01) and a significant group by P₀ interaction (p < 0.01). Follow-up pair-wise comparisons revealed significantly lower EE in EXP compared to both other groups (p < 0.01), but no difference was shown between NOV and PRAC (p = 0.15). A lower relative EE of 20, 22 and 32% was reported in the EXP group compared to the NOV group at 10, 18 and 26 W, respectively. In comparison to the PRAC group, the EE of the EXP group was 10, 16 and 26% lower in relative terms at the same P₀’s respectively. There was a main effect of P₀ for HR, RPE and VO₂, and a main effect of group for RPE and VO₂. Follow-up pair-wise comparisons revealed that, for RPE, the difference existed between EXP and NOV (p = 0.02) and, for VO₂, EXP had lower values than both NOV (p <0.01) and PRAC (p = 0.01). **Conclusion:** The EXP group had lower EE compared to both NOV and PRAC groups at fixed P₀’s, suggesting experience reduces the EE of sub-maximal wheelchair propulsion. Although practice reduced EE, no significant reductions were shown between PRAC and NOV.
6.2 Introduction

The O\textsubscript{2} cost and efficiency of wheelchair propulsion is affected by the P\textsubscript{O} of the wheelchair-user interface (van der Woude et al., 1988; Veeger et al., 1992a). Power output is affected by speed and drag forces, which are influenced by wheelchair configuration (contributing to the magnitude of internal friction), rear wheel size (affecting the rolling resistance), and floor surface characteristics (van der Woude et al., 2001). When P\textsubscript{O} is controlled, similar O\textsubscript{2} costs have been reported between individuals during cycle ergometry (Hansen et al., 1988; Ästrand et al., 2003). Pilot work for this study has shown that large variations in EE exist between paraplegic individuals during daily ambulation at fixed speeds on a motorised treadmill. It is clear that understanding the EE of wheelchair propulsion requires the P\textsubscript{O} to be controlled (van der Woude et al., 1988). Nevertheless, EE during wheelchair propulsion could still vary depending upon the level of experience as reported in the able-bodied literature (Holmer, 1972; Pannier et al., 1980; Ingham et al., 2007). For example, lower O\textsubscript{2} cost is evident in experienced athletes when compared to novices at the same absolute speed in swimming (Holmer, 1972) to novice runners at sub-maximal treadmill speeds (Pannier et al., 1980), and to club athletes in rowing at the same relative work load (Ingham et al., 2007). More recently, wheelchair propulsion practice (Chapter 5) has been found to reduce EE at fixed speeds, thus suggesting that the level of experience and practice between individuals may affect the EE of daily wheelchair propulsion when pushing at a fixed P\textsubscript{O}.

Research into hand-rim wheelchair propulsion has demonstrated that experienced wheelchair users report significantly greater GE values than novice able-bodied individuals at the same propulsion velocity (van der Woude et al., 1986) or the same relative exercise intensity (Lenton et al., 2008a). At a fixed P\textsubscript{O}, a consistently higher GE and lower VO\textsubscript{2} in SCI individuals are seen when compared to novice able-bodied individuals during wheelchair propulsion (Brown et al., 1990; Dallmeijer et al., 2004). This may suggest that the reduced EE of the experienced group may be the result of a more efficient propulsion technique (van der Woude et al., 1986). Consequently, measurement of the absolute EE of both experienced and novice wheelchair users will provide further information about the metabolic cost of wheelchair propulsion in relation to experience.

Energy expenditure decreases after 36 minutes (Chapter 5), three weeks (Chapter 5) and seven weeks of wheelchair propulsion practice (van den Berg et al., 2010). Gross mechanical efficiency is greater as a result of propulsion experience (van der Woude et al.,
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1986; Brown et al., 1990; Lenton et al., 2008a) and increases with practice or training (de Groot et al., 2002a; 2005; 2007; 2008). These findings, alongside data that has demonstrated reductions in O$_2$ cost during motor skill practice in rowing (Sparrow et al., 1999), would suggest that EE will be lower with increased levels of wheelchair experience and propulsion practice. Reduced EE may also be influenced by improved temporal parameters of wheelchair propulsion which can occur after practice (Chapter 5, Dallmeijer et al., 1999b; de Groot et al., 2003; Goosey-Tolfrey et al., 2011).

With the O$_2$ cost of wheelchair propulsion directly affected by P$_O$ (Woude et al., 1988; Veeger et al., 1992a), standardisation of this parameter should reduce its influence on EE (van der Woude et al., 2001) when comparing different groups of individuals. By assessing the EE of wheelchair propulsion over the course of learning the skill and through years of experience, recommendations can be provided for individuals in the early stages of rehabilitation and also for habituated wheelchair users. Therefore, the purpose of this study was to investigate the effects of experience on EE during wheelchair propulsion at fixed P$_O$'s. It was hypothesised that, despite the control of P$_O$, the refined technique of experienced paraplegic wheelchair users would result in lower absolute EE when compared to NOV and PRAC groups. Although Chapter 5 reported a similar reduction of EE after 36 minutes and three weeks of wheelchair practice, it was hypothesised that three weeks of practice would elicit lower EE values than during wheelchair propulsion for the first time.

6.3 Methods

6.3.1 Participants

Thirty-one male participants volunteered and gave written informed consent to participate in this study. Approval for the study was obtained from the University Ethical Advisory Committee. Body mass was recorded to the nearest 0.1 kg using double beam wheelchair scales (300 series, Marsden, London, UK). Body length was recorded in the able-bodied individuals using a Leicester height measure (SECA Ltd) and in the paraplegics in the supine position to the nearest 0.1 cm (Luftkin tape). Body composition was obtained using the skinfold technique, taken with Harpenden skin callipers (FitnessAssist, Wrexham, UK) on the right hand side of the body in accordance with Marfell-Jones et al. (2006). The four sites measured were the triceps, biceps, sub-scapular and iliac crest.
6.3.2 Design

Participants were assigned to one of three groups in accordance with their level of wheelchair propulsion experience: 1) an able-bodied novice group (NOV; n = 11), 2) an able-bodied group habituated to three weeks of practice (PRAC; n = 11), and 3) an experienced group of paraplegic daily-wheelchair users (EXP; n = 9). Participant characteristics are shown in Table 6.1. All able-bodied participants were tested in the same daily activity wheelchair (Invacare Top End Crossfire Titanium, Bromakin, UK, configured with 0.592 m diameter wheels, 4° camber, solid tyres and a total mass of 12.5 kg). The PRAC group took part in three weeks of wheelchair propulsion practice, consisting of two 4-minute stages at fixed Po’s (10 and 18 W) at 1.1 m·s⁻¹ (described previously in Chapter 5, sections 5.3.4 and 5.3.8). The EXP group were tested in their own daily wheelchair however, with the standardised 0.592 m diameter wheels and solid tyres. The EXP group all had at least six years of experience in daily wheelchair propulsion. All groups were tested on one occasion and attended the laboratory between 08:00 – 09:00 hours after a 12-hour fast. All testing was performed on a motor-driven treadmill (HP Cosmos Saturn, Nussdorf-Traunstein, Germany). Gross efficiency, EE and push frequency were determined during the sub-maximal exercise test at each fixed Po.

6.3.3 Test protocol

The sub-maximal exercise testing consisted of four 4-min stages at 10, 18, 26 and 34W (0% gradient) with a 5-minute rest period between each stage. Power outputs were determined in accordance to previous values reported in the literature (van der Woude et al., 1999; de Groot et al., 2002a; 2008). The data obtained during the final 34 W stage was not used in subsequent analysis due to high RER values measured in the novice individuals. For the PRAC and NOV group, five sub-maximal stages were completed before this protocol took place (for separate analysis as part of Chapter 5) and these results were not included in the current study. This resulted in the NOV group completing the protocol for the current study after 20 minutes of wheelchair propulsion. During the final minute of each stage, push frequency and RPE were recorded. Each participant received detailed instructions about the use of the 15-point Borg scale (Borg, 1970) and was given an example of how they might score their RPE. Expired gas was collected using the Douglas bag technique as described in Chapter 5, section 5.3.3. Heart rate was recorded continuously (PE4000 Polar Sport Tester, Kempele, Finland) via radio telemetry. On completion of the sub-maximal stages, participants in EXP and PRAC groups received a
20-minute recovery period. Following this, participants performed a \( \bar{V}O_{2\text{peak}} \) test as described in Chapter 5 section 5.3.3. The \( \bar{V}O_{2\text{peak}} \) test speeds ranged from 1.3 – 2.6 m·s\(^{-1}\), and all participants satisfied the criteria for a valid \( \bar{V}O_{2\text{peak}} \). However, four PRAC participants did not reach the HR\(_{\text{peak}} \geq 95\% \) of the age-predicted maximum (Goosey-Tolfrey and Price, 2010).

### 6.3.4 Energy expenditure and GE

Energy expenditure and GE were calculated according to the methods described in Chapter 5, section 5.3.5 & 5.3.6.

### 6.3.5 Calculation of fixed \( P_0 \)

Calculations of the fixed \( P_0 \) were obtained as previously documented in Chapter 5, section 5.3.8.

### 6.3.6 Statistical analyses

Data were reported as mean (±SD). The SPSS (version 18; Chicago, Illinois, USA) was used for all statistical analyses. A one-way ANOVA was used to examine any significant differences between all three groups for physical characteristics. A 3x3 mixed design ANOVA was used to establish if any statistically significant differences existed between groups for EE, GE, HR, \( \bar{V}O_2 \), RPE and push frequency at 10, 18 and 26 W. Bonferroni and Games-Howell post-hoc tests were used to examine further significant effects between groups. The significance level was set at \( p \leq 0.05 \) for all analyses. RPE data was log transformed to satisfy normal distribution. Means (±SD) are reported from the original data.

### 6.4 Results

#### 6.4.1 Physical characteristics

Age and body length of the able-bodied NOV and PRAC groups did not differ, yet the EXP group had a greater age and were smaller (\( p \leq 0.03 \)) (Table 6.1). Although no significant difference was shown between groups for body mass, NOV were 13.2 kg heavier than the EXP. Follow-up pair-wise comparisons revealed that the sum of skinfold measurements tended to be higher for EXP compared with PRAC (\( p = 0.05 \); Table 6.1).
**Table 6.1.** Participant characteristics and \( \dot{V}O_{2\text{peak}} \) of NOV, PRAC and EXP. Values are means (±SD).

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yrs)</th>
<th>Body length (m)</th>
<th>Body mass (kg)</th>
<th>Sum of skinfolds at 4 sites (mm)</th>
<th>( \dot{V}O_{2\text{peak}} ) (L∙min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOV</td>
<td>21.7(3.1)</td>
<td>1.81(0.67)</td>
<td>81.8(15.1)</td>
<td>47.9(25.9)</td>
<td>~</td>
</tr>
<tr>
<td>PRAC</td>
<td>20.6(2.9)</td>
<td>1.83(0.71)</td>
<td>75.4(8.9)</td>
<td>34.0(7.1)</td>
<td>2.5 (0.5)</td>
</tr>
<tr>
<td>EXP</td>
<td>32.6(10.0)*</td>
<td>1.70(0.15)*</td>
<td>68.6(14.4)</td>
<td>52.8(17.7)*</td>
<td>2.2 (0.3)</td>
</tr>
</tbody>
</table>

**Key:** *denotes a significant main effect of group (p < 0.05).

*Note:* A \( \dot{V}O_{2\text{peak}} \) test was not completed in the NOV group. This was due to the novice status of this group and the assumption that a true \( \dot{V}O_{2\text{peak}} \) would not be reached due to lack of technique and practice.

**6.4.2 Energy expenditure**

Energy expenditure at all \( P_O \)'s for the three groups is shown in Figure 6.1. There were significant main effects for \( P_O \) and group (p < 0.01) and a significant group by \( P_O \) interaction (p < 0.01). Follow-up pair-wise comparisons applied at each \( P_O \) revealed that EE was significantly lower for the EXP compared to both other groups (p < 0.01) and that there was no significant difference between NOV and PRAC (p = 0.15). In relative terms, over the three intensities, EE of the EXP group was up to 32% lower than the NOV group and up to up to 26% lower than the PRAC group.

**6.4.3 Gross mechanical efficiency**

Gross efficiency at each \( P_O \) for the three groups is also displayed in Figure 6.1. There were significant main effects for \( P_O \) and group (p < 0.01) and a significant group by \( P_O \) interaction (p < 0.01). Follow-up pair-wise comparisons applied at each \( P_O \) revealed GE was significantly higher for EXP when compared to the other groups (p < 0.01). The margins by which EXP showed a greater GE equated to 26, 28 and 47% and 13, 18 and 38% at 10, 18 and 26 W for NOV and PRAC respectively.
Figure 6.1. Mean (±SD) EE (kcal·h\(^{-1}\)) and GE (%) for NOV, PRAC and EXP groups during wheelchair propulsion at 10, 18 and 26 (W). *denotes a significant main effect for group (p < 0.01); \(^a\) denotes a significant main effect for P\(_O\) (p < 0.01); \(^b\) denotes a significant group by P\(_O\) interaction (p < 0.01).

### 6.4.4 Physiological variables and perceptions of effort

Table 6.2 shows the HR, RPE and \(\dot{\text{V}}\text{O}_2\) across each P\(_O\) for each group. There were significant main effects for P\(_O\) for all the aforementioned variables (p ≤ 0.01) and a main effect of group for RPE and \(\dot{\text{V}}\text{O}_2\) (p ≤ 0.01). Follow-up pair-wise comparisons applied at each P\(_O\) revealed that there was a difference in RPE between EXP and NOV (p = 0.02).
The EXP group had a lower $\dot{V}O_2$ than both NOV and PRAC ($p \leq 0.01$). For both RPE and $\dot{V}O_2$, the group differences were proportional to $P_O$, increasing with greater $P_O$. There was no main effect of group when considering HR.

### 6.4.5 Push frequency

There was a significant main effect of $P_O$ and a significant main effect of group with push frequency ($p \leq 0.05$). The push frequencies for all groups during wheelchair propulsion at each $P_O$ are shown in Figure 6.2. It was evident that EXP demonstrated higher push frequencies than PRAC at each workload ($p = 0.04$). Non-significantly lower push frequencies were evident in PRAC when compared to NOV ($p = 0.44$).

**Table 6.2.** Heart rate, $\dot{V}O_2$ and RPE for NOV, PRAC and EXP at 10, 18 and 26 W. Results of the ($P_O \times$ group) mixed design ANOVA are shown. Values are means (±SD).

<table>
<thead>
<tr>
<th>$P_O$ (W)</th>
<th>NOV</th>
<th>PRAC</th>
<th>EXP</th>
<th>$P_O$</th>
<th>Group</th>
<th>$P_O$*Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (b·min$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>10</td>
<td>82 (12)</td>
<td>73 (11)</td>
<td>76 (10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>96 (12)</td>
<td>86 (12)</td>
<td>83 (12)</td>
<td>$&lt; 0.01$</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>26</td>
<td>111 (18)</td>
<td>102 (18)</td>
<td>92 (13)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $\dot{V}O_2$ (L·min$^{-1}$) |
| 10 | 0.64 (0.09) | 0.57 (0.03) | 0.52 (0.09) |       |       |             |
| 18 | 0.88 (0.10) | 0.79 (0.06) | 0.70 (0.09) | $< 0.01$ | $< 0.01$ | $< 0.01$ |
| 26 | 1.19 (0.12) | 1.09 (0.11) | 0.86 (0.14) |       |       |             |

| RPE | 18 | 11 (1) | 10 (1) | 9 (2) | $< 0.01$ | 0.02 | $< 0.01$ |
| 26 | 13 (1) | 12 (1) | 10 (3) |       |       |       |
**Figure 6.2.** Mean (±SD) push frequency during wheelchair propulsion at 10, 18 and 26 W for NOV, PRAC and EXP groups. *denotes a significant main effect of group; a denotes a significant main effect of $P_O$.

### 6.5 Discussion

This study investigated the effect of experience on the EE of wheelchair propulsion at a $P_O$ of 10, 18 and 26 W on a motor-driven treadmill. Results supported the hypothesis that EE was lower in EXP compared to NOV and PRAC. Extending the work of Chapter 5 by controlling for work load, the present findings suggested that EE did not differ following practice when compared to the values obtained from the NOV group. Despite Chapter 5 showing reductions in EE after practice, the second hypothesis of the current investigation, that the reduction in EE would be greater after three weeks of practice when compared to a novice group, was again rejected.

### 6.5.1 Energy expenditure and GE

As expected, lower EE was observed for the EXP group in addition to improved GE at each $P_O$, which is in support of and extends previous work (van der Woude et al.,
The current study revealed that the margin between the EXP and both NOV and PRAC groups for EE clearly increases as $P_O$ increases. Consequently it could be suggested that the EXP group can work at a higher workload with a lower physiological cost. Similar patterns have been noted when $\dot{V}O_2$ has been compared between novice able-bodied and experienced paraplegic wheelchair users with increasing $P_O$ during sub-maximal daily wheelchair propulsion (van der Woude et al., 1986; Dallmeijer et al., 2004). A possible explanation for this may be due to a more favourable propulsion technique having been developed through experience. This will be discussed later, as pushing economy has been previously associated with propulsion technique (Goosey et al., 2000).

The EXP group displayed a lower EE when compared to NOV by up to 32% at 26 W. This difference could make a substantial contribution to nutritional requirements if wheelchair propulsion was conducted over extended periods of time. According to de Groot et al. (2005), GE increases rapidly in the first few months of rehabilitation due to the intensity of therapy within this period. This suggests the large amounts of energy needed in the first few weeks of rehabilitation would start to reduce during continual use of a wheelchair. In the current study, after only three weeks of practice, EE was shown to be lower (by around 6-11%) than no practice. Although this difference is not statistically significant, the level of this reduction should enable practitioners to appreciate the EE patterns during the course of rehabilitation. Nevertheless, experienced wheelchair users need correct guidance for nutritional requirements also. Thus EE values obtained during rehabilitation would not be a suitable estimate of metabolic cost in experienced wheelchair users.

Data has been provided to inform individuals of the EE over various propulsion surface conditions in experienced wheelchair users (Collins et al., 2010) and at specific exercise intensities in experienced children and young adult users (Hildebrandt et al., 1970). However, this earlier work of Hildebrandt and colleagues (1970’s) would have employed older model wheelchairs, much heavier than those found today (DiGiovine et al., 2006). Consequently it is expected that the EE values would be significantly higher in earlier studies when compared to recent work. To add to the recent work of Collins et al. (2010), the inclusion of NOV, PRAC and EXP wheelchair users in the current study has allowed for comparisons between individuals with different levels of wheelchair propulsion skill.
6.5.2 Physiological variables and perceptions of effort

Oxygen uptake displayed the same pattern to that described earlier for EE, with a significantly lower VO₂ shown in the EXP group compared to the NOV and PRAC groups. In terms of the HR responses, there was a tendency for the EXP to elicit a higher HR than the PRAC group at 10 W. This may indicate the additional strain of pushing at an unfamiliar low intensity which was demonstrated by Mukherjee et al. (2002). It must be noted however, that most of the HRs are below 100 b·min⁻¹ and demonstrated high inter-individual variations within group, representing a potential lack of meaningful values from HR alone. Nevertheless, as P0 increased, HR, RPE and VO₂ were lower in EXP than NOV and PRAC providing further evidence that the physiological demand of wheelchair propulsion is lower in experienced individuals at higher intensities of propulsion.

6.5.3 Physical capacity

As the majority of the literature has shown previously, wheelchair athletes have a higher aerobic capacity than that of untrained able-bodied individuals during upper body exercise (Zwiren and Bar-Or, 1975; Hooker and Wells, 1992; Huonker et al., 1998). However, the results of the current study reported no difference in VO₂peak values between PRAC and EXP, which is in agreement with Dallmeijer et al. (2004). With this in mind, it is suggested that aerobic capacity is not an important factor when considering a reduced O₂ consumption during sub-maximal wheelchair propulsion.

6.5.4 Propulsion technique

6.5.4.i Push frequency

Absolute O₂ cost and GE has been shown to be affected by propulsion technique (Veeger et al., 1992a; Dallmeijer et al., 1998; 1999b; de Groot et al., 2002a; de Groot et al., 2008). Propulsion technique is defined by force production and timing parameters including push frequency (van der Woude et al., 1989a). de Groot et al. (2003) also suggested a reduced cycle frequency and longer recovery may cause the increase in GE during wheelchair propulsion. In light of this, a reduction in push frequency has been reported alongside reduced O₂ cost after a 3-week wheelchair propulsion practice period (de Groot et al., 2002a; Chapter 5). It is not just the effect of practice that is causing these changes, as lower O₂ cost has also been shown together with lower push frequencies in experienced wheelchair racers (Goosey et al., 2000).
The current study’s findings however do not agree with previous literature, as the EXP wheelchair users had a higher push frequency when compared to both NOV (not significant) and PRAC (p = 0.04). It must be noted that the high push frequencies may be unique to the current study’s cohort and wheelchair configurations. Furthermore, the nature of the EXP group’s sporting background, such as wheelchair basketball, which involves high intensity intermittent sprints, could help explain this finding (Lenton et al., 2008a). In the activity of cycling, not too dissimilar to the cyclic movement of wheelchair propulsion, Marsh et al. (1997) found that trained cyclists adapt to higher pedalling cadences. Similarly, EXP wheelchair users may have developed an optimal push frequency and over time show an improvement in economy. de Groot et al. (2003) suggested a reduced stroke may minimise the \( O_2 \) cost of propulsion. Therefore the NOV and PRAC groups may have been using more energy through propulsion, with larger upper body movements, rather than the more frequent but potentially smaller movements of the EXP group. Use of kinematic analysis to measure the propulsion technique of experienced and novice wheelchair users may help answer this question in the future.

As explained earlier, the reason behind the larger margin in EE between NOV and PRAC and the EXP wheelchair users as \( P_O \) increases could be due to propulsion technique. As workload increases, EXP may adapt earlier to a change in propulsion pattern when compared to NOV and PRAC. This concept is highlighted by the observation of a changed stroke pattern in experienced wheelchair users as propulsion speed increased (Boninger et al., 2002). de Groot et al. (2004) suggested segmental accelerations at the beginning and the end of a push are needed when speed increases, which could potentially lead to a change in stroke pattern. It is also important to note that the PRAC group practiced at the two lower workloads of 10 and 18 W. Therefore, the higher workload may have been unfamiliar to them and consequently produced a larger EE when compared to EXP.

6.5.4.ii Effective force production

In Chapter 5 it was established that after three weeks of wheelchair propulsion practice, the magnitude of force application increased but not in the tangential direction and thus not producing a greater effective force on the hand-rim. Goosey-Tolfrey et al. (2011) also reported no change in the FEF after a 3-week wheelchair propulsion practice. Lack of effective force production in experienced wheelchair users (Rozendaal et al., 2003) and even decreased muscle efficiency during forward force production (Bregman et al.,
2009) have been shown during wheelchair propulsion. It can therefore be assumed that effective force production would not be the likely cause of a reduced EE (de Groot et al., 2002b).

6.5.5 Limitations and considerations

Within the wheelchair propulsion literature that compares novice to experienced individuals, age differences of approximately 10 years between the youngest able-bodied novice individuals and oldest experienced wheelchair users are evident (van der Woude et al., 1989b; Grange et al., 2002; Dallmijer et al., 2004; Lenton et al., 2008a). Likewise for this study, a difference in age existed, resulting in the EXP being significantly older than the NOV and PRAC groups. Future studies may wish to consider this. Yet, despite a negative relationship being established between age and EE due to a reduction of FFM (Bosy-Westphal et al., 2003), the older mean age of 30 years for the EXP group would still have resulted in them being placed in the young group category according to work by Bosy-Westphal et al. (2003). A second factor to consider is related to body composition as the sum of skin-folds and body mass was higher in EXP compared to NOV and PRAC. This may indicate that EE was higher in the NOV and PRAC due to a greater FFM (Buchholz et al., 2003a), but more detailed information on body composition through the use of DXA is warranted.

It must also be acknowledged that cardiovascular fitness during wheelchair propulsion is difficult to determine in novice individuals as they are learning the new skill, since peripheral fatigue may overshadow the cardiovascular capacity of these individuals (Keyser et al., 1999). The nature of a maximal exertion test needs individuals to exercise until volitional exhaustion. As this was a new skill for the NOV group, the decision was made that this activity would not be appropriate for unskilled wheelchair users to undertake. Moreover, the NOV group pushed for 20 minutes prior to the main experimental protocol. This amount of time may have been sufficient to cause improvements in timing parameters leading to an improved propulsion technique (de Groot et al., 2003). For this reason it is important to acknowledge the difficulty in including a control group in wheelchair propulsion studies.
6.6 Conclusions

The first hypothesis of the current study was accepted, as experienced wheelchair users demonstrated a lower EE compared to both NOV and PRAC at fixed $P_O$’s of 10, 18 and 26 W, suggesting that experience reduces the EE of propulsion. The second hypothesis was rejected, as there was no difference found in the EE between the NOV and PRAC groups. The 20 minutes of pushing by the NOV group may have been sufficient to cause improvements in timing parameters and led to a reduction in EE, which highlights the problems associated with a control group. The margin in EE values between EXP and the other 2 groups increased with greater $P_O$, suggesting EXP became more economical as workload increased. The EE of daily life wheelchair propulsion should not be reported as a generic value, and it is important that the different wheelchair user populations are taken into account. This is true particularly in relation to level of experience and propulsion practice which need to be acknowledged, to be able to tailor nutritional needs accordingly.
Chapter 7  
Energy expenditure and physiological responses between classification groups in wheelchair basketball

7.1 Abstract

Purpose: To examine the physiological demands of elite competitive wheelchair basketball play in relation to the International Wheelchair Basketball Federation (IWBF) classification categories, and to estimate competitive game play EE. Methods: Fourteen elite wheelchair basketball players were categorised into low classification (LOW (n=7): IWBF class 1-2.5) and high classification (HIGH (n=7): IWBF class 3-4.5) groups. Participants performed a sub-maximal and VO$_{2peak}$ test on a specialised motorised treadmill. Heart rate, VO$_2$ and [BLa] were measured. Heart rate and EE were measured during whole basketball play (WBP), including timeouts and end of quarters, and during actual play (APT), excluding timeouts and end of quarters, at an international wheelchair basketball competition. Results: VO$_{2peak}$ was similar between classification groups but HR$_{peak}$ was lower in the LOW group. HIGH had significantly higher propulsion speed, VO$_2$ and HR at both LT (p = 0.03, 0.03 & 0.001 respectively) and a 2 mmol·L$^{-1}$ [BLa] reference point (p = 0.005, 0.05 & 0.005 respectively). During WBP, the LOW group spent 50 (16) minutes on court vs. 40 (17) minutes in the HIGH group, and during APT the LOW group spent 42(13) minutes on court vs. 34 (16) minutes in the HIGH group. There was a tendency for mean EE during WBP to be lower for the LOW group when compared to the HIGH group (687 (189) vs. 822 (161) kcal·h$^{-1}$; p = 0.09; effect size = 0.47). Similar trends were also noted for mean EE during APT (709 (122) vs. 845 (170) kcal·h$^{-1}$; p = 0.10 (LOW and HIGH respectively)) with a medium effect size of 0.44. The HR was 8 b·min$^{-1}$ lower for LOW during both WBP (p = 0.07) and APT (p = 0.05). Conclusions: Wheelchair basketball players with a higher classification tend to have higher EE during a competitive game. The results further suggest that players with a higher functional capacity have greater potential to work at higher exercise intensities before the onset of blood lactate accumulation. This study supports the IWBF classification system and provides data on the EE of national and international wheelchair basketball competition for athletes and practitioners.
7.2 Introduction

Wheelchair basketball is a physically demanding team sport that requires a high degree of skill and technical expertise, with anaerobic and aerobic capabilities (Vanlandewijck et al., 2001; Goosey-Tolfrey, 2005; Tweedy and Diaper, 2010). International games last 40 minutes and are divided into four quarters for both men and women. This internationally recognised Paralympic sport operates a classification system which enables individuals with a range of disabilities to compete equitably against each other. This International Wheelchair Basketball Federation (IWBF, 2009) classification system ranges from 1.0 - 4.5 points, based on player functional ability to complete skills including pushing, pivoting, shooting, rebounding, dribbling, passing and catching (Tweedy and Diaper, 2010). Players with 1.0 point have the least functional ability, and players with 4.5 points have most functional ability.

Previous wheelchair basketball research has reported high peak aerobic capacities of between 2.3 and 3.0 L·min⁻¹ (Bloxham et al., 2001; Goosey-Tolfrey, 2005; Pérez et al., 2007; Bernardi et al., 2010), average game play HR of 128 to 154 b·min⁻¹ (Bernardi et al., 1988; Coutts, 1988; Bloxham et al., 2001, Pérez et al., 2007; Bernardi et al., 2010) and average game play VO₂ consumption between 1.35 and 1.95 L·min⁻¹ (Bernardi et al., 1988; Bernardi et al., 2010). Previous work has estimated the EE of wheelchair basketball training in male paraplegic players at various competitive levels to range from 246 to 516 kcal·h⁻¹ (Burke et al., 1985; Usita et al., 2003; Abel et al., 2008) but not at elite international competitive level.

As noted earlier, functional classification in wheelchair basketball is based on a players’ ability to complete certain movements and skills specific to the sport. That said, higher VO₂peak, PO, anaerobic and sprint performances are associated with greater functional classification (van der Woude et al., 1998; 2002), and there is emerging literature that supports the present IWBF classification system based upon physiological parameters (de Lira et al., 2010). For example, significant correlations have been found between IWBF classification and VO₂peak, VO₂ at ventilatory threshold and PO (Vanlandewijck et al., 1994b; Vanlandewijck et al., 1995; de Lira et al., 2010) suggesting that other physiological parameters, namely EE, may be linked with classification level.

The EE and physiological responses for able-bodied athletes have been shown to be dependent on positional requirements (Duthie et al., 2003; Stolen et al., 2005; Drinkwater et al., 2008) and demands of the sport (McArdle et al., 2001). Whilst these are
considerations also for the sporting populations with a disability, another important factor to consider is the specific disability and level of impairment (Price, 2010). Therefore, in the context of wheelchair basketball, the IWBF classification with respect to differences in EE should be considered. To illustrate this further, using an approximated reference value of 5 kcal·L⁻¹ O₂ (Péronnet and Massicotte, 1991) to convert the reported VO₂ into EE, the recent findings from Bernardi et al. (2010) clearly reported sport-specific contributions to the range of estimated hourly EE during the following activities: Nordic sit ski 800 kcal·h⁻¹; wheelchair racing 778 kcal·h⁻¹; wheelchair basketball 584 kcal·h⁻¹; and wheelchair tennis, 497 kcal·h⁻¹. This work did not distinguish between disabilities, unlike the work of Burke et al. (1985) who reported the EE of wheelchair basketball players of differing levels of spinal cord injury (SCI). From this study, a player with less function (an SCI at the thoracic lesion level T8) expended less energy when compared to a player with more function (T10 SCI) (294 vs. 612 kcal·h⁻¹ respectively). For some studies it is difficult to distinguish the difference in EE between sports when disability cannot be controlled.

The amount of metabolically active tissue an individual has may impact on exercise EE (Price, 2010). Previous work has shown that the REE of elite, trained tetraplegic and paraplegic individuals is similar (Abel et al., 2008; refer to chapter 4). Nevertheless, participants with a greater physiological capacity will be able to maintain a higher rate of work and, therefore, higher EE throughout the game. An athlete’s classification can influence playing position and time spent on court (Vanlandewijck et al., 1995; 2003; 2004), which may impact on their EE during a game.

Although physiology is not directly related to valid classification, and functional ability is the prime determinant (Gil-Agudo et al., 2010), interpretation of physiology between classifications within a team can be important for coaches and athletes for individual specificity whilst training. It is also useful to monitor the capabilities of individuals within the team and the team as a whole. Therefore, the purpose of the present study was to: 1) examine the physiological demands of elite competitive wheelchair basketball play in relation to the IWBF classification categories and 2) estimate competitive game play EE.
7.3 Methods

7.3.1 Participants

Fourteen male, Great Britain wheelchair basketball players participated in this study. From this pool, two groups were created according to their IWBF disability classification as in previous research (Goosey-Tolfrey et al., 2003). Group 1 (LOW) consisted of participants from the 1 to 2.5 class (n=7) and group 2 (HIGH) consisted of participants from the 3 to 4.5 class (n=7) (IWBF, 2009). The University Ethical Advisory Committee approved the study and written consent was obtained by all participants prior to testing. Participant characteristics are given in Table 7.1.

Table 7.1. Participant characteristics for LOW & HIGH groups. The LOW group consists of players from the IWBF Classification (1.0 – 2.5) and the HIGH group of players from the IWBF Classification (3.0– 4.5). Values are means (±SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>LOW (n = 7)</th>
<th>HIGH (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>30.3 (8.7)</td>
<td>25.3 (3.2)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>71.1 (13.2)</td>
<td>76.1 (15.1)</td>
</tr>
<tr>
<td>Sum of 4 site skin-folds (mm)</td>
<td>41.5 (12.4)</td>
<td>34.9 (5.9)</td>
</tr>
<tr>
<td>Onset of disability (yrs)</td>
<td>22.3 (3.9)</td>
<td>18.4 (6.2)</td>
</tr>
<tr>
<td>Wheelchair sport experience (yrs)</td>
<td>14.7 (3.6)</td>
<td>10.6 (4.7)</td>
</tr>
<tr>
<td>Weekly training ( h·wk⁻¹)</td>
<td>17.1 (2.1)</td>
<td>17.1 (2.4)</td>
</tr>
<tr>
<td>Wheel diameter (m)</td>
<td>0.63 (0.02)*</td>
<td>0.66 (0.03)</td>
</tr>
</tbody>
</table>

Key: *denotes a significant difference between HIGH and LOW, p = 0.01.

7.3.2 Experimental design

There were two parts to this study: (a) a physiological laboratory assessment; and (b) HR data collection during either an international or national wheelchair basketball competition ± 2 weeks of the lab assessment. All participants were tested in their own
basketball sports wheelchair, and wheelchair tyre pressure was individually standardised between laboratory testing and competition. For the laboratory measurements, the participants were tested using a specialised motorised treadmill (HP Cosmos Saturn, Nussdorf-Traunstein, Germany).

7.3.3 Laboratory assessment

Body mass was recorded to the nearest 0.1 kg using a wheelchair double beam scale (300 series, Marsden, London, UK). Body composition was measured using the skinfold technique with Harpenden skin calipers (FitnessAssist, Wrexham, UK). Measurements were taken on the right hand side of the body (Marfell-Jones et al., 2006), and the four sites measured were the triceps, biceps, sub-scapular and iliac crest.

A standardised breakfast was given to all participants after a 12-hour fast, consisting of 0.86 g·kg\(^{-1}\) Corn Flakes and 3.43 mL·kg\(^{-1}\) semi-skimmed milk (Wee et al., 2005). Each participant completed an incremental sub-maximal exercise test comprising five or six 4-minute stages. The initial speed was pre-determined following a self-selected warm-up period of five minutes where HR was approximately 100 b·min\(^{-1}\). Subsequently, each exercise stage was increased by 0.2 to 0.4 m·s\(^{-1}\), ensuring that a profile was obtained that included 40-80% \(\dot{V}O_2\text{peak}\). The treadmill incline was constant at 1% gradient throughout this test. During the last minute of each stage, expired gas was collected and analysed using the Douglas bag technique as described in Chapter 5, section 5.3.3.

Heart rate was monitored continuously using radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland), and RPE were monitored throughout the test. Each participant received detailed instructions about the use of the 15-point Borg scale (Borg, 1970) and given an example of how to score their RPE. A small capillary blood sample was obtained from the earlobe, at the start of the test and within the 1-min break between stages, for determination of blood lactate concentration ([BLa]), using the YSI 1500 Sport (Yellow Springs, USA). The YSI was calibrated with a standard of 5 mmol·L\(^{-1}\) prior to testing. The lactate threshold (LT) was defined visually by two separate observers as the first workload before there was an initial increase in [BLa] (Ivy et al., 1981).

Following a fifteen minute rest period, an incremental gradient test was used to determine the \(\dot{V}O_2\text{peak}\). This test involved increases in external work until volitional exhaustion. Heart rate was monitored continuously, expired gas samples were collected over the last two consecutive stages of the test for calculation of \(\dot{V}O_2\text{peak}\) and the RPE at the
end of the test was recorded. On completion of the peak test, a capillary blood sample was also taken and analysed to determine [BLa] as previously described. All participants satisfied the criteria for a valid \( \dot{V}O_{2\text{peak}} \): a peak RER \( \geq 1.10 \) and HR\(_{\text{peak}} \geq 95\% \) of the age-predicted maximum (200 b\cdot min\(^{-1}\) minus chronological age in years), as used previously in this population (Diaper and Goosey-Tolfrey, 2009). The HR\(_{\text{peak}} \) was taken as the highest value recorded during the test. However, if a higher HR value was obtained during match play, then that value was used in subsequent analyses.

### 7.3.4 Competition data

All participants wore HR monitors (Polar team system, Kempele, Finland) during the pre-determined competitive wheelchair basketball match. The HR monitors were set to record at 5-second intervals, and the match start-time, substitutions and time-outs were all manually recorded. This allowed for the calculation of whole basketball play (WBP) including time outs, end of quarters and actual basketball playing time (APT) when an individual was on the basketball court. Heart rate during time on the bench and during half-time was not recorded. The average HR and HR\(_{\text{peak}} \) during the matches were calculated for each participant. Where possible, more than one match was analysed per player to try and obtain a typical match play response.

### 7.3.5 Calculation of EE

Energy expenditure was calculated for each sub-maximal stage (Frayn, 1983) by estimating carbohydrate and fat oxidation in g\cdot min\(^{-1}\) as described in Chapter 3, section 3.3.4.

### 7.3.6 Statistical analyses

Data were reported as mean (\( \pm \)SD), and standard descriptive statistics were obtained for all variables using SPSS (version 18.0, Chicago, Illinois, USA). Independent t-tests or the non-parametric equivalent (Mann-Whitney U test) were conducted to determine differences between classification groups for all physiological parameters. The \( \dot{V}O_2 \) and HR data at LT were expressed in absolute values and as a percentage of peak values. Point by point regression was performed on the [BLa] data to determine the \( \dot{V}O_2 \) and HR at a fixed moderate exercise intensity, representing a [BLa] of 2 mmol\cdot L\(^{-1}\) (Abel et al., 2003). The \( \dot{V}O_{2\text{peak}} \) data were presented as absolute (L\cdot min\(^{-1}\)), relative (mL\cdot kg\(^{-1}\)\cdot min\(^{-1}\))
and scaled (mL·kg\(^{-0.82}\)·min\(^{-1}\)) values (Goosey-Tolfrey et al., 2003). Estimated EE data from the sub-maximal stages in the laboratory assessment and HR data at each sub-maximal stage were used to create individual regression equations, and the Pearson’s r correlation for this relationship was calculated. This equation was used to estimate the EE during game play. Using HR from the game play, average EE was calculated using the individual regression equations. \(\dot{V}O_2\) was calculated at 2.6 and 3.6 m·s\(^{-1}\) between classification groups by using individual regression analysis between speed and \(\dot{V}O_2\). This was then used as a measure of pushing economy. Significance was accepted at \(p \leq 0.05\), and ES and 95% CI were used to complement the more traditional statistics as previously described in Chapter 3 section 3.3.5.

### 7.4 Results

#### 7.4.1 Base-line characteristics and peak physiological parameters

No between-group differences were shown for baseline characteristics (age, body mass, weekly training and body composition (\(p > 0.05\)). However, LOW self-selected wheelchair diameter was smaller than HIGH (\(p = 0.01\), Table 7.1). Table 7.2 shows that \(\dot{V}O_2\)\(_{\text{peak}}\) was similar between the groups, regardless of how it was expressed as was peak [BLa]; the only notable difference was the lower group average HR\(_{\text{peak}}\) for LOW (\(p = 0.03\)).

#### 7.4.2 Physiological responses in the laboratory

At LT, LOW had significantly higher [BLa] than HIGH (\(p = 0.05\)). Propulsion speed, \(\dot{V}O_2\) and HR, at both LT (\(p = 0.03, 0.03 & 0.001\) respectively) and the 2 mmol·L\(^{-1}\) [BLa] reference (\(p = 0.005, 0.05 & 0.005\) respectively), were significantly lower for LOW (Table 7.3). Relative values of HR at LT (\(p = 0.01\)) and \(\dot{V}O_2\) at 2 mmol·L\(^{-1}\) [BLa] (\(p = 0.03\) were also lower in LOW (Table 7.3). There was a trend for relative values of HR at 2 mmol·L\(^{-1}\) [BLa] to be lower in LOW (\(p = 0.06\)). At LT, RER and RPE did not differ between groups. Pushing economy did not differ between the groups at 2.6 m·s\(^{-1}\) or at 3.6 m·s\(^{-1}\) (Figure 7.1).
Chapter 7  
Energy expenditure between classification groups in wheelchair basketball

Table 7.2. \( \dot{V}O_{2\text{peak}}, HR_{\text{peak}} \) and peak [BLa] for LOW and HIGH groups during the laboratory physiological testing. Values are means (±SD).

<table>
<thead>
<tr>
<th>Variable</th>
<th>LOW (n = 7)</th>
<th>HIGH (n = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{V}O_{2\text{peak}} ) (L·min(^{-1}))</td>
<td>3.05 (0.54)</td>
<td>3.45 (0.44)</td>
</tr>
<tr>
<td>( \dot{V}O_{2\text{peak}} ) (mL·kg(^{-1} )·min(^{-1}))</td>
<td>43.9 (9.3)</td>
<td>46.1 (5.4)</td>
</tr>
<tr>
<td>( \dot{V}O_{2\text{peak}} ) (mL·kg(^{-0.82} )·min(^{-1}))</td>
<td>93.9 (18.1)</td>
<td>100.0 (8.7)</td>
</tr>
<tr>
<td>HR(_{\text{peak}} ) (b·min(^{-1}))</td>
<td>189 (6)*</td>
<td>196 (4)</td>
</tr>
<tr>
<td>Peak [BLa] (mmol·L(^{-1}))</td>
<td>7.1 (1.7)</td>
<td>7.8 (2.1)</td>
</tr>
</tbody>
</table>

**Key:** *denotes a significant difference between LOW and HIGH, p = 0.03.

7.4.3 Game time and physiological responses during competition

There was a tendency for mean EE during WBP to be lower for the LOW group when compared to the HIGH group (687 (189) vs. 822 (161) kcal·h\(^{-1}\)), as shown in Figure 7.2. Similar trends were also noted for mean EE during APT (709 (122) vs. 845 (170) kcal·h\(^{-1}\)). The HR was 8 b·min\(^{-1}\) lower for LOW during both WBP (p = 0.07) and APT (p = 0.05; Figure 7.3), but when mean HR was expressed relative to HR\(_{\text{peak}}\), no significant difference was shown between groups for WBP (p = 0.49) or APT (p = 0.41). During WBP, although there was no significant difference between groups in game duration, including time-outs and end of quarters (LOW 50(16) min; HIGH, 40(17) min), a medium ES was shown (ES = 0.30, 95% CI -10 to 29). Similarly, during APT there was no difference in on-court time (LOW, 42(13) minutes; HIGH, 34(16) minutes) but again, a medium ES was reported (ES = 0.30, 95% CI -8 to 25). When game duration was considered, there was no difference in total EE between LOW (586 (245) kcal) and HIGH (543 (240) kcal) during WBP; p = 0.74. There was also no difference in EE during APT, with the LOW group expending 517 (209) kcal and HIGH expending 499 (215) kcal.
Table 7.3. a) Absolute values and percentage of respective peak values for treadmill speed, \( \dot{V}O_2 \) and HR at LT and the reference 2 mmol.L\(^{-1} \) [BLa]; b) [BLa], RER and RPE at LT. Values are means (±SD).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Absolute value LT</th>
<th>% of peak value at LT</th>
<th>Absolute value at reference 2 mmol.L(^{-1} ) [BLa]</th>
<th>% of peak value at 2 mmol.L(^{-1} ) [BLa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill speed (m∙s(^{-1} ))</td>
<td>LOW</td>
<td>3.0 (0.22)*</td>
<td>3.6 (0.24)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
<td>3.5 (0.41)</td>
<td>4.1 (0.34)</td>
<td></td>
</tr>
<tr>
<td>( \dot{V}O_2 ) (L·min(^{-1} ))</td>
<td>LOW</td>
<td>1.43 (0.18)*</td>
<td>1.91 (0.4)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
<td>1.84 (0.40)</td>
<td>2.39 (0.38)</td>
<td></td>
</tr>
<tr>
<td>HR (b·min(^{-1} ))</td>
<td>LOW</td>
<td>119 (5)*</td>
<td>142 (7)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
<td>131 (5)</td>
<td>155 (7)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Classification</th>
<th>Absolute value LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>[BLa] (mmol:L(^{-1} ))</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
</tr>
<tr>
<td>RER</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
</tr>
<tr>
<td>RPE</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>HIGH</td>
</tr>
</tbody>
</table>

**Key:** *denotes a significant difference between LOW and HIGH, p < 0.05.
Figure 7.1. Mean (±SD) $\dot{V}O_2$ as a measure of pushing economy during wheelchair propulsion at 2.6 m·s$^{-1}$ and 3.6 m·s$^{-1}$ expressed as a) L·min$^{-1}$ and b) relative to body mass. Note: values were interpolated from individual regression equations between a range of speeds completed by all participants.
Chapter 7  Energy expenditure between classification groups in wheelchair basketball

Figure 7.2. Mean (±SD) EE (kcal·h⁻¹) during WBP and APT between LOW and HIGH classification groups; WBP, p = 0.09, ES = 0.47, 95% CI -295 to 25; APT, p = 0.11, ES = 0.44, 95% CI -308 to 36.

Figure 7.3. Mean (±SD) HR (b·min⁻¹) during WBP and APT between LOW and HIGH classification groups. *denotes a significant difference between LOW and HIGH groups in APT, p = 0.05. # denotes a trend towards significance in WBP, p = 0.07, ES = 0.50, 95% CI -16.3 to 0.61.
7.5 Discussion

7.5.1 Main findings

This study investigated the physiological characteristics of wheelchair basketball players according to the IWBF classification (LOW, 1.0 – 2.5; HIGH, 3.0 – 4.5) and estimated the EE during competitive wheelchair basketball game play. There was a tendency (p = 0.09) for the EE to be lower during WBP for LOW point players when compared to HIGH point players. In line with the lower HR_{peak} responses of the LOW group in the laboratory setting, match play HR was lower in LOW compared with HIGH for APT and WBP. There were group differences in [BLa], HR and \( \dot{V}O_2 \) at both the LT and the 2 mmol-L\textsuperscript{-1} [BLa] reference point, suggesting that those players with greater functional capacity have the potential to work at higher exercise intensities before the onset of blood lactate accumulation.

7.5.2 Playing standards and functional capacity

Physiological responses in wheelchair basketball need to be considered in relation to sex and body mass alongside anaerobic and aerobic fitness (McArdle et al., 2001; Vanlandewijck et al., 2004; de Lira et al., 2010). Another important variable that influences physiological parameters during wheelchair basketball is training. A novel feature of the present study is both classification groups’ high training status, evidenced by their average weekly training times (Table 7.1). Since weekly training times alongside the other characteristics were closely matched in LOW and HIGH, a primary distinguishing factor in relation to EE and physiological responses to competition was the groups’ functional ability.

The mean \( \dot{V}O_{2peak} \) of 3.25 L·min\(^{-1}\) is higher than reported in previous literature studying national squads of wheelchair basketball players (Veeger et al., 1991; Vanlandewijck et al., 1995; Goosey-Tolfrey, 2005; Pérez et al., 2007; de Lira et al., 2010; Bernardi et al., 2010), which may suggest a superior endurance regimen in the current participants’ training. The \( \dot{V}O_{2peak} \) test elicited significantly lower mean HR_{peak} values for the LOW group, yet exceeded the HR criterion for maximal capacity testing, and all participants also met the criterion for peak RER (Diaper and Goosey-Tolfrey, 2009). For comparative purposes, \( \dot{V}O_{2peak} \) was also expressed using a body mass exponent of 0.82 (mL·kg\(^{-0.82}\)·min\(^{-1}\)) according to Goosey-Tolfrey et al. (2003). This has been deemed a
suitable method of comparing $\dot{V}O_2\text{peak}$ of different sized athletes and adds to the literature of other trained wheelchair athletes.

Previously, a higher functional capacity has been associated with greater aerobic fitness (Vanlandewijck et al., 1994b; 1995; van der Woude et al., 2002; Goosey-Tolfrey et al., 2003; de Lira et al., 2010). However, Vanlandewijck et al. (1994b; 1995) only found differences in aerobic capacity between the lowest class (1.0) vs. all other classes, suggesting this variable may not be directly related to functional capacity in the higher classifications. A possible reason why LOW and HIGH had similar aerobic capacities may be inclusion of six classification classes into only two separate groups. However, consideration must also be made of the fact that the LOW point players had four years more wheelchair sport experience, together with the fact that seven of the LOW players were using a daily wheelchair when compared to only three individuals in the HIGH group.

7.5.3 Physiological responses in the laboratory

Notably, it has been suggested that [BLa], HR and $\dot{V}O_2$ values at sub-maximal thresholds are more sensitive physiological markers than aerobic capacity in wheelchair basketball players because of the intermittent, highly anaerobic nature of the sport (Bernardi et al., 2010; Bambhani, 2011), confirming the importance of these measurements. Ivy et al. (1981) showed no difference between the LT and the first initial increase in ventilation, suggesting the two physiological markers can be used as a measure of the same exercise intensity. However, caution must be used when comparing the results of different studies as there are many ways of interpreting LT (Bourdon et al., 2000).

Previous studies in the area of wheelchair sport have used the ventilatory threshold (VT) as a measure of physiological capacity in wheelchair basketball players (Bloxham et al., 2001; De Lira et al., 2010; Bernardi et al., 2010). This physiological ‘marker’ occurs at a workload where a greater increase in CO$_2$ production with respect to O$_2$ consumption is shown (Bernardi et al., 2010). The VT has been shown to occur when a rapid rise in blood lactate is seen, which can be observed at higher intensities than the LT (Bourdon et al. 2000). That said, $\dot{V}O_2$ at LT for both groups in the present study was higher than at VT in a mixed classification group of 17 Brazilian wheelchair basketball players (De Lira et al., 2010). Furthermore, the HIGH group demonstrated similar $\dot{V}O_2$ at LT to that of a Canadian...
wheelchair basketball team at VT (Bloxham et al., 2001). This suggests a greater level of physiological capacity in the players in the current study.

At both LT and the 2 mmol-L⁻¹ [BLa] reference point, the LOW group’s propulsive speed was 0.5 m·s⁻¹ slower, suggesting the HIGH group has the potential to work at higher exercise intensities before the onset of fatigue. Moreover, players in the LOW group displayed lower \( \dot{V}O_2 \) at both the LT and 2 mmol-L⁻¹ [BLa] reference point than players in the HIGH group, although this was not significant at LT when \( \dot{V}O_2 \) was expressed as a percentage of \( \dot{V}O_2 \)peak, also confirming the lower absolute intensity of the LOW group at the onset of [BLa] accumulation. These results are in agreement with de Lira et al. (2010), who reported a significant positive correlation between absolute \( \dot{V}O_2 \) values at VT and functional capacity.

The pushing economy data highlights an interesting phenomenon. The HIGH group were working at higher exercise intensities at LT and 2mmol·L⁻¹ [BLa]. Consequently, this could suggest the HIGH group may have a greater pushing economy when working at the same exercise intensity as the LOW group. However, this was not found as results demonstrate a similar pushing economy between groups at the two fixed speeds (2.6 m·s⁻¹ and 3.6 m·s⁻¹). Pushing economy is one characteristic of manual wheelchair propulsion experience (Chapter 6), of which the LOW group have a greater number of years. This suggests that, although the HIGH group can work at higher intensities before the onset of [BLa] accumulation, the LOW group’s experience may counteract the HIGH group’s efficiency at sub-maximal levels of wheelchair propulsion.

Heart rate was significantly lower at LT and the 2 mmol·L⁻¹ [BLa] reference point in the LOW group. The LOW and HIGH groups worked at a similar % HRpeak at 2 mmol·L⁻¹ [BLa], suggesting that although absolute differences in HR occur during sub-maximal exercise, in relative terms the groups are displaying similar responses to exercise. On the other hand, at LT, % HRpeak was actually higher in HIGH. Nevertheless, the day-to-day variability found in HR for intra- and inter-individual measurement has to be considered and cannot be ruled out as a confounding factor (Achten and Jeukendrup, 2003; Bagger et al., 2003). As the difference in % HRpeak in the two groups was only 4% at LT and 3% at 2 mmol·L [BLa], it raises the question of whether these are meaningful differences or, more probably, that the two groups are working at a similar relative intensity when expressed as a function of HR. It can be suggested that the small percentages seen here are not big enough to be of practical significance and, therefore, the
% HR in both the LOW and HIGH are considered similar. From the majority of the data provided from the laboratory measures, it can be suggested that the HIGH group is able to work at a higher exercise intensity before the onset of [BLa] accumulation; thus, attention should be given to individualised or classification-specific training to optimise an individual’s physiological capacities, especially when monitoring HR during training.

7.5.4 Energy expenditure during competition

In the current study the participants expended more energy (range 687 to 845 kcal·h⁻¹) than reported previously during simulated wheelchair basketball play (Burke et al., 1985; Usita et al., 2003; Abel et al., 2008; Price, 2010), perhaps due to the greater demands of the high standard of play evaluated from national and international competitive match play. Estimated EE during non-elite wheelchair basketball training was only 246 kcal·h⁻¹ (Usita et al., 2003) compared with 375 kcal·h⁻¹ in elite wheelchair basketball training (Abel et al., 2008). During simulated match play, four regional level wheelchair basketball players demonstrated an average EE of 516 kcal·h⁻¹ (Burke et al., 1985). Bernardi et al. (1988; 2010) reported the \( \dot{\text{VO}}_2 \) values of Paralympic wheelchair basketball players during competition and in simulated match play respectively. Using an approximated reference value of 5 kcal·L⁻¹ O₂ (Péronnet and Massicotte, 1991) to convert the reported \( \dot{\text{VO}}_2 \) into EE, this equates to 404 kcal·h⁻¹ and 584 kcal·h⁻¹ respectively. There is clearly a difference in EE during actual and simulated basketball competition, and the current study’s results highlight the importance of verifying actual exercise in specific cohorts for accurate metabolic assessment.

From a classification and metabolic cost perspective, disability class did not significantly influence estimated hourly EE during competitive wheelchair basketball game play. However, medium effect sizes of 0.46 (WBP) and 0.44 (APT) may suggest a meaningful difference in EE between the two groups. In WBP, the 95% CI of -298 to 25 suggests a tendency of LOW expending less energy during a game amounting to almost 300 kcal·h⁻¹. In APT, the same pattern emerges with a 95% CI of -312 to 36 suggesting that LOW could expend over 300 kcal less than HIGH per hour during a competitive match. This is a large metabolic difference if considering nutrition, as this equals the equivalent of over 2 standard bottles of Lucozade sport drink.
This kcal difference however, no longer exists when duration of a match is considered. There is no difference in the EE between LOW and HIGH in both WBP and APT due to the longer time the LOW group spend on court in a typical game. So, for each classification group, a comparable amount of energy is expended, suggesting both groups may need a similar amount of calories when considering competition. Practitioners must account for both the similarities shown during actual competition and for the slightly higher EE per hour in the HIGH group, and factor this in to training days and camps where in fact, the HIGH group may expend more energy if training hours are equal in length.

7.5.5 Heart rate during match play
The LOW group demonstrated lower average HR’s during wheelchair basketball match play compared to the HIGH group. This finding is in agreement with Pérez et al. (2007), who reported a lower average HR in wheelchair basketball players with no hip control (passive pelvic stabilisation - classification 1 – 2, IWBF, 2009). However, in relative terms, both LOW and HIGH groups in the current study had the same average match HR in both WBP and APT when expressed as a percentage of HR_{peak}. So, regardless of actual HR or the amount of absolute EE during a game, both groups were working at a similar relative HR intensity. This data could be useful for training practices in this cohort.

Training recommendations for the able-bodied population are not directly transferable to wheelchair athletes due to the underestimation of relative exercise intensity (Tolfrey et al., 2001; Goosey-Tolfrey and Tolfrey 2004). For the same reason, it is worth appreciating that, within the sport of wheelchair basketball, players vary considerably due to their functional capacity, hence the existence of the IWBF classification system. Access to larger pools of athletes through international collaboration which enables the complete IWBF classification spectrum (1.0 – 4.5), and hence to more robust sample sizes, could lead to a greater in-depth understanding of the energy requirements and key physiological responses in each specific class.

7.5.6 Limitations
It is worth highlighting that, although no significant difference was found, body mass was slightly higher and sum of skinfolds was slightly lower in HIGH compared to LOW. This may suggest a greater FFM in the HIGH group potentially contributing to the higher EE in this group. Due to methodological constraints neither the REE nor FFM of the
Chapter 7  Energy expenditure between classification groups in wheelchair basketball

athletes were measured in this study, and so this potential contribution to the overall EE cannot be confirmed.

As the EE is estimated through HR measurement, an appreciation of variability in HR during competition needs to be mentioned. However, it has been shown previously that there is a strong relationship between \( \text{VO}_2 \) and HR during non-steady-state exercise in wheelchair propulsion (Bot and Hollander, 2000), so this analysis was deemed appropriate to estimate EE during competition.

Although the importance of estimating the EE of elite sports competition is apparent, the results of this study should be interpreted with caution when applying the findings to wheelchair basketball players who are sub-elite. The data collected from international elite wheelchair basketball competition may not be an accurate measure of recreational game play.

7.6 Conclusions

There was a tendency for mean EE to be higher in the HIGH group compared to the LOW group, which was reflected by their higher HRs during APT and WBP. The absolute HR, \( \text{VO}_2 \) and treadmill speed were higher at LT and 2 mmol·L\(^{-1}\) [BLa] in the HIGH group. With this in mind, wheelchair basketball players with a higher classification have greater potential to work at higher absolute exercise intensities before the onset of [BLa] accumulation. This study supports the IWBF classification system (2009) and provides data on the metabolic cost of national and international wheelchair basketball competition for athletes and practitioners.
Chapter 8

A comparison of the physiological demands and energy expenditure of wheelchair basketball and wheelchair tennis

8.1 Abstract

Purpose: To examine the physiological profiles of wheelchair basketball and tennis and specifically to identify if there are differences in the physiological demands and physiological fitness of wheelchair basketball and tennis players of international playing standard, with special reference to EE. Methods: Twelve elite athletes (8 male, 4 female) from the two sports performed a sub-maximal and a \( \dot{V}O_2 \) test in their sport-specific wheelchair. Heart rate, \( \dot{V}O_2 \) and [BLa] were measured. Heart rate was monitored during international competitions, and EE was calculated from this using linear regression equations. Results: Despite no differences in the laboratory assessment of HR_{peak}, the \( \dot{V}O_2 \) showed a trend towards being higher for the basketball players when compared to the tennis players (2.98 ± 0.91 vs. 2.06 ± 0.71 L·min⁻¹; \( p = 0.08 \)). Average match EE (703 ± 215 vs. 439 ± 171 kcal·h⁻¹; \( p = 0.04 \)) and average match HR (166 ± 11 vs. 146 ± 16 b·min⁻¹; \( p = 0.03 \)) were higher during actual playing time of basketball (A-BPT) when compared to whole tennis play (WTP) respectively. When a whole basketball game (WBP; including time-outs) was compared to WTP, average match EE tended to be higher for the WBP (672 ± 207 vs. 439 ± 171 kcal·h⁻¹; \( p = 0.06 \)). There was a trend for average match HR in WBP to be higher than in WTP (162 ± 11 vs. 146 ± 16 b·min⁻¹) (\( p = 0.07 \)). Consequently, differences in the time spent in the different training zones between the two sports existed. Conclusions: EE is higher per hour during A-BPT and WBP when compared to WTP. It is therefore suggested that wheelchair basketball requires predominately high-intensity training, whereas tennis requires training across the intensity spectrum.
8.2 Introduction

Wheelchair basketball and wheelchair tennis are two of the most popular and renowned sports within the Paralympics, with International competitions being held worldwide. Coaches and sport scientists with an interest in these sports are continually seeking to improve and optimise sport-specific training (Roy et al., 2006; Pérez et al., 2007; Bernardi et al., 2010). However, as with able-bodied sports, to ensure that training reflects the demands of the sport, an understanding of the physiological competitive demands is required (Bernardi et al., 1988; Achten and Jeukendrup, 2003; Pérez et al., 2007). It is evident that wheelchair basketball competition involves periods of high-intensity, intermittent activity with large physiological demand put on players (Coutts, 1988; Bloxham et al., 2001; Pérez et al., 2007). Likewise, wheelchair tennis is intermittent in nature and, during a game, a significant amount of stress is put on the aerobic system (Roy et al, 2006).

Measurement of EE during wheelchair sports competition can inform training practices, but so far there is a lack of data to provide this (Price, 2010). From the literature available, it appears that the reported EE values for wheelchair basketball training are between 246 - 516 kcal∙h\(^{-1}\) (Burke et al., 1985; Usita et al., 2003; Abel et al., 2008). Using an approximated reference value of 5 kcal\(\cdot\)L\(^{-1}\) \(\cdot\)O\(_2\) (Péronnet and Massicotte, 1991) to convert \(\dot{V}O_2\) into EE, EE was measured in simulated competition (584 kcal\(\cdot\)h\(^{-1}\)) (Bernardi et al., 2010) and actual competition (404 kcal\(\cdot\)h\(^{-1}\)) (Bernardi et al., 1988). These values seem to be generally higher than the values reported for simulated wheelchair tennis competition (312 - 497 kcal\(\cdot\)h\(^{-1}\)) (Roy et al., 2006; Bernardi et al., 2010) or training (325 kcal\(\cdot\)h\(^{-1}\)) (Abel et al., 2008). To fully understand these values, comparisons must control for trained status of individuals, physical impairment with respect to disability type, and functional classification.

Work is available that extrapolates HR and \(\dot{V}O_2\) from laboratory assessments to estimate EE during field evaluation of athletes with a disability (Roy et al., 2006). However, the use of arm-crank ergometry, which involves increases in intensity every minute (Roy et al., 2006), is unlikely to demonstrate a physiological steady state in these short exercise stages. Moreover, arm-crank exercise would most likely not reflect the physiological responses seen during wheelchair exercise (Sawka et al., 1980). Of the other estimated EE data that is available in the field, most have focused on training
scenarios (Burke et al., 1985; Abel et al., 2008; Bernardi et al., 2010) and not official competition.

Most of the research to date has involved male wheelchair athletes, with only a few recent studies examining the physiological aspects and demands of female athletes participating in wheelchair exercise (Schmid et al., 1998b; Barfield et al., 2009; Diaper and Goosey-Tolfrey, 2009). Including female athletes in elite competition adds to this literature. To extend the work previously reported in this area, it is necessary to examine the [BLa] profile so that specific HR training zones can be developed to provide athletes with targeted and optimised training (Godfrey and Whyte, 2006). This is of interest when comparing wheelchair sports with the objective of providing specific sports training information, since the distances covered, rest to work ratios and length of matches vary considerably. For example, wheelchair basketball matches involve 10-minute quarters with time-outs and game stoppage throughout, whereas tennis matches last from under 1 h to over 3 h (Pérez et al., 2007; Diaper and Goosey-Tolfrey, 2009). Therefore the purpose of this study was to examine (a) if there are differences in the physiological profiles of wheelchair basketball players and tennis players of a similar playing standard, (b) to determine whether the competitive physiological demands and EE of these two sports differed, and (c) to explore the relationship between the [BLa] response to exercise and identify sport-specific trends of HR training zones that may help develop coaches’ knowledge of training for these sports.

8.3 Methods

8.3.1 Participants

Six wheelchair basketball players (4 male, 2 female) were matched with 6 wheelchair tennis players (4 male, 2 female) from previously obtained data, all of whom were presently competing internationally and therefore considered elite. After consultation with medical records, all participants were matched on playing ability, trunk mobility and classification according to the International Wheelchair Basketball Federation (IWBF, 2004). Approval was gained from the University Ethical Advisory Committee and written consent was obtained by all participants and their guardians (for those under 18 yrs old) before testing. Body mass was recorded to the nearest 0.1 kg using either a seated balance scale (Seca 710, seated scales, Hamburg, Germany) or a
wheelchair double beam scale (300 series, Marsden, London, UK). Participant characteristics are given in Table 8.1.

8.3.2 Experimental design

There were two distinct phases to this study, (a) a laboratory assessment within a two week period either side of the selected sports competition and (b) data collection during international wheelchair basketball and tennis competitions. All participants were tested in their own sports-specific wheelchair. For the laboratory measurements, the tennis players were tested using a wheelchair ergometer as previously described (Goosey-Tolfrey, 2005), whilst the basketball players were tested using a specialised motorised treadmill (HP Cosmos Saturn, Nussdorf-Traunstein, Germany).

8.3.3 Laboratory assessment

Each participant completed an incremental sub-maximal exercise test comprising of five or six 4-minute stages. The initial speed was pre-determined following a self-selected warm-up period of five minutes where HR was approximately 100 b·min⁻¹. Subsequently each exercise stage was increased by 0.2 to 0.4 m·s⁻¹, ensuring that a profile was obtained that included intensities ranging from 40-80% \(\dot{V}O_2\text{peak}\). For the treadmill testing the incline was kept constant at 1% gradient throughout this test. During the last minute of each stage, expired gas was collected and analysed using the Douglas bag technique, described in Chapter 5, section 5.3.3.

\[1\] Data collected from the 6 tennis players in the laboratory and during tennis competition was completed by Mr John Lenton prior to the start of this PhD.
Table 8.1: Participant characteristics of wheelchair basketball and wheelchair tennis players. Group values are means (±SD).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sport</th>
<th>Sex</th>
<th>Age (yrs)</th>
<th>Body mass (kg)</th>
<th>Disability</th>
<th>SCI completeness</th>
<th>IWBF Sports Classification (IWBF, 2009)</th>
<th>Years playing sport</th>
<th>Training (h·wk⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basketball</td>
<td>Male</td>
<td>26</td>
<td>77.6</td>
<td>SCI T12</td>
<td>Incomplete</td>
<td>3.0</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Basketball</td>
<td>Male</td>
<td>27</td>
<td>70.7</td>
<td>Spina bifida</td>
<td>-</td>
<td>3.0</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>Basketball</td>
<td>Male</td>
<td>27</td>
<td>93.8</td>
<td>Avascular necrosis</td>
<td>-</td>
<td>4.5</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Basketball</td>
<td>Male</td>
<td>34</td>
<td>94.2</td>
<td>SCI T12</td>
<td>Complete</td>
<td>2.0</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>Basketball</td>
<td>Female</td>
<td>29</td>
<td>58.3</td>
<td>SCI T9</td>
<td>Complete</td>
<td>1.5</td>
<td>10</td>
<td>16</td>
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<tr>
<td>6</td>
<td>Basketball</td>
<td>Female</td>
<td>17</td>
<td>50.0</td>
<td>Acute motor neuropathy</td>
<td>-</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Mean          | 26.7   | 74.1  |           | 2.8           | 10.3                             | 15.8            |
SD            | (5.5)  | (18.1)|           | (1.0)         | (4.6)                           | (3.7)           |

| 1           | Tennis | Male   | 30        | 99.0         | SCI T12                           | Incomplete      | 2.5                                    | 6                   | 15               |
| 2           | Tennis | Male   | 18        | 64.1         | Brittle bones                     | -               | 4.0                                    | 12                  | 25               |
| 3           | Tennis | Male   | 15        | 67.8         | Transverse Myelitis T12           | Incomplete      | 3.0                                    | 2                   | 7                |
| 4           | Tennis | Male   | 34        | 64.7         | SCI T 8/9/10                      | Complete        | 1.5                                    | 8                   | 21               |
| 5           | Tennis | Female | 26        | 51.9         | SCI T4/5                          | Complete        | 1.0                                    | 4                   | 15               |
| 6           | Tennis | Female | 15        | 47.5         | Brittle bones                     |                 | 4.0                                    | 12                  | 5                |

Mean          | 23.0   | 65.8  |           | 2.7           | 7.3                              | 14.7            |
SD            | (8.2)  | (18.1)|           | (1.3)         | (4.1)                           | (7.7)           |
Heart rate was monitored continuously using radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland) and RPE was monitored throughout the test. Each participant received detailed instructions about the use of the 15-point Borg scale (Borg, 1970) and given an example of how to score their RPE. A small capillary blood sample was obtained from the earlobe as described in Chapter 7, section 7.3.3. The LT was defined visually by two separate observers at the first workload before there was a non-linear rise in [BLa] (Ivy et al., 1981). A second breakpoint known as the lactate turn point (LTP) was identified and was used to describe the workload where [BLa] accumulates rapidly (Godfrey and Whyte, 2006). Based upon the aforementioned parameters, six different HR training zones were identified (Table 8.2). Zone 1 represents a recovery period where the athlete trains aerobically below the lactate threshold. Zone 2 represents an aerobic zone which allows the athlete to work at a slightly higher intensity than lactate threshold. Zone 3 represents an intensity which is just below the lactate turnpoint and therefore still aerobic in nature. Zone 4 is the intensity an athlete would maintain around lactate turnpoint when blood lactate starts to accumulate, therefore, exercise at this intensity would be relatively short in duration. Zone 5 represents an intensity than is around the athlete’s VO$_{2}$max (Bourdon, 2000; Godfrey and Whyte, 2006). Following a 15-minute rest period, an incremental gradient test (treadmill) and an incremental speed test (wheelchair ergometer) were used to determine the VO$_{2}$peak. This test is described in Chapter 7, section 7.3.3.

**Table 8.2.** The training zones classification in relation to LT and LTP (adapted from Bourdon 2000; Godfrey and Whyte 2006).

<table>
<thead>
<tr>
<th>Zone number</th>
<th>Description</th>
<th>Blood lactate relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Recovery</td>
<td>&lt;LT</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Extensive Aerobic</td>
<td>LT to LT+ (LTP – LT/2)</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Intensive Aerobic</td>
<td>LTP to LTP- (LTP – LT/2)</td>
</tr>
<tr>
<td>Zone 4</td>
<td>Threshold</td>
<td>LTP (5 beat range)</td>
</tr>
<tr>
<td>Zone 5</td>
<td>VO$_{2}$ max</td>
<td>&gt;LTP</td>
</tr>
<tr>
<td>Zone 6</td>
<td>Sprint/ power</td>
<td>n/a (maximal effort)</td>
</tr>
</tbody>
</table>
Chapter 8  Energy expenditure of wheelchair basketball and wheelchair tennis

8.3.4 Competition data

Heart rate monitors (Polar team system, Kempele, Finland) were placed on the players at least 20 minutes prior to the start of competitive play. The players wore the HR monitors throughout the matches, with data being recorded at 5-s intervals. Basketball HR data were collected during the Paralympic World Cup 2009/2010 in England. The match start time, and, during the basketball games, the substitutions and time-outs, were all manually recorded, thus allowing calculation of whole basketball play (WBP) and basketball actual playing time (B-APT) excluding rests. Tennis HR data were collected from singles matches during international wheelchair tennis tournaments in Florida and England in 2009. For each match, the start and end time were recorded, and the HR data collection period included all the activities during this time, representing whole tennis play (WTP). The average HR and HR_{peak} during the matches were calculated for each player from both sports. Where possible, more than one match was analysed per player to try and obtain a typical match play response.

8.3.5 Calculation of EE

Energy expenditure was calculated for each sub-maximal stage (Frayn, 1983) by estimating carbohydrate and fat oxidation in g·min^{-1} as described in Chapter 3, section 3.3.4.

8.3.6 Statistical analyses

Data were reported as mean (±SD) and standard descriptive statistics were obtained for all variables using SPSS (version 18.0, Chicago, Illinois, USA). Independent t-tests or the non-parametric equivalent (Mann-Whitney U) were conducted to determine any differences between groups for mean and total EE, mean and HR_{peak}, and duration of games. The VO_{2} and HR data at each sub-maximal stage were expressed as percentages of their respective peak values. For each participant a linear regression was conducted using the paired data points of sub-maximal VO_{2} and [BLa] values, and the Pearson’s r correlation for this relationship was calculated to determine the [BLa] at fixed exercise intensities of 40, 50, 60, 70 and 80% VO_{2peak}. The data for the whole group were not pooled together for a single linear regression equation as this would statistically obscure the individual relationships.
Estimated EE data from the sub-maximal stages in the laboratory assessment and HR data at each sub-maximal stage were used to create individual regression equations, and the Pearson’s r correlation for this relationship was calculated. Using HR from the game play, \( \dot{V}O_2 \) was predicted to calculate EE. The HR at the six training zones was also determined for each player. A two-way mixed ANOVA was performed to examine the main effect of time spent in zones, main effect of group on time spent in zones and to examine if there was an interaction effect. Significance was accepted at \( p \leq 0.05 \). Effect size of the difference between sports was calculated as previously described in Chapter 3, section 3.3.5.

8.4 Results

8.4.1 Physiological profiles

The two groups did not differ with respect to age, body mass, hours training per week or years playing wheelchair sport (Table 8.1; \( p = 0.38 \), \( p = 0.45 \), \( p = 0.75 \), \( p = 0.26 \) respectively). The HR-EE relationship was found to have a strong correlation in all participants (\( r^2 = 0.95 \) to 0.99). Table 8.3 shows there was no difference between wheelchair basketball players and tennis players in HR\(_{\text{peak}}\), but \( \dot{V}O_2\text{peak} \) was showing a trend towards being significantly higher for the basketball players when compared to the tennis players (\( p = 0.08 \)). Table 8.3 shows that, during the sub-maximal lab testing, wheelchair basketball players had a higher HR at LT when compared to wheelchair tennis players (\( p = 0.01 \)) and significantly higher HR at LTP (\( p = 0.005 \)). A higher \( \dot{V}O_2 \) at LT when compared to wheelchair tennis players was shown (\( p = 0.05 \)), as was a trend towards a higher \( \dot{V}O_2 \) at LTP when compared to wheelchair tennis players (\( p = 0.06 \)). The female players had a \( V\dot{O}_2\text{peak} \) and \( V\dot{O}_2 \) at LT equivalent to 50\% of the males in each of their specific cohort.

When expressed as a percentage of peak values, HR was significantly higher in the basketball players (68.2 (7.2)\%) when compared with tennis players (58.5 (5.0) \%) at LT (\( p = 0.02 \)), and also higher in this group at LTP (75.1 (2.33) \% vs. 72.0 (1.6) \%; \( p = 0.03 \)). Percentage \( \dot{V}O_2 \) values were not different between sports at LT (\( p = 0.41 \)) or at LTP (\( p = 0.54 \)). Figure 8.1 shows the [BLa] response at fixed exercise intensities for the wheelchair basketball versus tennis players. There were no significant differences between the two groups (\( p > 0.05 \)).
### Table 8.3. Individual physiological profile of the basketball and tennis players. Group values are means (±SD).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sport</th>
<th>HR&lt;sub&gt;peak&lt;/sub&gt; (b·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>VO&lt;sub&gt;2peak&lt;/sub&gt; (L·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>HR at LT (b·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>VO&lt;sub&gt;2&lt;/sub&gt; at LT (L·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>HR at LTP (b·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>VO&lt;sub&gt;2&lt;/sub&gt; at LTP (L·min&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basketball</td>
<td>199</td>
<td>3.42</td>
<td>138</td>
<td>1.75</td>
<td>153</td>
<td>2.15</td>
</tr>
<tr>
<td>2</td>
<td>Basketball</td>
<td>200</td>
<td>3.18</td>
<td>134</td>
<td>1.82</td>
<td>151</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>Basketball</td>
<td>193</td>
<td>3.86</td>
<td>134</td>
<td>2.08</td>
<td>147</td>
<td>2.50</td>
</tr>
<tr>
<td>4</td>
<td>Basketball</td>
<td>189</td>
<td>3.74</td>
<td>122</td>
<td>1.41</td>
<td>144</td>
<td>2.15</td>
</tr>
<tr>
<td>5</td>
<td>Basketball</td>
<td>178</td>
<td>1.74</td>
<td>143</td>
<td>1.19</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>6</td>
<td>Basketball</td>
<td>204</td>
<td>1.95</td>
<td>119</td>
<td>0.71</td>
<td>145</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>194</td>
<td>2.98</td>
<td>132</td>
<td>1.49</td>
<td>148</td>
<td>(4) 1.99</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>(9)</td>
<td>(0.91)</td>
<td>(9)</td>
<td>(0.50)</td>
<td>(4)</td>
<td>(0.59)</td>
</tr>
<tr>
<td>1</td>
<td>Tennis</td>
<td>191</td>
<td>2.85</td>
<td>107</td>
<td>1.24</td>
<td>138</td>
<td>1.97</td>
</tr>
<tr>
<td>2</td>
<td>Tennis</td>
<td>197</td>
<td>2.54</td>
<td>112</td>
<td>1.24</td>
<td>146</td>
<td>1.75</td>
</tr>
<tr>
<td>3</td>
<td>Tennis</td>
<td>202</td>
<td>2.47</td>
<td>125</td>
<td>1.06</td>
<td>141</td>
<td>1.34</td>
</tr>
<tr>
<td>4</td>
<td>Tennis</td>
<td>185</td>
<td>2.11</td>
<td>124</td>
<td>1.13</td>
<td>136</td>
<td>1.21</td>
</tr>
<tr>
<td>5</td>
<td>Tennis</td>
<td>196</td>
<td>1.10</td>
<td>107</td>
<td>0.50</td>
<td>139</td>
<td>0.70</td>
</tr>
<tr>
<td>6</td>
<td>Tennis</td>
<td>194</td>
<td>1.30</td>
<td>106</td>
<td>0.56</td>
<td>139</td>
<td>0.88</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>194</td>
<td>2.06</td>
<td>114 *</td>
<td>0.96*</td>
<td>140 *</td>
<td>1.31</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>(6)</td>
<td>(0.71)</td>
<td>(9)</td>
<td>(0.34)</td>
<td>(3)</td>
<td>(0.49)</td>
</tr>
</tbody>
</table>

**Key:** *Significant difference between groups (p < 0.05).

<sup>v</sup> No LTP detected for this individual.
8.4.2 Energy expenditure and match duration

Mean EE in B-APT (703 (215) kcal-hr⁻¹) was significantly higher when compared to WTP (439 ± 171 kcal-hr⁻¹; p = 0.04), and there was a trend towards EE in WBP (672 (207) kcal-hr⁻¹) being higher than the average EE during WTP (p = 0.06) (Figure 8.2a). This trend actually had a large ES of 0.56, showing a meaningful difference between the average EE in wheelchair tennis and wheelchair basketball when all rests, time-outs and half-time were included. Figure 8.2b shows the duration of WTP was significantly longer than that of A-BPT (68.5 (14.2) to 39.0 (15.1) minutes respectively, p = 0.006). Therefore, when this is taken into consideration, wheelchair tennis players actually expended a similar amount of energy in WTP (522 (283) kcal) when compared to wheelchair basketball players in A-BPT (460 (254) kcal) during a typical game for each sport (p = 0.70). When WBP and WTP were compared, the duration of a wheelchair tennis match was significantly longer (68.5 (14.2) minutes) than a wheelchair basketball match (46.5 (18.2) minutes; p = 0.04). As tennis players were playing for longer than the wheelchair basketball players, figure 8.2c shows a similar amount of energy was expended during both WTP (522 (283) kcal) and WBP (527 (288) kcal), p = 0.98.
Figure 8.2. a) Mean (±SD) EE (kcal·h\(^{-1}\)) b) duration of game play (minutes) and c) total EE (kcal) during each game in WTP, WBP, and B-APT.*denotes a significant difference p < 0.05 and # denotes p = 0.06.
8.4.3 Match HR

Figure 8.3 shows the HR response during WBP and indicates the maximum and average HR, and actual playing time (B-APT) for one participant. Between the two sports, there was a 9 b·min\(^{-1}\) difference in HR\(_{\text{peak}}\) during game play, although these values did not significantly differ (191 (10) in WBP/B-APT vs. 182 (15) b·min\(^{-1}\) in WTP, \(p = 0.28\)). As Figure 8.4a shows, the wheelchair basketball players showed a higher average match HR during B-APT than the wheelchair tennis players (WTP) (166 (11) vs. 146 (16) b·min\(^{-1}\); \(p = 0.03\)). During WBP and WTP, there was a trend towards a difference in average HR between sports (162 (11) vs. 146 (16) b·min\(^{-1}\) for wheelchair basketball and tennis respectively; \(p = 0.07\)), with a large ES of 0.64. When average match HR was expressed as %HR\(_{\text{peak}}\) and compared between sports during B-APT and WTP, there was a significant difference (85.8 (2.3) vs. 75.3 (7.8) % respectively; \(p = 0.01\)). There was also a significant difference between % HR\(_{\text{peak}}\) (83.6 (2.5) vs. 75.3 (7.8) % \(p = 0.02\)) during WBP and WTP respectively (Figure 8.4b).

Figure 8.3. An example of a wheelchair basketball player’s HR trace during a match showing HR\(_{\text{peak}}\) (black horizontal line), average HR (grey line), and time spent on court (dashed line).
8.4.4 Heart rate zones

Figure 8.5 shows the relative percentage the wheelchair basketball and tennis players spent in each training HR zone. This was measured during WBP, B-APT and WTP. Analysis for the whole game in both sports (WBP and WTP) as a percentage of the total game time showed a significant main effect for zone (p < 0.01). Pairwise analysis revealed that more time was spent in zone 5 (79 and 69 % for wheelchair basketball and tennis respectively) compared to other zones (< 15% in each other zone). There was no zone * group interaction, suggesting both wheelchair basketball and tennis HR responded in a similar pattern. Furthermore, there was no main effect of group suggesting the two groups spent a similar relative time in each zone.

A comparison between B-APT and WTP as a percentage of a whole game showed there was a significant main effect of zone (p < 0.01). Pairwise analysis revealed more time was spent in zone 5 (basketball 88% and tennis 69%) compared to any other zone (<15% in each other zone). When time spent in minutes was compared between zones, there was a main effect of group. Observation of the results suggest that wheelchair basketball players spent less minutes in zone 3 (1.0 vs. 9.1 minutes) and zone 5 (32.3 vs. 52.4 minutes) when compared with the tennis players respectively. When relative time spent in each zone was analysed, there was no main effect of group (p = 0.08).
Figure 8.4. a) Mean HR during competition (b·min⁻¹) and b) % HR_{peak} during competition in WTP, WBP and B-APT. *denotes a significant difference p < 0.05 and # denotes p = 0.07.
Figure 8.5. A comparison of the percentage of time spent in each training zone during wheelchair basketball actual playing time (B-APT), whole match play (including rests, WBP) and whole match wheelchair tennis play (WTP). Values are means (±SD). * denotes a significant difference between zone 5 and all other zones, p < 0.05.

8.5 Discussion

The aim of this study was to examine the physiological profiles of wheelchair basketball and tennis and specifically to identify if there were any differences in the physiological demands and fitness of wheelchair basketball and tennis players, with special reference to EE. The main findings were that HR and $\dot{V}O_2$ at LT and HR at LTP were significantly higher in wheelchair basketball players when compared to wheelchair tennis players. Mean EE (kcal·h$^{-1}$) during competition was significantly higher during A-BPT when compared to WTP. As expected the duration of wheelchair tennis play
was longer than basketball yet the total EE during competition was similar between both sports (WTP vs. both WBP and A-BPT).

8.5.1 Physiological profile

There was a tendency for \( \dot{V}O_{2peak} \) to be higher in the wheelchair basketball players when compared to the tennis players. The \( \dot{V}O_{2peak} \) of the elite wheelchair basketball players in the present study was found to be similar to Pérez et al. (2007) or slightly higher than that reported in the literature for wheelchair basketball players (Burke et al., 1985; Veeger et al., 1991; Vanlandewijck et al., 1995; Goosey-Tolfrey, 2005; de Lira et al., 2010; Bernardi et al., 2010). Yet similar values were found for the tennis players when compared to the literature (Roy et al., 2006). As evident in the literature, female wheelchair athletes demonstrated lower \( \dot{V}O_{2peak} \) values than their male counter-parts (Bhambhani, 2002; Goosey-Tolfrey and Tolfrey, 2004). In agreement with previous research (Abel et al., 2008), the present study found no difference between sports in HR\(_{peak}\). There were differences found between sports in HR and \( \dot{V}O_2 \) at LT and HR at LTP, with the basketball players recording higher values. The higher absolute \( \dot{V}O_2 \) and HR at LT would suggest the wheelchair basketball players are exercising at a higher intensity before the onset of [BLa] accumulation. The results show that both groups were exercising at the same % \( \dot{V}O_{2peak} \) at LT and LTP and produced a similar amount of [BLa] at the same % \( \dot{V}O_{2peak} \), suggesting that both groups were working at the same relative intensity during the sub-maximal protocol. Of the limited data available that focuses on the HR and \( \dot{V}O_2 \) at LT and LTP, it is interesting to note that the current study found similar ranges of \( \dot{V}O_2 \) values at LT as that of Flandrois et al. (1986). However, when expressed relative to \( \dot{V}O_{2peak} \), the current study identified that this threshold occurred at 50 and 48% \( \dot{V}O_{2peak} \) for wheelchair basketball and tennis respectively, as compared to 63 and 54% \( \dot{V}O_{2peak} \) of high and low lesion level paraplegics found by Flandrois et al. (1986). The range of disabilities makes it hard to compare the two studies, and the protocols differed between studies, making results hard to interpret. In addition, these values may differ slightly depending upon the LT definition used and the number of stages employed (Weltman, 1995; Bourdon, 2000).
8.5.2 Energy expenditure

The mean EE during B-APT was significantly higher than the EE during WTP. There was also a trend towards a difference in EE between WBP and WTP. The EE of wheelchair tennis reported in the literature (Roy et al., 2006) is around 29% lower than that of the wheelchair tennis players in the present study. The wheelchair basketball players also expended a larger amount of energy, both during B-APT and during WBP, than the EE values reported during training and competition (375 - 584 kcal·h⁻¹) (Burke et al., 1985; Bernardi et al., 1988; Abel et al., 2008; Bernardi et al., 2010). It is important to highlight that participants within our study were highly trained and considered elite. Moreover, the data collected was from international competition, which would have been more physically demanding when compared to training or simulated competition. Interestingly however, Burke et al. (1985) reported the range of EE in four athletes during a typical 30-minute training session. The highest value, which was obtained by two of the participants, was 612 kcal·h⁻¹, a value closer to that reported in the present study.

It is clear from the results that, per hour, wheelchair basketball players expend more energy than wheelchair tennis players. It is interesting to note that the duration of WTP (68.9 minutes) is significantly longer than that of B-APT (39.0 minutes). So, taking this into consideration, wheelchair tennis players expend a similar amount of energy in WTP (522 kcal), when compared to wheelchair basketball players during A-BPT (460 kcal), during typical game play for each sport. When WBP and WTP were compared, the duration of a tennis match again is longer than a wheelchair basketball game (46.8 minutes), but the total estimated EE is only 5 kcal different. This could suggest nutritional advice for both sports may need to be similar on competition days. However, the groups show a comparable amount of training hours per week. Therefore, depending on the sport specificity of the exercise, wheelchair basketball players may expend more energy during training due to the higher intensity of their sport.

8.5.3 Match HR

Average HR was higher in B-APT and trended towards being higher in WBP when compared to WTP, which supports the work of Coutts (1988) and, more recently, Bernardi et al. (2010). The fact that wheelchair basketball is shown to have a larger competitive demand is a reflection of the amount of the court covered during
competition and the long sprints involved in game play (Coutts, 1992; Bloxham et al., 2001). Interpretation of this data would suggest that the highly intermittent nature of wheelchair basketball, with a work-to-rest ratio of 1:1 (Pérez et al., 2007), may be more physiologically demanding than the intermittent play of wheelchair tennis (with a work-to-rest ratio estimated in the able-bodied game of 1:3 – 1:5, Kovacs, 2007).

Average HR during B-APT (166 b·min⁻¹) was higher than that reported by other literature for wheelchair basketball players (range 128 to 155 b·min⁻¹) (Burke et al., 1985; Bernardi et al., 1988; Coutts, 1988; Schmid et al., 1998b; Bloxham et al., 2001; Pérez et al., 2007; Bernardi et al., 2010). Percentage HR in wheelchair basketball relative to HR_peak was higher in the present study, with an average HR 86% and 75% of HR_peak (B-APT and WBP respectively) compared to 71% (Bloxham et al., 2001). In tennis, average HRs of 121 b·min⁻¹ (Roy et al., 2006; Barfield et al., 2009) to 128 b·min⁻¹ (Coutts, 1988) compared to 146 b·min⁻¹ in the current study have been reported. Percentage HR in tennis relative to HR_peak was higher in the present study with HR averaging 75% of HR_peak compared to 69% and 68% of HR_peak (Roy et al., 2006; Barfield et al., 2009 respectively). Higher percentage and absolute values of HR in the current study could be due to the specificity of the current study focusing on elite athletes in international competition. From the available literature, club to national level standard players (Bloxham et al., 2001; Roy et al., 2006; Barfield et al., 2009) and females (Schmid et al., 1998b) have been measured, or literature has focused on training scenarios (Coutts, 1988; Abel et al., 2008).

It is important to note that in the present study the wheelchair tennis match data was analysed from the start of play to the end of play, including any breaks and rests (WTP). These rests were not manually recorded and could not be excluded from the analysis. The wheelchair basketball data however, included a whole game with rests and time outs (WBP) as well as analysis excluding time-outs, end of quarters and substitutions (B-APT). Basketball players may not play the whole match due to substitutions which vary greatly between matches. Tennis players compete for the whole match and breaks are included within the rules of the match and are consistent from match to match. That said, tennis match length is variable, and court surface and ball type can change between tournaments which can influence the physiological demands of the sport (Kovacs, 2007). In wheelchair basketball, excluding time-outs,
end of quarters and substitutions during competitive play is a truer reflection of the demands of this particular sport (Pérez et al., 2007).

8.5.4 Heart rate training zones

The HR training zones obtained from the current study are informative, since they can be used to help specialise training for the different sports. Interestingly, it was apparent that when comparing time spent in zones between B-APT and WTP one of the differences between sports occurred at HR zone 3, which is one of the zones just below LTP. This finding may help explain the differences found between the characteristics of the athletes between sports at LTP. The slightly higher absolute $\dot{V}O_2$ at LTP for the basketball players may be due to these players demonstrating a higher aerobic capacity, as relatively, there was no difference in $\dot{V}O_2$ at LTP between sports. From these data, a wheelchair tennis match lasts on average 30 to 40 minutes longer than a wheelchair basketball match. So in absolute terms, wheelchair tennis players are spending more time in the zones around and above LTP. However, the wheelchair basketball players spend a higher (although not significant) relative percentage of time in zone 5 when compared with wheelchair tennis even when taking rests into account. If more time is spent around or above the LTP, this may promote a more efficient lactate removal, which would result in LTP occurring at higher exercise intensities (Weltman, 1995).

Training in the different HR zones would be achieved through varying the work-to-rest ratios and the intensity of the activity. It has been suggested that zone 1 to 2 would incorporate lower intensities of longer duration to build an aerobic base whereas zone 5 would have a lower work-to-rest ratio and involve higher exercise intensities with more interval-related training (Bourdon, 2000). Training could incorporate a combination of the HR zones, with zones 1 to 2 being used as a recovery between training at the higher zones. Different drills could be implemented and could reflect important aspects of the sport such as movement patterns and agility, along with more sport-related actions such as passing in basketball (Owen, 1982; Frogley, 1999). Bullock and Pluim (2003) highlight that it is important that training reflects competitive play; for example wheelchair tennis training can be done holding a racket, so that the tennis racket eventually does not become a constraint to the pushing technique (Goosey-Tolfrey and Moss, 2005). Heart rate monitors can be used to help examine exercise training for participants with a low to moderate spinal cord injury. It is important
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however, that athletes are re-tested (Diaper and Goosey-Tolfrey, 2009) as, through training, the LT and LTP will occur at higher exercise intensities and thus it is likely that the HR training zones will change (Godfrey and Whyte, 2006).

Basketball training literature has highlighted the need for frequent repetitions involving different speeds and high intensity drills (Owen 1982; Frogley et al., 1999). Similarly, drills are also available to the tennis player which replicate the movements on the tennis courts (Bullock and Pluim, 2003). Even though some literature has suggested more aerobic training should be undertaken for wheelchair tennis players which could involve continuous pushing for 45 to 60 minutes or longer (Bullock and Pluim, 2003), emphasis should also be placed on anaerobic, intermittent training (Kovacs, 2007). The HR training zones themselves vary between researchers; however, to date, this has involved able-bodied participants (Bourdon, 2000). Differences were also shown to occur between participants within the same sport in the current study. Individual variance, the problems associated with competitive play and the varying match demands between matches discussed earlier, all contribute to these differences. However, where possible several matches from a number of participants were used to represent the typical match play response.

8.5.5 Limitations

As wheelchair basketball and tennis are intermittent in nature then there can be a delay in the HR response to actual play, so excluding time-outs could obscure the true reflection of the physiological demands of the game. Thus, using average HR to determine the EE of intermittent games players may not be the most accurate way of measuring metabolism (Spurr et al., 1988). Changes in HR due to excitement or stress and the environmental changes to HR can also have an effect on the data. One of the major difficulties facing research into elite wheelchair athletes is the small population available, resulting in small sample sizes along with the variation in disability within population groups. Although it is considered preferable to use a homogenous same sex cohort for data collection to reduce the variation in the results, there is always a practical trade-off between such homogeneity in study design and the need to ensure sample size is as large as possible in order to analyse variation and associations. For practical reasons, more data in this study could be analysed by including both male and female athletes from both sports to form the largest possible cohort. This also made pair
matching between sports more appropriate. Despite this study matching participants, differences in disability between subjects could affect the findings. It also can help explain the physiological differences compared with other studies. Both LT and LTP were determined visually by separate investigators. However, there was sometimes an element of uncertainty. The warmer temperatures and the humidity during tournaments within Florida when tennis data were collected could also have resulted in higher HRs (Price, 2006) than those played in England. Finally, when investigating competitive intermittent sport activity, an appreciation of the different opposition, environment and physiological demands between matches must be acknowledged (Kovacs, 2007; Pérez et al., 2007).

8.6 Conclusions

The current study demonstrated that wheelchair basketball players have higher aerobic capacities and can exercise at a higher intensity before the onset of blood lactate accumulation when compared with wheelchair tennis players of similar playing experience. Furthermore, wheelchair basketball players expend more energy during B-APT and WBP when compared to wheelchair tennis players during WTP. Wheelchair tennis players spend longer on court during a game, compared to wheelchair basketball players, but absolute total EE is the same between sports regardless of time-outs and end of quarters. Our findings suggest that it is possible that the times spent in basketball competitive play might be associated with the improved physiological profile of the wheelchair basketball players when compared with the tennis players. Close inspection of the HR profile during match play would suggest that wheelchair basketball players would benefit from high intensity training, whilst tennis players training should cover the exercise intensity continuum (Bullock and Pluim, 2003). Future research needs to address how athletes and coaches quantify training by taking into account both exercise volume and intensity and monitoring weekly training for adequate assessment of EE.
The primary focus of this thesis was to investigate the EE of wheelchair athletes. It would appear that this is a large area to study, given the complexities of data interpretation with respect to the nature and time of onset of disability, wheelchair type and experience. To gain a greater understanding of EE in this cohort, various aspects of physiology and wheelchair propulsion were considered, including body composition, wheelchair propulsion experience and classification in disability sport. As the current guidelines for fuel provision during sport are typically based on data from able-bodied athletes, there is limited information available to help wheelchair athletes optimise their nutritional practices (Price, 2010). In light of this, the present thesis investigated the EE i) during rest in wheelchair athletes; ii) during daily wheelchair propulsion in novice and experienced wheelchair users; and iii) during sports competition in wheelchair athletes. As outlined in section 1.2, three main objectives were formed:

1) To investigate the relationship between body composition and REE in athletes with a disability and to compare measured values of REE to predicted equations from the able-bodied population (Chapters 3 and 4).

2) To explore the effect of wheelchair propulsion practice and experience on the EE of wheelchair propulsion during daily ambulatory speeds (Chapters 5 and 6).

3) To analyse the physiological variables and the EE of wheelchair sports competition, with comparisons between sports and between disability classifications (Chapters 7 and 8).

This chapter reviews the primary findings from the experimental chapters, addressing each of the aforementioned objectives, and provides a summary of EE in relation to the three previously mentioned themes. This chapter also provides an overview of how this research could be used by practitioners to understand the nutritional needs and energy requirements of wheelchair athletes to help improve performance and optimise training. The chapter concludes with the practical implications of the findings and recommendations for further studies.
9.1 Resting energy expenditure in relation to predictive equations and body composition

To fully understand the REE of wheelchair athletes, the initial studies (Chapters 3 and 4) were conducted by grouping individuals according to their disability categorisation. Inclusion of specialised techniques such as DXA increased the validity of the data collected for this cohort. The REE of an individual accounts for the largest portion of daily EE (Ravussin et al., 1982), so it was an important aspect of total EE to consider. From previous literature it was evident that sedentary and/or rehabilitating individuals with an SCI have lower REE than able-bodied individuals (Monroe et al., 1998; Buchholz et al., 2003a; Jeon et al., 2003; Liusuwan et al., 2007). Moreover, SCI individuals also display lower REE values than those derived from validated able-bodied prediction equations (Mollinger et al., 1985; Sedlock and Laventure, 1990). Results in Chapters 3 and 4 revealed that the REE of tetraplegic athletes (63.4 kcal·h⁻¹) was significantly lower than the prediction equations from the able-bodied cohort, which confirmed earlier work. In contrast to this finding, the paraplegic athletes in both Chapters 3 and 4 showed comparable REE (70.0 and 71.8 kcal·h⁻¹ respectively) to that predicted for them using the able-bodied equations (72.3 and 72.6 kcal·h⁻¹ respectively). There was a tendency for the REE to be slightly higher in the paraplegics when compared to the tetraplegics in the two experimental studies. An initial justification was that this could be explained by the greater FFM evident in the paraplegic athletes. Nevertheless, when body composition was measured in Chapter 4, total-body FFM was similar between the tetraplegic and paraplegic athletes. This study extends the current literature exploring REE in relation to FFM within the general SCI population (Buchholz et al., 2003a) to that of an elite sports context.

Chapter 4 revealed similarities in REE in both tetraplegic and paraplegic athletes, contradicting the findings from a rehabilitation setting (Cox et al., 1985; Mollinger et al., 1985). The similarities in FFM found in Chapter 4 are also in disagreement with Spungen et al. (2003). From the findings, it was proposed that sports training resulted in similar physiology, supporting the work of Abel et al. (2008) who found similar results to the current thesis in tetraplegic and paraplegic athletes regarding REE. Chapter 3 also highlighted the higher REE in non-SCI individuals compared to their predicted value. This raised the question of whether able-bodied prediction equations for REE in athletic populations are affected by the potential increase in metabolically active mass through sports training.
Chapter 4 explored the relationship between REE and FFM but these results were not straightforward. Statistically, no difference was found between tetraplegic and paraplegic athletes for both REE and FFM. However, further analysis revealed that the patterns of FFM distribution showed a higher value in the upper limbs of the paraplegic individuals, which is in agreement with values in the SCI rehabilitation context (Maynard et al., 1997; Spungen et al., 2003; Jacobs and Nash, 2004). The finding of greater FFM in the lower limbs of the tetraplegic individuals when compared to paraplegic individuals was not expected, due to the majority of both cohorts having a complete SCI and therefore no sympathetic innervation to the lower limbs. One possible explanation, supported through regression analysis, was the difference between groups with respect to the onset of disability (a shorter time for the tetraplegic athletes). Although there was a 6.6 and 8.4 kcal·h⁻¹ difference in REE between the tetraplegics and paraplegics (Chapter 3 and 4 respectively), the absence of any major difference in REE between the two cohorts was likely to be due to the similarities in upper-body FFM alongside the somewhat unexpected greater lower-limb FFM found in the tetraplegic individuals.

9.2 The effect of practice and experience on the EE of wheelchair propulsion during daily ambulation.

To further understand the EE of wheelchair users, participants were grouped according to propulsion experience (Chapters 5 and 6). Moreover, using the SMARTWheel allowed a greater understanding of propulsion technique and consequently helped explain patterns of EE whilst learning wheelchair propulsion (Chapter 5). There is a large amount of literature that has measured the $O_2$ cost and GE of wheelchair propulsion in a laboratory setting. The variables that contribute to the $O_2$ cost of propulsion include: pushing velocity (Veeger et al., 1992a), properties of the wheelchair (Beekman et al., 1999; van der Woude et al., 1989a; van der Woude et al., 2009), wheelchair propulsion experience (de Groot et al., 2002a; 2005; 2007; 2008), and push strategy (van der Woude et al., 1989b; Goosey et al., 2000; Lenton 2008a; 2008b; 2009). Chapters 5 and 6 were designed to extend this work by reporting EE during daily wheelchair propulsion, so that nutritional advice could be given according to real values of EE. The purpose of this second section of the thesis was not just to focus on wheelchair athletes (Chapter 6) but also to account for the learning process of manual wheelchair propulsion and cover a wide spectrum of wheelchair
propulsion experience. This is of great importance, since nutritional advice may vary for specific wheelchair user groups in accordance with their wheelchair propulsion experience.

It was evident from Chapter 5 that EE during daily wheelchair propulsion reduces after three weeks of practice. Surprisingly, those participants who took part in no wheelchair propulsion practice other than the 36-minutes of initial baseline measurements were also found to have reduced EE during their post-testing session. These findings confirm earlier work which has found that both technical adaptations and physiological parameters are affected by the initial stages of learning wheelchair propulsion (de Groot et al., 2003; Dallmeijer et al., 1999b; van der Woude et al., 1999). With this in mind however, it is important to note that three weeks of practice induces greater reductions in EE than the shorter 36-minute period of propulsion, so there seems to be a continual reduction in the EE of wheelchair propulsion as this skill is being learnt. These findings can allow practitioners to appreciate the pattern of EE in novice individuals learning the skill of wheelchair propulsion.

The subjective measures of effort during daily propulsion (RPE) in Chapter 5 were significantly lower after practice when compared to the control group. The importance of understanding how an individual subjectively rates exercise intensity is a key issue in the rehabilitation setting where individuals practice wheelchair skills. This is also important for the general wheelchair user population, where adherence to physical activity may improve as it becomes subjectively easier to do. Our findings suggest that after three weeks of practice, RPE is lowered, so if RPE is used as a tool to monitor exercise intensity then the practitioner must be aware of these changes over time.

Chapter 6 provided evidence that experienced wheelchair users expend less energy at the same exercise intensity as novice individuals with only 20-minutes prior propulsion practice and novice individuals with three weeks of practice (108 minutes). This gave further evidence that EE obtained during wheelchair propulsion tasks must be related to the experience of the cohort. No difference in EE was found between novice individuals and individuals with three weeks of propulsion practice, suggesting the 20-minute practice may be sufficient to reduce the EE of wheelchair propulsion. In addition to this, it is clear that EE is greater in both a novice and practice group when compared to a group of habitual wheelchair users with at least six years of experience. Chapters 5 and 6 have shown that the EE of daily propulsion reduces with practice and reduces further with habitual
wheelchair use. This highlights the necessity of providing specific databases on the EE of wheelchair activities, depending on propulsion experience rather than generic values which may not be appropriate for all wheelchair users.

### 9.3 Physiological variables and EE of wheelchair sports competition with comparisons between sports and between classifications.

An examination of competitive wheelchair sports game play was conducted using data from 26 wheelchair athletes (Chapters 7 and 8). This provided an awareness of the physiological requirements and, combined with controlled laboratory testing, the EE of competitive play. The results revealed that the physical capacity of the GB international wheelchair basketball players was higher than the GB international tennis players. Within a team of wheelchair basketball players, those who displayed a greater physiological capacity belonged to the higher IWBF classification group, supporting the present classification system of the IWBF (2009). The wheelchair basketball players participating in the studies of Chapters 7 and 8 had a higher physical capacity compared with groups described in previous literature as shown in figure 9.1, confirming their elite status of training and competing at an international level.

When the EE of wheelchair basketball competition was considered, Chapter 7 revealed that high point players (IWBF class 3 - 4.5) expended 135 kcal·h⁻¹ more energy than low point players (IWBF class 1 - 2.5), although this difference did not quite reach significance. However, as the low point players spent ~10 minutes longer on court during a game, the EE was similar during actual playing time for both groups (517 vs. 499 kcal for LOW and HIGH respectively). This suggests a similar amount of calories are needed by both classification groups when considering competition. Regardless of these similarities however, the greater EE per hour in the high point player must be considered for training day nutritional advice and at camps where game duration may be of equal length. This finding, alongside the information provided regarding the physiological capacities of each group, suggests that training should be individualised in wheelchair basketball. Understanding the physiological differences and EE between classification groups can help provide coaches with information to make informed decisions about training.
Results from Chapter 8 showed a similar pattern in relation to the EE of wheelchair basketball and wheelchair tennis competition. It was revealed that the EE of a wholewheelchair basketball game was 233 kcal·hr⁻¹ higher than the EE of a wheelchair tennis game. However, results confirmed a significantly longer time spent on court by the wheelchair tennis players (up to 30 minutes when compared to wheelchair basketball players). With this in mind, the average EE seen in tennis players of 522 kcal is then comparable to that of basketball players who expended 527 kcal during a typical game in each sport. This is an important finding as EE per hour and EE during elite competition will need to be considered when applying training principles to each sport.

As wheelchair basketball players had a higher physiological capacity than wheelchair tennis players, these individuals may be subject to a higher exercise demand during training. Drills and skills practice will reflect the nature of each sport, so training principles should vary to fit with the demands of the sport (Owen, 1982; Frogley, 1999;
Bullock and Pluim, 2003; Kovacs, 2007). As chapter 8 has highlighted similar EE during a typical game in wheelchair basketball and tennis, advice on kcal needed during competition ought to be similar, especially if sport-specific training reflects the typical game duration of each sport. However, this chapter also emphasised the similar weekly training hours between groups. As wheelchair basketball players expend more energy per hour than wheelchair tennis players, they may need a higher energy intake on a weekly basis.

In conclusion, the results of this thesis indicate that there are several important physiological considerations to appreciate when investigating the EE of wheelchair athletes. Findings suggest that disability and time of onset of disability, wheelchair propulsion experience and sport classification are all important considerations for the accurate assessment of EE in this particular cohort of individuals.

9.4 Practical Implications

This thesis has provided researchers, athletes, coaches and practitioners with information regarding the EE of habitual wheelchair use through to the EE specifically in elite wheelchair athletes. Databases that provide information regarding the EE of the able-bodied individual, at rest and during specific activities, have taken a generalised approach, albeit taking into account sex and/or body mass. The transferability of this information has been questioned and, in the context of the wheelchair user, other factors become predominant when the energy costs of living and sports performance are to be considered.

1 Disability and body composition must be considered when estimating REE. Able-bodied predictive equations seem to be useful for the evaluation of paraplegic athlete’s metabolic rate although care must be taken when comparing values between the K4b2 and the Douglas bag technique. The equations should not be used to estimate the REE of tetraplegic athletes. Individual assessment of REE related to FFM is similar in tetraplegic and paraplegic athletes suggesting that total FFM may be comparable through elite sports training in these groups. However, caution must be taken to assess other factors affecting body composition and a shorter time since disability onset in tetraplegic athletes investigated in this thesis may account for the similar FFM between this particular group and paraplegic athletes.
Wheelchair propulsion experience influences the EE of wheelchair propulsion at speeds seen during daily activity. Typical values of EE seem to be 20-30% lower in habitual wheelchair users of at least six years, in comparison to novice wheelchair users. Nutritional advice must therefore be given in relation to experience and stage of learning and should not be provided as a generic value for all participants undertaking wheelchair propulsion. A reduction in EE of up to 13% is also evident after three weeks of wheelchair propulsion practice in novice individuals. In absolute terms, novice wheelchair users expended 180 kcal·h⁻¹ compared to 162 kcal·h⁻¹ in a group who have practiced wheelchair propulsion at a speed of 1.1 m·s⁻¹. At 1.5 m·s⁻¹ novice individuals expended 230 kcal·h⁻¹, 32 kcal more than their practiced counterparts. At a faster speed of 1.9 m·s⁻¹, novice individuals expended 298 kcal·h⁻¹ compared with the practiced individual’s 259 kcal·h⁻¹. Although these differences are small, extrapolated over an average day of wheelchair propulsion, this could equate to a reduction of energy expenditure of over 100 kcal if, throughout a 24 hour period an individual was active for at least 4 hours. Although consideration must be taken for the other physiological variables that may predominate during rehabilitation, practitioners may want to consider this 13% reduction in metabolic cost when assessing rehabilitation if weight management is an important aspect of an individual’s programme. It could also be useful for controlling the amount of activity completed if fatigue and over expenditure may be a concern.

Following on from the practice situation, when pushing at the same power output of 10 W, novice wheelchair users expend more than experienced wheelchair users by 36 kcal·h⁻¹. When pushing at a harder intensity of 26 W, the novice individuals expended 110 kcal·h⁻¹ more than the experienced wheelchair users. Values such as these can help practitioners better understand the metabolic differences between individuals at different stages of their rehabilitation.

Energy expenditure during sports competition is influenced by classification and physiological capacity. Wheelchair basketball players expend more energy per hour than wheelchair tennis players during competition. However, due to the longer duration of wheelchair tennis matches, the EE during a typical game in each sport is similar. Individuals with a higher classification in wheelchair basketball have a greater physiological capacity, alongside a non-significantly larger EE per hour when compared to those with a low classification. From the data in figure 9.1, it is clear that international standard wheelchair basketball players expend a higher amount of energy...
when compared with lower level of competition and also when compared with training in this sport. This suggests nutrition on competition day should be increased to meet the greater metabolic demands. However, during heavy training periods, practitioners and coaches should consider an increased energy intake for the athlete. From the absolute values provided in this thesis alongside the literature already published, EE may be estimated during competition and training if classification, aerobic fitness and hours of competition and training are considered.

9.5 Future directions

As a result of conducting the experimental research studies included in this thesis, a number of new research questions have arisen.

9.5.1 Resting energy expenditure in relation to body composition

The collection of REE from sedentary tetraplegic and paraplegic individuals would be extremely advantageous. This would provide a comparative study, alongside the data collected from the elite athletes, to explore whether a relationship exists between REE and differences in body composition that may be expected from a cohort who are not habitually sports trained after SCI. An additional sub-group of tetraplegic and paraplegic athletes with the same time since onset of disability would also help provide clearer conclusions about the body composition of SCI athletes. It would help to extend knowledge of whether time since onset of disability is a key factor driving the larger lower-limb FFM in the tetraplegic participants.

9.5.2 Energy expenditure in daily wheelchair propulsion

Results confirmed the reduction in EE during wheelchair propulsion in novice able-bodied individuals after a practice period. This reduction occurred after 36 minutes as well as three weeks, so further investigation should explore the duration and type of wheelchair propulsion practice. Future studies must also seek to confirm if this reduction in EE is seen after three weeks in participants undergoing SCI rehabilitation, in order to make the research more relevant to individuals who must start to use a wheelchair as part of their daily routine. As Chapter 6 revealed lower EE in experienced wheelchair users compared to that of novice individuals, it would also be helpful to understand the technical adaptations in relation to wheelchair experience that may be causing the energy reduction.
To facilitate this, measurement of the application of hand rim forces using the SMART\textsuperscript{Wheel} in a group of experienced wheelchair users alongside that of novice individuals is warranted.

### 9.5.3 Energy expenditure in wheelchair sports competition

Chapters 7 and 8 revealed that disability classification and the nature of the sport influences EE during elite wheelchair competition, and there still remain some Paralympic sports that would benefit from this type of research design. There is a need for larger sample sizes, and this, plus the need to obtain measures for each classification group within Paralympic sports competing at an international standard, means world-wide collaboration would be necessary. An alternative approach would be to gain physiological data from each classification group at a national level, although this would not provide sufficient data regarding the elite athlete. To progress this further, collection of data regarding other wheelchair sports would give a greater picture of the demands of these activities. To encourage individuals to be active, knowledge of the demands of certain activities is paramount if we are to provide information regarding EE of wheelchair sports.
Chapter 10

References


Appendix 1

A Comparison of the Physiological Demands of Wheelchair Basketball and Wheelchair Tennis

Louise Croft, Suzanne Dybrus, John Lenton, and Victoria Goosey-Tolfrey

Purpose: To examine the physiological profiles of wheelchair basketball and tennis and specifically to: (a) identify if there are differences in the physiological profiles of wheelchair basketball and tennis players of a similar playing standard, (b) to determine whether the competitive physiological demands of these sports differed (c) and to explore the relationship between the blood lactate \([\text{Bla}^-]\) response to exercise and to identify the sport specific heart rate (HR) training zones. Methods: Six elite athletes (4 male, 2 female) from each sport performed a submaximal and VO\(_{2}\)peak test in their sport specific wheelchair. Heart rate, VO\(_{2}\), and \([\text{Bla}^-]\) were measured. Heart rate was monitored during international competitions and VO\(_{2}\) was calculated from this using linear regression equations. Individual HR training zones were identified from the \([\text{Bla}^-]\) profile and time spent within these zones was calculated for each match. Results: Despite no differences in the laboratory assessment of HRpeak, the VO\(_{2}\)peak was higher for the basketball players when compared with the tennis players (2.98 ± 0.91 vs 2.06 ± 0.71; \(P = .08\)). Average match HR (163 ± 11 vs 146 ± 16 beats min\(^{-1}\); \(P = .06\)) and average VO\(_{2}\) (2.26 ± 0.06 vs 1.36 ± 0.42 L min\(^{-1}\); \(P = .02\)) were higher during actual playing time of basketball when compared with whole tennis play. Consequently, differences in the time spent in the different training zones within and between the two sports existed (\(P < .05\)). Conclusions: Wheelchair basketball requires predominately high-intensity training, whereas tennis training requires training across the exercise intensity spectrum. Keywords: Paralympic sport, training, wheelchair propulsion, heart rate, lactate threshold

Wheelchair basketball and tennis are two of the most popular and renowned sports within the Paralympics, with International competitions being held worldwide. Coaches and sport scientists with an interest in these sports are continually seeking to improve current training methods and optimize sport-specific training.\(^1,2\) With that in mind, it is evident that these wheelchair sports involve the aerobic system along with short periods of high-intensity intermittent activity.\(^3,4\) However, as with able-bodied sports, to ensure that training reflects the demands of the sport, an understanding of the physiological competitive sporting demands is required.\(^2,5\)
It is well documented that heart rate (HR) and blood lactate [Bla−] are useful tools for training prescription in able-bodied participants. Yet limited sports specific HR training guidance is available for wheelchair participants. Of the work available, which has covered wheelchair basketball, tennis and rugby the extrapolation of laboratory data to the field has been limited. Firstly, test protocols have been based on arm-crank ergometry and for one study this test involved increases in intensity every minute. For this later work, it is unlikely that the participants would have demonstrated anything even close to a physiological steady state in these short exercise stages. Moreover, it is doubtful whether the mode of exercise would reflect the physiological responses seen during wheelchair exercise. The work of Moody et al involved examining the VO₂-HR relationship in participants with limited or no sympathetic cardiac innervation. Previous studies in this area have suggested that using HR to estimate the exercise intensity in quadriplegics may not be appropriate due to the reductions in venous return and the lack of sympathetic innervation to the heart. These aforementioned methodological aspects limit the application of the research findings reported to field settings.

Nevertheless, these studies have found the average match HR of wheelchair tennis to range from 121 beats min⁻¹ (bpm) to 128 bpm and basketball at a slightly higher value between 132 to 151 bpm. Most of the research to date has involved male wheelchair athletes, with only a few recent studies examining the physiological aspects and demands of female athletes participating in wheelchair exercise. To extend the work previously reported in this area, it is necessary to examine the [Bla−] profile so that specific HR training zones can be developed providing athletes with targeted training and thus optimizing training. This is of interest when comparing wheelchair sports with the objective to provide specific sports training information since the distances covered, rest to work ratios and length of matches vary considerably. For example, basketball matches involve 10 min quarters whereas tennis matches last from under 1 h to over 3 h.

Therefore the purpose of this study was to examine (a) if there are differences in the physiological profiles of wheelchair basketball players and tennis players of a similar playing standard, (b) to determine whether the competitive physiological demands of these two sports differed (c) and to explore the relationship between the [Bla−] response to exercise and to identify sport specific trends of HR training zones that may be beneficial to develop coaches knowledge of training for these sports.

**Methods**

**Participants**

From a pool of 30 wheelchair athletes players, 6 wheelchair basketball players (4 male, 2 female) were matched with 6 wheelchair tennis players (4 male, 2 female), all of whom were presently competing internationally and therefore considered elite. After consultation with medical records, participants were matched on playing ability, trunk mobility and classification according to IWBF. Approval was gained from University Ethics Committee and written consent was obtained by all participants and their guardians (for those under 18 y old) before testing. Body mass was recorded to the nearest 0.1 kg using either a seated balance scale (Seca 710, seated scales, Hamburg, Germany) or a wheelchair double beam scale (300 series, Marsden, London, UK). Participant characteristics are given in Table 1.
Table 1  Sport, sex, age, disability and training characteristics of the wheelchair tennis and basketball players

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sport</th>
<th>Sex</th>
<th>Age (y)</th>
<th>Body Mass (kg)</th>
<th>Disability</th>
<th>SCI Completeness</th>
<th>Years Playing Sport</th>
<th>Training Hours Per Week</th>
<th>IWBF Sports Classification¹⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basketball</td>
<td>Male</td>
<td>26</td>
<td>77.6</td>
<td>SCI T12</td>
<td>Incomplete</td>
<td>5</td>
<td>21</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>Basketball</td>
<td>Male</td>
<td>27</td>
<td>70.7</td>
<td>Spina bifida</td>
<td>—</td>
<td>14</td>
<td>18</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>Basketball</td>
<td>Male</td>
<td>27</td>
<td>93.8</td>
<td>Avascular necrosis</td>
<td>—</td>
<td>12</td>
<td>15</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>Basketball</td>
<td>Male</td>
<td>34</td>
<td>94.2</td>
<td>SCI T12</td>
<td>Complete</td>
<td>16</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>5</td>
<td>Basketball</td>
<td>Female</td>
<td>29</td>
<td>58.3</td>
<td>SCI T9</td>
<td>Complete</td>
<td>10</td>
<td>16</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>Basketball</td>
<td>Female</td>
<td>17</td>
<td>50.0</td>
<td>Acute motor neuropathy</td>
<td>—</td>
<td>5</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>26.7</td>
<td>74.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td>5.5</td>
<td>18.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 1           | Tennis     | Male  | 30      | 99.0           | SCI T12                           | Incomplete       | 6                   | 15                       | 2.5                           |
| 2           | Tennis     | Male  | 18      | 64.1           | Brittle bones                     | —                 | 12                  | 25                       | 4.0                           |
| 3           | Tennis     | Male  | 15      | 67.8           | Transverse Myelitis T12           | Incomplete       | 2                   | 7                        | 3.0                           |
| 4           | Tennis     | Male  | 34      | 64.7           | SCI T 8/9/10                      | Complete         | 8                   | 21                       | 1.5                           |
| 5           | Tennis     | Female| 26      | 51.9           | SCI T 4/5                         | Complete         | 4                   | 15                       | 1.0                           |
| 6           | Tennis     | Female| 15      | 47.5           | Brittle bones                     |                  | 12                  | 5                        | 4.0                           |
| Mean        |            |       | 23.0    | 65.8           |                                   |                  |                     | 7.3                      | 14.7                          | 2.7                           |
| SD          |            |       | 8.2     | 18.1           |                                   |                  |                     | 4.1                      | 7.7                           | 1.3                           |
Experimental Design

There were two distinct phases to this study: a laboratory assessment within a 2-wk period either side of the selected sports competition and data collection during international wheelchair basketball and tennis competitions. All participants were tested in their own sports specific wheelchair. For the laboratory measurements, the tennis players were tested using a wheelchair ergometer as previously described,12 while the basketball players were tested using a specialized motorized treadmill (H/P/Cosmos, Germany).

Laboratory Assessment

Each participant completed an incremental submaximal exercise test that comprised five or six 4-min stages. The initial speed was predetermined following a self-selected warm-up period of 5 min where heart rate (HR) was approximately 100 bpm. Subsequently each exercise stage was increased by 0.2 to 0.4 m·s\(^{-1}\), and this ensured that we obtained a profile that included 40% to 80% VO\(_2\) peak. For the treadmill testing the incline was kept constant at 1% gradient throughout this test. During the last minute of each stage, expired air was collected and analyzed using the Douglas bag technique. The concentration of oxygen and carbon dioxide in the expired air samples was determined using a paramagnetic oxygen analyzer (Series 1400, Servomex Ltd., Sussex, UK) and an infrared carbon dioxide analyzer (Series 1400, Servomex Ltd., Sussex, UK). Expired air volumes were measured using a dry gas meter (Harvard Apparatus, Kent, UK) and corrected to standard temperature and pressure (dry). Oxygen uptake (VO\(_2\)), carbon dioxide output, expired minute ventilation, and respiratory exchange ratio were calculated. Heart rate was monitored continuously using radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland) and the rating of perceived exertion (RPE) was monitored throughout the test. A small capillary blood sample was obtained from the earlobe at the start of the test and as quickly as possible during a 1-min break between stages for determination of whole blood lactate concentration [Bla\(^{-}\)] using a YSI 1500 Sport (Yellow Springs, USA), which had been calibrated with a lactate standard of 5 mmol·L\(^{-1}\) before testing. The lactate threshold (LT) was defined visually by two separate observers at the first workload before there was “an onset of blood lactate accumulation.”15 A second breakpoint known as the lactate turn point (LTP) was identified and is used to describe a second workload where [Bla\(^{-}\)] begins to accumulate quickly.13 Based upon the aforementioned parameters six different HR training zones were identified (Table 2).13,16

Following a 15-min rest period, an incremental gradient test (treadmill) and an incremental speed test (wheelchair ergometer) was used to determine the peak oxygen uptake (VO\(_2\)peak). This test involved increases in external work until volitional exhaustion. Heart rate was monitored continuously, expired air samples were collected over the last two consecutive stages of the test and the final RPE was recorded. On completion of the peak test a capillary blood sample was also taken and analyzed to determine [Bla\(^{-}\)] as previously described. The criteria for a valid VO\(_2\)peak were a peak RER ≥ 1.10 and peak HR ≥ 95% of the age-predicted maximum (200 bpm minus chronological age in years) as previously used in this population group.12 All of the participants satisfied both criteria. Peak HR was taken as the highest value recorded during the test; however, if a higher HR value was obtained during match play then that value was used.
Heart Rate monitors (Polar team system, Finland) were placed upon the players at least 20 min before the start of competitive play. The players wore the HR monitors throughout the matches with data being recorded at 5-s intervals. Basketball HR data were collected during the Paralympic World Cup in England. The match start time, and during the basketball games the substitutions/ time outs were all manually recorded, thus allowing us to calculate whole basketball play (WBP) and basketball actual playing time (B-APT). Tennis HR data were collected from singles matches during international wheelchair tennis tournaments in Florida and England. For each match, the start and end time were recorded and the HR data collection period included all the activities during this time period, as representing the whole tennis play (WTP). The average HR and HRpeak during the matches were calculated for each player from both sports.

Statistical Analyses

Standard descriptive statistics were obtained (mean and standard deviation) for all variables using SPSS (16.0, Chicago). Independent t tests or the nonparametric equivalent were conducted to determine differences between groups for physiological parameters. The VO$_2$ and HR data at the end of the peak VO$_2$ test and each submaximal steady-stage were expressed as percentages of their respective peak values. For each participant a linear regression was conducted using the paired data points of %peak VO$_2$ and %peak HR values and the Pearson $r$ correlation for this relationship was calculated. Data obtained at each completed submaximal exercise stage and peak values were included in the analyses. The percentage peak VO$_2$ values were included in the analyses as the independent variable. The data for the whole group were not pooled together for a single linear regression equation as this would statistically obscure the individual relationships. Using HR from the game play VO$_2$ was predicted and the relative percentages of VO$_2$peak were determined. Point-by-point regressions were performed on the [Bla$^-$]%-VO$_2$peak data to determine the [Bla$^-$] at fixed exercise intensities of 40, 50, 60, 70 and 80% VO$_2$peak. The HR at the six training zones was determined for each player. A two-way mixed
ANOVA was performed to examine the main effect of time spent in zones, main effect of group on time spent in zones and to examine if there was an interaction effect. An independent sample $t$ test was used to examine any differences between groups for the time spent in the HR zones. Significance was accepted at $P \leq .05$.

**Results**

The two groups did not differ with respect to age, body mass, hours training per week or years playing wheelchair sport (Table 1; $P = .38$, $P = .34$, $P = .75$, $P = .26$ respectively). The HR-VO$_2$ relationship was found to have a strong correlation in all participants (0.96 to 0.99). During this submaximal testing, no differences were seen between the two groups in VO$_2$ at LT ($P = 0.08$; Table 3). However, HR was significantly higher at LT ($P = 0.02$) and LTP ($P = .006$) and VO$_2$ showed a strong trend toward being higher ($P = .06$) at LTP in basketball players compared with tennis players (Table 3). When expressed as a percentage of peak values, HR was significantly higher in the basketball players when compared with tennis players at LT ($P = .04$) and showed a trend toward significance at LTP ($P = .06$). Percentage VO$_2$ values were not different between sports at LT ($P = .59$) or at LTP ($P = .60$). Figure 1 shows the [Bla–] response at fixed exercise intensities for the basketball versus tennis players. There were no significant differences between the two groups ($P > .05$). Despite no significant difference in the HRpeak, the VO$_2$peak was higher

![Figure 1](image_url) — The mean (± SD) blood lactate concentration of wheelchair basketball and wheelchair tennis players at fixed exercise intensities.
Figure 2 — An example of a basketball player’s heart rate trace during a match showing peak heart rate, average heart rate and playing time. Peak heart rate (black horizontal line), average heart rate (gray line) and time spent on court (dashed line).

for the basketball players when compared with the tennis players (2.98 ± 0.91 vs 2.06 ± 0.71; P = .08).

Figure 2 shows the HR response during whole basketball play (WBP) and indicates the maximum and average HR, and actual playing time (B-APT) for one participant. Peak VO₂ was significantly higher during WBP when compared with WTP (2.90 ± 0.93 vs 1.80 ± 0.58 L·min⁻¹; P = .03) and there was a 10 beat difference in peak HR although these values did not significantly differ (190 ± 12 vs 180 ± 18 bpm respectively). The basketball group showed a trend toward a higher average match HR during B-APT (163 ± 11 vs 146 ± 16 bpm; P = .06, Figure 3) and a higher estimated average VO₂ (2.26 ± 0.06 vs 1.36 ± 0.42 L·min⁻¹; P = .02) than the tennis players (WTP). During WBP and WTP, there were no differences in average HR between sports (154 ± 15 vs 146 ± 16 bpm; P = .40). Yet, the basketball players still showed a higher estimated average VO₂ (2.03 ± 0.57 vs 1.36 ± 0.42 L·min⁻¹; P = .04). When average match HR was compared as %HRpeak between sports during B-APT and WTP, there was a significant difference (83.9 ± 1.9% vs 75.3 ± 7.8% respectively; P = .03). The corresponding average %VO₂peak for B-APT and WTP was found to be 75.9 ± 5.5% vs 68.3 ± 11.8% respectively (P = .18). There was no significant difference between %HR (79.2 ± 4.4 vs 75.3 ± 7.8% P = .3) and %VO₂peak (68.9 ± 7.7 vs 68.2 ± 11.8% P = .90) between sports whole play.

Table 4 shows the relative percentage and actual time the basketball and tennis players spent in each training HR zone. This was measured during WBP, B-APT and WTP. Analysis for the whole game in both sports in actual minutes and as a percentage of the total game time showed a significant main effect for zone (P < .01). Pairwise analysis revealed that more time was spent in HR zone 5 (36.1 ± 17.6 and 44.2 ± 23.9 minutes for basketball and tennis respectively) compared with
Appendix I

Figure 3 — Top panel: Peak (± SD) heart rate during a wheelchair basketball and wheelchair tennis match, average (± SD) match heart rate during WBP and WTP and average (± SD) match heart rate during B-APT. Bottom panel: Peak (± SD) VO₂ during a wheelchair basketball and wheelchair tennis match, average (± SD) match VO₂ during WBP and WTP and average (± SD) match VO₂ during B-APT (b). Note. *Significant difference between sports; WBP = whole basketball play, WTP = whole tennis play and B-APT = basketball actual playing time.
Table 3  The physiological profile of the basketball and tennis players

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sport</th>
<th>HRpeak (bpm)</th>
<th>VO₂peak (L·min⁻¹)</th>
<th>HR at LT (bpm)</th>
<th>VO₂ at LT (L·min⁻¹)</th>
<th>HR at LTP (bpm)</th>
<th>VO₂ at LTP (L·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basketball</td>
<td>199</td>
<td>3.42</td>
<td>138</td>
<td>1.77</td>
<td>153</td>
<td>2.15</td>
</tr>
<tr>
<td>2</td>
<td>Basketball</td>
<td>200</td>
<td>3.18</td>
<td>134</td>
<td>1.81</td>
<td>151</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>Basketball</td>
<td>193</td>
<td>3.86</td>
<td>134</td>
<td>2.08</td>
<td>147</td>
<td>2.50</td>
</tr>
<tr>
<td>4</td>
<td>Basketball</td>
<td>189</td>
<td>3.74</td>
<td>113</td>
<td>1.13</td>
<td>144</td>
<td>2.15</td>
</tr>
<tr>
<td>5</td>
<td>Basketball</td>
<td>178</td>
<td>1.74</td>
<td>143</td>
<td>1.19</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>Basketball</td>
<td>204</td>
<td>1.95</td>
<td>119</td>
<td>0.71</td>
<td>145</td>
<td>0.97</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>194</td>
<td>2.98</td>
<td>130</td>
<td>1.45</td>
<td>148</td>
<td>1.99</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>9</td>
<td>0.91</td>
<td>12</td>
<td>0.52</td>
<td>4</td>
<td>0.59</td>
</tr>
</tbody>
</table>

| 1           | Tennis   | 191          | 2.85               | 107            | 1.24                | 138            | 1.97                |
| 2           | Tennis   | 197          | 2.54               | 112            | 1.24                | 146            | 1.75                |
| 3           | Tennis   | 202          | 2.47               | 125            | 1.06                | 141            | 1.34                |
| 4           | Tennis   | 185          | 2.11               | 124            | 1.13                | 136            | 1.21                |
| 5           | Tennis   | 196          | 1.10               | 107            | 0.50                | 139            | 0.70                |
| 6           | Tennis   | 194          | 1.30               | 106            | 0.56                | 139            | 0.88                |
| Mean        |          | 194          | 2.06               | 114 *          | 0.96                | 140 *          | 1.31                |
| SD          |          | 6            | 0.71               | 9              | 0.34                | 3              | 0.49                |

* Significant difference when compared with basketball (P < .05).
Table 4: A comparison of the percentage of time spent in each training zone during actual playing time (APT) and whole match play (including rests) in wheelchair basketball with whole match wheelchair tennis play

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total game time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Relative</td>
<td>Absolute</td>
<td>Relative</td>
<td>Absolute</td>
<td>Relative</td>
<td>Absolute</td>
</tr>
<tr>
<td>Sport</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheelchair Basketball (APT)</td>
<td>7.4</td>
<td>2.7</td>
<td>3.7</td>
<td>1.8</td>
<td>2.7</td>
<td>1.3 *</td>
</tr>
<tr>
<td>Wheelchair Basketball (WBP)</td>
<td>18.2</td>
<td>9.6</td>
<td>5.6</td>
<td>3.7</td>
<td>4.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Wheelchair Tennis (WTP)</td>
<td>7.6</td>
<td>4.2</td>
<td>11.9</td>
<td>7.0</td>
<td>14.7</td>
<td>9.7</td>
</tr>
</tbody>
</table>

* Denotes a significant difference (P < .05) with wheelchair tennis.

a Denotes a significant difference (P < .05) between time spent in zone 5 to all other zones when analyzed with tennis.

b Denotes a significant difference (P < .05) between time spent in zones 2–4 and 5 when analyzed with tennis.
any of the other HR zones in minutes (both groups spent <10 min in each zone). As a percentage, more time was spent in zone 5 (67.6 ± 16.5 and 57.9 ± 30.7% for basketball and tennis respectively) than zone 2, 3 and 4 (both groups < 10% in each zone). There was no main effect of sport ($P = .24$; $P = .99$ respectively) and no interaction effect ($P = .50, 0.10$ respectively). A comparison between B-APT and WTP in minutes and as a percentage of a whole game, results showed that there was a significant main effect of zone ($P < .001$). Pairwise analysis revealed more time was spent in zone 5 (basketball 33.1 ± 15.8 min (82 ± 7.4%); tennis 44.2 ± 23.9 min (57.9 ± 30.7%) when compared with all the other zones (all other zones < 10 min [<15%]). When time spent in minutes was compared between zones, there was a main effect of sport. Analysis revealed that basketball players spent less minutes in zone 3 (1.3 ± 1.1 vs 9.6 ± 5.3 min) and zone 4 (1.6 ± 1.0 vs 5.8 ± 3.9 min) when compared with tennis players. When relative time spent in each zone was analyzed there was no main effect of sport ($P = .39$).

**Discussion**

The VO$_2$peak of the elite basketball players in the current study were found to be slightly higher than that reported in previous literature,$^4,17$ yet similar values were found for the tennis players.$^1$ As evident in the literature the females demonstrated lower VO$_2$peak values to their male counterparts.$^{18}$ There was a tendency for VO$_2$peak to be higher for the basketball players when compared with the tennis players (2.98 ± 0.91 vs 2.06 ± 0.71; $P = .08$). Moreover, in contrast to previous research, the current study found a difference between sports in the HRs (148 ± 4 vs 140 ± 3 bpm) at LTP, with again the basketball players recording higher values.$^{19}$ To the authors knowledge limited data exists that focuses around the LT and corresponding work rates. Of that available, it is of interest to note that the current study found similar VO$_2$ values at LT to the work of Flandrois et al.$^{20}$ But when expressed relative to VO$_2$peak the current study identified that this threshold occurred at only 49.6 and 48% VO$_2$peak for basketball and tennis respectively when compared with the 63% and 54% of high and low paraplegics in Flandrois et al.$^{20}$ The range of disabilities makes it hard to compare the two studies and the protocols differed between studies making results hard to interpret. In addition, these values may differ slightly depending upon the LT definition used, which, although was similar in both studies, in the present work, was perhaps limited due to the number of exercise stages employed,$^6,16$ we will revisit this methodological consideration later.

Average match HRs in the current study were found to be higher in both sports when compared with other previously reported research.$^1,2,4,11,21,22$ Basketball average actual play, match HRs (163 bpm) were higher than that reported by other literature (range 128 to 151 bpm).$^2,4,21,22$ In tennis, average HRs of 121 to 127 bpm compared with 146 bpm in this study have been reported.$^1,4,11$ Average tennis values relative to %HRpeak were higher in this study with 75% compared with 69%.$^1$ A similar case in tennis reported average VO$_2$ as %VO$_2$peak at a higher 68% in this study when compared with Roy and coworkers$^1$ finding of 49.9%. In fact this value is more similar to that of able-bodied tennis players which is reported at 60% to 70% VO$_2$peak.$^{23}$
Average HR, VO_{peak} and average VO_{2} were all higher during actual play in a basketball match (B-APT) when compared with tennis (WTP) which supports the work of Coutts.\textsuperscript{4} The novelty of this study is that it extends the work of Coutts\textsuperscript{4} to now include estimates of VO_{2} through the HR-VO_{2} relationship. The fact that basketball is shown to have a larger competitive demand will be a reflection of skills involved, court covered and activities performed such as longer sprints.\textsuperscript{22} Basketball also has a higher work to rest ratio with actual playing time accounting for 50\% of total match time (excluding substitution time) compared with tennis actual playing time only accounting for 15 to 20\%.\textsuperscript{1,2} Comparison of the two sports including all rest and time out periods in basketball showed no difference in average HR but results still showed a significantly higher average VO_{2} during a basketball game when compared with tennis. Further work is warranted in this area to include time-motion match analysis which would enable a greater understanding of the relative importance of these factors.

It is important to note that in the current study the tennis match data were analyzed from the start of play to the end of play, including any breaks or rests whereas basketball data includes a whole game with rests and time outs and also analysis excluding time outs, end of quarters and substitutions. Basketball players may not play the whole match due to substitutions, and substitutions and time outs vary greatly between matches. Tennis players compete for the whole match and breaks are included within the rules of the match and are consistent from match to match. This may have been influential upon the difference between the sports and excluding time outs, end of quarters and substitutions during basketball play may be a truer reflection of the demands of this particular sport. Roy et al\textsuperscript{1} included only actual playing time of tennis matches and despite only accounting for 15\% of total time, average HR values were similar to that of other literature. The slightly higher VO_{2} and HR values reported here highlights a major issue when investigating competitive intermittent sport activity as the opposition, environment and match demands can vary greatly between matches.\textsuperscript{2,23} Additionally in tennis, match length is variable, thus longer matches can result in higher physiological demands and court surface and ball type can change between tournaments; these will all play a role in the physiological demands of the sport.\textsuperscript{23}

The HR training zones obtained from the current study are informative, since they can be used to help specialize training for the different sports. Interestingly, it was apparent that when comparing B-APT with WTP the main differences between sports occurred at HR zones 3 to 4, which are the zones just below and at LTP. This finding may help explain the differences found between the characteristics of the sportsmen and women between sports where the VO_{2} and HR at LTP differed. The higher absolute VO_{2} and HR at LTP for the basketball players may be due to these players demonstrating a higher aerobic capacity, as relatively, there was no difference in VO_{2} at LTP between sports. From these data, a tennis match lasts on average 40 to 50 min longer than a basketball match and so in absolute terms, tennis players are spending more time in zones above LTP. However, relatively speaking, the basketball players spend a higher (although not significant) percentage of time in zone 5 when compared with tennis even when taking rests into account (67.6 ± 16.5 vs 57.9 ± 30.7\% respectively). If more time is spent above the LTP, this may promote more muscular adaptations enhancing the removal of lactate which would thus result in LTP occurring at a higher exercise intensity.\textsuperscript{6}
Training in the different HR zones would be achieved through varying the work to rest ratios and the intensity of the activity. It has been suggested that zone 1 to 2 would incorporate lower intensities of longer duration to build the aerobic base whereas zone 5 would have a lower work to rest ratio but involve higher exercise intensities with more interval related training. Training could incorporate a combination of the HR zones, with HR zones 1 to 2 being used as a recovery between training at the higher HR zones. Different drills could be implemented and could reflect important aspects of the sport such as movement patterns and agility along with more sport-related actions such as passing in basketball. Bullock and Pluim highlight that it is important that training reflects competitive play; for example tennis training can be done holding a racket, so that the tennis racket eventually does not become a constraint to the pushing technique. Heart rate monitors can be used to help monitor exercise training for participants with a low to moderate spinal cord injury, as it still remains unclear whether RPE can be used successfully by all athletes with the prescription of exercise. It is important however, that athletes are retested as through training the LT and LTP will occur at higher HR and thus it is likely that the HR training zones will change.

Basketball training has highlighted the need for frequent repetitions involving different speeds and more high intensity drills such as fast break basketball. In fact, a number of high-intensity interval-training drills for basketball many of which reflect the basketball movements such as U-turns and clovers are available in the coaching literature. Similarly, adapted versions of these drills are also available to the tennis player replicating the movements on the tennis courts. However, more aerobic training would be undertaken at a lower intensity within tennis which could involve continuous pushing for 45 to 60 min or longer duration less intensive interval programs. Weight and resistance training have been recommended for both sports to develop endurance, while also helping to develop upper body and trunk strength.

The HR training zones themselves vary between researchers; however to date, all the research has been involved able-bodied participants. Differences were also shown to occur between participants within the same sport. Individual variance, the problems associated with competitive play and the varying match demands between matches discussed earlier contribute to these differences. However, where possible we used several matches from a number of participants to represent the typical match play response.

One of the major difficulties facing research into elite wheelchair athletes is the small population available resulting in small sample sizes along with the variation of injuries within population groups. Despite this study trying to match participants, differences in injuries between subjects could affect findings and help explain the physiological characteristically differences with other studies. To determine the precise LTP more stages around the LTP should be conducted. Both LT and LTP were determined visually by separate investigators, however due to the large jumps in values there was sometimes an element of uncertainty. One basketball player was also excluded due to their LTP not being identified, however this subjects’ HR at LT was higher than most of the tennis players’ HR at LTP and thus their results would probably tie in with the findings above. Data from this study was conducted within international competition, whereas some of other studies organized matches solely for the study. The warmer temperatures...
and humidity during tournaments within Florida when tennis data were collected could also have resulted in higher HR. This may have bias the HR recordings toward a higher percentage time in zones 3 to 5 between sports which is opposite from the findings from this study.

In conclusion this study demonstrated that wheelchair basketball players have higher aerobic capacities when compared with tennis players of a similar playing experience. Despite the simplicity of HR data collection, the demands of wheelchair basketball actual play were shown to be more physiologically demanding than tennis. Our findings suggest that it is possible that the times spent in basketball competitive play might be associated with the improved physiological profile of the basketball players when compared with the tennis players. Close inspection of the HR profile during match play would suggest that wheelchair basketball players would benefit from high intensity training, while tennis players training should cover the exercise intensity continuum. Future research needs to address how athletes and coaches quantify training by taking into account both exercise volume and intensity and how stable or reliable the use of ratings of perceived exertion (RPE) may be in this process.

References