Physiological demands and court-movement patterns of wheelchair tennis

By

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Abstract

The wheelchair tennis evidence base has developed considerably in recent years. For those with a spinal cord injury (SCI), or severe physical impairment, tennis participation represents an opportunity for skill and motor development, and potential for disease risk reduction (Abel et al., 2008). However, as a complex series of technical, tactical and physical elements are implicated, participation for novice, developmental or low-skill players can be challenging. Hence, extension of the evidence base to consider the responses of such groups during play is of considerable value.

Initial experimental studies in this thesis investigated the validity, reliability and applicability of instrumentation for the assessment of wheelchair tennis court-movement. Comparisons were made between a global positioning system (GPS) and the data logger (DL) device (Study 1). GPS underestimated criterion distance in tennis-specific drills and reported lower match-play values than the DL. In contrast, DL placed on the outside wheel offered an accurate representation of distance. However, underestimations for DL were revealed at speeds > 2.50 $m \cdot s^{-1}$ during treadmill testing. Consequently, Study 2 extended this work with consideration of DL applicability for wheelchair tennis match-play. Examination of speed profiles revealed that time spent below the threshold for accuracy was trivial, confirming DL applicability for court-movement assessment. Further between-group comparisons for rank [highly-ranked (HIGH), low-ranked (LOW)], sex (male, female) and format (singles, doubles) revealed that LOW were stationary for longer than HIGH and spent more time at low propulsion speeds. Time in higher speed zones was greatest for HIGH and doubles players.

Between-group differences (*rank*) were further scrutinised in Study 3 with attention paid to describing the physiological response of competitive match-play aligned to court-movement. Set outcome (*result*) was also examined. Independent of result, HIGH covered greater overall, forwards, reverse and forwards-to-reverse distances than LOW. Interestingly, HIGH winners covered greater distances than HIGH losers and had a higher mean average and minimum heart rate (HR) than LOW winners. In contrast, LOW losers had a higher mean average and mean minimum HR than LOW winners. Collectively, these outcomes suggest an enhanced ability for HIGH to respond to ball movement and the physiological and skill challenges of match-play.

While this thesis confirmed that the activity duration and playing intensity is sufficient to confer health-related effects (Study 3), differences identified for rank suggested that strategies to

enable performance improvements in LOW were merited. The International Tennis Federation (ITF) has suggested that all starter players should be able to serve, rally and score from their first lesson (ITF, 2007). The reality however, is that chair propulsion whilst holding a racket is complex, and therefore, tennis play is challenging for novice and developmental players. Hence, the remainder of experimental work focused on interventions to enable increased court-movement and development of wheelchair tennis-specific court-mobility for LOW. The ITF have endorsed the use of a low-compression ball (LCB) for novices. An LCB bounces lower and moves more slowly through the air than a standard-compression ball (SCB). Novel findings from Study 4 revealed that greater total and forwards distances, greater average speeds and less time stationary result from use of the LCB. Increased movement activity occurred without associated increases in physiological cost, but was considered advantageous, with players adopting stronger positions for shot-play. Further examination of the linkage between movement and physiological variables were explored in the final experimental investigation (Study 5). A short period of organised practice enabled higher overall and forwards distances, and peak and average speeds to be achieved during match-play, without associated increases in physiological cost. Changes were desirable and represented enhanced court-mobility and mechanical efficiency (ME). Wheelchair tennis players were also more self-confident in tennis-specific chair-mobility, post-practice. The racket was a constraint, with lower distances and speeds, and a lower peak physiological response, achieved during tennis practice completed with a racket.

This thesis advocates the use of an LCB and a short period of pre-match court-mobility practice for the novice wheelchair tennis player. Collectively, these interventions are likely to prompt greater court-movement enabling better court-positioning, develop confidence in court-mobility and shot-play, develop competence in racket handling whilst pushing, and enhancing ME. These characteristics are likely to enable participation with the likely inference being that greater competence, skill and self-confidence promotes greater enjoyment and therefore enhances longer-term compliance. This is of considerable practical significance given that tennis typically attracts new players to the game, but is less successful at retaining them (ITF, 2007).

Key words: Data logger, exercise testing, health, participation, spinal cord injury, wheelchair propulsion.

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Preface

An overview of all publications and communications relating to work presented within this thesis is presented below:

Peer-reviewed publications

Sindall, P., Lenton, J.P., Whytock, K., Tolfrey, K., Oyster, M., Cooper, R.A. & Goosey-Tolfrey, V.L. (2013). Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court-movement. *Journal of Spinal Cord Medicine*, 36(4), 383–393.

Sindall, P., Lenton, J.P., Tolfrey, K., Cooper, R.A., Oyster, M. & Goosey-Tolfrey, V.L. (2013). Wheelchair tennis match-play demands: effect of player rank and result. *International Journal of Sports Physiology & Performance*, 8(1), 28–37.

Sindall P., Lenton, J.P., Malone, L.A., Douglas, S., Cooper, R.A., Hiremath, S., Tolfrey, K. & Goosey-Tolfrey, V.L. (2014). Effect of low-compression balls on wheelchair tennis match-play. *International Journal of Sports Medicine*, 35(5), 424–431.

Sindall, P., Lenton, J.P., Cooper, R.A., Tolfrey, K. & Goosey-Tolfrey, V. (2015). Data logger device applicability for wheelchair tennis court-movement. *Journal of Sports Sciences,* 33(5), 527–533.

Conference communications

Sindall, P., Lenton, J.P., Tolfrey, K., Cooper, R.A., Oyster, M. & Goosey-Tolfrey, V.L. Wheelchair tennis match-play demands: the effects of player experience and player ranking. *International Paralympic Committee VISTA Conference* 2011, Bonn: Germany.

Sindall, P., Lenton, J.P., Whytock, K., Tolfrey, K., Oyster, M., Cooper, R.A. & Goosey-Tolfrey, V.L. Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court-movement. *Loughborough University School of Sport, Exercise & Health Sciences Postgraduate Research Student Conference* 2012, Loughborough University, Loughborough: United Kingdom.

Sindall P., Lenton, J.P., Malone, L.A., Douglas, S., Cooper, R.A., Hiremath, S., Tolfrey, K. & Goosey-Tolfrey, V.L. Effect of low compression balls on wheelchair tennis match-play. *International Paralympic Committee VISTA Conference* 2013, Bonn: Germany.

Sindall, P., Lenton, J.P., Whytock, K., Tolfrey, K., Oyster, M., Cooper, R.A. & Goosey-Tolfrey, V.L. Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court-movement (Poster). *UK High Performance Conference for Paralympic Sports Science & Sports Medicine* 2013, Burton-On-Trent, Staffordshire: United Kingdom.

Symposium communications

Sindall, P. Wheelchair tennis and physical activity. *Peter Harrison Centre for Disability Sport Twilight Presentation, Coca Cola Advisory Board Meeting* 2013, Loughborough University, Loughborough: United Kingdom.

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Abbreviations

AB	able-bodied
ACSM	American College of Sports Medicine
AHA	American Heart Association
ANOVA	analysis of variance
BLa^-	blood lactate
BLa^-_{peak}	peak blood lactate
CHD	coronary heart disease
CV	coefficient of variation
DL	data logger
DLL	left wheel data logger
DLR	right wheel data logger
EE	energy expenditure
ES	effect size
GPS	global positioning system
HDOP	horizontal dilution of precision
HDL	high-density lipoprotein
HIGH	highly-ranked
HR	heart rate
HR_A	age-predicted maximum HR
HR_L	laboratory-measured peak HR
IMU	inertial movement unit
ITF	International Tennis Federation
IQR	interquartile range
LDL	low-density lipoprotein
LOW	low-ranked
LCB	low-compression ball
ME	mechanical efficiency
η^2_p	partial Eta squared
MET	metabolic equivalent
MFT	multi-stage fitness test
NR	without-tennis racket (*group*)
PA	physical activity
R	with-tennis racket (*group*)
RER	respiratory exchange ratio
RPE	rating of perceived exertion
SCB	standard-compression ball
SCI	spinal cord injury
SD	standard deviation
TDf.m	distance (forwards direction)
TDfr.m	distance (forwards-to-reverse counter-movement)
TD.m	distance (overall)
TDr.m	distance (reverse direction)
TE	typical error
VAS	visual analogue scale
$\dot{V}O_2$	oxygen uptake
$\dot{V}O_{2P}$	average oxygen uptake during organised practice
$\dot{V}O_{2peak}$	peak oxygen uptake
$\dot{V}O_{2T}$	average oxygen uptake during tennis match-play
95% CI	ninety-five percent confidence intervals
$\%HR_{avg}$	mean average HR expressed as a percentage of HR_A / HR_L
$\%HR_{max}$	mean peak HR expressed as a percentage of HR_A / HR_L
$\%HR_{min}$	mean minimum HR expressed as a percentage of HR_A / HR_L
$\%\dot{V}O_{2P}$	relative exercise intensity during organised practice
$\%\dot{V}O_{2T}$	relative exercise intensity during tennis match-play

Expressions are written in full when first mentioned and subsequently abbreviated for the remainder of the thesis.

1

General Introduction

The popularity of the Paralympic Games has prompted a global interest in disability sports and in particular the wheelchair court-sports, most notably basketball, rugby and tennis. For the scientific community, these developments have provided a wealth of opportunities for research to focus on both the optimisation of physical performance and to explore issues related to health and well-being. Hence, investigations have determined the physiological profiles of these wheelchair sports (Leicht et al., 2012; Goosey-Tolfrey et al., 2006; Goosey-Tolfrey, 2005), created normative values for those with an SCI (Janssen et al., 2002), developed field-related testing protocols (Goosey-Tolfrey & Leicht, 2013), considered the effectiveness of specific interventions to enhance performance (Goosey-Tolfrey et al., 2010), identified the nutritional practices of elite athletes (Goosey-Tolfrey & Crosland, 2010) and examined the physiological responses and movement patterns of wheelchair sports of elite player groups competing at a national or international level (Bernardi et al., 2010; Croft et al., 2010; Sarro et al., 2010; Sporner et al., 2009; Goosey-Tolfrey et al., 2006). Studies of this nature are helpful in profiling the demands of competition, and identifying highly effective training strategies.

Additionally, there is growing interest in the role of sport for recreational exercisers with a disability (Sahlin & Lexell, 2015; Conger & Bassett, 2011; Collins et al., 2010; Ginis et al., 2010a; Hettinga et al., 2010; Nash, 2005). As physical activity (PA) levels are typically low in such groups (van den Berg-Emons et al., 2008), structured exercise is likely to be required to offset chronic problems associated with sedentary living (Buchholz et al., 2003). Exercise training programmes are highly effective in improving wheelchair propulsion capacity (Zwinkels et al., 2014) and although energy expenditure (EE) is lower for wheelchair sports participation when compared with able-bodied (AB) populations (Price, 2010), attainment of targets for health enhancement are possible with engagement in structured wheelchair exercise (Abel et al., 2008). Due to the complexity and variability of movement demands, sport specifically offers a mechanism for improvements in wheelchair skills, enhancing executive function and improving stability of motor responses (Di Russo et al., 2010). Indeed, engagement is sport may be considered essential given that everyday wheelchair propulsion does not offer a sufficient stimulus to improve chair skills in the period post-discharge from rehabilitation (Fliess-Douer et al., 2013). As elite wheelchair athletes report high levels of self-actualisation in comparison to AB populations, sport offers potential for personal fulfilment and fosters a sense of physical capability (Sherrill et al., 1990). Further, increases in self-confidence and self-esteem (Kosel, 1993) and social integration (McVeigh et al., 2009) can be realised through sports participation. However, much of the work completed to-date makes these associations with reference to elite or highly trained participants. Hence, research opportunities exploring the responses for novice and developmental players during sports participation should not be ignored and should form a central focus in future experimental work.

While wheelchair tennis is advocated as a sport for all, and a natural choice for individuals with a physical impairment (ITF, 2007), the number and scope of experimental studies exploring the characteristics of training and match-play conditions are limited currently. While associations have been made between wheelchair tennis and an appropriate EE (Abel et al., 2008) and exercise intensity (Barfield et al., 2009) for health enhancement, the emphasis has been on the recruitment of highly athletic (Abel et al., 2008) or experienced (Barfield et al., 2009) player groups. This is also the case for studies involving comparisons between the different court-sports (Croft et al., 2010; Sporner et al., 2009). Therefore, studies which are designed to make inference about novice, low-level, recreational or developmental participation are required. Quantification of movement via assessment of distance and speed, alongside consideration of concomitant physiological responses is likely to increase the understanding of the demands associated with wheelchair tennis participation and performance. As there is limited evidence currently supporting this area, consideration of the characteristics of match-play is an important line of investigation; outcomes can thereafter be used to plan appropriate training and development strategies for players who are new to the sport, and thereby maximise associated health gains.

1.1 Organisation of the thesis

To introduce the research area, and to provide an overall context for this thesis, the evidence base is examined in detail in Chapter 2. The focus of this initial phase is to consider current participation levels in sport for wheelchair users, and evaluate the requirements for health-enhancing exercise. Specifically, the health-related benefits of tennis are explored. Due to the lack of a stringent classification system, wheelchair users with a diverse range of physical impairments are eligible to take part in tennis. Hence, due consideration is given to defining the range of disability types that may be implicated within the sport. The literature review concludes with consideration of the evidence surrounding measurement of court-movement and physiological variables. Common methodological approaches to data collection are thereafter presented in Chapter 3. The main content of the thesis follows, with five experimental studies presented in separate chapters (further detail in Sections 1.3 & 1.4). The final chapter offers an overall synthesis of the research findings, offering practical recommendations and future directions for research.

1.2 Aims and objectives

This thesis had two central aims within the context of wheelchair tennis. First, to develop a profile of wheelchair tennis demands and characteristics related to match-play conditions for players of differing ability levels, and for play with modified tennis balls. Second, to provide recommendations to enhance the ability and skill of novice players. In overall terms, the intention was to enable increased understanding of strategies for increasing and optimising participation in the sport. Objectives were as follows:

- To determine the accuracy of measurement and quantify the degree of measurement error for commonly used wheelchair tennis court-movement assessment devices
- To identify differences between high- and low-skill players in match-play performance
- To compare court-movement and resultant physiological responses for play with different ball properties
- To examine the impact of practice on tennis-specific court mobility and skill development

1.3 Overview of experimental chapters

The initial phase involved the validation of measurement devices for assessment of court-movement variables (**Study 1** - Chapter 4), to allow for accurate profiling of tennis match-play distance and speed characteristics (**Study 2** - Chapter 5). A detailed match-play analysis involving comparisons between high- and low-skill players (**Study 3** - Chapter 6) thereafter prompting further investigations concerning interventions designed to enhance participation and ensure chronic health-effects for novice groups. First, comparisons in court-movement and physiological responses were made for play using different types of compression ball (**Study 4** - Chapter 7). Second, the effects of organised practice on wheelchair tennis mobility and skill development were considered (**Study 5** - Chapter 8). A summary of the progression of experimental work completed is presented in Figure 1.1.

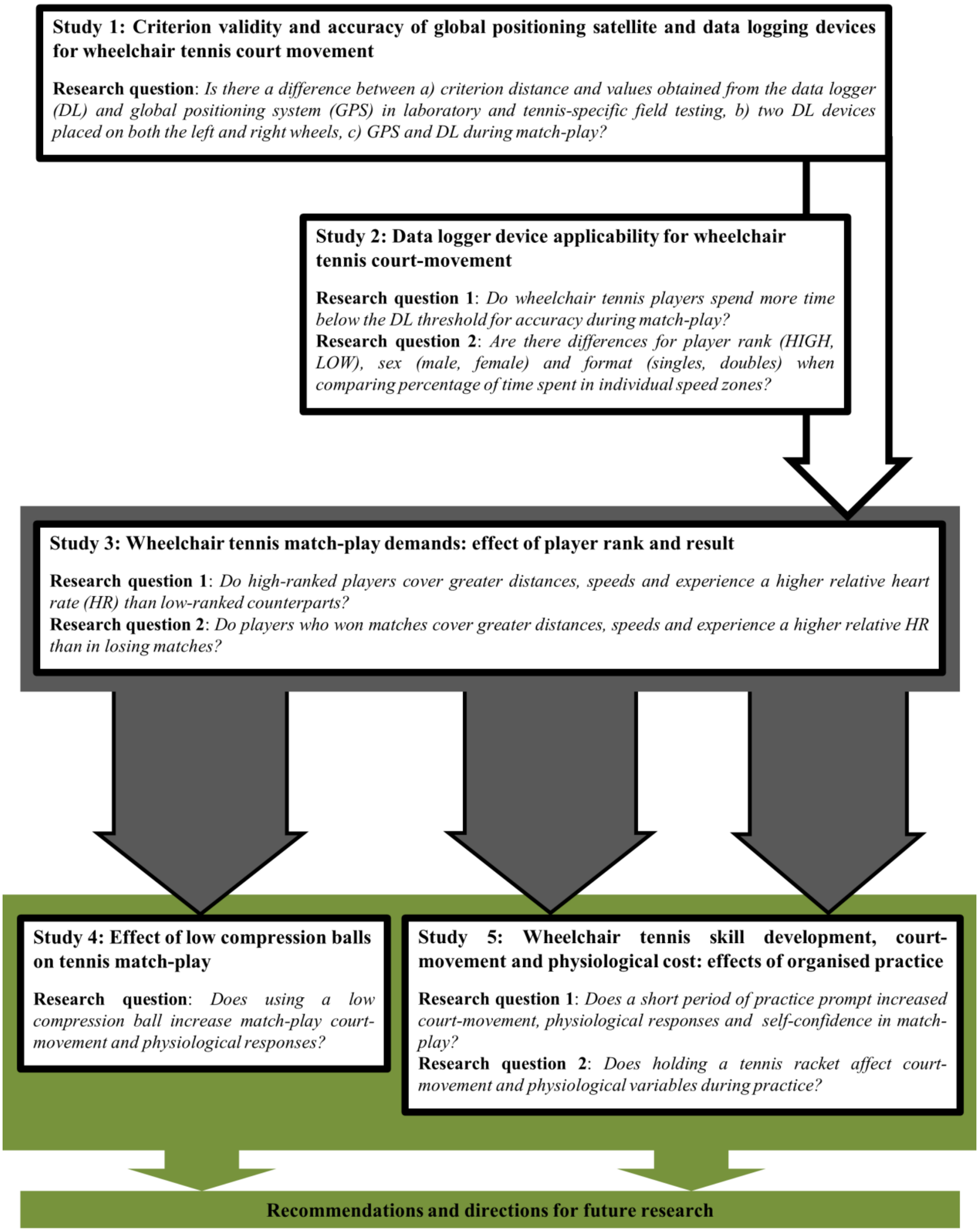

Figure 1.1 Schematic representation of experimental progression

2

Literature Review

2.1 General fitness of persons who require a wheelchair for mobility

Confinement to a wheelchair following an SCI or related physical impairment has a debilitating impact on peak physical capacity for work. Low peak power outputs (~20 to 50 W) are typically observed when patients are received at the start of the rehabilitation phase (van Koppenhagen et al., 2013a) and hence, the functional capacity of wheelchair users with an SCI is considered low in comparison to AB populations (Haisma et al., 2006). Paraplegics have a significantly higher functional capacity than tetraplegics (Simmons et al., 2014) but have similar upper-body strength to AB populations (Haisma et al., 2006). However, considerable inter-individual differences in aerobic capacity exist, with motor level of injury responsible for a considerable proportion (~22 %) of the observed variability (Simmons et al., 2014).

When confined to a chair, new motor skills must be learnt and individual physiology must be adapted to facilitate effective and efficient chair propulsion. Therefore a number of studies have considered the rate and type of improvement in performance variables over short- to mid-range time periods (de Groot et al., 2016b; de Groot et al., 2015; Vegter et al., 2015; Vegter et al., 2014; Vegter et al., 2013; de Groot et al., 2008b). As active muscles in the arm and shoulder regions are not configured for the loading more commonly associated with ambulatory muscles (Dalyan et al., 1999), propulsion presents a challenge and emphasises the importance of post-injury rehabilitation programmes for optimisation of technique. Fitness levels are typically low upon discharge from such rehabilitation programmes (van den Berg-Emons et al., 2008). Hence, additional options for the development of physical capacity must be explored.

Assessment of peak power is a popular means for determination of wheelchair-specific fitness (de Groot et al., 2016b; van der Scheer et al., 2015a) and allows for comparison to standards for maximally attainable performance with a disability (Veeger et al., 1991). Importantly, increases in work capacity have been noted between the start and 5 years post-discharge (van Koppenhagen et al., 2013a). However, personal, lesion-level and functional characteristics influence the degree of individual improvement (van Koppenhagen et al., 2013a). Increases in peak oxygen uptake ($\dot{V}O_{2peak}$) have also been revealed in this period (van Koppenhagen et al., 2013b) which suggests an improvement in fitness levels over time. However, this includes the rehabilitation phase which is associated with higher daily levels of PA (van den Berg-Emons et al., 2008) where compliance with regular, progressive exercise of sufficient dose and frequency is ensured. In contrast, no differences in $\dot{V}O_{2peak}$ are associated with the period between 1 and 5 years after rehabilitation commences (van Koppenhagen et al., 2013b). Therefore, manipulation of ongoing lifestyle behaviour is clearly required for inclusion of a sufficient exercise dose to enable chronic fitness-related adaptations. This is consistent with previous work suggesting fitness levels are typically lower 1 year post-discharge (van den Berg-Emons et al., 2008), that persons with an SCI lead largely inactive lifestyles (de Groot et al, 2013) and that conscious changes in attitude and behaviour are required to stimulate increases in PA (de Groot et al, 2013). Particular attention should be given to those with a long-standing SCI as wheelchair-specific fitness is lower in those with a longer time since injury (de Groot et al., 2016b). For this reason, and to ameliorate the negative effects associated with chronic deconditioning, tailored exercise training strategies or sports participation should be developed to engage persons with impairments in regular exercise (de Groot et al., 2016b; van der Scheer et al., 2015a; Dallmeijer et al., 1997).

2.2 Exercise training options, related health outcomes and considerations for wheelchair users

2.2.1 Associations between exercise and health outcomes for wheelchair users

In general terms, persons with physical impairments should be encouraged to exercise to offset the many degenerative changes associated with chronic sedentary behaviour. Exercise has multiple applications as a treatment for acute and chronic SCI, with clear and positive cellular, biochemical and holistic effects (Sandrow-Feinberg & Houlé, 2015). In addition, regular training is of particular importance given that secondary conditions such as diabetes mellitus, hypertension and atherogenic lipid profiles are common in those with an SCI (Jacobs & Nash, 2004). Positive associations between exercise and health for SCI have been known for some time, with 20% and 40% improvements in $\dot{V}O_{2peak}$ and physical work capacity respectively reported over short- to mid-term training periods (Hoffman, 1986). Indeed, recommendations for health-enhancing exercise do not differ significantly from those provided for AB populations (Jacobs & Nash, 2004) and persons with an SCI should expect to increase muscular endurance and decrease cardiovascular risk even though the mode is in most cases, restricted to upper-body exercise (Jacobs & Nash, 2001). Favourable lipid profiles (de Groot et al., 2013a; Nooijen et al., 2012; Devillard et al., 2007) and higher high-density lipoprotein (HDL) concentrations (de Groot et al., 2013a) are found in active individuals with an SCI. Further associations between aerobic capacity and HDL, low-density lipoprotein (LDL) to HDL ratio, and the relation of total cholesterol to LDL concentrations suggest desirable effects as a consequence of improved fitness (de Groot et al., 2008a). While elevated total serum cholesterol represents a positive risk factor for the development of coronary heart disease (CHD) (Oster, 1979), the measurement of LDL cholesterol (Branchi et al., 1994) or the HDL to total cholesterol ratio (Luria et al., 1991) may offer a more conclusive estimation of individual risk. HDL cholesterol levels are strongly, inversely and independently associated with CHD (Kokkinos & Fernhall, 1999), with modest increases caused by aerobic exercise and the greatest change found in those with initially high cholesterol levels (Kodama et al., 2007). Likely mechanisms for improved health status in wheelchair users are derived from increases in $\dot{V}O_{2peak}$, cardiac and neural adaptations, enhanced catecholamine responses and positive effects on platelet aggregation (Devillard et al., 2007).

Remaining active is of prime importance for those with an SCI given that wheelchair fitness deteriorates over time (de Groot et al., 2015). A negative relationship is commonly associated with $\dot{V}O_{2peak}$ and age due to chronic decreases in cardiac output and a decline in skeletal muscle oxidative capacity with resultant decreases in peripheral tissue oxygen utilisation (Betik & Hepple, 2008). However, a larger, more complaint left ventricle which relaxes quickly, fills to a large end diastolic volume and ejects with greater force is associated with chronic endurance training (Levine, 2008), thereby increasing $\dot{V}O_{2peak}$. This effect occurs at all ages, and positive effects are not confined to those without physical impairments. Higher $\dot{V}O_{2peak}$ values have been reported for paraplegic exercisers over 50 years of age in comparison to paraplegic non-exercisers under the age of 40 (Lee et al., 2015). Additionally, circulatory responses in elite wheelchair athletes with SCI are consistent with those expected of ambulatory people (Cooper et al., 2001). This emphasises the importance of regular PA on the improvement of cardiovascular function in those with disabilities and emphasises that commencing an exercise programme is advantageous irrespective of an increasing age.

2.2.2 Increasing daily wheelchair propulsion

Increasing everyday PA through increased frequency and duration of manual wheelchair propulsion is one method to prompt such health-related adaptations, with higher $\dot{V}O_{2peak}$, peak power output and favourable lipid profiles reported in those with a recent SCI who increase daily propulsion (Nooijen et al., 2012). However, daily PA of this type is subject to external constraints including, but not restricted to, surface characteristics, lighting, weather, traffic, and availability of places for rest and shelter, especially in older wheelchair users (Rosenberg et al., 2013). Further, harmful effects such as autonomic hyperreflexia, orthostatic intolerance, thermal dysregulation and fracture are also associated with PA in some wheelchair users (Jacobs & Nash, 2001). Repetitive sustained movements have been linked to shoulder pain (Curtis et al., 1999) which, in-turn, are directly associated with decreased quality of life and levels of PA (Gutierrez et al., 2007). This suggests a counter-productive effect. As the shoulder girdle is not naturally configured as a load-bearing joint, upper extremity injury is often reported in wheelchair users (Curtis et al., 1999). Also, years since onset of injury and duration of wheelchair use are associated with an increased incidence of shoulder pain (Finley & Rodgers, 2004), which is unfortunate as participation frequency is a key factor in stimulating increases in HDL concentrations (King et al., 1995) and psychological status via decreased depression and trait anxiety scores (Muraki et al., 2000). As individual propulsion technique is highly variable, the issue of shoulder pain cannot be factored out entirely (Sosnoff et al., 2015). However, it can be improved with exercise training, with athletes reporting more years free of pain than non-athletic counterparts (Fullerton et al., 2003). While the attendant risks and discomforts should be carefully considered for optimisation and personalisation of the exercise experience, they should not be used as justification for a lack of involvement in PA. Even with due consideration of limitations and barriers, the overriding consensus is to advocate a commitment to regular exercise (Nash, 2005), for effective control of chronic conditions and reduction of cardiovascular disease risk in wheelchair users of all ages.

2.2.3 Structured exercise programmes and leisure time PA

Use of leisure centres and gyms for the design and delivery of personalised exercise programmes represent a further opportunity for enhancement of PA levels. The combined effect of an increased awareness of physical impairment and increased legislation surrounding accessibility for wheelchair users (Law Commission, 1995) has made structured exercise in leisure facilities and private health clubs a more attractive option for enhancement of fitness. An indoor hand-cycle is an accessible option for wheelchair users and is effective in decreasing body mass index, fasting insulin and insulin resistance (Kim et al., 2015) and is a less straining form of ambulation (Arnet et al., 2016). This exercise is easily accessible from a wheelchair. However, most gym-based exercises must be adapted (Learmonth et al., 2015) and equipment made accessible for wheelchair use (Learmonth et al., 2015; de Groot et al., 2013b). Positive effects may be found with adapted exercise, with encouraging preliminary findings indicating increased strength in posterior shoulder muscles for adapted rowing (Troy et al., 2015). However, not all community fitness facilities address mandatory requirements (Cardinal & Spaziani, 2003) and therefore, provision for persons with physical impairments is lacking, particularly with respect to equipment-specific factors (Dolbow & Figoni, 2015). Further, leisure facility personnel are not always equipped to meet the needs of disabled users (Skivington et al., 2002), trained to provide specialist guidance (Dolbow & Figoni, 2015), or capable of assisting with wheelchair transfers (Johnson et al., 2012). Given that staff-supported groups complete a higher volume of exercise than self-guided groups (Froehlich-Grobe et al., 2014) the role and potential impact of exercise leaders in engaging wheelchair users in exercise should not be underestimated. Additionally, where exercises are not perceived to be adequately adjusted to suit individual needs, non-compliance is high (Sluijs et al, 1993). Therefore, exercise programmes should always be personalised taking into account each individual's unique circumstances and characteristics (Spetch & Kolt, 2001). The relative difficulty of exercises is also an issue influencing participation. Complex activities, where task requirements are deemed beyond physical ability, are linked with non-adherence in rehabilitation programmes (Sluijs et al., 1993). The lack of adjustment and personalisation of exercise interventions, coupled with task complexity, explains why, participation in leisure facility activities is generally low. Indeed, even AB groups who by definition have less physical restrictions to act as barriers to participation, complete insufficient PA with reference to target government guidelines (Public Health England, 2015) with only 40% and 28% of English men and women meeting recommended levels respectively (Department of Health, 2016). This is also the case in global terms, with a lack of engagement with target ACSM guidelines for health and fitness enhancement (ACSM, 2011). For example, leisure time PA is low in Canadians with an SCI (Ginis et al., 2010b) and considerable variability exists in the daily patterns of active persons, with relatively few reporting engagement in heavy intensity work (Ginis et al., 2010a). Therefore, considerable work must be done at population-level to engage more people in health-enhancing exercise and PA programmes.

Adherence to programmes for those with permanent disabilities is an under-researched area currently. However, there are legitimate barriers to sustained participation in leisure time PA for wheelchair users (Ginis & Hicks, 2007). Hence, chronic physiological adaptations are reserved for those with adequate personal motivation, confidence and drive to continue to exercise on an ongoing basis. Unfortunately, these traits are not commonly associated with individuals with a physical impairment or disability, who more typically exhibit low self-esteem and confidence in the execution of physical tasks, with an association between higher lesion levels and lower self-efficacy (Nooijen et al., 2015).

2.2.4 Participation in organised sports

Sports participation represents a further option for the development of fitness attributes in wheelchair users (Dallmeijer et al., 1997). Due to its unpredictable nature, and high energetic demand, sport offers a more complex and challenging environment for chair movement than is commonly associated with everyday life. Basic wheeled mobility skills and essential sports propulsion skills are not fully learned in the clinical rehabilitation phase (Fliess Douer et al., 2012). Hence, sports participation could be considered an essential progression route post-rehabilitation, not only for the enhancement of performance, but to provide a stimulus for problem-solving and mastery in chair propulsion. Indeed, this is the means by which sport was first popularised for wheelchair users, as a form of rehabilitation to increase recreational PA (Ogata, 1994). Given that commencing sporting activity expeditiously after rehabilitation from an SCI is important for preventing decreases in bone mineral density (Miyahara et al., 2008) it appears desirable for wheelchair users to become active in sports immediately post-discharge.

Long-term sports participation offers the potential for the enhancement of self-worth, confidence and overall quality of life in those with physical impairments through the development of skill. In general terms, learning new physical skills gives a sense of competency, accomplishment and fulfilment (Podlog & Dionigi, 2009). For adults with physical impairments, the benefits are well documented. Better self-perceived health (Hosseini et al., 2012), higher life satisfaction (Garshick et al., 2016; Hosseini et al., 2012), higher scores for community integration and reintegration into normal living (Hosseini et al., 2012; McVeigh et al., 2009) and a higher employment rate (Anneken et al., 2010) are associated with persons with an SCI who actively participate in sports. Furthermore, persons with SCI who engage in higher total, vigorous sport subjectively rate their health status to be excellent (Washburn et al., 2002). Importantly, improvements in wheelchair skills, such as those achieved through regular sports participation, are associated with the facilitation of greater leisure time PA (Phang et al., 2012). This is critical in facilitating health outcomes as increased total daily EE is an advocated strategy for health improvement in inactive people with an SCI (Tanhoffer et al., 2012). Also, improvements in mental characteristics (i.e. attentiveness, mental processes and capacity for work) in SCI individuals have been observed independent of injury level in comparison to inactive controls (Skucas et al., 2014).

While the effects of sports participation are strong, long-term adherence is not assured. Adults with an SCI often perceive exercise to be too difficult (Cowan, 2013), and cite a lack of motivation (Cowan, 2012) as a key barrier. Accessibility of sports facilities should be considered a prerequisite for facilitation of an active lifestyle (de Groot et al., 2013), yet the lack of such has been identified (Jaarsma et al., 2014). Further, individuals who do not participate in sports prior to an SCI are typically harder to engage post-SCI (McVeigh et al., 2009). The timing and onset of a disability may also be a factor in sports participation as those with congenital disabilities have stronger self-perception of their athletic role, are more win-orientated and are more focused on specific goals than those with acquired disabilities (Kokaridas et al., 2009). Therefore, raising participation in any type of sporting activity should be considered a highly complex and challenging intervention, and consideration of strategies to influence skill development and motivation to participate are required. Where there is an attempt to raise participation levels, interventions should most certainly be multi-focal and geared around the enhancement of internal perceptions surrounding the motivation for exercise (Cowan, 2013).

Court-sports such as basketball and rugby have become increasingly popular options in recent years due to highly successful media promotion of the Paralympic Games (Cavedon et al., 2015; Churton & Keogh, 2013). Compared with a non-active group, a well-trained group of wheelchair basketball players had higher positive relations with others, environmental mastery, personal growth, purpose in life and self-acceptance (Fiorilli et al., 2013). Further, basketball players with and without a disability do not differ in their coping skills and score equally highly in self-determined motivation (Perreault & Vallarand, 2007), suggesting that this type of sports participation enhances perceived autonomy and that disabilities do not constrain this effect. However, while the performances of elite athletes should theoretically inspire others to participate for improved fitness (Perret, 2015), the reality is that widespread participation in these court-sports is limited by a series of factors. Wheelchair sports participants are highly competitive and more goal-orientated than AB athletes (Skordilis et al., 2002), and injuries are associated with attacking player-positions (Bauerfeind et al., 2015). Also, shoulder pain is more prevalent in wheelchair basketball players in the lower classes (i.e. 1.0 to 2.5) who exhibit inadequate trunk control (Yildrim et al., 2010) and have comparatively lower anaerobic power than those in the higher classes (Molik et al., 2010). Unfortunately, exposure to this cannot be easily reduced as strict and highly specific classification systems are in-place which dictates position, on-court role, time in-play and wheelchair set-up (IWRF, 2015; IWBF, 2014). Individual sporting activities, such as wheelchair racing and hand-cycling are also plausible options for health-enhancing exercise, but racing pace is associated with very high intensities (rating of perceived exertion (RPE) ~19 and HR ~190 $b \cdot min^{-1}$; Müller et al., 2004), which is not ideal for novice exercisers with a low functional capacity. Additionally, wheelchair racing sprint propulsion is a highly complex form of locomotion, characterised by the need for effective integration of propulsion and recovery cycles (Moss et al., 2005). Contextual barriers to hand-cycling participation can be overcome, but demographic factors and lesion characteristics currently restrict the participation of tetraplegics and females (Arnet et al., 2016) and urinary tract infections, bowel problems and pressure sores influence non-adherence (Valent et al., 2009). Extrinsic factors may also affect participation and enjoyment in outdoor events, with inclement and uncomfortable weather being major barriers to stimulation of leisure time activity (Spinney & Millward, 2011). Also, expensive equipment involving highly specialised configurations is likely to be required (Mason et al., 2013). This may negatively influence long-term compliance as chair simplicity has been linked to greater participation in an active lifestyle (de Groot et al., 2011) and financial constraints have been cited as a barrier (Arnet et al., 2016).

2.3 Wheelchair tennis

In contrast to other modalities, tennis is becoming an increasingly global sport and due to a rise in interest and popularity, this trend is unlikely to reverse (Filipčič et al., 2013). A major factor stimulating growth is that tennis is becoming increasingly accessible, even in developing countries where costs are a barrier (Richardson et al., 2015); this is in direct contrast to other exercise options. One of the main attractions is its relative simplicity. Basic tennis chairs are provided by the Tennis Foundation for tennis clubs and sessions (LTA, 2016) and while optimal (i.e. elite) performance is associated with a finely-tuned and highly specialised chair configuration (Mason et al., 2013), participation does not explicitly require it. Indeed, individuals can use their own chair without modification as long as the wheelchair has adequate stability (Mason et al., 2010), especially when turning (Medola et al., 2014). The UK Lawn Tennis Association promotes inclusive participation, whereby all should be able to participate in a full or modified format without prejudice of physical condition or prior ability level (Tennis Foundation, 2015). Social play is not restricted to particular types of tennis; disabled people can play against their non-disabled friends or family, participating in inclusive sessions and / or impairment-specific sessions (Tennis Foundation, 2015) on regular-sized courts using standard equipment. These factors are of significance, particularly for individuals who were inactive prior to an SCI, who commonly cite the lack of accessible facilities, unaffordable equipment and fear of injury as constraints to an active lifestyle (Kehn & Kroll, 2009). So eligibility for play is broad and unrestricted, and individuals are actively encouraged to play with and against other people irrespective of disability type. This is an important stance, with racket sports considered to be an exclusive pastime, with established associations between participation and high individual education, household and neighbourhood incomes (Karusisi et al., 2013).

2.3.1 Rules and format

Wheelchair tennis play is governed by the same regulations as the AB game, with one notable exception; a two-bounce rule applies in the former (ITF, 2016a). While this theoretically allows more time to respond to ball movement, standard-sized tennis courts are used at all levels of the game (Figure 2.1) and all of the common court surfaces are used (i.e. carpet, clay, grass and hard). In contrast to hard (resin) surfaces, a longer rally duration and playing time (Martin et al., 2011), higher blood lactate (BLa^-) concentrations and HR response (Reid et al., 2013; Martin et al., 2011), and a higher RPE (Reid et al., 2013) is associated with AB clay court tennis. For the wheelchair tennis player, grass surfaces are likely to represent the greatest physiological challenge. While this has yet to be proven directly, 1 metabolic equivalent (MET) for wheeling on grass (6.22 $l \cdot min^{-1}$) is considerably higher than the energy cost of common activities of daily living (Collins et al., 2010). Grass surfaces are only used for competitive tournaments. However, the fact that players, independent of level or degree of impairment, navigate within the same court dimensions and on equivalent surfaces to AB players is noteworthy. Collectively these factors create a challenging exercise environment for the unskilled, novice or developmental wheelchair tennis player.

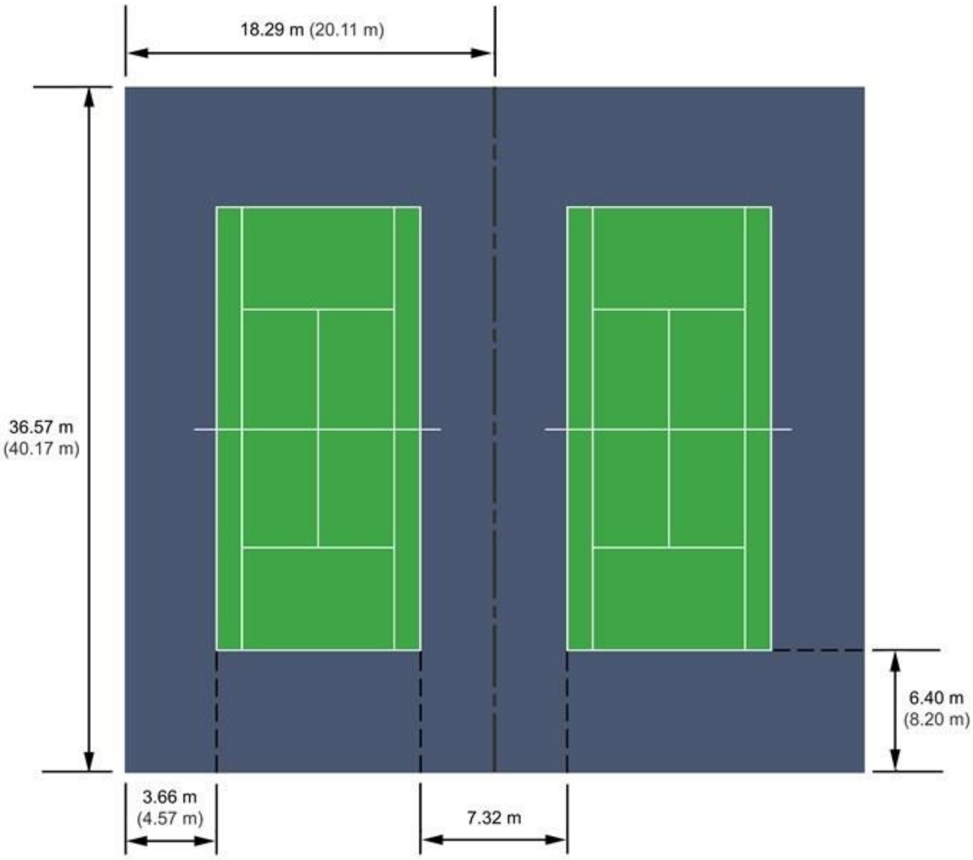

Figure 2.1 Recommended minimum court dimensions for wheelchair tennis (ITF, 2016b).

As the wheelchair is considered to be an extension of the body, all rules relating to the body also relate to the chair (ITF, 2016a). A player must be stationary prior to the service strike, and while one push is permitted before ball-to-racket contact is made, a player must remain behind the baseline during the service (ITF, 2016a). The feet must not make contact with the ground at any time during play and must remain seated at all times (ITF, 2016a). The only exception to this rule is where specific impairment-related factors dictate that an individual must use their foot to aid in propulsion (ITF, 2016a). However, this action is not permitted for any player during the forwards motion of a racket swing or during the service motion (ITF, 2016a).

Disabilities must be medically diagnosed, permanent and result in a substantial loss of function in one or both lower extremities (ITF, 2016a). Specific criteria apply to articulate eligibility for participation in the wheelchair tennis Open class and Quad division (Section 3.3.2) and in the main, is related, but not restricted to, neurological deficit caused by impaired, restricted or limited brain or spinal cord activity (Griggs et al., 2011). Level of function forms an important determinant of eligibility for play in respective groups (Figure 2.2).

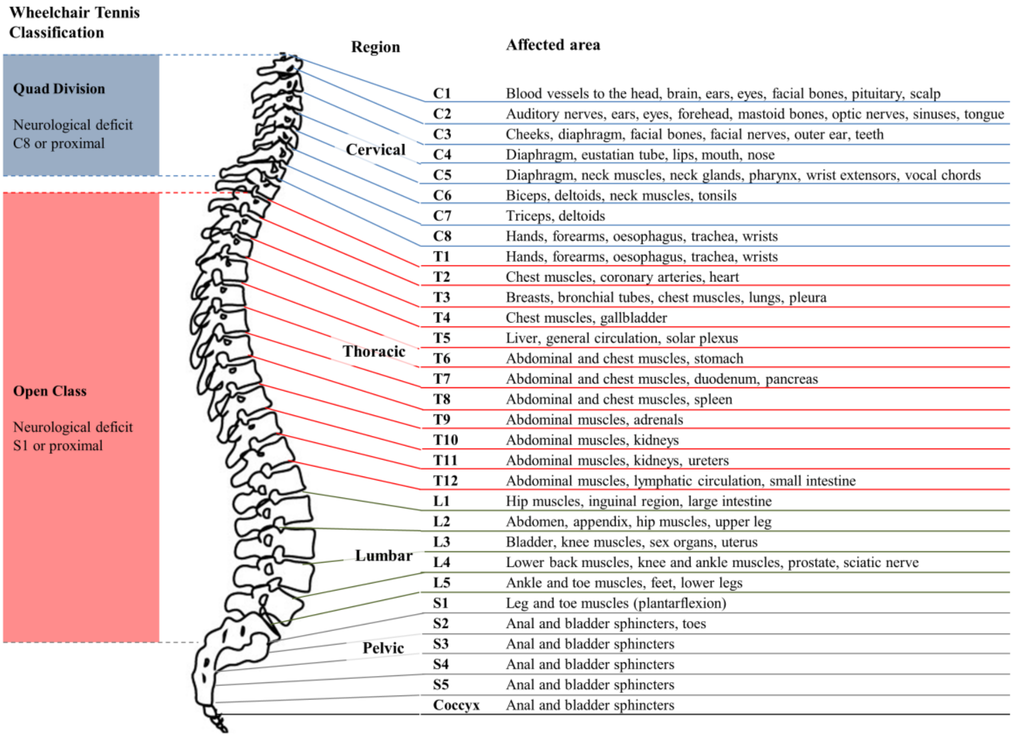

Figure 2.2 Criteria for classification of wheelchair tennis participation in the Open class and Quad division based on neurological deficit and somatic innervation

Due to loss of somatic innervation and associated reductions in active muscle mass, players in the Quad division typically have a considerably lower $\dot{V}O_{2peak}$ (0.7 to 2.2 $l \cdot min^{-1}$) when compared to persons eligible for the Open class (1.6 to 4.0 $l \cdot min^{-1}$) (Goosey-Tolfrey & Leicht, 2013). Also, due to inter-individual differences in lesion level and completeness, and the resultant extent of neurological deficit, considerable variability in $\dot{V}O_{2peak}$ is observed (Goosey-Tolfrey et al., 2006).

2.3.2 Condition-specific factors

No study has yet quantified wheelchair tennis participation rates relative to condition or physical impairment type(s). Therefore, participation profiles are not well understood currently. Visual inspection of the world rankings reveals a cross-section of impairment types, with the most functionally-able (i.e. lower-limb, single leg amputee) typically occupying the highest order places in the Open class. However, anecdotal discussions held with wheelchair tennis coaches in the planning stages of this PhD indicated that SCI is a commonly observed physical impairment at both a recreational and elite level. Studies involving wheelchair tennis players have targeted those with an SCI, either exclusively (Diaper & Goosey-Tolfrey, 2009; Abel et al., 2008) or in combination with lower-limb amputation (Richardson et al., 2015; Roy et al., 2006; Goosey-Tolfrey & Moss, 2005), brittle bones disease (Croft et al., 2010; Goosey-Tolfrey & Moss, 2005), polio (Richardson et al., 2015) and spina bifida (Barfield et al., 2009). The latter is similar to an SCI with respect to the extent and nature of physiological and motor losses (Figoni, 2003). In these cases, those with an SCI have formed the majority of the sample. Hence, consideration of the physical limitations imposed by an SCI is of particular importance.

Below the level of an SCI, overall sympathetic activity is reduced as a result of reduced supra-spinal control over the sympathetic nervous system (Grigorean et al., 2009). In contrast, parasympathetic outflow through the intact vagal nerve remains normal when compared with an AB controls (Rodrigues et al., 2015). The net result is unbalanced nervous system activity, with more dominant inhibitory messaging and less sympathetic drive. Irrespective of sport-type, athletes with complete lesions (i.e. where the spinal cord is completely severed) exhibit attenuated autonomic responses such as lower supine, seated and delta systolic blood pressure than those with incomplete (i.e. spinal cord damaged but intact) lesions (West & Krassioukov, 2016). The HR response is also affected, particularly in athletes with a high lesion or complete SCI (Janssen et al., 2001), with a reduced maximum HR associated with lesions >T6 (Figure 2.2) (Goosey-Tolfrey et al., 2013) and values ~130 $b \cdot min^{-1}$ at peak exertion (Jacobs & Nash, 2004). Disruption to normal central nervous system activity limits blood flow regulation (Webborn, 1996) with a loss of sudomotor and vasomotor control below the lesion level (Griggs et al., 2015). Therefore an abnormal sweating response should be expected in persons with an SCI (Goosey-Tolfrey et al., 2013). These issues can influence performance and are likely to make the activity environment more challenging for wheelchair users than equivalent AB populations. Wheelchair tennis players are exposed to direct heat from the sky and radiant heat from the court surface and chair during outdoor events (Girard, 2015). Therefore, regulation of body temperature during exercise is particularly challenging for wheelchair tennis players. While core body temperature is slightly higher for persons with an SCI during 45-min of wheelchair tennis, wheelchair users without an SCI also experience increases, with no differences in thermal sensation or RPE (Veltmeijer et al., 2014). The impact of this effect is likely to be greatest for play in the Quad division as greater core and skin temperatures are found in tetraplegics during intermittent physical activities (Griggs et al., 2015). Interventions such as hand cooling are effective in reducing core temperature (Goosey-Tolfrey et al., 2008b) but are not ideal for tennis players due to the requirement for racket-holding. Localised cooling garments worn on the head or neck are a more practical alternative but do not ameliorate dehydration due a counterproductive effect on water consumption (Goosey-Tolfrey et al., 2008a). Hence, it is important that future research offers a profile of the physiological demands of match-play and considers ways in which the activity environment may be adjusted to make play manageable for beginners.

2.3.3 Temporal characteristics

Evidence from the coaching literature suggests that matches may last between 50- to 80-min, with players hitting the ball between 15 to 20 % of the time (Sánchez-Pay et al., 2014). This is consistent with the only available formal research study assessing wheelchair tennis temporal characteristics, whereby the active component is ~20 % playing time (Filipčič & Filipčič, 2009). The playing-time characteristics of elite AB athletes have also been published (Filipčič & Filipčič, 2006). AB tennis matches are known to last between one and five hours (Christmass et al., 1998), but players are not active for the full duration, with 16 to 28 % of time spent moving (Fernandez et al., 2006). One single tennis match comprises a series of individual games, which reside within sets, and within an overall match (i.e. micro, meso, macro). Three to five sets are played before a winner is determined and hence, the number of games played will range considerably (26 to 51 games in top international tournament play involving AB athletes) (Filipčič & Filipčič, 2006). Individual points in single games are finished rapidly (~10-s) (Sánchez-Pay et al., 2016, Kovacs, 2007; Filipčič & Filipčič, 2009; Filipčič & Filipčič, 2006), involving three or fewer shots (Sánchez-Pay et al., 2016; Filipčič & Filipčič, 2009) and via one continuous effort, which emphasises the anaerobic nature of the sport (Kovacs, 2007). Due to the intermittent nature of wheelchair tennis (Roy et al., 2006) and the fact that AB and wheelchair tennis players are governed by the same rules, with minimal differences and standardised breaks between games and sets (ITF, 2014), a similar profile is likely to be found in the wheelchair variant of the sport. However, this is yet to be confirmed. Also, competitive wheelchair tennis involves the best of three (not five) sets. The lack of national PA guidelines for disabled persons is an issue which requires further investigation. Until such time, global ACSM (2011) and current UK guidelines for adults aged 19 to 64 years are the most suitable alternative reference points. These state that PA can be accumulated in 10-min bouts to enable a target of 30-min on five days per week (Department of Health, 2016; ACSM, 2011). As physiological responses have been monitored in wheelchair tennis bouts lasting only 10-min (Coutts, 1988), monitoring of whole matches may not be necessary for experimental studies. No study has been undertaken to measure average wheelchair tennis set length. However, preliminary discussions held with coaches during the planning phase of this PhD indicated that average set duration would approximate 20-min. This is consistent with previous work identifying that a typical two-set match might last for 45-min (Veltmeijer et al., 2014) or between 50- and 70-min (Sánchez-Pay et al., 2014; Bernardi et al., 2010). Hence, 20-min represents an appropriate minimum duration for simulated play (Bernardi et al., 2010). Also, moderate to vigorous exercise of this duration is consistent with Canadian PA guidelines for health-enhancement (Pelletier et al., 2015). Therefore, research designs involving experimental bouts of match-play should consider 20-min to be the minimum allocated time period for assessment of physiological demands and court-movement patterns.

2.3.4 Health benefits of tennis

Regular tennis play has been linked with positive health outcomes in AB populations (Pluim et al., 2007; Marks, 2006). For the wheelchair user, the sport provides potential for similar outcomes, with both practice and game play conditions eliciting sufficiently strenuous HRs to be considered as beneficial PA (Croft et al., 2010; Barfield et al., 2009). Higher absolute values for HR and oxygen uptake ($\dot{V}O_2$) are associated with continuous, distance activities such as Nordic skiing and wheelchair racing (Bernardi et al., 2010).Therefore, such activities have a higher propensity for developing aerobic fitness levels. However, due to the intermittent nature of the wheelchair court-sports, cardiorespiratory fitness could be considered to be less of a determinant (de Lira et al., 2010). Nevertheless, the average exercise intensity across a 20-min bout of play exceeds 40 to 50 % of $\dot{V}O_{2peak}$ or 55 to 65 % of peak HR (Bernardi et al., 2010). This intensity exceeds respective American Heart Association (AHA) (Pluim et al., 2007) and American College of Sports Medicine (ACSM) criteria for the maintenance and enhancement of aerobic fitness (Bernardi et al., 2010; Pluim et al., 2007). Therefore, tennis offers the propensity for a desirable, health-enhancing exercise dose. Chronic participation in wheelchair tennis results in important physiological adaptations, with regular players exhibiting moderate to high levels of aerobic capacity (Roy et al., 2006). Well-established physiological research has identified peripheral and central adaptations to exercise training, which explain the link between regular tennis play and improved physical fitness capacity. Altered skeletal muscle properties

(Saltin, 1977), increased arteriolar density and diameter (Duncker & Bache, 2008) and increased stroke volume (Hagberg et al., 1983) offer explanation in general terms for respective peripheral, vascular and central mechanisms for the increased $\dot{V}O_{2peak}$ associated with exercise training. Desirable alterations in vascular architecture can be expected for wheelchair users performing chronic upper-body exercise, with favourable health-related effects. Decreases in carotid intima-media thickness, which is an important marker for development of coronary atherosclerosis, are associated with long-term (5 years) participation in wheelchair tennis (Matos-Souza et al., 2015).

A review into the energy cost of popular wheelchair activities resulted in the development of a compendium of exercise, sports and general PA-based options (Conger & Bassett, 2011); this included wheelchair tennis. These studies are useful for their synthesis of the available evidence, stratification of options, and facilitation of decision-making regarding exercise mode. However, considerable variability was implicated with respect to population demographics (i.e. elite athletes to manual wheelchair users), limiting usefulness and inferences made to health. More recent research involving persons with an SCI associated 43-min of manual daily wheelchair propulsion with sufficient EE to confer health-related effects (McCormick et al., 2016). Such a dose of activity is equivalent to recommendations for intensity and duration for AB individuals (total weekly expenditure ~1000 $kcal \cdot min^{-1}$) and is therefore consistent with maintenance of cardiovascular health (McCormick et al., 2016). However, while wheelchair tennis is not as intense as wheelchair basketball (Croft et al., 2010), it is likely to be a more intense activity than daily manual wheelchair propulsion. EE is typically higher for sporting activities than daily pushing (Conger & Bassett, 2011) and wheelchair tennis is intermittent (Roy et al., 2006), involving intense intervals of activity (Croft et al., 2010). Therefore, an individual taking part in tennis may do so less frequently to achieve a similar volume of weekly exercise. Wheelchair tennis play for 55 to 65 min should ensure an EE of between 300 to 350 kcal (Abel et al., 2008) in a single bout of exercise. Such a dose is consistent with the greatest possible reduction in risk for myocardial infarction (Paffenbarger et al., 1993). So, while associations have been made, they are tentative currently. Hence, further work is required to specifically identify the EE associated with match-play for different wheelchair tennis practice and match-play conditions. Outcomes will enable inferences to be made to support the promotion of novice and developmental participation.

For the wheelchair tennis player, the psychological benefits of participation include increased self-confidence, increased opportunities and independence, and improved perceptions of disability (Richardson et al., 2015). Increasing skill within an individual sport such as singles tennis confers additional desirable effects when compared with team sports. Participation at higher competitive levels associated with even greater scores for community integration, through enhanced physical ability and psychological status (McVeigh, et al., 2009). Indeed, the desire to be competitive in racket sports is not as strong as the drive for mastery of skill in overall terms (Molanorouzi et al., 2015). Hence, while it would appear plausible to assume that the desire to win acts as an important motivator for all players, more important is the need for development of competence and confidence in playing the sport. Even though males express a higher motivational drive to remain competitive during match-play than females (Molanorouzi et al., 2015), little is known currently regarding sex-specific differences and wheelchair tennis participation and performance.

Social integration is a powerful determinant of health, with greater integration associated with reduced mortality risk and enhanced mental health (Seeman, 1996). However, architectural factors and the attitudes of persons without a disability are commonly cited barriers to social inclusion for wheelchair users with an SCI (Akyüz et al., 2014). Tennis potentially removes such barriers, offering a level playing field and a platform for those with a disability to demonstrate their potential. Due to the opportunity for reverse integration (i.e. AB and wheelchair-dependant individuals training and competing together), tennis facilitates social integration with relative ease (Murphy, 2012). As this process is associated with the development of positive athletic identities and a closing of the void between perceptions of disability and able-bodiedness (Spencer-Cavaliere & Peers, 2011), it is a powerful strategy for the development of self-efficacy, and thereby overall health status, in wheelchair users. While society normally segregates people by physical ability, tennis brings people together, and can often be the first opportunity for interaction between what are conventionally seen as incompatible populations (Murphy, 2012). Tennis rules are easily adapted for play in this manner, with the AB player permitted one bounce, and the wheelchair dependent player permitted two (ITF, 2016a). Mixed-sex recreational play is easily achieved and play is not restricted by age. Research studies should therefore target an appropriately wide range of player groups to ensure adequate representation of the sport at all levels. This is of particular relevance and importance for the wheelchair variant of the sport, where the participation rates are typically low (Bernardi et al., 2010), and links to health have not been fully explored.

2.3.5 Court-movement: requirements and demands

Successful court-movement is a key determinant of success in AB tennis, with those who combine net approach-play with aggressive play at the baseline having the most successful outcomes (Filipčič et al., 2008). However, comparatively less is known about the movement demands and characteristics of the wheelchair variant of the sport. Consequently, research designs that profile distances and speeds attained during wheelchair tennis are important to enable greater understanding of sport-specific characteristics. Tennis movement dynamics are similar to those of basketball and rugby whereby players are required to sprint, brake and turn (Goosey-Tolfrey, 2010), with the ability to turn rated by players as a highly important skill (Mason et al., 2010). In any of the court-sports, the player-chair interface, combined with the requirement for timely reactions to ball movement, collectively represent a significant physiological and skill challenge (Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005). Players manoeuvre their chair in a reaction to the movement and speed of the ball (Mason et al. 2010), and the actions of their opponent. Indeed, the playing style of the opponent (Kovacs, 2007) and match-play characteristics (Croft et al., 2010; Kovacs, 2007) dictate ball placement and therefore determine the movement response. Hence, tennis can be defined as an intermittent activity (Croft et al., 2010; Roy et al., 2006), characterised by highly variable, multidirectional and random movement patterns (Roy et al., 2006). Observation of the game suggests that forwards movement predominates during play, but players also perform a reverse propulsion action and this is known to be more physiologically demanding (Mason et al., 2015b). However, as current research considers elite or skilled player groups exclusively (Croft et al., 2010; Barfield et al., 2009; Abel et al., 2008), it is important that further work is completed to consider the interplay between court-movement and resultant physiological demands for low-level player groups.

Sports-based wheelchair propulsion is complex, with the interaction between the player and the chair determining sport-specific movement dynamics (Goosey-Tolfrey, 2010). What distinguishes tennis from the other court-sports is the requirement for coordination of chair movement whilst holding a racket (Figure 2.3). This represents a significant skill challenge (Diaper & Goosey-Tolfrey, 2009). In a sample of highly ranked, experienced tennis players, reduced speeds and distances were associated with propulsion while holding a racket during repeated-pushing (Goosey-Tolfrey, 2010; Goosey-Tolfrey & Moss, 2005). Tennis players rate the first two pushes as most important in building up acceleration to react to an opponent’s shot (Mason et al., 2010). By the third push, players cover 0.16 m less distance when they are tested while holding a racket (Goosey-Tolfrey, 2010; Goosey-Tolfrey & Moss, 2005). Such restricted movement may have an impact on a player’s ability to adopt an appropriate body and court-position for shot play, and may make both shot-play and chair propulsion too difficult to coordinate. Consideration therefore of the effectiveness of with- and without-racket training strategies is required to enable an understanding of how to refine and improve propulsion technique for tennis. Further, while it seems plausible to assume that less skilled players will experience similar responses to those observed in trained athletes when holding a racket

(Goosey-Tolfrey et al., 2010; Mason et al., 2010; Goosey-Tolfrey & Moss, 2005), no evidence to support this notion is available currently.

Figure 2.3 Novice wheelchair tennis player holding a racket whilst pushing the chair

Observe the contorted body position and elevated left shoulder which appears to be a consequence of holding the racket while pushing.

Once positioned adequately, experienced players obtain more useful information from their opponent's racket arm action during the stroke phase than less skilled counterparts (Reina et al., 2007). Also, faster motor responses enable a more experienced player to return a service stroke effectively (Reina et al., 2007). Confidence in skill development in wheelchair sports originates from a perceived ability to successfully overcome training barriers, maintaining a positive approach without distraction from distressing thoughts (Martin, 2008). Therefore, if task-execution is too difficult when a player takes up a sport, the likely outcome will be attrition. To counter this, the ITF suggests that beginners of all ages would benefit from playing tennis with slow moving balls. However, the evidence to support this notion is limited. No significant difference was observed in skill learning between an LCB and SCB in AB children (Hammond & Smith, 2006). However, positive technique development, longer rallies and greater playing time were reported in beginners using an LCB (Hammond & Smith, 2006). Furthermore, using a larger than standard size tennis ball is associated with delayed onset of volitional fatigue, increased ground stroke accuracy, and lower HR, RPE and BLa^- concentrations in healthy AB tennis players (Cooke & Davey, 2005). Hence, while the movement-induced physiological changes of AB participants has been considered, it remains unclear whether similar responses are to be expected in wheelchair users as a result of an extended playing time and rallies using modified balls.

2.3.6 Playing intensity

Low-intensity wheelchair training is considered to be insufficient for substantial effects in inactive people with long-term SCI (van der Scheer, 2015b). As a result, there is a clear requirement for exercise modalities which confer sufficient exercise intensities to ensure adequate health gains for wheelchair users. Average HR and $\dot{V}O_2$ for competitive wheelchair tennis match-play is 146 b·min^{-1} and 1.36 l.min^{-1} respectively (Croft et al., 2010). This is consistent with play at 73% of $\dot{V}O_{2peak}$ which aligns closely with laboratory-measured ventilatory threshold (Bernardi et al., 2010). Relative work-to-rest ratios have not been revealed until recently (1.0 : 4.6-s, work : rest) (Sánchez-Pay et al., 2016). However, the nature of the research (i.e. pilot study) and very low sample (n = 4) means that observations remain tentative at present. A higher propulsion time versus time spent braking (64 *vs.* 36%) has been reported for wheelchair basketball (Coutts, 1992). Wheelchair tennis is characterised by similar intervals of exertion and rest, with match-play requiring rapid movement responses as players respond to changes in ball placement and the position of their opponent. However, the average HR (Croft et al., 2010; Coutts, 1988), $\dot{V}O_2$ and $\dot{V}O_{2peak}$ (Croft et al., 2010) reported for tennis are lower than basketball. Moreover, basketball players spend a greater proportion of time at intensities above lactate turn point (Croft et al., 2010). Nevertheless, tennis is known to involve intense bouts of play. Players reach intensities above ventilatory threshold, and similar match-play and laboratory values for $\dot{V}O_{2peak}$ have been reported (Bernardi et al., 2010). Hence, there is a greater dependency on the anaerobic pathway for energy production (Bhambhani, 2002). As a chronic effect of intermittent play, elite wheelchair tennis players typically demonstrate physiological profiles that are representative of a well-trained population (Goosey-Tolfrey et al., 2006). Chronic effects of high intensity training environments include increased maximal upper-extremity muscle strength, sprint power output and maximal power output (Devillard et al., 2007), leading to improved ME and therefore, improved wheelchair propulsion ability. Interestingly, increases in peak power and $\dot{V}O_{2peak}$ are associated with greater life satisfaction (van Koppenhagen et al., 2014), which indicates a relationship between increases in functional capacity and related increases in subjective wellbeing. So whilst development of peak performance attributes should be a general aim of exercise training, further work should consider the specific physiological demands of wheelchair tennis. This will be of use, most notably for novice players, who participate recreationally for health-related benefits.

2.4 Instrumentation for wheelchair sports movement quantification

2.4.1 Considerations in measurement device selection

For research purposes and clinical application, measurement device selection should be dictated by the particular aspect of wheelchair mobility under investigation (Wilson et al., 2008). Conger et al. (2014) developed a model for prediction of EE based on power output, HR and movement speed using a modified PowerTap track hub. While the prediction model was strong (r^2 = 0.87), considerable modifications need to be made to the wheel to accommodate the device. Further, device weight is considerable (460 g). Therefore, application for measurement is questionable in a sport such as wheelchair tennis, which requires considerable agility (i.e. turning, braking and changes in movement direction) for adequate court-coverage.

2.4.2 Methods for determination of court-movement and associated limitations

Accelerometers have been used for the collection of wheelchair propulsion movement data variables. Wheel orientation is indicated by measurements of acceleration taken along two perpendicular axes in the plane of the wheel. Therefore, with wheel rotation, measures of distance and speed can be obtained. The activePAL accelerometer (PAL Technologies, Glasgow, UK) has been adapted for collection of wheelchair mobility data, with good functional applicability for collection of distance and speed in a free-living environment (Wilson et al., 2008). The device offers an accurate and reliable assessment of wheel revolutions, absolute angle and duration of movement for subsequent calculation of distance and speed (Coulter et al., 2011). However, convenience samples have been used (Wilson et al., 2008), with small numbers of individuals with SCI operating at very low to low speeds (~1 $m \cdot s^{-1}$) (Sonenblum et al., 2012; Coulter et al., 2011; Wilson et al., 2008). Such a device is likely to be suitable for monitoring of everyday propulsion trends over long periods, and for conditions where the terrain is non-uniform. However, high frequencies of wheel rotation exceeding plausible angular wheel rotations may be rejected (Sonenblum et al., 2012). More recently, the inertial movement unit (IMU) has become an option for court-movement monitoring. Devices, which are lightweight (~ 10 g) and have small dimensions, include a gyroscope alongside an accelerometer for instantaneous assessment of position, orientation and velocity. Acceptable validity and reliability for IMU have been revealed at speeds consistent with wheelchair court-sports activity (1.0 to 6.0 $m \cdot s^{-1}$) (Mason et al., 2014b). However, as a motorised treadmill was used for linear motion, ecological validity, which is an important benchmark for wheelchair sports-specific testing (Goosey-Tolfrey & Leicht, 2013), cannot be assured for wheelchair tennis. Consideration has been given to IMU performance during wheelchair basketball with minimal error for frame displacement and speed, including rotational speeds (van der Slikke et al., 2015). This is encouraging given that an important aspect of performance in the court-sports is the turning action (Mason et al., 2010). However, play was simulated (i.e. series of drills), a relatively low-cost reference system was used, and proportionately higher (but acceptable) error rates for high speed movements were obtained.

Movement during sports are much higher than those observed in the accelerometer studies, with wheelchair racers known to attain speeds > 5 $m \cdot s^{-1}$ (Campbell et al., 1995). Comparatively lower mean speeds are expected in the wheelchair court sports (i.e. basketball, rugby and tennis), as players navigate around a smaller area in a non-linear manner. However, speeds > 1 $m \cdot s^{-1}$ should most certainly be expected. Peak speeds ranging from 2.99 ± 0.28 to 3.82 ± 0.31 $m \cdot s^{-1}$ have been reported for wheelchair rugby players with varying playing roles and positions (Rhodes et al., 2014) and average speeds of 1.26 $m \cdot s^{-1}$ (Mason et al., 2014a). As stated previously, surface conditions are an influencing factor in AB tennis (Reid et al., 2013; Martin et al., 2011) and while it is not known currently, the same may be true for wheelchair tennis. However, most often, court-based sports events and tournaments are held on hard surfaces and hence, devices validated for use on uneven terrain are not required. Also, events are mostly held in an indoor environment, precluding some mainstream devices (i.e. GPS). Collectively, these observations suggest a preference for movement logging technologies which have greater applicability, and appropriateness for, the natural sporting environment.

The telemetry-based velocometer is placed on the wheel and provides velocity (Moss et al., 2003) but is most likely limited to research-based testing (Goosey-Tolfrey et al., 2012) due to its considerable mass, time-consuming calibration and fitment. Given that complex movement requirements are associated with wheelchair tennis (Diaper & Goosey-Tolfrey, 2009), chair-borne recording devices need to be light, small, and suitably accurate to be useful. However, most cannot be configured easily in this way, giving rise to the popularity of tracking methods external to the chair. Distance, average velocity and direction have been collected using a video tracking method in wheelchair rugby (Sarro et al., 2010) and previously for ambulant sports like soccer (Barros et al., 2007). More recently, a radio-frequency based tracking system has been used to good effect in wheelchair rugby (Rhodes et al., 2015b; Mason et al., 2014a), with validity and reliability confirmed (Rhodes et al., 2015a). However, the time consuming set-up and calibration processes may preclude use of tracking systems in scenarios where a more expedient approach is required, for example, during tennis tournaments whereby players are required to move between courts. Also, tracking systems can only be used indoors which limits their applicability for tennis. In contrast, DL and GPS units are relatively easy to place on the chair or body respectively with minimal invasiveness and are lightweight and portable. However, neither device has been tested for wheelchair tennis applicability. As there appears to be no consensus regarding the most appropriate device for quantification of court-movement, scrutiny of the most common, portable and lightweight measurement devices for wheelchair tennis is merited.

2.5 Physiological variables during wheelchair tennis

Physiological responses have been recorded during AB tennis using measures of BLa^- (Fernandez-Fernandez et al., 2007; Mendez-Villanueva et al., 2007), HR (Christmass et al., 1998), RPE (Fernandez-Fernandez, et al., 2008), $\dot{V}O_2$ (Smekal et al. 2001) and video analysis (Filipčič et al., 2008; Mendez-Villanueva et al., 2007). Measurements have been used to profile the sport-specific physiological demands for AB populations, where more is known than the wheelchair variant of the sport. In contrast, fewer studies have collected physiological data during wheelchair tennis match-play. Studies have obtained measures of BLa^- (Sánchez-Pay et al., 2016; Croft et al., 2010; Goosey-Tolfrey et al., 2008b), HR (Sánchez-Pay et al., 2016; Croft et al., 2010; Barfield et al., 2009; Goosey-Tolfrey et al., 2008b; Goosey-Tolfrey et al., 2006; Roy et al., 2006; Coutts, 1988), direct assessment of $\dot{V}O_{2peak}$ (Bernardi et al., 2010; Croft et al., 2010; Goosey-Tolfrey et al., 2008a; Goosey-Tolfrey et al., 2006; Roy et al., 2006), indirect estimation (Croft et al., 2010; Roy et al., 2006) and direct assessment (Bernardi et al., 2010) of $\dot{V}O_2$ during performance, and RPE for consideration of thermal sensation (Veltmeijer et al., 2014; Goosey-Tolfrey et al., 2008b) and match-play perceptual load (Sánchez-Pay et al., 2016). In these cases, research has been concerned with identifying the differences in physiological variables between wheelchair sports (Bernardi et al., 2010; Croft et al., 2010; Abel et al., 2008; Coutts, 1988) or comparing the physiological responses of wheelchair tennis players with AB controls (Barfield et al., 2009; Goosey-Tolfrey et al., 2008a). No evidence is available currently comparing physiological responses of different wheelchair tennis player groups, with only one study offering comparison between experienced and novice groups for visual and motor responses to the tennis serve (Reina et al., 2007). Therefore, consideration of the physiological response aligned to tennis court-movement is merited for an increased understanding of population-specific training requirements.

2.5.1 *Blood lactate concentration*

While few studies in wheelchair tennis have assessed BLa^- concentrations (Sánchez-Pay et al., 2016; Croft et al., 2010; Goosey-Tolfrey et al., 2008b), data collection and procedures for analysis are straightforward and values can be used to inform wheelchair exercise prescription (Leicht et al., 2012). Testing of this type is therefore suited to field-testing environments (Goosey-Tolfrey & Leicht, 2013). In comparison to wheelchair basketball, wheelchair tennis players spend less time in specific training zones according to laboratory-based BLa^- measures (Croft et al., 2010). However, very low sample sizes (n = 4, Sánchez-Pay et al., 2016; n = 6, Croft et al., 2010) of highly experienced athletes suggests that outcomes should be treated with caution. Further, generalisations concerning the match-play demands of lower skilled, less fit players should be reserved for further investigations.

2.5.2 *Oxygen uptake and HR*

Portable open-circuit spirometry has been used to measure $\dot{V}O_2$ during simulated wheelchair tennis play (Bernardi et al., 2010). Systems of this type report accurate resting, submaximal and maximal values for $\dot{V}O_2$ (Overstreet et al., 2016) and are therefore suitable for field-based testing. However, as wheelchair tennis rules (ITF, 2016) preclude the use of monitoring equipment during competitive tournaments, this approach is unsuitable for assessment in a competitive environment. Also, preliminary discussions with wheelchair tennis players suggest a reticence for invasive monitoring, with potential interference in court-movement and shot-play. Qualitative research in the area of optimal chair configuration has been completed (Mason et al., 2010). However, athlete perception of physiological monitoring is an under researched area currently. A greater understanding of what is permissible from the individual's perspective would be useful as obtrusiveness and impact on daily life are themes associated with activity monitoring, albeit in a slightly different context (Tierney et al., 2013). In situations where assessment of physiological load is required, use of radio-telemetry to record HR at pre-determined intervals is a viable option. HR : $\dot{V}O_2$ relationships from laboratory assessment of $\dot{V}O_{2peak}$ can be used to generate individual regression equations for estimation of exercise intensity during performance. Indeed, this approach has been adopted previously for wheelchair tennis (Croft et al., 2010; Roy et al., 2006). In this instance, the only requirement is for the athlete to wear a HR chest strap during match-play. Comparison between mean regression slopes for low-lesion (T1 to T6), high-lesion (T7 to T12) and AB groups revealed no differences in HR : $\dot{V}O_2$ relationships (Hooker et al., 1993). Also, no differences were reported for comparisons between elite female wheelchair athletes and healthy AB controls (Goosey-

Tolfrey & Tolfrey, 2004). Hence, HR: $\dot{V}O_2$ relationships appear appropriate for the identification of exercise intensity across player groups (i.e. recreational to elite), and are therefore a viable option when more accurate, but more obtrusive methods, are not practicable. A further option for identification of match-play intensities is HR expressed as a percentage of age-predicted maximum HR (HR_A). This method has been adopted previously in wheelchair tennis (Barfield et al., 2009) and is most applicable where laboratory facilities are not available or large groups need to be assessed simultaneously. However, time and facilities permitting, assessment of laboratory-measured peak HR (HR_L) is preferable.

2.5.3 Laboratory and field- based testing for wheelchair athletes

Wheelchair ergometers used in a laboratory setting offer an adequate simulation of short term exercise and offer an appropriate testing mode for wheelchair tennis (Hutzler, 1988). Arm-crank ergometers are also an option for accurate assessment of submaximal and peak function. As arm cranking is more mechanically efficient than wheelchair propulsion, higher peak power outputs can be attained (Bhambhani, 2002). Therefore, this mode has been adopted in previous studies involving wheelchair tennis players (Goosey-Tolfrey et al., 2006; Roy et al., 2006) and may also be suitable for AB individuals who have no experience in wheelchair propulsion. In contrast, for some groups, for example children with spina bifida, wheelchair-based testing facilitates a higher peak HR and $\dot{V}O_{2peak}$ than arm ergometry and therefore may be more suitable (Bloemen et al., 2015). Therefore, modality is an important consideration when testing persons with an SCI (Goosey-Tolfrey & Leicht, 2013) and due consideration should be given to the testing population and purpose. Clearly, the availability of testing equipment is also a consideration.

For an understanding of specific match-play demands, accurate quantification of movement patterns in a field setting (i.e. during competitive tennis match-play or practice) is required. A general advantage to this approach is the facilitation of large-scale data collection with relative ease (Goosey-Tolfrey & Leicht, 2013). More specifically, testing in a natural environment, using individually personalised sports wheelchair configurations offer the potential for more relevant outcomes than can be gained from laboratory-based testing (Goosey-Tolfrey & Leicht, 2013) and may allow a truer indication of peak cardiometabolic responses in persons with a high-lesion SCI (West et al., 2016). Indeed, for AB populations, laboratory-based treadmill testing cannot simulate the demands of tennis (Fernandez, 2005), and combined field and laboratory testing is likely to provide a more systematic evaluation of fitness status (Girard et al., 2006). The multi-stage fitness test (MFT), which was validated for use with AB populations, is associated with repeatable results in wheelchair users, but does not offer an accurate determination of $\dot{V}O_{2peak}$ (Goosey-Tolfrey & Tolfrey, 2008). Hence, a number of novel field-based tests have been developed to enhance understanding of wheelchair sports performance. A modified MFT has been proposed for indirect assessment of $\dot{V}O_{2peak}$ (Vanderthommen et al., 2002) but without acceptable criterion validity to be of widespread use. Further modifications to this test have proven to be ineffective, with overestimations reported for $\dot{V}O_{2peak}$ in comparisons to reference measures (Weissland et al., 2015). For wheelchair tennis players, an incremental shuttle wheel test gives a good indication of peak wheelchair performance but also does not accurately predict $\dot{V}O_{2peak}$ (de Groot et al., 2016a). The 'Hit & Turn' test has been validated for assessment of tennis-specific endurance in AB players (Ferrauti et al., 2011). This test includes shot-play and is therefore more tennis-specific. However, the applicability of this test for wheelchair tennis is not known currently. As tests validated for AB peak performance assessment are not directly transferable to wheelchair users (Goosey-Tolfrey & Leicht, 2013), further work is required to consider popular testing methods to ensure that they offer an accurate assessment of court-movement variables.

2.6 Summary and considerations for this thesis

As noted in previous studies that involve wheelchair sportspersons, recruitment is challenging. Target populations tend to be small (Croft et al., 2010) and of a heterogeneous nature with respect to either skill level or physical impairment type. This is particularly evident within wheelchair tennis as classification dictates that players with a broad range of disabilities can participate (ITF, 2016a). Consequently, sampling of wheelchair tennis players for research studies invariably means that considerable variation in motor performance and function are introduced into the design. Therefore, the challenge is to balance the requirements for statistical power with selection of appropriately homogenous groups in future work. The use of AB populations should be advocated due to their complete lack of experience in wheelchair propulsion. A significant volume of studies have used these populations to good effect, for example, identifying changes in ME with practice (Lenton et al., 2010; de Groot et al., 2008b; de Groot et al., 2002), and differences between asynchronous and synchronous propulsion techniques (Lenton et al., 2014; Lenton et al., 2013). Hence, sampling this group is ideal for prospective research designs concerned with the rate and / or the magnitude of improvement from baseline, and to enable comparisons to be made between modes, methods or training-type.

From inspection of the available literature, relatively little is known about wheelchair tennis court-movement and its associated impact on the physiological responses. Further, limited inference has been made to novice players or those at developmental phases. A focus on such groups is important to enable a better understanding of the potential for tennis to confer increases in skill, fitness, confidence and overall health. Hence, the following questions will underpin this thesis:

- Do GPS and DL devices offer an accurate representation of wheelchair tennis court-movement? And if so, do such devices have appropriate applicability for quantification of distance and speed during wheelchair tennis?
- Do HIGH cover greater distances and speeds at a higher relative HR than LOW counterparts?
- Do players who win matches cover greater distances and speed at a higher relative HR than those who lose matches?
- Does using an LCB increase match-play court-movement and physiological responses?
- Does a short period of organised practice prompt increased court-movement, physiological responses and self-confidence in match-play?
- Does holding a tennis racket affect court-movement and physiological variables during practice?

3

General methods

Within this PhD, a series of common approaches to data collection and analysis were completed. To avoid unnecessary duplication of content within individual chapters, general methodological procedures are identified within this chapter. Retrospective reference is thereafter made to these general methods within each individual experimental chapter, alongside additional details pertaining to the specific nature of each experimental design.

3.1 Recruitment and informed consent

Approval for study procedures was obtained from the Loughborough University Research Ethics Committee and research was conducted in accordance with the Declaration of Helsinki and Ethical Standards in Sport and Exercise Science Research (Harriss & Atkinson, 2011). Written consent was obtained by all participants and their guardians (if < 18 years) prior to testing. Standard university informed consent and health questionnaire forms were completed prior to involvement in any testing. Participant descriptors were obtained including wheelchair experience, exercise training and disability characteristics. Participants freely volunteered for all studies. All involved gave consent for a DL unit to be attached to the inside spokes of their sports wheelchair (Section 3.2) and for physiological measurements to be taken at predetermined times (Section 3.4).

3.2 Data logging for quantification of court-movement

The custom DL used in this thesis had been validated for collection of travel distance and speed data using manual wheelchairs used for daily ambulation (Tolerico et al., 2007). The device, which is easily attached to the inside spokes of a chair wheel (Figure 3.1), is powered by a 1/6D wafer-cell lithium battery. The self-contained, lightweight device measures approximately 5 cm in diameter and 3.8 cm in depth. Housed within the unit are a magnetic pendulum and a combination of three reed-switches, which are mounted equidistantly on the back of a printed circuit board. Reed-switches rotate within the unit during chair wheel rotation, while the pendulum maintains its position due to gravitational force. When wheel rotation exceeds 120° (one third of a full revolution), a reed-switch makes contact with the pendulum and creates a time stamp in a coded format on an integrated flash memory (Ding et al., 2005). Hence, sampling frequency is directly related to wheel rotation speed.

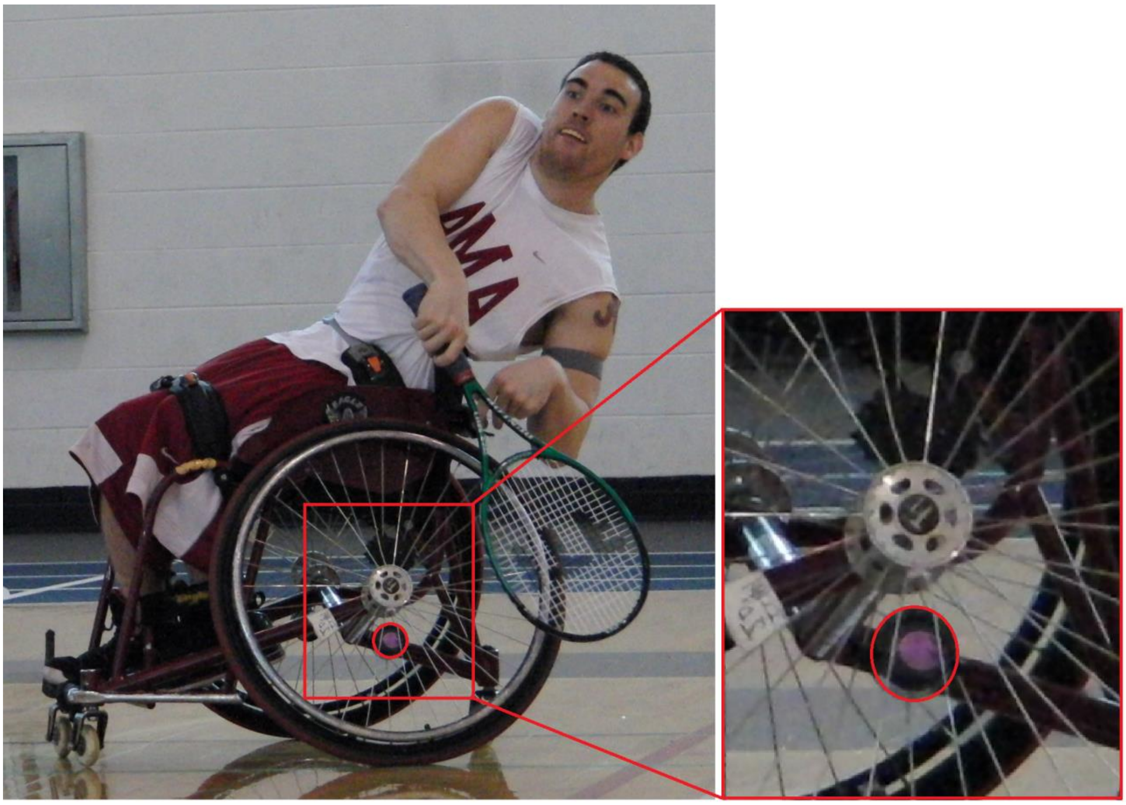

Figure 3.1 DL placement on the wheelchair spokes for assessment of tennis court-movement variables

Raw data collected by the DL was firstly treated using a custom Matlab® code, converting logged output into a spreadsheet (Microsoft® Excel) to include individual time stamps (hh:mm:ss:00) for each triggered reed-switch. At this stage, treated output included latent data (i.e. logged movement prior to commencement of match-play). Therefore, match start and finish times were used to identify functional proportions of total recording time. After these data were extracted and saved as separate files, a second Matlab® code was applied to the data, with testing year and wheel diameter (cm) specified. While data retrieval for 1, 2, 3, 4 or 5-s intervals was enabled in the code, court-movement indices were averaged over 5-s intervals to allow for alignment with averaged values for exercise intensity (i.e. HR), to enable quantification of time spent stationary (i.e. no reed switch activation in a 5-s interval ~ no chair movement) and to ensure consistency with previous work in wheelchair tennis (Roy et al., 2006). The second layer of analysis created additional data to include instantaneous distance and speed. As reed-switches are numbered (0, 1 and 2) motion direction can be easily quantified. Hence, distance in a forwards direction (pushing wheelchair forwards independent of court position), distance in a reverse direction (pulling wheelchair backwards independent of court position) and distance moving in a forwards-to-reverse pattern (relatively small movements incorporating intermittent forwards and backward motion) were obtained, and presented alongside total (overall) distance. For movement speed, peak and average values were determined, with the former identified as the highest recorded interval. Percentage of total time spent stationary (0 $m \cdot s^{-1}$) in nine individual speed zones (0.01 to 4.49 $m \cdot s^{-1}$; at 0.50 $m \cdot s^{-1}$ intervals) was calculated. In all instances, speed was determined from distance values (divided by time).

In this thesis, the terms ‘court-movement’ and court-mobility’ are used to describe wheelchair tennis activity. The former is used with reference to measured variables (i.e. distance and speed). The latter describes movement an attribute of fitness and / or a function of tennis-specific skill whereby movement occurs as a response to external stimuli (e.g. ball placement or a coach’s instruction).

3.3 Wheelchair tennis match-play

3.3.1 Format and type

This thesis involved match-play data collection in two distinct formats, during official ITF tournaments and during experimental bouts of match-play. Both involved compliance with relevant iterations of the ITF rules of play (ITF, 2014; ITF, 2011; ITF, 2009b). All play was conducted on standard sized tennis courts conforming to ITF guidelines for court dimensions (ITF, 2013). Official time limits for changeovers and breaks were strictly enforced. Matches were umpired for the purposes of keeping score, but players were required to retrieve balls between points. No external coaching was permitted during play. Organising Committee approval was obtained for matches to be filmed using a Sony HDR HC7 Mini DV Handycam connected to a Raynox HD Superwide Angle Conversion Lens (0.5 x conversion factor). Video footage was used to cross-check all recorded times.

3.3.2 Player eligibility for tournament match-play

For the present thesis, classification in competitive tournament match-play (i.e. ITF tournaments and the Paralympic Games) was based on criteria relating to individual suitability for participation in the ITF Open Class or Quad Division. Hence, the degree and nature of an individual's physical impairment dictated their eligibility for participation in wheelchair tennis match-play. All participants had a medically diagnosed, permanent, mobility-related physical disability (ITF, 2014). Within the thesis players participated in one of two categories: the ITF Open class or Quad division. They included men and women with a permanent physical disability and substantial loss of function in one or both lower extremities (Open) and in one or both upper and lower extremities (Quad). As stated previously, for participation in the Open class, a player would have neurological deficit at the S1 level or proximal, and this would be associated with loss of motor function (Figure 2.2). Alternatively, an individual may have had one of the following restrictions (ITF, 2014):

- Ankylosis and/or severe arthrosis and/or joint replacement of the hip, knee or upper ankle joints
- Amputation of any lower extremity joint proximal to the metatarsophalangeal joint
- A player with functional disabilities in one or both lower extremities equivalent to one of the above-listed points

While participation in the Quad division is associated with a neurological deficit at the C8 level or proximal, with associated loss of motor function (Figure 2.2), players with any of the following would also be permitted to compete (ITF, 2014):

- Upper extremity amputation
- Upper extremity phocomelia

- Upper extremity myopathy or muscular dystrophy
- Functional disabilities in one or both upper extremities equivalent to one of the above-listed points

In addition to the above, the reduced motor function associated with players competing in the Quad division would preclude an ability to perform 1) an overhead service, 2) a normal forehand and backhand stroke and / or 3) manual wheelchair propulsion (ITF, 2014). As players in this division do not have sufficient gripping action to hold the racket, taping and the use of assistive devices are permitted (Figure 3.2).

Figure 3.2 Taping the arm to the racket to enable tennis play is permitted for those with severe upper limb impairments

No further restrictions or classifications are specified to preclude an individual from participation in wheelchair tennis.

3.3.3 Determination of playing-time characteristics

To avoid unnecessary interpretation of data collected whilst inactive on-court (during breaks between play), game start and finish times were recorded to enable calculation of actual playing time (APT). One block of APT was defined as time from first service strike, to the end of a game-deciding point (i.e. a third bounce, shot into the net or shot landing outside of the boundaries of play). Treated DL data were then cross-compared to APT to generate per-game values for distance and speed. Game distances were subsequently accumulated to allow total values for each variable to be presented for individual sets. Match duration was determined by calculating the sum of APT for all sets.

3.4 Laboratory-based exercise testing

3.4.1 Arm-ergometer

An electromagnetically-braked arm-ergometer (Lode Angio, Groningen, The Netherlands) with adjustable cranks (range: 80 to 170 mm) was used for graded and peak exercise testing. The device was mounted to the floor using an automatic stand which an integrated motor controlling height adjustment (Figure 3.3). Scapula-humeral joint alignment with crank pedal axle and a slight elbow bend at maximal arm extension was ensured. Wheelchair-dependent participants were seated in their own chair for testing on the arm-ergometer. Wheel brakes were engaged and the wheels were lightly held by an investigator to minimise unwanted chair movement. In contrast, AB participants used a standard chair without arms for testing. As alterations in cadence influence oxygen consumption / efficiency during arm crank ergometry (Smith, et al., 2001), crank rate was fixed at 75 $rev \cdot min^{-1}$.

Figure 3.3 Electromagnetically-braked arm-ergometer mounted to a fixed stand with motorised height adjustment

3.4.2 Blood lactate concentration

BLa^- concentrations were assessed under laboratory conditions as part of initial physiological profiling, with small capillary blood samples extracted from the right earlobe after individual steady-state bouts and immediately post peak-exercise. Due to the opportunity for data collection in different locations, and the availability of testing equipment, slightly different collection methods were employed in this thesis. Therefore, detailed methods for the collection and analysis of blood samples for lactate concentrations are reserved for individual chapters (Chapters 7 & 8). In both cases, the main purpose of BLa^- collection was to enable provision of personalised training zones for participants, in-line with published thresholds for wheelchair court-sports activity (Croft et al., 2010).

3.4.3 Heart rate

HR was measured using radio telemetry (RS400 Polar Sport Tester, Kempele, Finland) during laboratory-testing (graded and peak) and for field-based measurement. During all testing, HR was monitored continuously and recorded at the end of each submaximal stage. For match-play, coded watches and chest straps were used to prevent interference. The recording interval was determined and watches were set to record. All HR data were downloaded to a personal computer using dedicated software (Polar Precision Performance, Polar, Kempele, Finland).

3.4.4 Oxygen uptake

Expired air samples were collected and analysed in controlled laboratory conditions using an online metabolic cart (Chapter 7: Parvomedics TrueOne 2400 Metabolic Measurement System, Parvomedics Inc, Utah, USA; Chapter 8: MetaLyzer 3B, Cortex Biophysik GmbH, Leipzig, Germany). Measurements were recorded in breath-by-breath mode, enabling estimation of $\dot{V}O_2$ (Figure 3.4). Prior to testing, manufacturer's recommendations for system calibration of gases (2-point calibration using reference values: O2 = 17.0 %, CO2 = 5.0 %) and flow (rates ranging from 0.5 to 3.0 L using a 3 L syringe) were completed. Data collected during the final 60-s of each steady-state exercise stage were averaged and used to indicate $\dot{V}O_2$ during graded testing. Peak capacity was defined as the highest 30-s average $\dot{V}O_2$ value observed during peak testing.

Figure 3.4 Assessment of $\dot{V}O_2$ using the Parvomedics TrueOne 2400 metabolic cart for breath-by-breath analysis of spirometric data

The rationale for measurement of $\dot{V}O_2$ in laboratory conditions was twofold. First, to enable quantification of peak physiological capacity. This was deemed important to identify the functional characteristics of the sample and to ensure that between-group comparisons were not confounded by variability in fitness levels. Second, to enable estimation of $\dot{V}O_2$ during performance. In this case, individual HR and $\dot{V}O_2$ relationships from laboratory testing were regressed against each other using a standard linear model. Thereafter, HR values collected during field-assessment were used to estimate relative exercise intensity (i.e. expressed as a percentage of $\dot{V}O_2$).

4

Study 1: Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court-movement

This chapter has been published in a slightly modified form in the *Journal of Spinal Cord Medicine*:

Sindall, P., Lenton, J.P., Whytock, K., Tolfrey, K., Oyster, M.O., Cooper, R.A., & Goosey-Tolfrey, V.L. (2013). Criterion validity and accuracy of global positioning satellite and data logging devices for wheelchair tennis court-movement. *Journal of Spinal Cord Medicine*, 36, 383-393.

4.1 Abstract

Purpose: To compare the criterion validity and accuracy of a 1 Hz non-differential GPS and DL device for measurement of wheelchair tennis court-movement variables.

Methods: Initial validation of the DL device was performed in a controlled laboratory environment. For field-based assessment of devices, GPS and DL were fitted to the wheelchair and used to record distance (m) and speed ($m \cdot s^{-1}$) during a) tennis-field b) linear-track and c) match-play test scenarios. Fifteen participants were monitored at the Wheelchair British Tennis Open.

Results: Data logging validation showed underestimations for distance in left wheel data logger (DLL) and right wheel data logger (DLR) devices at speeds > 2.50 $m \cdot s^{-1}$. In tennis-field tests, GPS underestimated distance in five drills. DLL was lower than both a) criterion and b) DLR in drills moving forwards. Reversing drill direction showed DLR was lower than a) criterion and b) DLL. GPS values for distance and average speed for match-play were significantly lower than equivalent values obtained by DL (distance: 2816 ± 844 *vs.* 3952 ± 1109 m, $P = 0.0001$; average speed: 0.7 ± 0.2 *vs.* 1.0 ± 0.2 $m \cdot s^{-1}$, $P = 0.0001$). Higher peak speeds were observed in DL (3.4 ± 0.4 *vs.* 3.1 ± 0.5 $m \cdot s^{-1}$, $P = 0.004$) during tennis match-play.

Conclusions: Sampling frequencies of 1 Hz are too low to accurately measure distance and speed during wheelchair tennis. GPS units with a higher sampling rate should be advocated in further studies. Modifications to existing DL architecture may be required to increase measurement precision. Further research into the validity of movement devices during match-play will further inform the demands and movement patterns associated with wheelchair tennis and address concerns associated with measurement limitations at high speeds.

4.2 Introduction

An evaluation of the physiological demands and movement-based characteristics of match-play allows for the development of highly specialised training (MacLeod et al. 2009). Direct measurement during competitive match-play also ensures that training is aligned with the demands of competition and performance (Edgecomb & Norton, 2006). Consequently, there has been an increasing interest amongst coaches and sports scientists in the area of physiological and movement-based profiling within both individual and team sports.

The requirement for accurate match-play information, coupled with the difficulties of directly measuring physiological variables during match-play has prompted interest in alternative monitoring methods. A telemetry-based velocometer attaches to the rear wheel of the chair and provides data on propulsion velocity (Moss et al., 2003). While this device demonstrates good validity, a number of limitations are associated with its practical application. First, as device mass is ~1.1 to 1.4 % of total wheelchair-wheelchair user mass, disruption to normal propulsion technique may be implied. Second, velocometer calibration and wheel fitment is time consuming. Third, data turnaround time for coaches and athletes is typically protracted. Hence, the device may be more useful as a research tool than a practical device for field-based movement assessment (Goosey Tolfrey et al., 2012). A video tracking method based on image processing technology has been used for elite male wheelchair rugby players to record distance, average velocity and movement trajectories (Sarro et al., 2010). This technology had previously been used in field assessments of soccer players (Barros et al., 2007). While the technique was deemed appropriate for rugby, the automatic tracking rate of 20 % was much lower than the 95 % value observed for soccer players (Barros et al., 2007). Hence it appears that monitoring the complex movements associated with the wheelchair court-sports is challenging.

GPS offers an alternative means to quantify the physiological and movement challenges associated with sports activity such as wheelchair tennis (MacLeod et al., 2009), but do not function effectively indoors. While data in wheelchair sports is limited, GPS has been validated for the collection of distance and speed in AB populations participating in field sports (Coutts & Duffield, 2010; Petersen et al., 2009; Edgecomb & Norton, 2006). With limited information on the demands of match-play, coaches can only apply a basic intervention. Short sprints, agility drills, hand-cycling and general pushing are typically advocated by coaches to improve performance in wheelchair sports (Goosey-Tolfrey et al., 2006). GPS tracks common movement patterns, allowing coaches to optimise tactics and court-movement strategies. Modern GPS devices also supply information on body load and the associated stresses linked to acceleration, deceleration and changes of direction, an important factor for tennis players who highly rate the ability to turn during play (Mason et al., 2010).

While there appears to be a clear rationale for GPS application in tennis, underestimations for distance and speed have been noted in confined spaces using Vicon Motion Systems as the criterion (Duffield et al., 2010). Tennis court size is standardised, with an active playing area of only 11.0 by 8.2 m for singles match-play (ITF, 2013). Such an area should be considered a confined space, and hence, consideration of GPS accuracy in this context is merited. Criterion-related validity refers to the systematic relationship between an approved criterion measure and an alternate method used to measure the criterion (Morrow et al., 2011). With criterion-related concurrent validity, the new method meets the criterion measures and can subsequently be used as an alternative technique (Safrit and Wood, 1995). The DL has been validated for collection of speed and distance data (Tolerico et al., 2007) and used to monitor activity patterns of manual wheelchair users (Oyster et al., 2011), children (Cooper et al., 2008) and wheelchair rugby players (Sporner et al., 2009). The DL could thereby theoretically be used as a reference measure for GPS validation. However, such a proposition is problematic. Validity and intra-model reliability (i.e. comparison of data from two DL recording in tandem) were assessed during linear motion (Tolerico et al., 2007). As repeated turns and changes of direction are associated with court sports, DL accuracy in this context is unclear. Hence in the current study, validity for both devices was first determined using known distance as the criterion. Second, GPS and DL values for match-play were compared. Therefore, the purpose was threefold; to examine 1) criterion validity for GPS and DL against known distance, 2) intra-model reliability for DL and 3) differences between GPS and DL during match-play.

It was hypothesised that no differences between 1a) DL and known distance during treadmill validation, 1b) GPS and DL for court-movement variables during tennis-field and linear-track testing, and 2) DLR and DLL would be observed. Based on previously reported underestimations for distance and speed in GPS, it was also hypothesised that 3) GPS will underestimate DL values during match-play.

4.3 Methods

4.3.1 Participants

Fifteen skilled wheelchair tennis players (11 male and 4 female) volunteered for this study. Individual physical and physiological characteristics have no effect on GPS accuracy (Schutz & Herren, 2000) or DL performance. Hence, player rank was not controlled. At the time of competition, twelve players held a world ITF rank of ≤ 25, whilst three held an ITF rank of ≤ 100.

4.3.2 Experimental design

Following an initial validation of the DL in controlled laboratory conditions, tennis-field and linear-track testing drills were completed to compare GPS and DL accuracy against known distances. Further observations were made during tournament match-play to assess inter-device values for court-movement.

4.3.3 GPS unit

A lightweight (76g), portable GPS tracking device with integrated accelerometer (SPI Elite™, GPSports System, Canberra, Australia) was also used for collection of travel distance and speed data. All matches were played outdoors, and hence, effective operation of GPS was ensured. The unit was securely taped to the sports wheelchair in clear view of the sky (Figure 4.1) and powered within 30-min prior to the official match start time. Sampling frequency for GPS was 1 Hz, whereas the integrated accelerometer was defined at 100 Hz. Once activated, the GPS unit calculated the precise distance to operational satellites based on receipt of satellite time and position data. By calculating distance to four satellites (minimum) the position of the GPS unit could be determined trigonometrically (Townshend et al., 2008), generating an exact three dimensional position. Distance was calculated from changes in position of the GPS. Speed was determined using the Doppler shift (Schutz & Herren, 2000). The unit was operational for the full match duration, and switched off directly afterwards. Raw data were downloaded to a personal computer and analysed using GPS software (GPSports Team™, AMS V2.1, Canberra, Australia) to retrieve distance and speed.

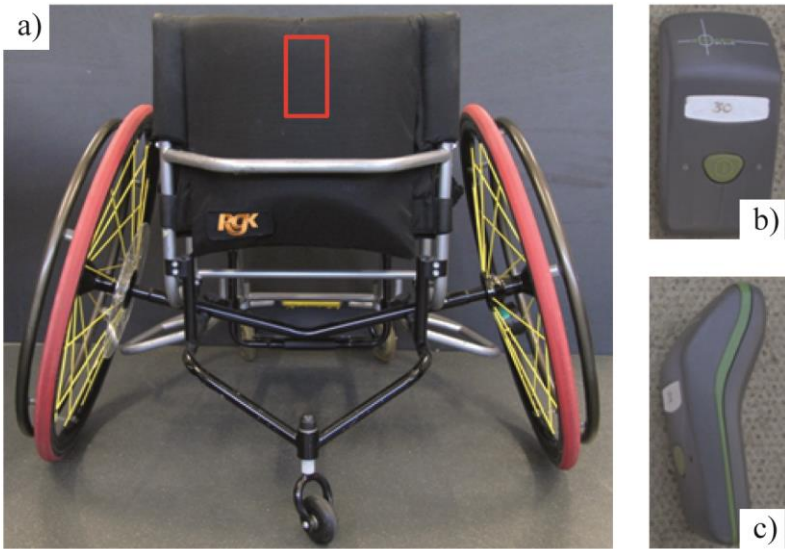

Figure 4.1 GPS unit and positioning

The position (red rectangle) of the GPS unit on the back of the sports wheelchair (a). Anterior (b) and lateral (c) views of the SPI Elite™ GPS unit

4.3.4 DL validation

The DL described in Section 3.3 was previously used to measure distance and speed in a sporting context (wheelchair rugby; Sporner et al., 2009), but only validated at moderate speeds ranging from 0.8 to 1.8 $m \cdot s^{-1}$ (Tolerico et al., 2007). The movement speed of wheelchair tennis players is not known currently. However, wheelchair sports performers are known to operate at speeds above these levels (Campbell et al., 1997). Consequently, an initial validation was performed. A sports wheelchair with a 26” wheel diameter (tyre pressure 120 $lb \cdot in^2$) was mounted onto a motor-driven treadmill (H/P/Cosmos Saturn, Nussdorf-Traunstein, Germany) to allow for passive wheel rotation. To examine intra-model reliability (i.e. compare two DL devices of the same model), two DL units were attached to each wheel (Figure 4.2), and their data compared. The treadmill was calibrated (i.e. distance was checked) prior to data collection. Further, whilst the treadmill was programmed to cover 500 m, actual distance was also recorded to ensure precision in the comparison between wheel rotation and actual belt movement. Speed was increased for each bout by 0.5 $m \cdot s^{-1}$ (minimum to maximum: 0.5 to 5.0 $m \cdot s^{-1}$). Range for speed was designed to encompass the range of values reported for high-level wheelchair sports performers (Campbell et al., 1997). To prevent unwanted wheel slippage, a male participant remained seated in the chair for all testing bouts.

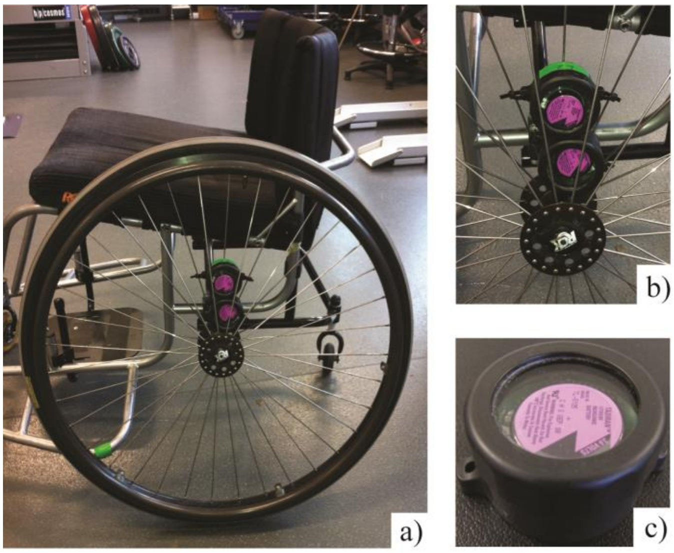

Figure 4.2 DL configuration for validation against criterion distance on a motor-driven treadmill

Two DL units positioned on the inside spokes of the sports wheelchair and secured using cable ties (a) & (b), tilted anterior view of the DL unit (c). Two units used to allow for assessment of intra-model reliability

4.3.5 Validation against criterion distance

GPS and DL were compared using a) tennis-field and b) linear-track testing drills. To ensure consistency of pushing technique and speed, one male participant competent in wheelchair propulsion was selected to perform all tests; this was the same participant as noted in Section 4.3.4. Forwards propulsion was adopted throughout, with the participant seated in the chair. GPS and DL were attached to a sports wheelchair (Figures 4.1 and 4.2). In tennis-field testing, one DL was attached to each wheel to assess the impact of turning on movement variables. Three drills (I, II and III) were devised to replicate patterns associated with match-play (Figure 4.3). Drills were completed on a tennis court with standardised court markings conforming to ITF guidelines. Hence, known distances were used. However, markings were also checked using an extendable tape measure. Ten sets of each drill were performed. Drills were then repeated for movement in the opposite direction (I*, II* and III*). Linear-track testing involved repeated trials on an outdoor athletics track. Known distances were used, and checked as per tennis-field testing (Trial A: 10 x 100 m; Trial B: 10 x 200 m; Trial C: 10 x 400 m; Trial D: 10 x 800 m).

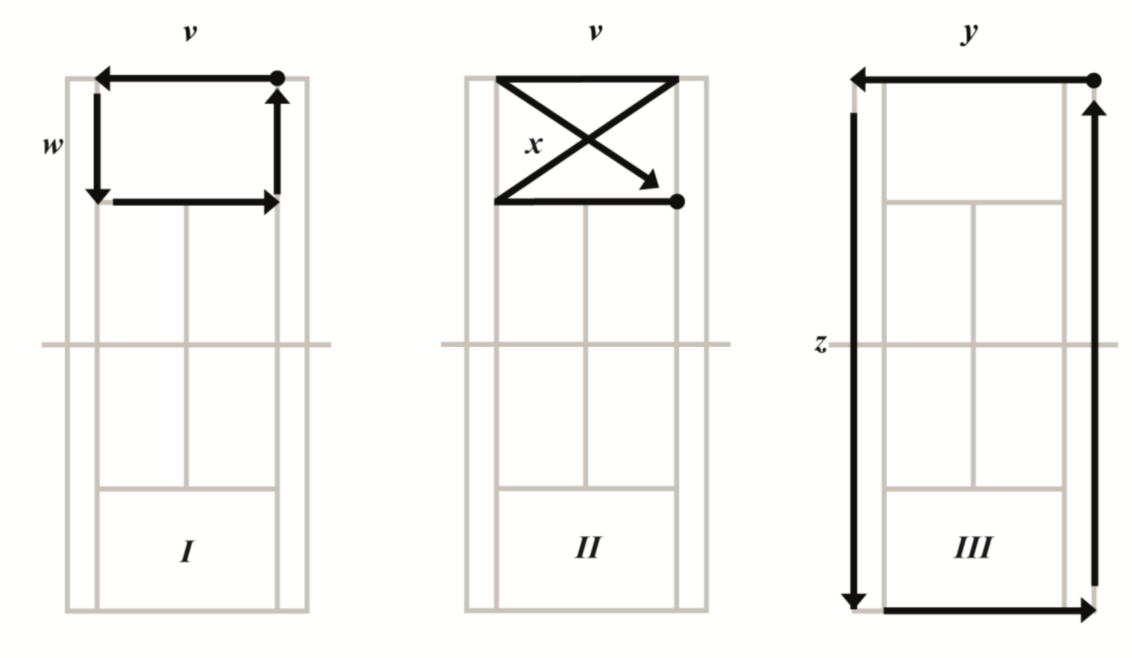

Figure 4.3 Tennis-field testing drills

Dot indicates starting point. Arrow indicates wheelchair movement direction. Distance (m): v = 8.2, w = 5.5, x = 9.9, y = 11.0, z = 23.7. Drill: ***I*** = Back court box (27.4 m), ***II*** = Figure-8 (36.3 m), ***III*** = Full court box (69.5 m)

4.3.6 Tennis tournament match-play

Data collection took place at the 2010 Wheelchair Tennis British Open (Nottingham, UK). Hence, ITF rules and regulations for match-play were applied (ITF, 2009b). Specific detail regarding match-play format can be found in Section 3.4. A total of 26 tennis matches were tracked with 17 and 9 matches from the Open class and Quad division respectively. Following tournament registration, wheelchair tennis players gave consent for the attachment of a GPS and a DL unit to their sports wheelchair. For monitoring during competitive play, GPS was attached (Figure 4.1), and one DL unit fitted to each chair on the non-racket side. Questionnaires were completed as explained previously in Section 3.1. All matches were played under competitive conditions, and were won or lost in 3 sets.

4.3.7 Data processing and statistical analyses

Data analyses were conducted using SPSS version 19.0 (SPSS, Inc., Chicago, IL). Descriptive statistics [mean ± standard deviation (SD)] were obtained for all participants. Normality and homogeneity of variance were confirmed by Shapiro-Wilk and Levene’s tests respectively.

Student's paired *t*-tests were used to identify within group differences for DL treadmill testing. Intra-model reliability was determined using the typical error (TE) and coefficient of variation (CV) (Hopkins, 2000). Ninety-five percent confidence intervals (95% CI) were calculated (Armitage et al., 2002). GPS and DL values for distance were compared with known distances for tennis-field and linear-track tests using the Bland Altman method (Bland & Altman, 1986). Subsequent one-way analysis of variance (ANOVA) with Tukeys' post hoc testing was used to examine the differences between measurement devices for distance and speed. Match-play data were presented independently for the Open class and Quad division, with student's paired *t*-tests used to identify within-group differences. In addition, combined values (Open and Quad) were presented. Statistical significance was accepted at a level of $P < 0.05$.

4.4 Results

4.4.1 DL validation

Mean treadmill distance across all fixed speed conditions was 502 ± 2 m. During the treadmill test, lower values for distance were observed in DLR (434 ± 84 m; $t = 2.525$, $P = 0.032$) and DLL (451 ± 64 m; $t = 2.488$, $P = 0.035$) when compared to fixed values. The intra-model reliability for distance measured by DLR and DLL is shown in Table 4.1. Both DL units reported good reliability at speeds < 2.50 m·s$^{-1.}$ Comparatively less stable scores were observed at higher speeds in both units. Figure 4.4 shows a progressive underestimation for distance and speed at treadmill speeds > 2.50 m·s^{-1}.

Table 4.1 Intra-model reliability measures for DL treadmill testing
Values are TE (95% CI) [CV]

	Distance (m)	
	DLR	**DLL**
Treadmill speed (m·s^{-1})		
< 2.50	0.3 (503 - 508) [0.1%]	2.1 (499 - 505) [0.4%]
> 2.50	72.3 (259 - 477) [19.9%]	17.5 (339 - 478) [4.4%]

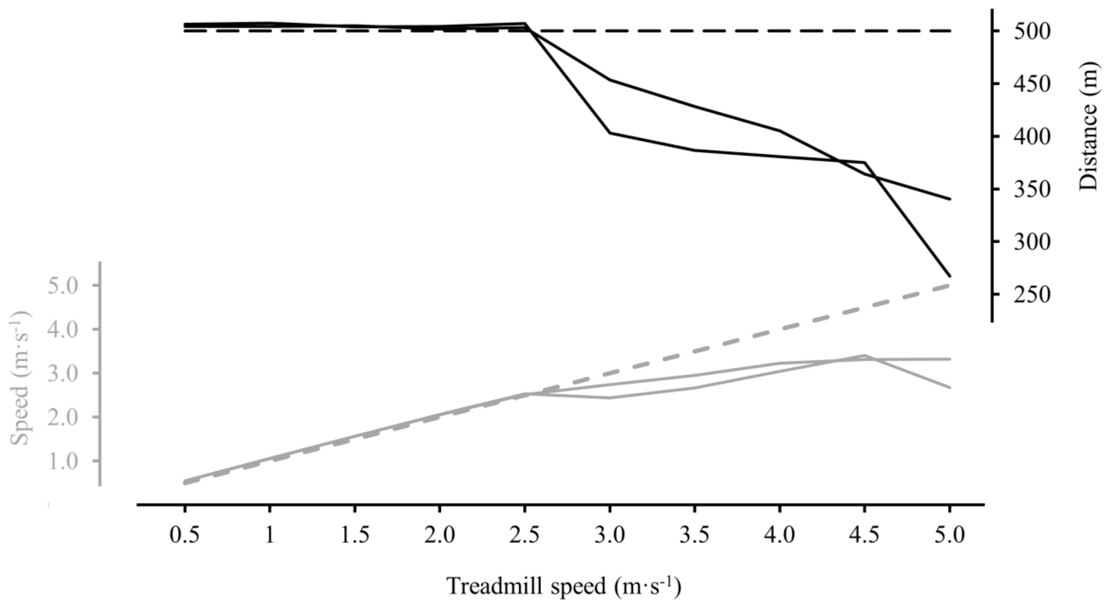

Figure 4.4 Distance and speed for DL during an incremental, passive wheel rotation validation test on a motor-driven treadmill

Values for DLR and DLL (solid lines) are presented against fixed values for distance and speed (dashed line)

4.4.2 Tennis-field testing

Three drills (range, 27.4 to 69.5 m) were performed in two directions. GPS underestimated distance in five of six drills (Table 4.2) and recorded lower values than DLR in drills *I*, *II* and *III*, and DLL in drills *I** and *III**. Figure 4.5 shows DLR and DLL recorded distances closest to the criterion (drills *I*, *II* and *III* and *I**, *II** and *III** respectively). DLL was significantly lower than criterion and DLR in drills *I*, *II* and *III*. Reversing the direction of movement resulted in the opposite effect, with a difference between the criterion and DLR, and higher values for DLL (drills *I** and *III**). The tendency for DLL underestimation in forwards and DLR underestimation in reversed movement directions can be seen in Figure 4.5. Highest values for CV were observed during drills involving a figure-of-8 movement (Figure 4.3) for all devices. A one-way ANOVA with Tukeys' post hoc test revealed a lower mean speed for DLR against GPS (1.62 ± 0.21 *vs*. 1.54 ± 0.14 $m \cdot s^{-1}$, $P = 0.039$).

Table 4.2 Distance for GPS and DL devices during tennis-field and linear-track testing

Values are mean (SD) 95% CI [CV]. *Denotes drill repeated in the opposite direction. Significantly different ($P < 0.05$) to the criterion [a], GPS [b], DLR [c] & DLL [d]

		Distance (m)									
		Criterion	GPS			DLR			DLL		
Tennis Field Test											
Drill	*I*	27.4	24.6 (1.3) [a,c,d]	23.7 - 25.5	[5.2]	26.5 (0.7) [b,d]	27.2 - 28.2	[2.5]	21.2 (0.7) [a,b,c]	20.7 - 21.7	[3.1]
	II	36.3	31.4 (1.3) [a,c]	30.5 - 32.3	[4.3]	38.4 (3.0) [b,d]	40.5 - 44.7	[7.9]	33.4 (1.9) [a,c]	32.1 - 34.7	[5.5]
	III	69.5	62.1 (1.3) [a,c,d]	61.2 - 63.0	[2.1]	70.4 (0.7) [b]	71.2 - 72.2	[4.1]	66.4 (1.3) [a,b,c]	65.5 - 67.3	[1.9]
	*I**	27.4	25.0 (1.3) [a,c]	24.1 - 25.9	[5.1]	21.3 (0.8) [a,b,d]	20.7 - 21.9	[3.7]	25.2 (0.8) [a,c]	24.6 - 25.8	[3.3]
	*II**	36.3	34.1 (2.7) [a,d]	32.2 - 36.0	[7.9]	34.2 (1.3) [a,d]	33.3 - 35.1	[3.7]	38.6 (0.6) [a,b,c]	38.2 - 39.0	[1.5]
	*III**	69.5	63.1 (3.0) [a,d]	61.0 - 65.2	[4.8]	65.8 (0.5) [a,d]	65.4 - 66.2	[0.8]	69.4 (0.8) [b,c]	68.8 - 70.0	[1.1]
Linear Track Test											
Trial	*A*	100	96 (4) [a]	93 - 99	[4.3]	98 (1)	98 - 99	[1.2]	98 (2)	97 - 99	[1.6]
	B	200	202 (7) [d]	197 - 207	[3.4]	198 (4)	195 - 201	[0.9]	195 (4) [b]	192 - 198	[1.9]
	C	400	409 (4) [a,c,d]	407 - 412	[0.9]	399 (5) [b,d]	395 - 402	[1.2]	393 (5) [a,b,c]	389 - 396	[1.3]
	D	800	804 (15) [c]	793 - 814	[1.8]	817 (5) [a,b]	814 - 821	[0.6]	811 (7) [a]	806 - 816	[0.9]

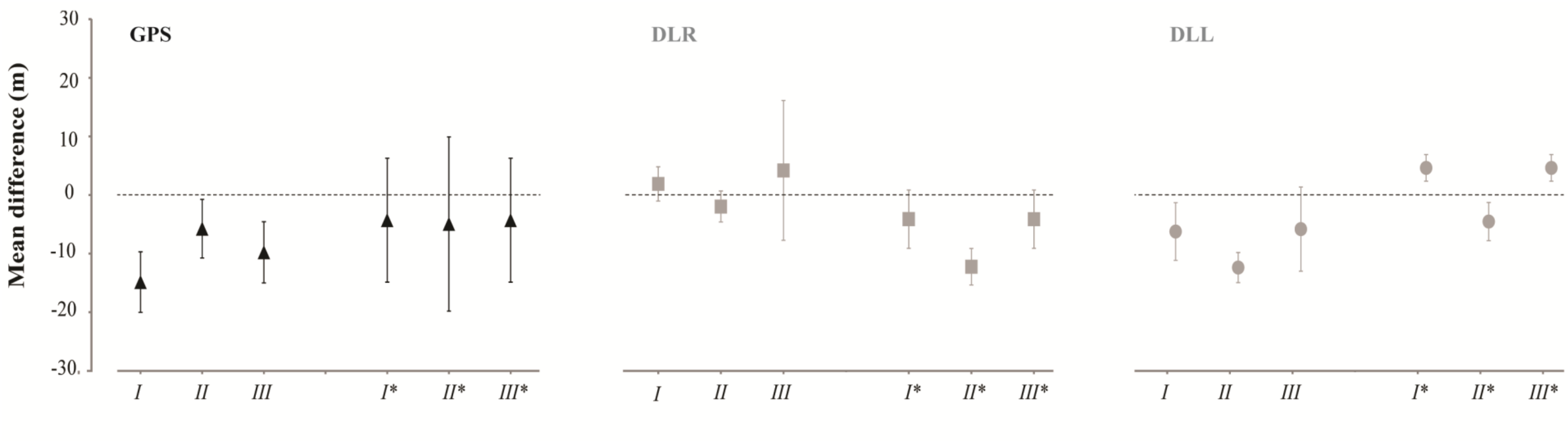

Figure 4.5 Plot of mean difference (bias) during tennis-field testing drills for GPS (▲), DLR (■) and DLL (●)

Drill: ***I*** **=** Back court box (27.4 m), ***II*** = Figure 8 (36.3 m), ***III*** = Full court box (69.5 m). Error bars represent 95% limits of agreement. *Denotes drill repeated in the opposite direction

4.4.3 Linear-track testing

Four trials (range: 100 to 800 m) were performed in one direction. Figure 4.6 shows the agreement between measurement devices and the criterion during linear-track testing. One-way ANOVA revealed GPS underestimated criterion distance at 100 m (*P* = 0.001). At 200 m, values for DLL were lower than GPS (*P* = 0.006). GPS distance at 400 m was higher than values for DLR, DLL and the criterion (*P* = 0.0001). At the same distance, DLL reported lower values than the reference value (*P* = 0.001) and DLR (*P* = 0.006). Both DLR and DLL significantly overestimated criterion distance at 800 m (*P* = 0.0001 and *P* = 0.040 respectively), with DLR reporting higher values than GPS (*P* = 0.005). A decrease in CV was observed with an increase in distance (100 to 400 m) for GPS. All trials were undertaken at speeds < 2.50 $m \cdot s^{-1}$. No significant difference was observed for average speed between measurement devices (*P* = 0.474).

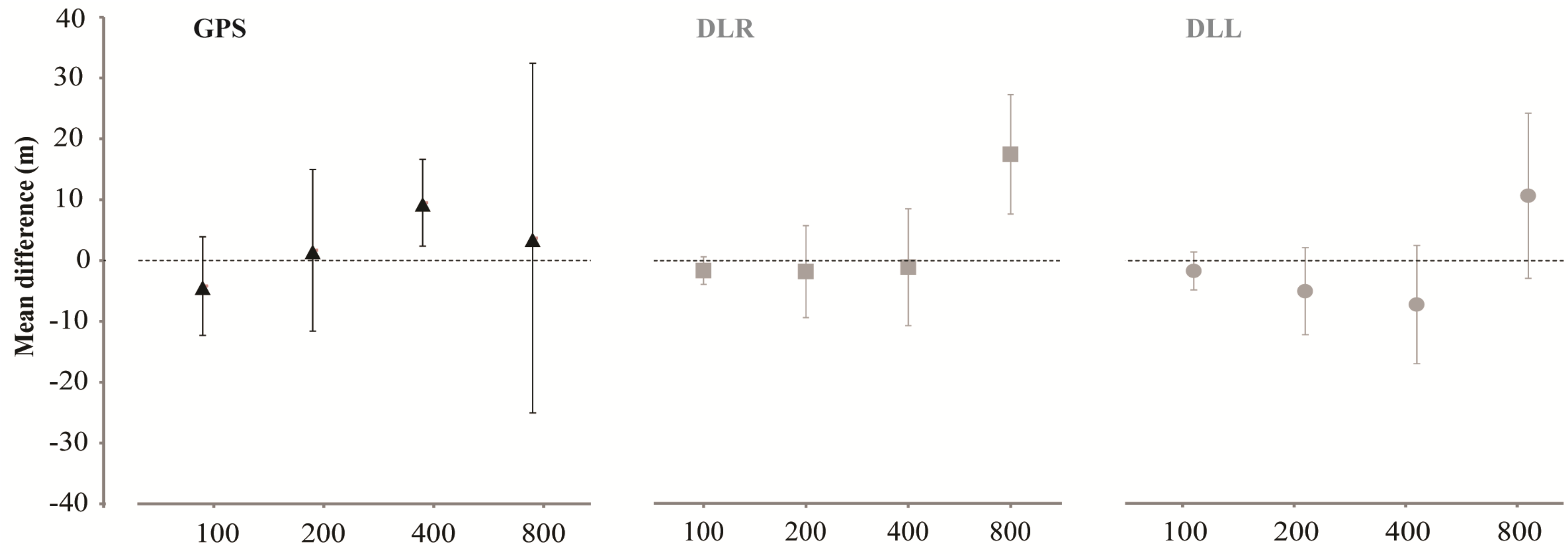

Figure 4.6 Plot of GPS (▲), DLR (■) and DLL (●) mean difference (bias) during linear-track testing drills

Error bars represent 95% limits of agreement

4.4.4 Competitive match-play

Table 4.3 presents descriptive statistics for tennis match-play. Significantly higher distances and average speeds were associated with DL for all playing categories. Peak speed was higher for GPS in both the open (P = 0.035) and combined categories (P = 0.004).

Table 4.3 Distance and speed for GPS and DL during competitive match-play

Values are mean (SD) 95% CI. *Denotes significant difference between GPS and DL (P < 0.05)

	GPS		DL		*t*	P
Distance (m)						
Open	2891 (1000)	2377 - 3405	3963 (1340)	3274 - 4652	8.673 *	0.0001
Quad	2675 (438)	2339 - 3012	3931 (505)	3543 - 4319	14.144 *	0.0001
Combined	2816 (844)	2475 - 3157	3952 (1109)	3504 - 4400	13.050 *	0.0001
Peak speed ($m \cdot s^{-1}$)						
Open	3.5 (0.4)	3.3 - 3.7	3.3 (0.6)	3.0 - 3.5	-2.302 *	0.035
Quad	3.1 (0.2)	2.9 - 3.3	2.8 (0.4)	2.5 - 3.2	-2.090	0.070
Combined	3.4 (0.4)	3.2 - 3.5	3.1 (0.5)	2.9 - 3.3	-3.129 *	0.004
Average speed ($m \cdot s^{-1}$)						
Open	0.8 (0.1)	0.7 - 0.9	1.0 (0.2)	0.9 - 1.1	7.862 *	0.0001
Quad	0.6 (0.1)	0.5 - 0.7	0.9 (0.0)	0.8 - 0.9	5.440 *	0.001
Combined	0.7 (0.2)	0.7 - 0.8	1.0 (0.2)	0.9 - 1.1	9.600 *	0.0001

4.6 Discussion

4.6.1 Main findings

The purpose of this study was to examine 1) criterion validity for GPS and DL against known distance, 2) intra-model reliability for DL and 3) differences between GPS and DL during match-play. In this study, significant differences were observed between DL and known distance during initial treadmill validation. In tennis-field testing, GPS underestimated criterion distance. For DL, movement direction influenced the level of agreement with criterion distance values. In linear-track tests, higher values for GPS and DL were noted at 400 and 800 m respectively. Significant differences between

GPS and DL for distance and speed were observed during tennis match-play, with GPS reporting lower values for distance and average speed, and higher values for peak speed.

4.6.2 Application of GPS for assessment of court-movement

The validity and accuracy of GPS for performance monitoring has been considered in a range of sports, including tennis (Duffield et al., 2010). However, comparisons between sporting disciplines are problematic due to variation in systems used and methods employed for testing. In particular, differences exist between triangulation algorithms for calculation of receiver position, Kalman (exclusion criteria) formula for logical positioning, and smoothing techniques used to exclude anomalies (Petersen et al., 2009). On an oval circuit, GPS distances of 125 to 1386 m are associated with a mean error of 4.8 ± 7.2 %, the magnitude of which decreases with an increase in distance (Edgecomb & Norton, 2006). For track-based testing, this study shows a reduced CV with increased distance for GPS within trials conducted over a similar distance (range: 100 to 800 m). Hence, GPS reliability is improved with increased distance. Comparatively smaller underestimations (0.4 %) for measurement over longer distances (600 to 8800 m) suggest that accuracy is improved over increased distances (Edgecomb & Norton, 2006). The results of this study report a value of 2816 ± 844 m for combined distance during match-play (Table 4.3). GPS units thereby have a potential application for quantification of distance during tennis. However, such a proposition may be problematic. First, the data in this study reveal a significant underestimation for GPS against criterion distance for five of six drills completed within the confines of a tennis court. This finding is consistent with previous findings reporting an increase in the mean difference between GPS and reference values for distance during non-linear motion at increasing speeds (Gray et al., 2010). Second, a larger CV was observed during tennis-field testing for GPS, particularly for drills involving the figure-8 pattern. Such a drill is characterised by movement within a small space, and a complex series of sharp turns. This type of movement, which is typical in tennis, may represent a challenge to measurement precision for GPS.

GPS records non-linear movements as a sum of measured chords within the actual curve based on position estimates. Higher sample rates allow more chords to be measured and the path defined by the chords becomes closer to the actual curve (Gray et al., 2010). An increased circle diameter also allows for increased chord measurement and hence, a more accurate estimation. Tennis court-movement is multidirectional and non-random (Roy et al., 2006), with repetitive sharp turns and alterations of pace. Hence, GPS may be unable to accurately track the entire distance covered, predicting the distance of several chords within these turns and leading to distance underestimation. Further, a moderate but significant correlation for satellite number and GPS accuracy suggests that the number of active satellites may also influence error magnitude (Gray et al., 2010). As horizontal dilution of precision

(HDOP) is dependent on satellite geometric position and number, a reduction in active satellites therefore causes a reduction in HDOP. Greater variability is seen in HDOP during small circle experiments (Witte & Wilson, 2004) and side-to-side movements may influence measurement accuracy. Satellite recruitment data were not collected in this study and therefore cannot be confirmed as a contributing factor. However, the enclosed space of a tennis court could theoretically influence the number of satellites that the GPS is able to utilise, and therefore increase HDOP. This seems plausible as GPS has been shown to underestimate distance in confined tennis court drills at varied speeds when compared with a highly accurate Vicon Motion System (Duffield et al, 2010).

In the track trials, no significant difference was observed for average speed between measurement devices. These findings are in agreement with values presented for linear movement in hockey (MacLeod et al., 2009). GPS accuracy has been confirmed for speed determination in curved-path (16 and 30 m diameter), and straight-line trajectories (Gray et al., 2010). However, curves were much larger in circumference than those associated with this study. As discussed previously, a larger circumference means more chords are sampled, which in turn influences the accuracy of the prediction. Speed is calculated by dividing the distance by time taken. Hence, factors influencing distance determination have a direct impact on equivalent values for speed. In addition, the mathematical algorithm in GPS smooths out the peaks and troughs for rapid accelerations and decelerations, causing further inaccuracies (Gray et al., 2010). With a 1 Hz sampling rate, one sample is recorded every second. Therefore movements lasting less than this may be missed or underestimated.

4.6.3 Application of DL for assessment of court-movement

Data generated from DL may also lead to inaccurate estimations of speed and distance. This study shows agreement and good reliability between DL and treadmill for speeds < 2.50 $m \cdot s^{-1}$. This finding is consistent with initial validation of the device which reports agreement at speeds ranging from 0.8 to 1.8 $m \cdot s^{-1}$ (Tolerico et al., 2007). However, at higher speeds (> 2.50 $m \cdot s^{-1}$), we report a decrease in measurement accuracy and reliability for DL, with the degree of underestimation increasing with an increasing speed. In addition, a lower average speed was noted for DLR against GPS in the more confined tennis drills. DL calculates speed and distance indirectly, through consecutive reed-switch activation (Ding et al., 2005). If a reed-switch is missed, a time stamp is not created, theoretically leading to underestimations for both distance and speed. Average speed during match-play was ~0.7 $m \cdot s^{-1}$. Whilst this speed is consistent with those associated with the initial validation of the device, it is important to note that tennis is a highly intermittent sport, involving rapid movements interspersed with active rest. Participants will clearly attain higher speeds as they respond to the movement of the ball. This study reports peak speed values of ~3.5 $m \cdot s^{-1}$ for players in both the Open class and Quad division. Due to the outcomes of DL treadmill validation, these reported values are likely to represent an underestimation of peak speed, and consequently, an underestimation of actual on-court tennis movement dynamics. Hence, a modified DL for use within sports may be required.

In the 100 m linear-track trial, GPS underestimated criterion distance. However at 400 m, GPS provided an overestimation and yielded higher values than DLR and DLL. The reasons for this shift are not entirely clear but are most likely related to fluctuations in satellite availability. At 800 m, values for DLR and DLL were higher than the criterion. Whilst the mechanisms for DL underestimation are clear, the factors influencing overestimation are less obvious, although most likely related to the pendulum design of the device. DL is a sealed unit, and thus, reed-switch position cannot be identified prior to testing. Lack of control over standardisation of reed-switch positioning will inevitably cause a discrepancy. However, due to wheel sizes involved, such a discrepancy is likely to be small. Other factors may be related to inconsistencies relating to time stamping. Further work is required to assess such causes.

4.6.4 Impact of chair turns

A tendency for a lower CV was noted for linear-track testing, suggesting that devices yield more reliable scores with straight-line movement. During tennis-field testing, CV was higher, hence a reduced reliability. DLL significantly underestimated criterion and DLR distance in drills containing left hand turns (*I, II* and *III*) while in contrast, DLR underestimated criterion and DLL distance values in drills containing right hand turns (drills *I** and *III**). These data suggest that the outside wheel covered greater distance and was more closely associated with criterion distances during turning movements. During left turns, the left wheel is likely to remain stationary to pivot whilst the right wheel continues to rotate to make the turn. In addition, values for GPS were consistently lower than the outside wheel DL. These data suggest collectively that for tennis-field drills in confined spaces, outside wheel DL offered the best representation of actual distance. However, due to the non-random nature of movement during match-play (Roy et al., 2006), the number of turns are not likely to be consistent or equal. This raises important considerations regarding DL placement on the chair, and the general application of DL systems for accurate movement profiling within wheelchair sports. Reporting one single inter-model average for distance and speed parameters would not completely counteract the effect of turns during match-play, but would offer a more accurate representation of actual court-movement during match-play. Hence, where it is both possible and practical, two DL devices (one on each wheel) should be used.

4.6.5 Match-play observations and inferences

Match-play data significantly show that higher distances and average speeds were associated with DL for all playing categories. Peak speed was higher for GPS in Open class (P = 0.035) and combined categories (P = 0.004), with higher average speeds for DL. However, concerns with GPS and DL accuracy add uncertainty to inferences on actual distance and speed covered during match-play. The relationship between GPS and reference values for maximal speed is stronger at higher distances using 1 Hz systems (Barbero-Alvarez et al., 2010). Criterion distances were not available for match-play. Future work should ensure that an appropriate reference measure is provided. The Vicon Motion System (Duffield et al., 2010), or a computer-based tracking system (Barbero-Alvarez et al., 2010) may be suitable options. However, the present study has identified important questions regarding the application of movement tracking systems in wheelchair tennis. For GPS, an appropriately high sample rate should be advocated. Sampling frequencies of 1 and 5 Hz underestimate average and peak speed by 10 to 30 % in court-based movement drills (Duffield et al., 2010), and may lack sensitivity for the monitoring of movement during tennis. GPS units sampling at 15 Hz are now available and may give a more accurate estimation of distance and speed. Regarding application of DL, the purpose of monitoring is an important consideration. As differences between units were related to wheel movement, one device should be placed on each wheel for measurements during wheelchair tennis match-play. While this should counteract the impact of turns, it should be noted that this strategy will not address more fundamental concerns surrounding DL validity at higher speeds. Modifications to existing technology are required to address potential reed-switch activation and timing issues. DL devices incorporating six switches have been developed and are currently undergoing preliminary testing. While provision of additional reed-switches may not eliminate timing issues completely, it does seem plausible to assume that measurement accuracy may be increased using this approach. Further research therefore should address the accuracy and reliability of any newly developed DL devices for movement profiling in wheelchair sports.

4.7 Conclusions

GPS and DL units provide quick and non-labour intensive methods of supplying information on movement dynamics to enable coaches to effectively plan and monitor training. This study reports significant differences for distance and speed between devices in tennis-field, linear-track and match-play test scenarios. Distance for GPS was underestimated in tennis-field tests. The requirement for repeated turns in a confined space may have influenced measurement accuracy. As rapid changes in direction in a small space is a defining aspect of wheelchair tennis play, and court dimensions are fixed, GPS may not offer the most appropriate method to collect court-movement data. However, GPS units with a higher sampling frequency may offer increased sensitivity for the quantification of movement patterns. The DL is lightweight, non-invasive and collects movement data in both an indoor and outdoor environment with relative ease and limited adjustment. Hence, DL devices may be more suitable for tennis than contact-based open-court sports such as rugby or basketball. When DL is used, consideration should be given to placement and positioning to increase the precision of measurement, but further testing and development is required to evaluate DL application within a sporting context. Between-device differences were observed for DL units placed on opposing wheels. In tennis-field testing, DL placed on the outside wheel provided the most accurate distances in comparison to reference values. At speeds > 2.50 $m \cdot s^{-1}$, values for DL distance and speed were significantly lower than known values. Rapid changes of pace may disrupt normal reed-switch activation and cause underestimations in distance and speed, and this raises doubts about DL applicability. However, due to the confines of court dimensions and the nature of play, tennis players are unlikely to reach high peak speeds with great frequency. To further assess and subsequently confirm device-specific applicability, future research should quantify time spent at high speeds during match-play.

5

Study 2: Data logger device applicability for wheelchair tennis court-movement

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5.1 Abstract

Purpose: Assessment of movement logging devices is required to ensure suitability for the determination of court-movement variables during competitive sports performance and allow for practical recommendations to be made. Hence the purpose of this study was to examine wheelchair tennis speed profiles to assess DL device applicability for court-movement quantification, with match-play stratified by rank (HIGH, LOW), sex (male, female) and format (singles, doubles).

Methods: Thirty-one wheelchair tennis players were monitored during competitive match-play. Mixed sampling was employed (male = 23, female = 8), with singles and doubles matches used.

Results: Friedman's test with Wilcoxon signed-rank post hoc testing revealed a higher percentage of time below 2.50 $m \cdot s^{-1}$ (< 2.50 *vs*. ≥ 2.50 $m \cdot s^{-1}$: 89.4 ± 5.0 *vs*. 1.2 ± 3.5 %, $Z = -0.480$, $P = 0.0005$, $r = 0.87$) with the remaining time (9.0 ± 4.9 %) spent stationary. LOW were stationary for longer than HIGH counterparts (12.6 ± 8.7 *vs*. 8.2 ± 5.1 %, $U = 30.000$, $P = 0.011$, $r = 0.46$) with more time at low propulsion speeds (< 1.00 $m \cdot s^{-1}$). HIGH and doubles players spent more time in higher speed zones (*vs*. LOW and singles players respectively). Females spent more time in the 1.00 - 1.49 $m \cdot s^{-1}$ zone ($U = 48.000$, $P = 0.047$, $r = 0.36$).

Conclusions: For health gains and performance improvement, strategies to improve court-movement speed should be considered for LOW. The doubles match-play format may offer potential for a higher speed environment. Regardless of rank, sex or format, propulsion speeds during wheelchair tennis match-play are consistent with DL accuracy. Hence, data logging is appropriate for court-movement quantification.

5.2 Introduction

Data logging technologies are becoming increasingly widespread, with studies in wheelchair basketball and rugby (Mason et al., 2014a; Sporner et al., 2009), and now wheelchair tennis (Chapter 4), popularising this approach to court-movement assessment. Initial validation revealed speeds of 0.79 ± 0.19 $m \cdot s^{-1}$ for everyday propulsion (Tolerico et al., 2007). Interestingly, the same group of wheelchair users achieved significantly higher speeds (0.96 ± 0.17 $m \cdot s^{-1}$) when participating in a range of sports at the National Veterans Wheelchair Games (Tolerico et al., 2007). However, in relative terms, wheelchair propulsion speeds are low. Persons without mobility impairments walk at speeds ranging from 1.23 to 1.48 $m \cdot s^{-1}$ (Fisher & Gullickson 1978; Blessey et al., 1976); therefore, they benefit from chronic health adaptations associated with a higher physiological cost. While long-term health consequences of insufficient wheelchair propulsion speed have not yet been studied, and generalisations cannot easily be made, an increased risk of premature death is found in those without impairment in the lowest tertile for walking speed (males and females: < 1.26 and < 1.09 $m \cdot s^{-1}$) (Elbaz et al., 2013). Studies concerned with measurement of wheelchair propulsion speed are important therefore, to consider the degree to which types of sporting participation offer potential for long-term health gains.

While average speed for wheelchair tennis match-play is not yet known, values of 1.33 ± 0.25 and 1.48 ± 0.13 $m \cdot s^{-1}$ have been reported for skilled rugby and basketball players respectively using the device (Sporner et al., 2009). Hence, values for average speed are typically below 2.50 $m \cdot s^{-1}$ (Sporner et al., 2009). This value delineates an important marker for device validity, as accuracy and intra-model reliability decrease proportionately with speed increases above this threshold (Chapter 4). As discussed previously, the mechanisms for inaccurate measurement at a given tempo are not understood fully, but issues relating to reed-switch activation represent the most likely cause (Chapter 4). Even though average speeds are typically lower than 2.50 $m \cdot s^{-1}$, wheelchair athletes are known to achieve peak speeds in excess of 5.0 $m \cdot s^{-1}$ (Campbell et al., 1997). However, the relative proportions of total playing time spent over the threshold for accurate measurement are not known. To ensure that values have good application for court-movement assessment, and to address present uncertainties regarding data obtained from the device, quantification of the percentage of total playing time spent above and below the threshold for accuracy is required.

Wheelchair tennis is intermittent and multi-directional (Roy et al. 2006), requiring short, sharp bursts of pace and periods of high intensity work. Hence, variability in average speed for individual sets and full matches is likely to be high, and consideration of values in isolation is, therefore, problematic. Recent studies using AB participants have reported time spent (as a percentage of total time) for elite hockey players (White & Macfarlane, 2013) and distance covered for rugby league referees (O'Hara et al., 2013) in specific speed zones. Such analyses are appropriate for intermittent sports as they allow an increased understanding of relative proportions of time spent at any given speed, and increase overall understanding of performance movement dynamics. However, these are not available currently for the wheelchair sports, including tennis.

Tennis studies are restricted currently to skilled males (Reid et al., 2007a; Roy et al., 2006; Goosey-Tolfrey & Moss, 2005) or sex has not been defined (Abel et al., 2008). Where court-movement variables (Chapter 4) and physiological data have been reported for mixed-sex samples (Croft et al., 2010; Barfield et al., 2009), no between-sex comparisons have been made. Singles match-play has been the only format (Barfield et al., 2009) with no studies reporting data from doubles match-play. Hence, sex and format-specific differences in court-movement variables are not known.

To provide practical recommendations for training and testing of wheelchair athletes and recreational sports performers, accurate determination of court-movement variables during competitive match-play conditions is required. Hence, the purpose of this study was to examine wheelchair tennis speed profiles to assess DL device applicability for quantification of court-movement during match-play. It was hypothesised that the majority of time will be spent below 2.50 $m \cdot s^{-1}$ in overall terms, and for comparisons involving rank (HIGH, LOW), sex (male, female) and format (singles, doubles). In contrast, it was expected that HIGH (*rank*), males (*sex*), and singles players (*format*) will spend a greater proportion of time in higher speed zones than respective counterparts.

5.3 Methods

5.3.1 Participants

Thirty one skilled wheelchair tennis players (23 male and 8 female) volunteered to participate in this study (Table 5.1). Participants presented with a range of disabilities [SCI = 11, (incomplete = 6, complete = 5), amputation = 8 (trans-femoral single limb = 5, trans-femoral double limb = 3), spina bifida = 4, other individual-specific impairments = 8]. All players were deemed eligible for participation in ITF Open class tournament match-play (Section 3.3.2). At the time of competition, 24 players held an ITF world rank < 35. As these elite players were involved in regular international tournament match play and eligible for ITF Grand Slam and Super Series events, they were thereby defined as HIGH. The remainder (n = 7), who were either unranked or positioned ≥ 350 in the world, were only eligible for ITF Futures match play events and were thereby classified as LOW. Matches selected for analysis ensured that both HIGH and LOW players played opponents from the equivalent playing category.

Table 5.1 Characteristics of wheelchair tennis players

Values are mean (SD). HIGH (< 35), LOW (≥ 350)

Group		n	Age (years)	Time since injury (years)	Wheelchair user for daily ambulation (years)	Wheelchair tennis playing experience (years)
OVERALL			30 (12)	13 (10)	12 (10)	8 (5)
RANK	HIGH	24	27 (7)	11 (6)	11 (7)	9 (4)
	LOW	7	38 (19)	18 (18)	16 (18)	4 (5)
SEX	MALE	23	31 (13)	12 (11)	11 (11)	7 (4)
	FEMALE	8	26 (6)	14 (7)	16 (5)	12 (5)
FORMAT	SINGLES	23	30 (13)	14 (11)	13 (11)	8 (5)
	DOUBLES	8	28 (7)	8 (5)	7 (6)	8 (2)

5.3.2 Experimental design

Data collection took place at three ITF tournaments, with play subject to ITF rules and regulations (ITF, 2009b). Specific detail regarding match-play format can be found previously (Section 3.3). Thirty-one tennis matches were monitored, with players participating in either singles (n = 23) or doubles (n = 8) matches. Players used their own sports wheelchair. Investigators did not manipulate chair configuration. Tyre type was self-selected, with tyres inflated to a level suitable for competitive match-play conditions.

Where feasible and practical, two DL units should be placed on each chair wheel (Chapter 4). However, this is not always possible in situations where professional athletes are monitored during competitive tournaments. Players are randomly allocated an opponent and court number immediately prior to first round match-play. Therefore, DL devices must be configured and allocated to willing participants without investigator awareness of when and where participants might play. Also, this process occurs without foresight of how many participants may be required to play simultaneously as the tournament progresses. A further consideration concerns sample size. Recruitment of those with physical impairments for PA-based studies is difficult (Foulon et al., 2013) and is made more challenging due to the relatively small populations involved (Croft et al., 2010). Also, participation in wheelchair tennis is typically low (Goosey-Tolfrey, 2010). Hence, where sufficient interest in study participation can be obtained, researchers should take steps to capitalise on this interest. Anecdotally, players have also expressed concerns about the placement of monitoring equipment on the racket side of the chair during competitive matches where ITF World-ranking points are at stake. In summary, DL availability, the opportunity to ensure a strong sample size, and the nature of competitive tournament match-play, are factors that dictated in this instance that one DL was attached to the wheel (non-racket side). Questionnaires were completed prior to participation (Section 3.1). All matches were filmed and timed (Section 3.3), played under competitive conditions, and won or lost in three sets.

5.3.3 Determination of speed zones using the DL

As stated previously, the DL relies on reed-switch activation and the generation of time stamps to measure distance travelled (Section 3.3). Four DL units were available for use in the present study. Devices record distance with minimal error during tennis-field (CV: 0.8 to 4.1 %) and linear-track (CV: 0.6 to 1.9 %) testing scenarios (Chapter 4). For more complex movements with repeated turns, measurement error increases slightly (CV: 3.7 to 7.9 %), but is consistent with other technologies for the quantification of court movement, including GPS (Chapter 4).

Treated DL output for instantaneous distance and speed were aligned to APT. The COUNT function (Microsoft® Excel) was used to determine the frequency of observations at a given speed. To determine percentage of total time within a specific zone, the frequency of occurrences were divided by the total number of observations within each block of APT. DL readings of 0 $m \cdot s^{-1}$ were taken to indicate the percentage of time spent stationary (no chair-movement). Further speed zones ranged from 0.01 to 4.49 $m \cdot s^{-1}$ (0.50 $m \cdot s^{-1}$ increments). Zones were defined to incorporate the potential range of speeds for chair movement during sports activity (Sporner et al., 2009; Campbell et al., 1997) and maximal 20 m sprint test performance while holding a racket (Goosey-Tolfrey & Moss, 2005). Time spent within each zone was expressed as a percentage of total time.

5.3.4 Data processing and statistical analyses

The SPSS 21.0 statistical package (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Descriptive statistics (mean ± SD) were reported for all participants. Normality was assessed using the Shapiro-Wilk test. Nonparametric data were reported as median ± interquartile range (IQR). IQR was calculated as the difference between the first (25 %) and third (75 %) quartiles. Separate Friedman tests were used to examine within-group differences for percentage of time spent stationary (0 $m \cdot s^{-1}$), below and above the reported threshold for DL accuracy (2.50 $m \cdot s^{-1}$) for all participants (overall), rank (HIGH *vs*. LOW), sex (males *vs*. females) and match-play format (singles *vs*. doubles). Subsequent post hoc analyses were completed using Wilcoxon signed-rank testing using a Bonferroni correction with adjusted alpha level ($P < 0.017$). Mann-Whitney tests for independent samples were used to examine differences in rank, sex and format at each individual speed zone (zones: 0 to 9; speeds: 0.01 to 4.49 $m \cdot s^{-1}$). Statistical significance was accepted at a level of $P < 0.05$. Appropriate determinations of effect size (ES) for non-parametric tests were calculated using Cohen's *r* (Fritz et al., 2012) with alignment to accepted descriptors for the determination of worthwhile effects (very large ≥ 0.7, large ≥ 0.5, medium ≥ 0.3, small ≥ 0.1) (Rosenthal, 1996; Cohen, 1988).

5.4 Results

Friedman's test (Table 5.2) revealed overall differences in percentage time spent in speed zones (χ^2 = 56.581, $P < 0.0005$). Post hoc analyses revealed that significantly more time was spent at speeds below 2.50 $m \cdot s^{-1}$ than above during match play (89.4 ± 5.0 *vs.* 1.2 ± 3.5 %, Z = −4.860, $P < 0.0005$).

ES was very large (r = 0.87). Time spent stationary was 9.0 ± 4.3 %. Consideration of rank, sex and format revealed a similar trend (Table 5.2) with all within-group comparisons revealing a large to very large ES ($0.50 \leq r \geq 0.89$). Median match duration was 55 ± 17 min.

Table 5.2 Percentage of time spent stationary (0 m·s^{-1}), below (< 2.50 m·s^{-1}) and above (≥ 2.50 m·s^{-1}) the reported threshold for DL accuracy during wheelchair tennis match-play

Outcomes presented for all participants (overall) and stratified for rank, sex and format. Values are median (IQR). Chi-square (χ^2) and alpha level (P) presented for each within-group comparison

	Group	Time spent in speed zones (%)			χ^2	P		
		0 m·s^{-1}	**< 2.50 m·s^{-1}**	**≥ 2.50 m·s^{-1}**				
OVERALL		9.0 (4.9)	89.4 (5.0)	1.2 (3.5)	56.581	< 0.0005	*	a,b,c
RANK	HIGH	8.2 (5.1)	90.2 (4.9)	2.1 (3.9)	42.750	< 0.0005	*	a,b,c
	LOW	12.6 (8.7)	87.2 (8.3)	0.0 (0.3)	14.000	0.001	*	a,b,c
SEX	MALE	9.1 (7.0)	89.2 (5.6)	1.5 (4.5)	40.783	< 0.0005	*	a,b,c
	FEMALE	8.6 (3.3)	90.4 (5.0)	0.8 (2.1)	16.000	< 0.0005	*	a,b,c
FORMAT	SINGLES	9.0 (3.8)	90.1 (4.4)	0.4 (2.4)	42.348	< 0.0005	*	a,b,c
	DOUBLES	8.5 (9.0)	86.6 (11.0)	4.4 (6.1)	14.250	0.001	*	a,b

* Significant difference for within-group comparison (P < 0.05)

[a.] Significant difference between 0 and < 2.50 m·s^{-1} (P < 0.017)

[b.] Significant difference between < 2.50 and ≥ 2.50 m·s^{-1} (P < 0.017)

[c.] Significant difference between 0 and ≥ 2.50 m·s^{-1} (P < 0.017)

Figure 5.1 shows the percentage of time in each individual speed zone for rank, sex and format comparisons. Players spent ≤ 3.7 % total time in individual zones at speeds ≥ 2.50 m·s^{-1}. Maximum time and minimum time ≥ 2.50 m·s^{-1} for any individual group were 3.7 ± 4.7 % (doubles players) and 0.0 ± 0.3 % (LOW), respectively. LOW spent more time stationary (12.6 ± 8.7 *vs.* 8.2 ± 5.1 %, U = 30.000, P = 0.011, r = 0.46) and at speeds < 1.0 m·s^{-1} when compared with HIGH (Figure 5.1). In contrast, HIGH spent more time in higher speed zones, both below (1.50 to 2.49 m·s^{-1}, r = 0.51 to 0.58) and above (2.50 to 3.49 m·s^{-1}, r = 0.53 to 0.64) the threshold for DL accuracy. Females spent more time at 1.00 to 1.49 m·s^{-1} than males (U = 48.000, P = 0.047, r = 0.36). While outcomes were not significant, small-to-medium sex-specific ES' indicated a tendency for more time in higher speed zones for males (3.00 to 3.99 m·s^{-1}, r = 0.22 to 0.34). Doubles tennis players spent less time in the slowest speed zone (U = 27.000, P = 0.003, r = 0.53), but were more active than singles players at

2.50 to 2.99 m·s^{-1}, (U = 31.000, P = 0.006, r = 0.50) and 3.00 to 3.49 m·s^{-1}, (U = 34.000, P = 0.006, r = 0.49).

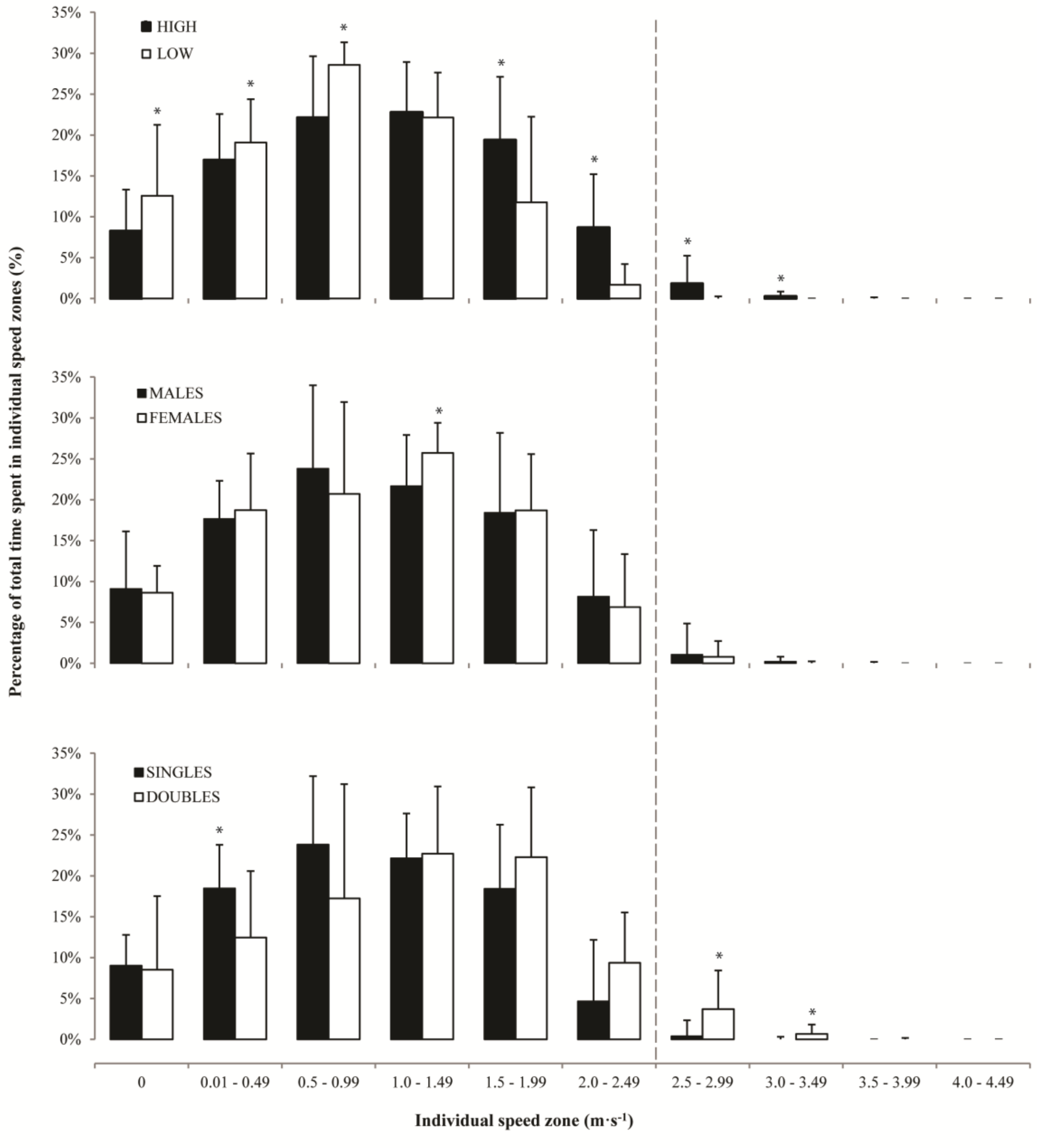

Figure 5.1 Percentage of time spent in individual speed zones for rank, sex and format during wheelchair tennis match-play

Dashed line indicates the reported threshold for DL accuracy (2.50 m·s^{-1}). *Denotes significant difference for comparisons between values at each individual speed zone

5.5 Discussion

5.5.1 Main findings

The purpose of this study was to examine speed profiles obtained during wheelchair tennis match-play to assess DL device applicability for the quantification of court-movement. Key findings from the present study were that significantly more time was spent at propulsion speeds below the threshold for accuracy, with players either remaining stationary or operating at relatively low speeds for most of the time. Further, this study shows significant proportions of total match-play time were spent below the threshold irrespective of rank, sex or format. Therefore, in practical terms, data logging is appropriate for collection of distance and speed for players spanning low to high, different sexes and for singles and doubles match-play.

5.5.2 Time above threshold for DL accuracy

While percentage of time at higher speeds was minimal, players did exceed 2.50 $m \cdot s^{-1}$. Values for distance are not consistent between logger units, or accurate at speeds above this threshold (Chapter 4). Therefore, the interpretation of average speed data obtained from this device should be cautioned. This study revealed that LOW spent more time stationary and in speed zones below 1.00 $m \cdot s$-^{1} compared to HIGH. LOW also spent no time above 2.50 $m \cdot s$-^{1}. Hence, monitoring court-movement using the logger is justified for all players irrespective of the rank. In contrast, HIGH spend significantly more time than LOW at higher speeds (range: 2.50 to 3.49 $m \cdot s^{-1}$) suggesting a higher margin for error in this group. Similarly, doubles matches were spent in higher speed zones than singles matches (4.4 ± 6.1 *vs.* 0.4 ± 2.4 %). Doubles tennis shares similar characteristics with singles play and is governed by the same rules (ITF, 2014). However, subtle differences exist in playing conditions between formats. Differences have not been studied in tennis, but format-specific characteristics are known to influence the movement response. For example, the same group of female soccer players covered longer distances at high intensities and sprinted further in international versus domestic matches (Andersson et al., 2010). However, independent of any between-group differences, maximum time above threshold for accuracy was low for any one group (doubles, 3.7 ± 4.7 %). Second, across all participants, percentage time in any one speed zone above the threshold was also minimal (≤ 1.2 ± 3.5 %). As median match duration was 55 ± 17 min, such a value is equivalent to ~40 s of active court time. This suggests inaccuracies in average speed are likely to be negligible.

As HIGH and doubles players spend more time in higher speed zones than respective counterparts, caution should also be noted for type and format-specific peak speed values. These data may be confounded by device inaccuracy at high propulsion rates. However, while peak values over 2.50 $m \cdot s^{-1}$ were attained, time spent at very high speed (≥ 3.5 $m \cdot s^{-1}$) was very low (~0.1 %). So while caution should be noted with interpretation of peak values, these data suggest inaccuracies are likely to be small.

5.5.3 Sex- and format-specific effects

These data do not confirm a sex-specific effect for speed. Other than females spending more time at 1.0 to 1.49 $m \cdot s^{-1}$, a similar response was noted at each individual speed zone. However, medium ES' were reported for males at three of the higher speed zones. While differences were not statistically significant, a small-to-medium ES was reported for males at two of the higher speed zones, suggesting a tendency for higher-speed activity in this group. Male spinal cord injured wheelchair racers achieve higher mean velocities than female counterparts (Bhambhani, 2002). However, there are fundamental differences between sports. Unlike racing, tennis involves rapid changes of direction. Repeated turns and chair movement for shot-play are considered important skills (Mason et al., 2010). That said, based on the established physiological differences between sexes, it is plausible to assume that males would perform at higher speeds more often. However, the time spent at high speeds was relatively low and other considerations, including the size of the female sample, opponent's court-movement patterns and variation in ability levels may have influenced the strength of this outcome in the present study. Also, investigators did not manipulate chair configurations or specify the tyre type. Therefore, there may have been inter-individual differences in rolling resistance (Mason et al., 2015; Kwarciak et al., 2009). However, ITF wheelchair tennis regulations do not stipulate a specific configuration for performance, and players are autonomous in personalising their set-up. Hence, studies concerned with match-play will invariably involve different configurations.

Doubles matches are played over a larger surface area than singles tennis (ITF, 2014; ITF, 2013). However, two players work together to navigate the court. Hence, it is unclear if this format offers potential for increased court-movement. Combining movement with skill execution is a challenge for the less-able performer. For example, amateur soccer players are less capable of reproducing high-intensity movements whilst executing technical skills during competitive play (Dellal et al., 2011). This study reveals that players spend significantly more time in two speed zones above the threshold during doubles match-play (2.50 to 2.99 and 3.00 to 3.49 $m \cdot s^{-1}$). Faster movements are likely to increase match-play intensity, thereby increasing EE and physiological cost. These increases are likely to confer desirable cardiovascular training effects for a novice. Further, in group scenarios where performance information is available from another individual, there is increased motivation to exert higher effort levels (Weber & Hertel, 2007). This is of relevance for spinal cord-injured individuals who cite lack of motivation as a main barrier to exercise participation (Cowan et al., 2012; Scelza et al., 2005). As doubles match-play appears to offer a more intense activity environment, it may be an appropriate format of tennis for the beginner, novice or recreational player, where enhancement of cardiovascular health and long-term compliance to activity are primary goals. However, as physiological data were not collected in the present study, and the sample comprised highly-skilled doubles players, further research is required to consider the differences between singles and doubles match-play and whether physiological responses are elevated in low-skill players as a result of increased court-movement.

Where conclusions are made about performance using DL data over 2.50 $m \cdot s^{-1}$, caution should be noted. In overall terms, the low percentage of time spent over 2.50 $m \cdot s^{-1}$ could be explained by the relative inaccuracy of the DL at speeds over this threshold. However, it is important to note that the device under- as opposed to over-estimates distance and speed (Chapter 4). So time spent in individual speed zones could theoretically have been higher than values presented here. However, as inter-device underestimations appear to be uniform, inferences made are not likely to have been confounded.

The present study indicates that a proportion of time is spent in zones across a speed continuum ranging from 0.01 to 4.49 $m \cdot s^{-1}$. Such activity is characteristic of tennis, which requires intermittent activity interspersed with active recovery (Roy et al., 2006). Therefore, while this study concurs in general terms that tennis requires exercise training across a spectrum of exercise intensities (Croft et al., 2010), consideration of player level is required to inform training priorities. In comparison to HIGH, our study reveals LOW spend significantly more time stationary during a match. Decreases in the static component are likely to result in proportionate increases in EE, and may confer important health gains. Hence, consideration of strategies to increase on-court activity is of significant interest. However, as physiological variables have not been assessed alongside court-movement variables during wheelchair tennis, match-play demands are not understood fully. Optimal and appropriately specialised training strategies are therefore still unclear. Further analysis of the interplay between court-movement and the resultant physiological cost in playing groups of varying ability levels will provide much needed clarity in this area.

5.6 Conclusions

The results of this study reveal that significant proportions of total match-play time are spent at speeds below the previously reported threshold for DL accuracy. This outcome is regardless of player rank, sex or match-play format. In practical terms, using a DL for collection of distance and speed data is not likely to be disadvantageous, and the device is appropriate for quantification of wheelchair tennis court-movement.

6

Study 3: Wheelchair tennis match-play demands: effect of player rank and result

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6.1 Abstract

Purpose*:* To examine the HR response and court-movement variables during wheelchair tennis match-play for HIGH and LOW performance-ranked players. Analysis of physiological and movement-based responses during match-play offers an insight into the demands of tennis, allowing practical recommendations to be made.

Methods: Fourteen male, Open-class players were monitored during tournament match-play. A DL was used to record distance and speed. HR was recorded during match-play.

Results: Significant rank-by-result interactions revealed that HIGH winners covered more forwards distance than HIGH losers ($P < 0.05$) and had higher mean average ($P < 0.05$) and mean minimum ($P < 0.01$) HRs than LOW winners. LOW losers had higher mean average ($P < 0.01$) and mean minimum ($P < 0.001$) HRs than LOW winners. Independent of result, a significant main effect for rank was identified for peak ($P < 0.001$) and average ($P < 0.001$) speed, and total ($P < 0.001$), reverse ($P < 0.001$) and forwards-to-reverse ($P < 0.001$) distance, with higher values for HIGH. Independent of rank, losing players experienced higher mean minimum HRs ($P < 0.05$). Main effects for mean peak HR and APT were not significant. Median match duration was 50.5 ± 11.7 min.

Conclusions: These data suggest that independent of rank, tennis players were active for sufficient time to confer health-enhancing effects. While the relative playing intensity is similar, HIGH push faster and further than LOW. HIGH are therefore more capable of responding to ball movement and the challenges of competitive match-play. Adjustments to the sport may be required to encourage skill developmental in LOW, who move at significantly lower speeds and cover less distance.

6.2 Introduction

The growing interest in wheelchair sports participation has prompted sport and exercise scientists to consider the determinants of optimal performance across a range of wheelchair sports. Studies have generally focused on mainstream sports including basketball (Sporner et al., 2009; Goosey-Tolfrey, 2005), rugby (Barfield et al., 2010; Sarro et al., 2010), and racing (Cooper et al., 2003; Bhambhani, 2002). Comparisons between the physiological responses in different sports have also been made (Croft et al., 2010; Sporner et al., 2009). Wheelchair tennis is less well understood but requires considerable technical skill (Reid et al., 2007a) and moderate to high aerobic fitness (Roy et al., 2006). This thesis reports that DL devices are appropriate for logging wheelchair tennis court-movement for a range of player groups (Chapters 4 & 5). However, such devices have not yet been used to describe the effects of skill and experience on match-play court-movement.

Defining a skilled sample is problematic. Ten years of intense involvement and deliberate practice is required to enable reproducible expert performance in sporting tasks (Ericsson, 2008). However, the rate and speed of skill development vary between individuals (Boyle & Ackerman, 2004). In wheelchair tennis, Roy et al. (2006) defined a skilled sample as an average playing experience greater than 10 years, but with considerable variation around the mean (15 ± 9 years). In AB individuals, regular tennis improves aerobic fitness, the lipid profile, bone health, and reduces cardiovascular morbidity and mortality (Pluim et al., 2007). Wheelchair users are likely to experience similar benefits from participation, as match-play EE is consistent with other wheelchair sports and guidelines for the reduction of cardiovascular disease risk in healthy adults (Abel et al., 2008). While the element of competition is considered to be a factor encouraging participation in the sport post-SCI (Wu & Williams, 2001), highly competitive match-play conditions may not be required. Comparing the HR response between AB and wheelchair tennis players, Barfield et al. (2009) concluded that both practice and match-play elicit a sufficiently high HR to be considered beneficial PA.

For the developmental player, wheelchair tennis represents an opportunity to achieve a recommended dose of exercise for health enhancement, post-SCI. This is critical, as PA levels are typically lower in SCI patients one year post-discharge compared with matched AB controls (van den Berg-Emons, 2008). However, as tennis is an inclusive sport, not all participants present with an SCI. Sporner et al. (2009) reported that SCI accounted for only 43 % of participants in the National Veteran’s Wheelchair Games. Tennis profiling should therefore incorporate playing groups with a variety of disability profiles. At the elite level, the physiological responses are less well understood, but improvements in pushing economy and the BLa^- response to exercise have been observed after a course of wheelchair tennis training (Diaper & Goosey-Tolfrey, 2009).

Irrespective of player level, to improve performance within a given sport, there must be an understanding of the game dynamics and player requirements (Sarro et al., 2010), and the physiological capacity of the player must be considered (Goosey-Tolfrey, 2010). However, differences are apparent in these factors between developmental and elite athletes within the same sport. Tennis has been compared with other wheelchair sports (Bernardi et al., 2010; Croft et al., 2010; Abel et al., 2008; Wu & Williams, 2001) including the tennis-serve motor responses of experienced and novice players (Reina et al., 2007), but the physiological responses of match-play tennis and its relationship to playing rank have not been studied. Where physiological responses during match-play have been observed (Roy et al., 2006), match and set outcomes have not been considered. Consequently, it is not yet known whether opponents within the same match are exposed to similar physiological and movement-based demands. Inclusion of player rank should enhance understanding of the range of responses observed during tennis match-play. The ITF encourages participation at all levels and aims to 'expand the base of players of all ages and abilities around the world' (ITF, 2010b). Consequently, an understanding of playing demands for both HIGH and LOW is required. Collection of match-play data enables the development of appropriate training strategies, providing useful information with respect to distance covered, speed and exercise intensity. Hence, training intensities can be matched to the demands of match-play. Therefore, the purpose of this study was to assess the HR response and court-movement variables during wheelchair tennis match-play based on performance. It was hypothesised that HIGH (*rank*) and winners (*result*) would cover greater distances at higher speeds and experience higher HR's than LOW (*rank*) and losers (*result*) during tennis match-play.

6.3 Methods

6.3.1 Participants

Fourteen male wheelchair tennis players from the Open class participated in this study. The sample comprised of an equal number of HIGH and LOW players participating in singles matches (n = 7). Previously defined criteria were applied to establish respective HIGH and LOW player groups (Section 5.1). At the time of competition, players with a current world ITF rank ≤ 25 were defined as HIGH and those ≥ 350 as LOW. To ensure anonymity, characteristics (Table 6.1) identify the ITF ranking group as opposed to each participant's individual rank.

Table 6.1 Descriptive characteristics for wheelchair tennis players

* Denotes an incomplete spinal lesion

Participant	Age (years)	Nature of disability	Injury level	Time since injury (years)	Wheelchair user for daily ambulation (years)	Wheelchair tennis experience (years)	ITF rank
1	55	Common peroneal nerve lesion	n/a	3.0	1.0	1.0	≥ 350 (LOW)
2	59	SCI	T12*	41.0	41.0	14.0	≥ 350 (LOW)
3	27	SCI	T5	5.0	5.0	3.0	≥ 350 (LOW)
4	37	Amputee (right leg trans-femoral)	n/a	30.0	17.0	1.5	≥ 350 (LOW)
5	21	SCI	T5	2.0	2.0	1.0	≥ 350 (LOW)
6	58	SCI	T10	40.0	40.0	1.0	≥ 350 (LOW)
7	12	Perthes' disease	n/a	6.0	6.0	3.5	≥ 350 (LOW)
8	24	SCI	T10*	11.0	11.0	10.0	≤ 25 (HIGH)
9	21	Brittle bones	n/a	n/a	17.0	10.0	≤ 25 (HIGH)
10	18	Transverse myelitis	L2	n/a	6.0	6.0	≤ 25 (HIGH)
11	32	SCI	L2	9.0	9.0	9.0	≤ 25 (HIGH)
12	22	Arthrogryposis	n/a	n/a	22.0	15.0	≤ 25 (HIGH)
13	38	Amputee (left leg trans-femoral)	n/a	4.0	1.0	4.0	≤ 25 (HIGH)
14	24	SCI	T9*	6.0	6.0	4.0	≤ 25 (HIGH)
Mean	32.0			14.8	13.1	6.3	
SD	15.4			15.8	13.2	5.0	

6.3.2 Experimental procedures

Fourteen tennis matches were monitored at the 2009 British Open Wheelchair Tennis Championships and the 2010 North West Challenge Futures Tournament. Participation was dictated by ITF classification and current ITF rank (Section 3.3). All players were recruited in collaboration with the ITF and The British Tennis Federation. Approval and written consent was obtained prior to any data collection (Section 3.1). Tournament format and match-play were held in accordance with ITF rules and regulations (ITF, 2009b) and were filmed (Section 3.3) with start and finish times for each game recorded to calculate APT (Section 3.3.3). Matches selected for analysis ensured that both HIGH and LOW players played opponents from the equivalent playing category. The number of match winners and losers were matched across groups. All matches were won or lost in two sets.

Court-movement data were obtained using a DL unit using procedures described previously for data collection and analysis (Section 3.2). The preference for placement of one DL unit on each wheel (Chapter 4) and relative merits and constraints of monitoring (Section 5.3.2) have also been identified. As this study involved data collection during competitive tournaments, a DL unit was attached to one wheel on the non-racket side. To account for differences in playing time, distance (m) data were presented as mean per minute (m) for between-group comparisons.

6.3.3 Determination of match-play intensity

For assessment of exercise intensity, HR was recorded in 5-s intervals via short range radio telemetry using a Polar HR monitor (POLAR PE4000, Kempele, Finland). APT data were used to extract only the within-game HR values (excluding breaks between games and sets). Peak, minimum and average HR for each participant were identified. For initial comparisons between sets, absolute HR values were used and therefore, median peak, median minimum and median average HR values were presented. For between-group comparisons, HR data were presented in relative terms. This allowed for determination of mean average, mean peak, and mean minimum HR expressed as a percentage of HR_A ($\%HR_{avg}$, $\%HR_{max}$, and $\%HR_{min}$, respectively). The standard formula for estimation of peak HR (220 – age) has been adopted in a study involving wheelchair tennis players (Roy et al., 2006) and was used to calculate HR_A.

6.3.4 Data processing and statistical analyses

Data analysis was conducted using SPSS version 16.0 (SPSS, Inc., Chicago, IL). Descriptive statistics median (IQR) were obtained for all participants and presented for individual sets (1 and 2) and for match (overall). Wilcoxon signed-rank tests were conducted to examine between-set differences in dependent variables. As stated previously, distance and HR data were presented as mean per minute (m) and as a percentage of HR_A (%) for between-group comparisons, to account for respective differences in playing time and individual physiological capacity. For adjusted distance and HR data, normality and homogeneity of variance were confirmed by Shapiro-Wilk and Levene's tests respectively. Therefore $\%HR_{avg}$, $\%HR_{max}$ and $\%HR_{min}$ were used (in preference to median). Separate 2 x 2 (*rank*-by-*result*) between-measures ANOVAs were used to examine court-movement (overall distance, distance in a forwards direction, distance in a reverse direction, distance moving in a forwards-to-reverse pattern, peak and average speed) and physiological (percentage of median peak, minimum and average HR) variables. Simple main-effect analyses were used to follow up significant rank-by-result interactions. Values for each individual set of tennis match-play were used to form the basis of the statistical analysis. All sets were used. Statistical significance was accepted at a level of $P < 0.05$. ES was calculated using Cohen's r and d for respective nonparametric and parametric data comparisons (Fritz et al., 2012; Cohen, 1988) with adherence to established markers for worthwhile effects (d: very large ≥ 1.3, large ≥ 0.8, medium ≥ 0.5, small ≥ 0.3; r: very large ≥ 0.7, large ≥ 0.5, medium ≥ 0.3, small ≥ 0.1) (Rosenthal, 1996; Thomas et al., 1991; Cohen, 1988).

6.4 Results

Forwards propulsion was the dominant movement strategy (84 % of total distance). Less distance was covered using forwards-to-reverse (13 %) and reverse (3 %) propulsion strategies. There were no significant differences between sets 1 and 2 for any variables (Table 6.2).

Table 6.2 Individual-set and overall-match distance, speed, HR and time for all participants (n = 14) during wheelchair tennis match-play

Values are median (IQR). Alpha (*P*) value and ES (*r*) for comparison between sets 1 & 2

	Set 1	**Set 2**	**Match**	***P***	***r***
Total distance (m)	1540 (589)	1492 (753)	2967 (895)	0.551	0.11
Forwards distance (m)	1350 (458)	1286 (684)	2512 (768)	0.510	0.12
Reverse distance (m)	34 (33)	34 (33)	70 (50)	0.777	0.05
Forwards to reverse distance (m)	156 (72)	153 (153)	306 (160)	0.683	0.08
Peak speed ($m \cdot s^{-1}$)	2.69 (0.72)	2.53 (1.00)	2.69 (0.96)	0.240	0.22
Average speed ($m \cdot s^{-1}$)	0.95 (0.30)	0.93 (0.33)	0.95 (0.32)	0.683	0.08
Peak HR ($b \cdot min^{-1}$)	165 (29)	164 (45)	166 (28)	0.916	0.02
Minimum HR ($b \cdot min^{-1}$)	109 (16)	107 (29)	106 (19)	0.379	0.17
Average HR ($b \cdot min^{-1}$)	135 (26)	130 (30)	130 (26)	0.221	0.23
APT (min)	23.0 (5.9)	27.4 (8.0)	50.5 (11.7)	0.397	0.16

Figure 6.1 profiles the HR and speed response to individual games within a single set for one participant. Median speed was consistent across sets (set 1 *vs.* 2, 0.95 ± 0.30 *vs.* 0.93 ± 0.33 $m \cdot s^{-1}$, P = 0.683, r = 0.08). A similar median HR response was observed within both sets, but with large variation in median peak (126 to 199 $b \cdot min^{-1}$), minimum (45 to 143 $b \cdot min^{-1}$) and average HR (109 to 160 $b \cdot min^{-1}$) responses.

The rank-by-result interactions were significant for forwards distance (Figure 6.2), average HR and minimum HR (Figure 6.3). Simple main-effects analyses indicated that HIGH had greater forwards distances than LOW in both winning (66 ± 11 *vs.* 44 ± 5 m, P = 0.0001) and losing (55 ± 8 *vs.* 46 ± 6 m, P = 0.035) sets. HIGH winners covered more forwards distance than HIGH losers (P = 0.018) and had higher mean average (P = 0.016) and mean minimum (P = 0.005) HRs than LOW winners. In contrast, LOW losers had higher mean average (P = 0.002) and mean minimum (P = 0.0002) HRs than LOW winners. Higher mean minimum HRs were also observed in LOW losers (*vs*. HIGH losers; P = 0.027).

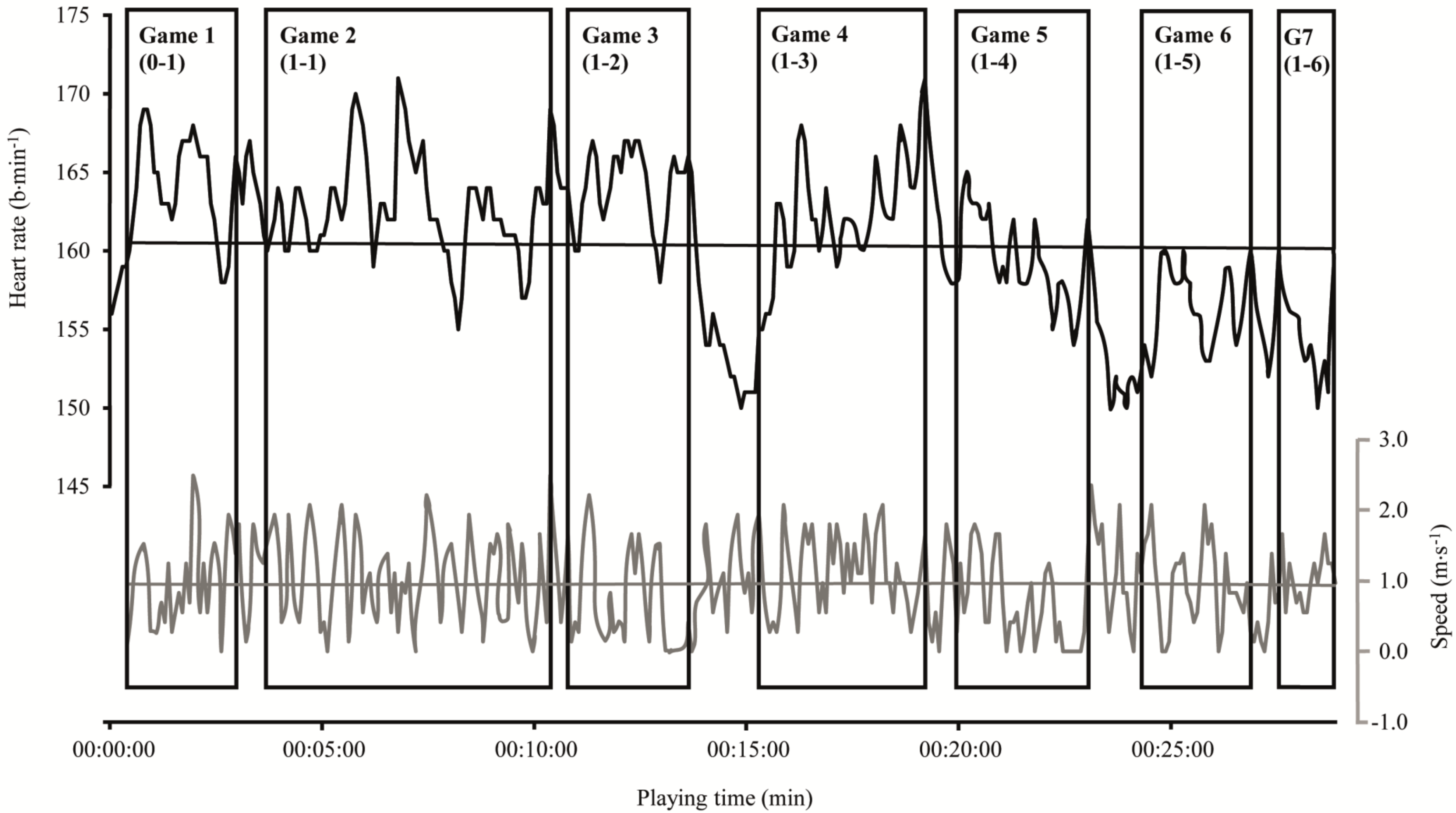


Figure 6.1 Example of one player's HR response and movement speed based on individual games in one single set

Horizontal lines indicate average values. Individual games are indicated by blocked sections (match score denoted in parentheses).

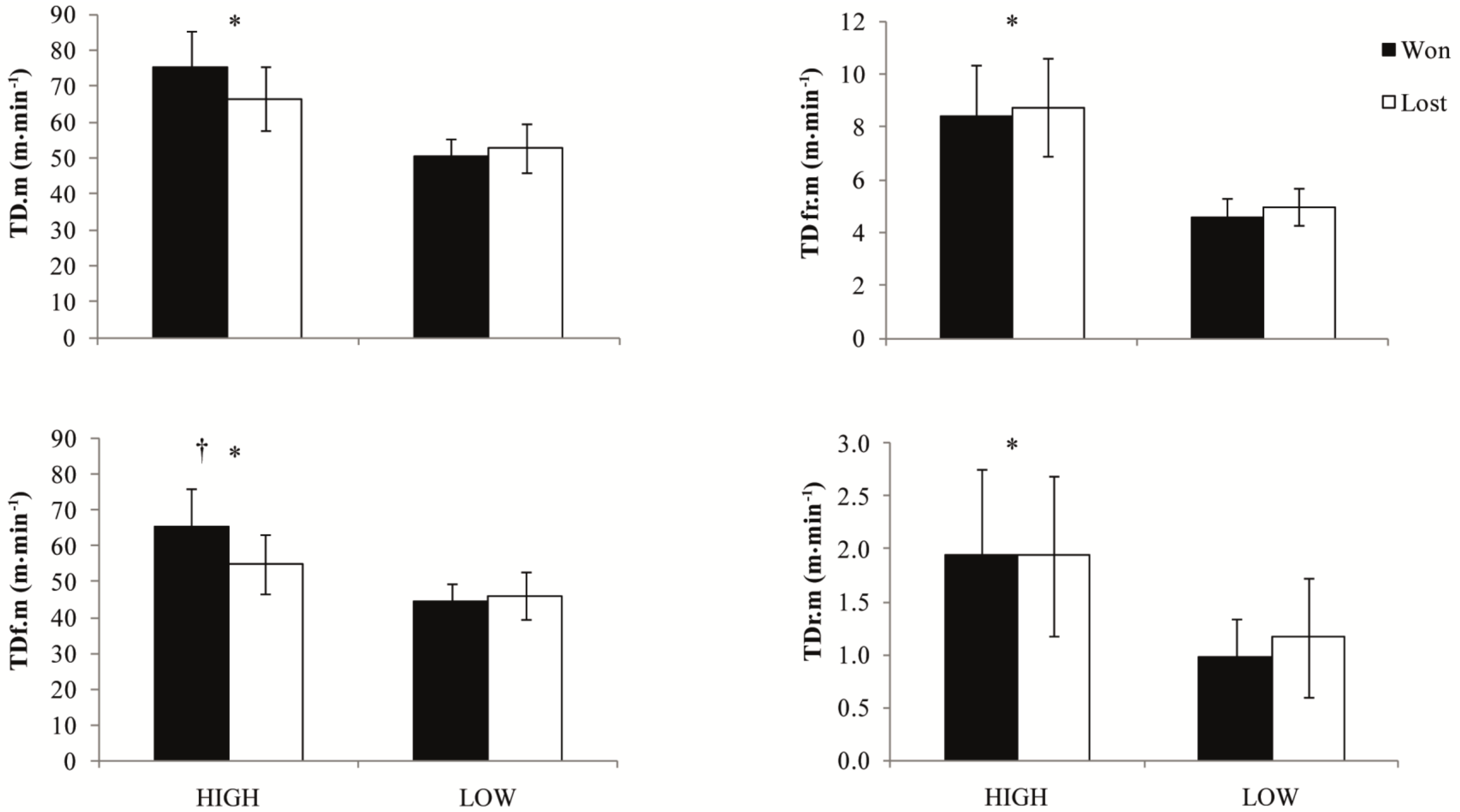


Figure 6.2 Rank-by-result interaction of tennis match-play distance

Mean values per minute. Error bars denote SD. Overall distance (TD.m); forwards (TDf.m), reverse (TDr.m), and forwards-to-reverse counter-movement (TDfr.m) per minute. *Significant main effect for rank ($P < 0.05$). †Significant rank-by-result interaction

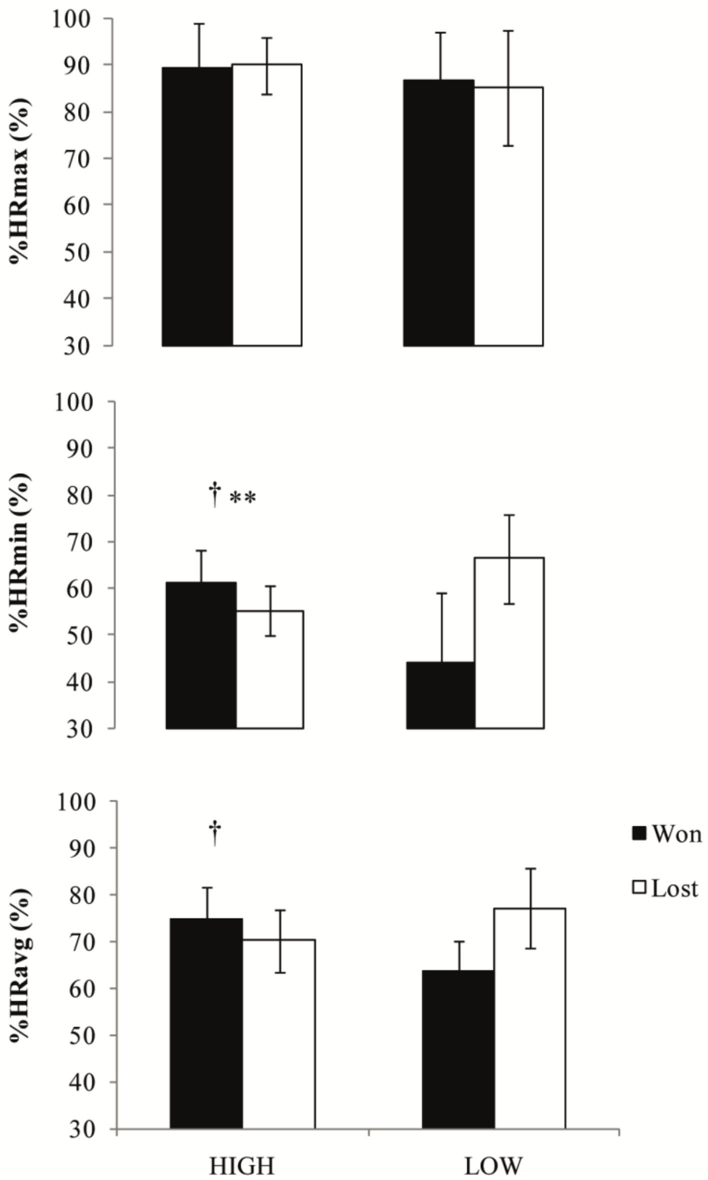


Figure 6.3 Rank-by-result interactions of tennis match-play HR indices

Relative exercise intensity: mean peak (%HR_{max}), mean minimum (%HR_{min}), and mean average ((%HR_{avg}) HR expressed as a percentage of HR_A. Error bars denote SD. **Significant main effect for result (P < 0.05). †Significant rank-by-result interaction

Independent of set outcome, HIGH had higher peak (3.18 ± 0.41 *vs.* 2.40 ± 0.18 $m \cdot s^{-1}$, $P < 0.001$) and average (1.14 ± 0.16 *vs.* 0.84 ± 0.10 $m \cdot s^{-1}$, $P < 0.001$) speeds (Figure 6.4), and greater distances for overall ($P < 0.001$), reverse ($P < 0.001$) and forwards-to-reverse ($P < 0.001$) movements than LOW (Figure 6.2). Independent of rank, mean minimum HR was significantly lower during winning sets than during losing sets ($P = 0.036$). Further rank and result main effects for HR and APT were not significant, with a small ES for mean peak HR (*rank* and *result*, $d \leq 0.31$). The mean average HR response for rank was similar (HIGH *vs.* LOW, 72 ± 7 *vs.* 71 ± 10 %, $P = 0.471$). Range for APT and HR were 40.1 to 74.8 min and 109 to 157 $b \cdot min^{-1}$, respectively.

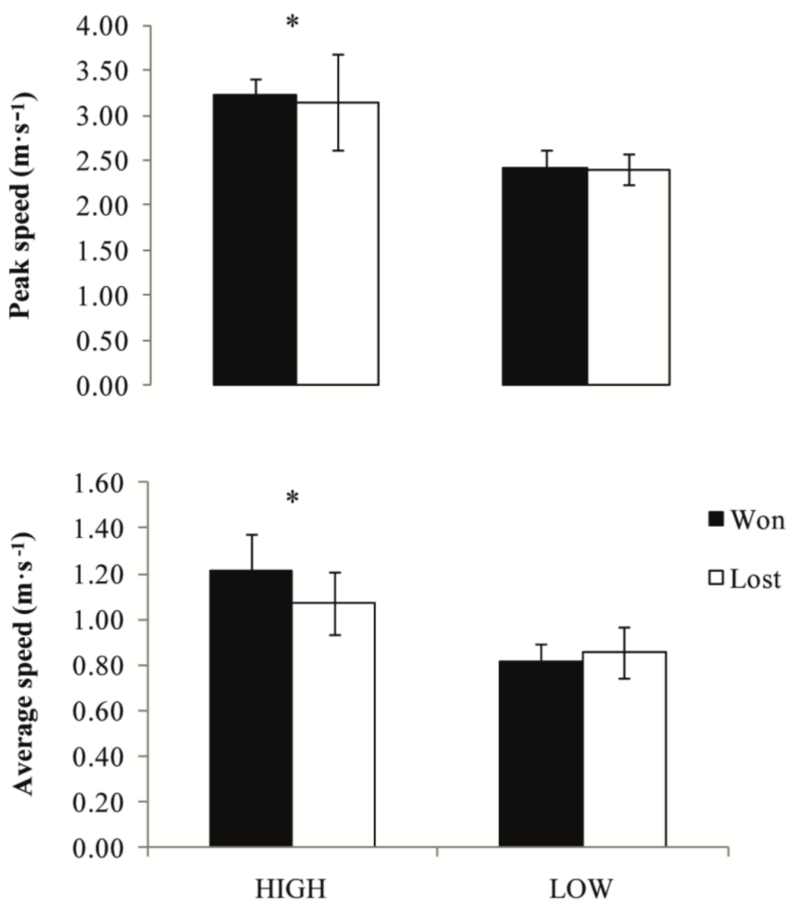


Figure 6.4 Rank-by-result interaction of tennis match-play speed

Mean values for peak and average speed. Error bars denote SD. *Significant main effect for rank ($P < 0.05$)

6.5 Discussion

6.5.1 Main findings

Per unit of time, HIGH players covered significantly greater overall, forwards, reverse and forwards-to-reverse distances than LOW players. While this is the first study to offer a comparison between the physiological responses of wheelchair tennis players based on rank, previous work has reported an association between high functional classification levels and greater distances and speeds in wheelchair rugby players (Sarro et al., 2010), and more activity in higher speed zones in HIGH (Chapter 5).

6.5.2 Court-movement and optimal outcomes

Wheelchair basketball players covered an average distance of 2680 m in 30-min of competitive game play (Sporner et al., 2009). While similar values of 2365 ± 956 m in 30.0 ± 11.8 min of play have been reported for wheelchair rugby (Sporner et al., 2009), total distance can vary from 3501 to 5657 m during a 66.8-min rugby game (Sarro et al., 2010). In this study, players covered similar total distances (2967 ± 895 m) but were active for longer (50.5 ± 11.7 min) than time reported previously for basketball players (Sporner et al., 2009). This finding is consistent with previous work that suggests tennis matches are typically longer than basketball games (Croft et al., 2010). Comparisons between rugby and tennis are problematic as playing time incorporates working and stopped-game-clock periods in rugby (Sarro et al., 2009), whereas this study offers an indication of the sum total of the active components. Prolonged activities are normally associated with positive health outcomes; for wheelchair users, moderate exercise lasting between 48 and 84 min results in an EE of 300 to 350 kcal and a reduction in the risk of heart attack (Abel et al., 2008). The values reported in the present study compare favourably, with an absolute range of 40.1 to 74.8 min for APT. While these findings show that wheelchair tennis provides a health-enhancing activity duration, the impact of an extended playing time on overuse injuries, particularly of the shoulder, should not be ignored.

Typical movements associated with wheelchair tennis are similar to those of wheelchair basketball and rugby, whereby players are required to sprint, brake and turn (Goosey-Tolfrey, 2010). The ability to turn was rated by players as the most important skill (Mason et al., 2010). This study revealed that forwards propulsion predominates during tennis match-play, and that significantly greater forwards distances are associated with HIGH winners (*vs.* HIGH losers). These data indicate that in highly skilled players, the ability to cover greater distance in a forwards direction is advantageous in match-play, with greater consistency in reaching the ball to enable a return shot being the most likely association. Similar outcomes and associations have been reported for AB tennis, with winners covering greater distances than losers (Martinez-Gallego et al., 2013). Forwards propulsion is associated with higher mean force output and lower push times and angles than reverse movement (Mason et al., 2015b). Consequently, all players should spend a high degree of training time on refining forwards-propulsion technique. As holding a tennis racket while pushing a chair is associated with reduced distance and speed (Goosey-Tolfrey, 2010), it is important that players develop their propulsion skills while using a racket. Similar movement strategies were adopted during both sets of match-play, with players spending a proportion of APT moving backwards (13 %) and using forwards-to-backwards counter-movements (~3 %). The requirement for investigation into sport-specific dynamics of backward propulsion has been raised previously (Goosey-Tolfrey, 2010). Higher $\dot{V}O_2$ and HR responses are associated with reverse propulsion at speeds ~2.2 $m \cdot s^{-1}$, but not at comparatively lower speeds ~1.1 and 1.7 $m \cdot s^{-1}$ (Mason et al., 2015b). This type of movement is physiologically more demanding than forwards propulsion and does not offer potential for improving wheelchair propulsion economy (Salvi et al., 1998). While reverse propulsion confers a greater physiological cost at elevated propulsion speeds, it is not yet known if this type of movement is advantageous in ensuring appropriate court-positioning for shot-play during tennis. Filipčič et al. (2008) completed a match analysis profile using male AB tennis players and found a series of measurable indicators were associated with winning and losing matches. A similar notational analysis profile for wheelchair tennis at different playing levels may be useful to explore the link between movement strategies and successful match-play outcomes.

6.5.3 Chair-propulsion speed

The present study suggests that through all movement directions HIGH cover a greater distance, and achieve and maintain higher speeds than LOW. HIGH achieved average speeds of 1.14 ± 0.16 $m \cdot s^{-1}$. These speeds are slower than those observed in a combined sample of basketball and rugby players (Sporner et al., 2009) yet similar to those of wheelchair rugby players (Sarro et al., 2010). However, it should be noted that court dimensions vary between sports. The average speed for LOW was significantly slower (0.84 ± 0.10 $m \cdot s^{-1}$) and was closer to speeds recorded by veterans using everyday manual wheelchairs (Tolerico et al., 2007). The ability of a tennis player to manoeuvre the chair into an optimal position for shot play is critical (Mason et al., 2010), as an attempt is made to react and respond to the movement of the ball. The significantly higher average and peak speeds for HIGH in this study suggest that better players are more able to make such adjustments. Therefore, developing chair-propulsion speed is an important consideration for LOW. Mastery is the main discriminating motive for continued participation in racket-based sports (Molanorouzi et al., 2015). Therefore, attempts to improve player-skill characteristics and thereby influence performance are highly important as improving player ability is likely to have a direct impact on adherence to PA levels. In turn, this will facilitate important health-related outcomes. However, as the playing style of the opponent (Kovacs, 2007) and match-play characteristics (Croft et al., 2010; Kovacs, 2007) are also important determinants of successful outcomes in tennis, caution should be used in the interpretation of these findings. Future studies may consider speed allied to court position for both player and opponent, which may provide a more sensitive measure of performance in this context.

6.5.4 Match-play intensity and implications for player groups

Despite the varying intensity and intermittent nature of wheelchair tennis, HR typically remains elevated throughout the full duration of a match (Kovacs, 2007). Mean average HR is, therefore, a valid indicator of the accumulated physiological stress associated with short, intense bouts of play. A match-play median of 130 ± 26 b·min^{-1} (range: 109 to 157) was observed in the present study. While these values were higher than those reported previously involving skilled (Roy et al., 2006) and experienced (Barfield et al., 2009) male wheelchair tennis players (122 ± 10 and 121 ± 14 b·min^{-1} respectively), higher average values of 146 ± 16 b·min^{-1} have also been reported in an elite, mixed sample (Croft et al., 2010). In relative terms, values of 69 to 75% peak HR have been reported previously for wheelchair tennis match-play (Croft et al., 2010; Barfield et al., 2009; Roy et al., 2006). In this study, the playing intensity was similar in relative terms when direct comparisons were made between HIGH and LOW (72 ± 7 *vs.* 71 ± 10 %, P = 0.471). As intensities of 60 to 75 % and > 75 % of peak HR are typically associated with moderate and vigorous exercise respectively (Pluim et al., 2007), this study reveals that regardless of ITF rank, tennis players are required to exercise at intensities approaching a vigorous level during match-play. However, relative intensities are best reported after direct measurement of peak responses (Bernardi et al., 2010; Croft et al., 2010; Barfield et al., 2009; Roy et al., 2006) so it should be reiterated that an estimation (220 – age) was applied in the present study. While such an intensity is linked with health-enhancing effects (Bhambhani et al., 1994) and compares favourably to other wheelchair sports (Barfield et al., 2010; Croft et al., 2010; Barfield et al., 2009; Roy et al., 2006), the intense nature of the activity environment raises a series of important considerations regarding participation and player development within the sport. First, as intermittent wheelchair sports depend on a significant contribution from the anaerobic energy pathway (Bhambhani et al., 1994) and tennis is highly dependent on aerobic capacity (Bernardi et al., 2010), elite players typically demonstrate physiological profiles that are representative of a well-trained population (Goosey-Tolfrey et al., 2006). It seems reasonable to assume, therefore, that elite players would be familiar with a moderate to vigorous intensity during match-play. In contrast, novice players who are typically less experienced and less well conditioned may find the intensity requirements more challenging, particularly given the significant skill challenge associated with the sport (Roy et al., 2006) coupled with their slower motor responses (Reina et al., 2007). Second, unlike other wheelchair sports where the physiological demand decreases as the match progresses (Sarro et al., 2010) this study suggests that the demand in tennis is sustained or increased for match duration. This is evidenced by comparable responses across sets 1 and 2 for all variables, and a small ES for APT, which suggests a slight increase in playing time with match progression. Third, there was no rank main effect on APT. This suggests that HIGH and LOW needed to be active for equivalent amounts of time. Finally, a significant main effect for result revealed that mean minimum HR was lower during winning sets. Such a low HR may reflect an ability to maintain a strong court position during match-play. It is accepted that for chronic health benefits, a chronic elevation in HR is required, with a strong, graded, inverse association between exercise intensity and relative risk of cardiovascular disease (Manson et al., 2002). It is interesting that the results of this study infer that with increases in skill, players could theoretically be placed at a physiological advantage in terms of match-play outcome, but a disadvantage in terms of exposure to optimal conditions for chronic health enhancement. Further research is required to examine if shot-play and decision-making is associated with decreased court-movement and concomitant physiological responses. Studies involving interventions to encourage increased movement or enhanced shot-play via coaching will, therefore, be important from a health perspective. The benefits of increasing EE through increased PA are widely accepted, with a negative association between levels of weekly PA and all-cause mortality (Paffenbarger et al., 1986). As tennis is an intense sport, and an extended playing time is associated with a greater physiological demand (Croft et al., 2010), consideration should be given to potential strategies to extend playing time, but also to optimise court-positioning during training. Hitting a standard tennis ball without due consideration of the match context in which skills are expressed is likely to be an ineffective training strategy (Reid et al., 2007a).

This study suggests that for accurate match-play profiling, consideration of player rank and playing level is required. Studies restricted to a sample of elite athletes are likely to overestimate the demands for less skilled counterparts, leading to inaccurate training prescription. Generalisations between groups cannot be made in tennis, where the demands are not equal. While there appears to be an equivalency in intensity for rank, there are significant differences relating to result. Higher mean minimum and mean average HRs were associated with LOW losers when compared to LOW winners. In low-skill players, an elevated playing intensity is likely to be caused by a combination of an opponent’s actions, and poor court-positioning strategies. However, as a lower submaximal HR response is associated with a higher level of aerobic fitness, these data may also indicate that level of aerobic conditioning is a factor in determining match-play outcomes in LOW. In direct contrast, HIGH winners achieve significantly higher minimum and average HRs than LOW winners. So in HIGH, a more intense match-play environment appears to be associated with optimal performance. Such differences suggest that training volume should be adjusted based on player level.

Hammond and Smith (2006) used an LCB in AB tennis players to develop technique and found larger mean differences in skill-test performance when using these modified balls. Also, increased rally speed, a lower ball strike and a higher proportion of net-shots are associated with an LCB (Kachel et al., 2015). More frequent net-approaches are linked with successful outcomes in AB players (Filipčič et al., 2008) and are therefore desirable. The present study revealed a moderately lower APT for LOW losers (*vs.* LOW winners) and this indicates that more successful outcomes are associated with an extended playing time. As an LCB is associated with longer rallies (Hammond & Smith, 2006; Cooke & Davey, 2005), an extended playing time, and therefore, elevated physiological cost and increased

EE may result from using modified balls. However, this notion is currently speculative. The role of an LCB in facilitating more appropriate and physiologically stimulating wheelchair tennis training and match-play environments should form a consideration in future research, particularly with respect to novice player groups.

6.5.5 Methodological considerations

As identified in previous work, recruitment for studies involving wheelchair sports is problematic due to the relatively small populations involved (Croft et al., 2010). In addition, participation in wheelchair tennis is relatively low (Bernardi et al., 2010). Such a limited availability means that in most instances, participants with a range of disabilities are typically recruited. In our study, 50 % of the sample population had experienced an SCI (n = 7). Disturbed cardiac innervation or a disturbed peripheral reflex response is associated with lesions at T5 or above and may have influenced the HR response during match-play in individuals with SCI. In contrast, remaining participants presented with conditions which are not associated with an abnormal HR response. Furthermore, HIGH do not compete alongside LOW, and data were collected at two separate ITF tournaments. Hence, ambient conditions could not be matched or controlled, and this may have influenced HR. All participants were male players participating in singles matches. As peak power, mean power and mean velocity are significantly higher in men (Bhambhani, 2002) and relative intensities are typically higher in individuals with tetraplegia (Bhambhani et al., 1994), generalisations cannot easily be made from our exclusively male sample. It is also important to note that both HR and $\dot{V}O_2$ tend to be lower during AB doubles match-play (Pluim et al., 2007), but this association has not yet been confirmed for the wheelchair variant of the sport. To develop a clearer profile of the physiological demands, further research should target play involving women from the open class, individuals with tetraplegia and players competing in doubles matches. Direct comparisons between play involving men and women would also be useful to help inform the training practices in this sport, both at a recreational and performance level. However, with so many opportunities for research in a relatively undiscovered, niche area, priorities for research need to be carefully considered, with those that offer the greatest potential for inferences to be made on health-related enhancement and increasing participation held within the scope of this thesis.

Finally, the chair configurations of the current study were not manipulated by the investigators for obvious reasons (i.e. players using their own chair for tournament match-play). Therefore it is important to note that there may have been differences in the rolling resistances experienced by individuals with their choice of tyre type and pressure (Kwarciak et al., 2009) with lower rolling resistance and power output associated with tubular tyres compared to clinchers (Mason et al., 2015a).

The wheelchair-user interface is a topic of great interest (Goosey-Tolfrey, 2010; Mason et al., 2010) and it is quite possible that the choice of chair configuration may have influenced EE and HR. Nevertheless, the strength of this study was that the configurations used were self-selected and the current choices according to playing experience and ability, facilitating ecological validity which is important for wheelchair sports testing (Goosey-Tolfrey & Leicht, 2013). Furthermore, while it is recognised that the use of an instrumented wheel − for example, a SMARTwheel − may provide additional kinetic information on wheelchair propulsion (Cowan et al., 2008), the DL devices used in the present study offered a practical alternative to the 4.9 Kg SMARTwheel by being lightweight and suitable for competitive match-play scenarios.

6.6 Conclusions

The results of this study support the notion that wheelchair tennis players are active for a duration associated with positive health-enhancing effects. Significant differences in the physiological and court-movement response to match-play were observed for ranking and result. Regardless of set outcome, HIGH covered greater overall and forwards distances, and maintained higher average speeds than LOW. Overall, higher peak speeds and more reverse and forwards-to-reverse movement were observed in HIGH. Collectively, these data suggest that HIGH are more capable of responding to ball movement and the physiological and skill challenges associated with competitive match-play conditions. Slower and lower bouncing balls, shorter and lighter rackets, and smaller courts are now mandatory for tournament match-play in those under 10 years of age (ITF, 2011). Not all manipulations may be feasible for a LOW, adult population, but similar adjustments to the sport may be required in some areas to encourage skill development, as this player-group move at significantly lower speeds and cover less distance than HIGH. Using the slower moving LCB may be advantageous in creating a slower tennis match-play environment, but further research is required to support this notion.

7

Study 4: Effect of low-compression balls on wheelchair tennis match-play

This chapter has been published in a slightly modified form in the *International Journal of Sports Medicine*:

Sindall P., Lenton, J.P., Malone, L.A., Douglas, S., Cooper, R.A., Hiremath, S., Tolfrey, K. & Goosey-Tolfrey, V.L. (2014). Effect of low-compression balls on wheelchair tennis match-play. *International Journal of Sports Medicine*, 35(5), 424-431.

7.1 Abstract

Purpose: To compare court-movement variables and physiological responses to wheelchair tennis match-play when using low- versus standard-compression (SCB) tennis balls. Analysis of match-play using a LCB allows for quantification of physiological demands and court-movement when playing conditions are modified, allowing for practical recommendations to be made.

Methods: Eleven wheelchair basketball players were monitored during repeated bouts of tennis (20-min) using an LCB and SCB. Graded and peak exercise tests were completed in a controlled laboratory environment. For match-play, a DL was used to record distance and speed. Individual linear HR : $\dot{V}O_2$ relationships were used to estimate match-play $\dot{V}O_2$.

Results: Significant main effects for ball type revealed that total distance (P < 0.05), forwards distance (P < 0.05), and average speed (P < 0.05) were higher for play using an LCB. A lower percentage of total time was spent stationary (P < 0.001) with significantly more time spent at speeds of 1.00 to 1.49 (P < 0.05), 1.50 to 1.99 (P < 0.05) and 2.00 to 2.49 (P < 0.05) $m \cdot s^{-1}$ when using the LCB. Main effects for physiological variables were not significant.

Conclusions: Greater total and forwards distance, and higher average speeds are achieved using a LCB. The absence of any measured difference in HR and estimated physiological responses would indicate that players move further and faster at no additional mean physiological cost. This type of ball will be useful for novice players in the early phases of skill development.

7.2 Introduction

The link between tennis and health is well-established (Pluim et al., 2007; Marks, 2006). Playing tennis can improve aerobic fitness, encourages a favourable lipid profile, improves bone health, and reduces the risk of cardiovascular morbidity and mortality (Pluim et al., 2007). While a cause and effect relationship cannot be confirmed, the health of tennis players is positively affected by lower body fat, greater strength, and less diminished cognitive function in comparison with less active controls (Marks, 2006).

For the wheelchair user, tennis provides potential for a stimulating and energetic environment. Even though tennis is less physiologically demanding than other wheelchair sports, most notably basketball (Croft et al., 2010), individuals with a low-level SCI can still maintain an intensity of 50 % peak HR during on-court tennis activity (Barfield et al., 2009). Such a dose satisfies the exercise recommendations of the ACSM and AHA for health-improvement (Pluim et al., 2007). Approximately one hour of wheelchair tennis play is associated with an EE of between 300 to 350 kcal, and thus a reduced risk of myocardial infarction (Abel et al. 2008). Positive outcomes are not exclusively limited to highly competitive match-play conditions, with both practice (Barfield et al., 2009) and game-play (Barfield et al., 2009; Roy et al., 2006) scenarios eliciting sufficiently high HRs to be considered beneficial PA. Hence, to ensure that individuals gain from the benefits of the sport, and to maximise the impact on cardiovascular health, it is necessary to find new ways to increase participation and raise EE in wheelchair tennis.

The ITF aims to increase the number of people playing tennis in their respective nations (ITF, 2009a) as ‘participating in sports, in particular in wheelchair tennis, increases self-belief and also provides people with a disability with the means and know-how for independent living and a more affirmative attitude towards their community and existence in general’ (ITF, 2010a). As the psychological benefits of wheelchair tennis are more prominent when the frequency is at least three times per week (Muraki et al., 2000), and tennis must be played regularly to influence fitness levels (Pluim et al., 2007), the overarching aim is to promote the sport through on-going participation and long-term compliance.

However, as wheelchair tennis is associated with high levels of technical competence (Reid et al., 2007a) and represents a significant physiological and skill challenge to the individual (Goosey-Tolfrey, 2010; Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005), participation and compliance are not guaranteed. Both experienced and inexperienced athletes have reported major problems in the learning and development of new skills associated with wheelchair tennis (Wu & Williams, 2001). In addition, while relative playing intensity is similar, higher ranked players push faster and further than lower ranked counterparts, and are therefore more capable of responding to ball movement and the challenges of competitive match-play (Chapter 6). This, coupled with a moderate to high level of aerobic fitness required for competitive match-play (Roy et al., 2006), has resulted in a growing interest on how the game might be adjusted or adapted to promote skill development for developmental players. The prospect of using an LCB to enable improved play for novice or developmental players has been raised previously (Chapter 3). While court-movement variables have been reported for wheelchair tennis (Chapter 6), these have not been reported for play using an LCB. Furthermore, skilled wheelchair users with no prior tennis playing experience have not yet been sampled.

Chair mobility has been described as the single-most important aspect of wheelchair tennis, providing a base and transition for timing, balance, motion and the execution of skills (Elderton, 2000). Without appropriate mobility skills, a player will be unable to respond to the movement of the ball and the challenges of match-play. Hence, for a study concerned with court-movement, selection of participants with no chair or tennis skills is problematic. Further, tennis requires a modified propulsion technique, as players push while holding a racket. Such a technique requires additional skill (Diaper & Goosey-Tolfrey, 2009), reduces maximum velocity (Goosey-Tolfrey & Moss, 2005), and is therefore physiologically and technically challenging (Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005). Those with sport-specific chair propulsion skills have an inherent ability to mobilise the chair in a sporting context, but are not skilled for tennis propulsion or play; participants are therefore appropriately skilled to perform court-movement, but display typical characteristics of the novice user. Further, a moderate to vigorous intensity is associated with match-play (Roy et al., 2006). Hence, for comparisons between conditions for court-movement and resultant physiological responses, recruitment of participants with a good level of aerobic fitness is justified.

An investigation into the physiological demands and court-movement patterns monitored during wheelchair tennis play using an LCB is required to assess the value and impact of altering tennis ball characteristics in individuals taking up the sport and/or for recreational players with low-skill levels. Lower minimum HR’s were observed in LOW-players who won sets of tennis, when compared with LOW-players who lost during competitive match-play (Chapter 6). Hence, for low-skill players, better performance outcomes are associated with a lower physiological cost. However, such findings are currently limited to play with an SCB. Use of an LCB is likely to facilitate greater court-movement and thereby increase the physiological cost of match-play. As more energetic play is likely to confer desirable cardiovascular health effects, it is important to identify the optimal playing conditions to maximise physiological cost.

It is likely that this investigation will pre-empt further interventions in wheelchair tennis, and provide a case for methods to enhance participation. Hence, the purpose of this study was to compare both the physiological responses and court-movement variables in wheelchair tennis match-play when using an LCB versus an SCB. It was hypothesised that the LCB would result in greater distance and speed covered during 20-min of tennis match-play and subsequently increased HR responses (exercise intensity).

7.3 Methods

7.3.1 Participants

Eleven wheelchair dependent basketball players were recruited for this study (Table 7.1). One further participant also gave consent to take part but was excluded due to incompatibility with the inclusion criteria. Trained wheelchair basketball players are efficacious about their sport and show strong efficacy cognitions for basketball-specific skill performance (Martin, 2008). Hence, by virtue of their sports participation and affiliation, all participants were deemed skilled in sports wheelchair propulsion. However, as none had previous tennis playing experience and held no ITF world ranking, participants were therefore representative of a group of novice players (i.e. able to propel the chair in general terms, but unskilled in propulsion while holding a racket). Players were recruited through contacts at the Lakeshore Foundation and the University of Alabama, USA. Approval was gained and written consent was obtained by all participants prior to testing (Section 3.1).

Table 7.1 Descriptive characteristics for wheelchair basketball players

Participants ordered by degree of physical impairment (ascending order), as indicated by International Basketball point classification. *Denotes an incomplete spinal lesion. †Wheelchair user for sport, but otherwise ambulant

Participant	Gender	Age (years)	Nature of disability	Injury level	Time since injury (years)	Wheelchair user for daily ambulation (years)	Wheelchair tennis experience (years)	International Basketball point classification
1	M	19	Amputee (both limbs: trans-femoral and trans-humeral)	n/a	18	$0^{\dagger}$	0	1.0
2	F	18	Caudal Regression Syndrome	T12*	18	18	0	1.0
3	F	18	Spina bifida	L3/4	18	18	0	1.5
4	M	22	SCI	T5	6	6	0	1.5
5	M	21	SCI	T12*	21	16	0	2.0
6	M	23	SCI	T12	6	6	0	2.0
7	F	28	Spina bifida	n/a	28	25	0	2.0
8	M	22	Spina bifida	L3/4*	22	22	0	2.0
9	M	24	Cerebral palsy	n/a	24	11	0	3.0
10	M	20	Spinal cord stroke	L3*	6	6	0	4.0
11	M	20	Amputee (right leg trans-femoral)	L1	20	$0^{\dagger}$	0	4.0
Mean		21			16.7	15.4	0	
SD		3			8.9	8.9	0	

7.3.2 *Experimental procedures*

All participants underwent initial anthropometric profiling, followed by graded and peak exercise tests in a controlled laboratory environment prior to involvement in tennis match-play. Physical characteristics were recorded (Table 7.2).

Table 7.2 Anthropometric and peak physical characteristics for all participants based on initial laboratory profiling

Participants ordered by degree of physical impairment (ascending order), as indicated by International Basketball point classification. *Physiological measures*: peak oxygen uptake ($\dot{V}O_{2peak}$); laboratory-measured peak HR (HR_L)

Participant	**Sex**	**Age** (years)	**Body Mass** (Kg)	**Sum of skinfolds** (mm)	$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	HR_L ($b \cdot min^{-1}$)	**Peak Power Output** (W)
1	M	19	61.1	71.9	1.78	161	80
2	F	18	35.7	42.5	1.13	188	80
3	F	18	47.3	58.1	1.57	182	90
4	M	22	61.9	25.1	1.99	177	140
5	M	21	57.4	32.4	2.51	206	170
6	M	23	73.4	29.1	2.85	190	230
7	F	28	56.0	71.6	1.60	178	90
8	M	22	69.8	45.5	2.79	208	200
9	M	24	66.9	59.5	2.34	191	110
10	M	20	78.8	58.2	2.84	184	160
11	M	20	69.8	49.9	2.85	188	160
Mean		**21**	**61.6**	**49.4**	**2.34**	**187**	**137**
SD		**3**	**12.3**	**16.2**	**0.62**	**13**	**51**

Harpenden skinfold calipers (British Indicators Ltd., Luton, UK) were used to measure skinfold thickness at three anatomical landmarks. Weight scales suitable for wheelchair access were used to assess body mass. An electromagnetically braked arm-ergometer was used for assessment of submaximal and peak responses (Section 3.4.1). Participants were seated in their own sports wheelchair. Once baseline resting data for oxygen consumption were obtained, participants completed a 3-min familiarisation stage. HR was monitored using radio telemetry (PE4000 Polar Sport Tester, Kempele, Finland).

7.3.3 Graded exercise test

The graded test protocol consisted of four to six 3-min steady-state exercise bouts. Power output for the stage one was determined taking into consideration a) HR response during the familiarisation stage, b) level of disability, c) basketball classification and d) sex. Workload was thereafter increased in 20 W increments. As alterations in cadence influence oxygen consumption / efficiency during arm crank ergometry (Smith, et al., 2001), crank rate was fixed at 75 $rev \cdot min^{-1}$. Verbal feedback was given when crank rate deviated by ~5 $rev \cdot min^{-1}$; the test was terminated after three warnings. Expired air was collected and analysed using a calibrated online metabolic cart (Parvomedics TrueOne 2400 Metabolic Measurement System, Parvomedics Inc, Utah, USA). HR was monitored continuously and recorded at the end of each submaximal stage. A small capillary blood sample was obtained from the earlobe during a 1-min break between stages for determination of BLa^- concentration (Figure 7.1) using a portable Lactate Pro™ analyser (KDK Corporation, Kyoto, Japan, Arkray factory inc., KDK corporation, Shiga, Japan). Device application within sports research has been confirmed, with good accuracy against reference measures, high reliability (Baldari et al., 2009) and acceptable overall measurement error (CV, 3.3 %) (Bonaventura et al., 2015).

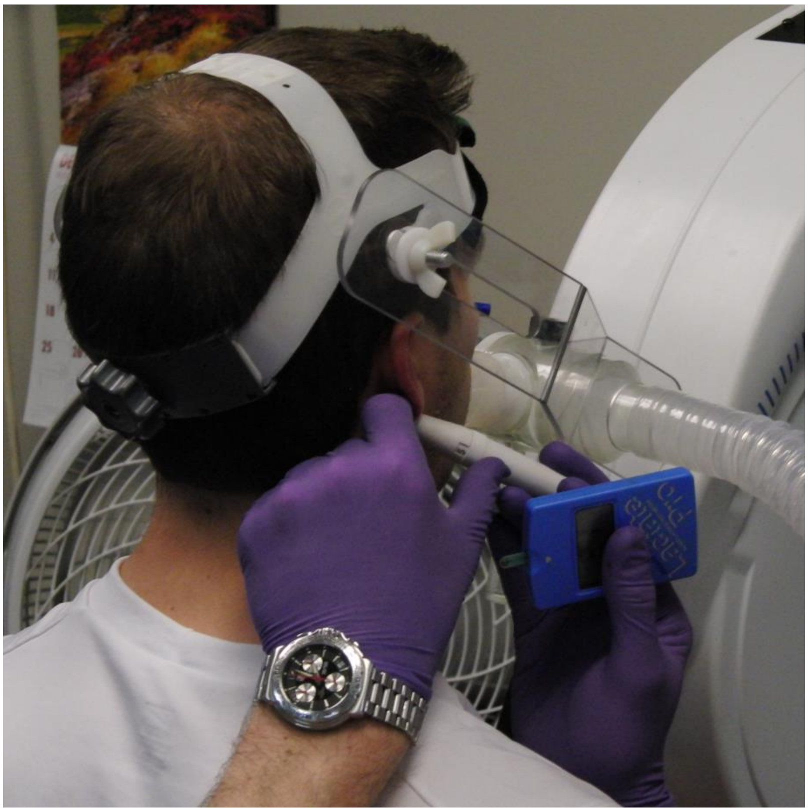


Figure 7.1 Measurement of BLa^- concentration during graded- and post peak-exercise testing

RPE (Borg, 1982) was monitored throughout the test. Environmental temperature and atmospheric pressure were consistent across all tests (23.3 °C, 725 mmHg); mean relative humidity was 24.4 ± 0.5 %.

7.3.4 Peak exercise test

Following a 5-min rest, each participant performed a further test to determine $\dot{V}O_{2peak}$. The starting power output was ascertained from graded testing, with the work rate advanced in 10 $W \cdot min^{-1}$ increments until volitional exhaustion. HR was monitored continuously. For $\dot{V}O_{2peak}$, expired air samples were collected and analysed using an online method. 3-min post-test, a capillary blood sample was obtained and analysed for BLa^- concentration. The final RPE was recorded. Criteria for a valid $\dot{V}O_{2peak}$ used was a peak RER value ≥ 1.10 and a peak HR ≥ 95% of HR_A (200 $b \cdot min^{-1}$ minus chronological age: Lockette & Keyes, 1994). The same testing equipment was used for all participants and all tests.

7.3.5 Experimental bouts of tennis match-play

Unlike previous studies (Chapters 4 & 5), the present study did not involve data collection during a competitive ITF tournament. The SCB is the only approved ball for competitive play. Hence, to test the effect of a modified ball, a mock tournament was designed by investigators. This included a series of experimental bouts of match-play. Aims were to mimic the conventional tournament format, while allowing for systematic unbiased testing of the intervention. Initially, a randomly assigned player number (1 to 11) was allocated and participants were assigned to one of three groups [n = 4 (x 2) and n = 3 (x 1)]. Each group underwent a habituation process prior to competitive match-play. Two 15-min practice sessions were played, one with an LCB and one with an SCB. An LCB is the same size and diameter as an SCB, but is softer and lighter (Hammond and Smith, 2006). For this reason, average mass (g) of all balls used during match-play were recorded. A single-blind design was adopted for ball type. The same colour [yellow ITF branded 'Play & Stay' (ITF)] balls were used, with LCBs marked with a small red circle (Figure 7.2). Players were not aware of the nature of this marking and hence, were blinded to ball compression rating. All matches were played indoors on a suspended floating hardwood floor. Playing area was defined, marked and checked in accordance with official ITF court dimensions (ITF, 2013). Ambient conditions were controlled across all matches (environmental temperature: 21 °C; humidity: 50 – 55 %).

Figure 7.2 Tennis equipment used for experimental bouts of match-play

Standard size and weight ITF 'Play & Stay' tennis rackets. Low- (yellow and red dot) and standard- (yellow) compression tennis balls

Following habituation, participants were invited to take part in competitive round-robin format match-play. Each player completed two or three matches, playing the other participants within their group once. Play was officiated in accordance with ITF rules and regulations (ITF, 2011), with two exceptions. First, matches involved two 20-min bouts of continuous play. Each bout involved play with either the LCB or SCB. Ball choice was randomised across bouts (Figure 7.3) using a cross-matched design (players in matches A and B used the LCB in bout one, while players in matches C and D used the SCB first). Second, players were only required to change ends after each 20-min bout.

The start and finish time for each game was recorded using a stopwatch. APT was defined in this instance as one 20-min bout of play, commencing from racket contact in the first service strike. Matches were filmed using previously described methods (Section 3.3). An overview of testing content and sequence can be seen in Figure 7.3.

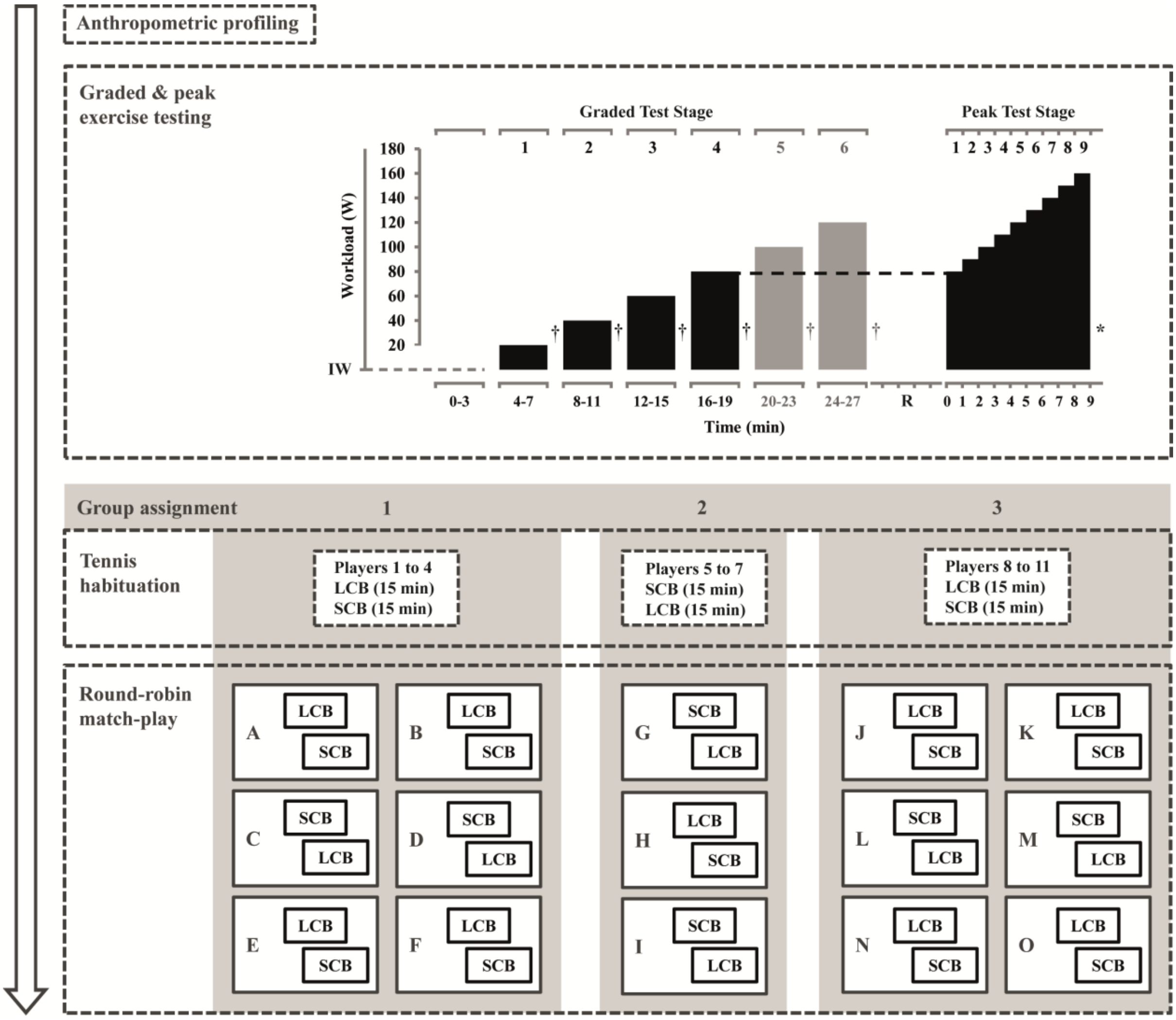


Figure 7.3 Schematic representation of laboratory and tennis match-play testing protocols

Vertical arrow indicates sequence of tests. *Graded & peak exercise testing*: incremental exercise stages represented in chronological order (left to right). Initial workload (IW - grey dashed line) determined during familiarisation. Workload increased above IW in 20W increments during graded testing. Minimum four stages, maximum six completed (black and grey blocks respectively). Post 5-min recovery period (R), peak testing commenced at an equivalent workload to final submaximal stage (black dashed line). 10W increments applied at 1-min intervals until volitional exhaustion. †Submaximal and *peak values for HR, $\dot{V}O_2$, BLa^- and RPE recorded. *Group assignment and tennis habituation*: random player number (1 to 11) and groups (1 to 3) assigned, with 2 x 15-min bouts of organised practice. *Round-robin match-play*: competitive tennis matches (A to O), with 2 x 20-min bouts per match. Ball type randomly assigned: LCB (low-compression ball), SCB (standard-compression ball)

7.3.6 Determination of exercise intensity during tennis match-play

HR during match-play was recorded in 5-s intervals. Absolute HR values for each participant were averaged for each bout and presented as mean values for group (i.e. mean peak, minimum and average HR). Mean average HR expressed as a percentage of HR_L ($\%HR_{avg}$) was also determined. While HR_A has previously been used for determination of peak capacity (Chapter 6), use of HR_L is preferred for accuracy where investigators are not constrained by facilities, cost or time restraints. Due to the intermittent nature of tennis, and to indicate the range of HR values during play, mean peak and mean minimum HR were also reported. For estimations of average oxygen uptake during tennis match-play ($\dot{V}O_{2T}$), HR and $\dot{V}O_2$ from laboratory testing were regressed against each other using a standard linear model. Values for average HR were then cross-compared for determination of $\dot{V}O_{2T}$. Relative exercise intensity during tennis match-play ($\%\dot{V}O_{2T}$) was calculated as a percentage of $\dot{V}O_{2peak}$ using the following equation:

$$\%\dot{V}O_{2T} = (\dot{V}O_{2T} \div \dot{V}O_{2peak}) \times 100$$

Total EE (kcal) was calculated on the assumption that one litre of oxygen is equivalent to 5 $kcal \cdot min^{-1}$ (Roy et al., 2006).

7.3.7 Court-movement

In this study, the DL was used to collect distance and speed data. The methods for DL data collection and analysis have been previously described in detail (Section 3.2). Potential reed switch activation and timing issues have been identified (Chapter 4) and subsequently addressed (Chapter 5) with recommendations made regarding optimal placement and configuration of the DL for assessment of court-movement. The present study did not involve data collection in competitive ITF tournaments where world ranking points were at stake. Hence, investigators were able to locate two DL devices on each chair wheel. The merits of this approach have previously been explained with respect to mitigating the effect of turns (Chapter 4). Time spent stationary (0 $m \cdot s^{-1}$) and within eight individual speed zones (range: 0.01 to 3.99 $m \cdot s^{-1}$) was calculated according to pre-described procedures (Chapter 5.3.3). While time in nine speed zones has previously been reported (Chapter 5), wheelchair tennis players spend no time in zone 9 (4.00 to 4.49 $m \cdot s^{-1}$). Therefore, this zone was deemed unnecessary for the present study.

7.3.8 Data processing and statistical analyses

The SPSS 19.0 statistical package (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Descriptive statistics (mean ± SD) were obtained for all participants and presented as 20-min average values. For all court-movement variables, an average value for logged data from DLR and DLL were used (Chapter 4). Normality and homogeneity of variance were confirmed by Shapiro-Wilk and Mauchley's tests respectively. Distance data were presented in absolute terms (per 20-min bout). HR indices (mean peak, minimum and average) were presented as absolute values and adjusted to indicate relative playing intensity (expressed as a percentage of HR_L). Separate 2 x 3 (ball-by-bout) within-measures ANOVA were used to examine the following dependent variables (total distance; forwards distance; reverse distance; forwards-to-reverse distance; peak and average speed; mean peak, minimum and average HR; $\%HR_{avg}$; $\dot{V}O_{2T}$; $\%\dot{V}O_{2T}$; EE; and percentage of time in individual speed zones). Simple main effect analyses were used to follow-up significant ball-by-bout interactions. Values for each individual bout of tennis match-play were used to form the basis of the statistical analysis. Statistical significance was accepted at a level of $P < 0.05$.

7.4 Results

7.4.1 Court-movement variables

The main effect for ball revealed that total distance during 20-min bouts of wheelchair tennis was significantly greater for LCB than SCB (956 ± 383 *vs.* 859 ± 339 m respectively; $P = 0.013$). Consequently, distance was also greater for LCB (48 ± 19 *vs.* 43 ± 17 m respectively; $P = 0.013$). Forwards distance was higher for LCB (835 ± 374 *vs.* 741 ± 323 m, $P = 0.021$), as was average speed (0.80 ± 0.32 *vs*. 0.72 ± 0.28 $m \cdot s^{-1}$, $P = 0.011$). There was no significant difference in mean peak speed (Table 7.3).

Table 7.3 Comparison of ball type for court-movement and physiological variables during 20-min bouts of wheelchair tennis match-play

Physiological measures: mean average HR as a percentage of HR_L ($\%HR_{avg}$); absolute ($\dot{V}O_{2T}$) and relative ($\%\dot{V}O_{2T}$) exercise intensity during tennis match-play. *Significant main effect for ball (P < 0.05). †Average value for a 20-min bout of activity. Values are mean (SD)

	LCB		SCB		***P***	
Total distance (m)	956	(383)	859	(339)	0.013	*
Forwards distance (m)	835	(374)	741	(323)	0.021	*
Reverse distance (m)	29	(13)	32	(15)	0.312	
Forwards-to-reverse distance (m)	61	(16)	58	(12)	0.366	
Peak speed ($m \cdot s^{-1}$)	2.34	(0.52)	2.36	(0.48)	0.751	
Average speed ($m \cdot s^{-1}$)	0.80	(0.32)	0.72	(0.28)	0.011	*
Peak HR ($b \cdot min^{-1}$)	136	(20)	132	(18)	0.089	
Minimum HR ($b \cdot min^{-1}$)	84	(15)	85	(15)	0.354	
Average HR ($b \cdot min^{-1}$)	109	(18)	107	(17)	0.223	
$\%HR_{avg}$	58	(9)	57	(9)	0.219	
$\dot{V}O_{2T}$ ($L \cdot min^{-1}$)	0.91	(0.41)	0.88	(0.37)	0.205	
$\%\dot{V}O_{2T}$	39	(13)	38	(12)	0.225	
Energy expenditure (Kcal) †	91	(40)	88	(37)	0.230	

Forwards propulsion was the dominant movement strategy (87 to 88 % of total distance). Considerably less distance was covered using forwards-to-reverse (8 to 10 %) and reverse (3 to 4 %) propulsion strategies. Figure 7.4 presents the results of time spent in specific speed zones and indicates a greater percentage of total time in zones 3, 4 and 5 for LCB (21.2 *vs*. 19.4 %, P = 0.029; 9.3 *vs*. 7.3 %, P = 0.019; 3.7 *vs*. 2.6 %, P = 0.012). Comparatively less time was spent stationary (speed zone 0) for play using an LCB (13.9 *vs*. 11.1 %, P = 0.001). Total time above 2.50 $m \cdot s^{-1}$ was small (< 1 %) for both ball types. No main effect for bout or ball-by-bout interaction was noted for court-movement variables.

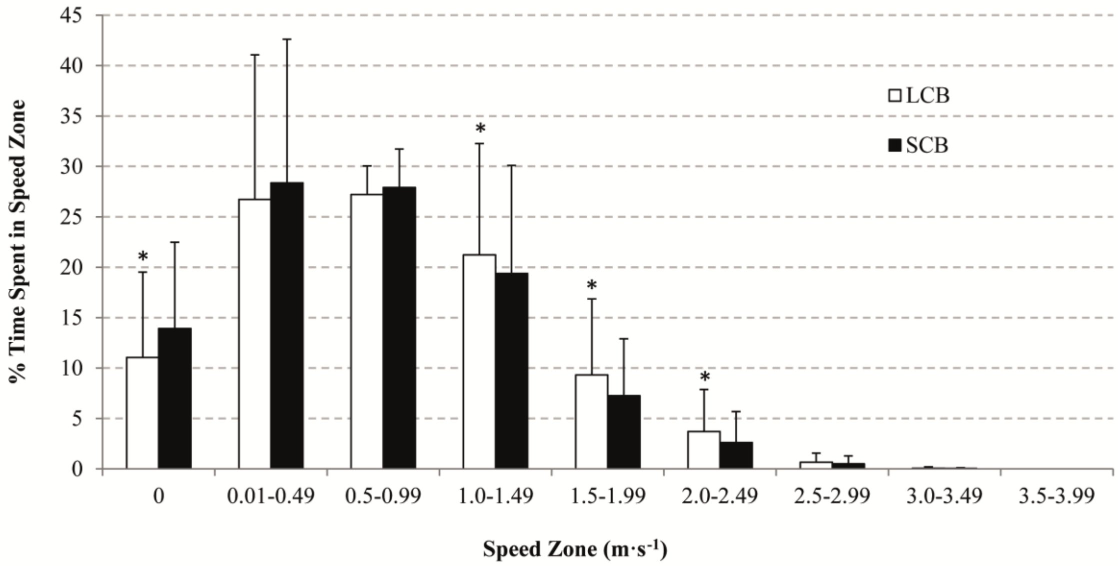


Figure 7.4 Percentage of time spent in speed zones during 20-min bouts of tennis match-play using the low- (LCB) and standard- (SCB) compression ball

Speed zones: percentage of time spent stationary (0 $m \cdot s^{-1}$); eight further individual zones (0.50 $m \cdot s^{-1}$ increments). *Significant difference LCB *vs.* SCB ($P < 0.05$)

7.4.2 HR and estimated physiological variables

Peak testing (Table 7.2) produced a mean $\dot{V}O_2$ of 2.20 ± 0.62 $L \cdot min^{-1}$ (range: 1.13 to 2.85), HR_L of 187 ± 13 $b \cdot min^{-1}$ (range: 161 to 208) and a peak power output of 137 ± 51 W (range: 80 to 230). Physiological data for participant 9 (cerebral palsy) were found to be within the 14^{th} to 50^{th} percentile of the studied population. Therefore, all data were entered for analysis. No significant main effect or ball-by-bout interaction was observed for measured HR (mean peak, mean minimum, mean average, $\%HR_{avg}$) or estimated physiological variables ($\dot{V}O_{2T}$, $\%\dot{V}O_{2T}$, EE). A similar mean average HR response was observed for ball type (LCB *vs.* SCB: 109 *vs.* 107 $b \cdot min^{-1}$) with large variation in mean peak (LCB: 97 to 161; SCB: 92 to 153 $b \cdot min^{-1}$), mean minimum (LCB: 52 to 109; SCB: 53 to 110 $b \cdot min^{-1}$) and mean average (LCB: 72 to 131; SCB: 70 to 130 $b \cdot min^{-1}$) HR. Relative playing intensity ($\%HR_{avg}$) was similar when mean average HR was expressed as a percentage of HR_L for LCB (58 ± 9 %, range: 45 to 77 %) and SCB (57 ± 9 %, range: 48 to 73 %). Further analysis revealed that match-play mean minimum and mean peak HR relative to HR_L were almost identical between conditions (LCB: 46 to 74 %; SCB: 46 to 72 %).

7.5 Discussion

The purpose of this study was to compare physiological responses and court-movement variables during wheelchair tennis match-play when using an LCB *vs.* an SCB. Such comparisons allow for greater understanding of methods for increasing participation and raising EE in wheelchair tennis.

Significant main effects for ball revealed that total distance (P = 0.013), forwards distance (P = 0.021) and average speed (P = 0.011) were higher for LCB tennis play. While players moved further and faster, this study reveals no significant differences in the physiological response for match-play using balls of different compression levels. Additional significant main effects for ball revealed that less time was spent stationary (speed zone 0), and more time was spent in zones 3, 4 and 5 (1.00 to 2.49 $m \cdot s^{-1}$) when players used the LCB. Previous work has found play involving the LCB to be associated with extended playing time, longer rallies and enhanced technique (Hammond & Smith, 2006). However, this is the first study to consider court-movement and its impact on the physiological demands of match-play using modified tennis balls.

In comparison to LOW counterparts, higher total distance, forwards distance and average speed are associated with HIGH wheelchair tennis players (Chapter 6). Hence, better players typically cover greater distances and operate at higher speeds. Successful court-mobility is essential in tennis. Players are required to respond to the unique patterns of opponent and ball movement. The present study suggests that greater total and forwards distance, and higher average speeds are achieved using the LCB. These data indicate that movement activity increases when using the modified ball. In addition, no differences were observed between measured HR and estimated physiological variables. Hence, while play with an LCB prompted increased court-movement, this occurred with little or no additional physiological cost. The ability to cover greater distance and speeds, with no associated increase in physical demand is likely to be highly advantageous, particularly for the inexperienced or developmental player. For such individuals, tennis is a highly complex sport. The significant physiological and skill requirement for wheelchair propulsion while interfacing with a racket (Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005), intermittent, multidirectional nature of the sport (Roy et al., 2006) and vigorous intensity (Chapter 6) combine to create a challenging activity environment.

The present study revealed a lower percentage of total time was spent stationary (speed zone 0; P = 0.001), and a higher percentage of time in speed zones 3 (P = 0.029), 4 (P = 0.019) and 5 (P = 0.012) while using the LCB. These data suggest that use of an LCB reduces inactive time and prompts a more consistent and frequent movement response during match-play. Increased activity is most likely linked to a response to ball placement. An LCB is softer, lighter and has a lower bounce (Hammond & Smith, 2006). Such characteristics may have a positive impact on a player's perceptual ability to reach the ball after an opponent's shot (i.e. if a player considers that he / she is likely to reach the ball, he / she is more likely to propel the chair). Collection of qualitative data around player confidence relating to court-movement would be useful in validating this notion in future work. Furthermore, measurement of confidence in chair-mobility, and therefore, assessment of perceptual ability to navigate the court surface may be a useful adjunct in determining the effectiveness of a variety of skill development strategies for wheelchair tennis.

With respect to a single 20-min bout of tennis activity, this study suggests that LCB and SCB use does not alter physiological cost. However, it is important to note that the relative exercise intensity in the present study was considerably lower than reported previously for tennis (Chapter 6; Croft et al., 2010; Barfield et al., 2009; Roy et al., 2006). Indeed, when compared with established guidelines on exercise quantity and quality (ACSM, 2011), this study reports a light activity classification for relative intensity (HR: 57 to 63 %; $\dot{V}O_2$: 37 to 45 %). As no physiological differences were observed for ball type, this light intensity environment is most likely explained by playing experience and skill. While all were skilled wheelchair users, participants were novice players (no prior tennis experience for either practice or match-play). Hence, intensity was limited by player skill development within each discrete 20-min bout. However, because no previous studies have targeted novices for assessment of court-movement and physiological demands, sampling strategy was a strength of the study. In addition, the ITF maintains that players should be able to 'play and stay' (i.e. serve, rally and score) from the first session, and that slower moving balls are 'essential kit for introducing disabled people to wheelchair tennis' (ITF, 2012). To assess the accuracy of this statement, recruitment of novice players (but skilled wheelchair users), was merited. Light activity is associated with lower EE than more intense exercise and is therefore less conducive to health enhancement. However, such conditions are likely to be advantageous for the novice, who is focused on skill development and chair propulsion while holding a racket in the palm of the hand. This study shows greater total and forwards distance and average speeds for the LCB. Hence, using the LCB influences court-movement. In turn, this suggests that performance was enhanced using the modified ball.

Average playing duration ranges from 40 to 75 min in wheelchair tennis (Chapter 6). In the present study, players completed shorter (20-min) bouts of exercise. While this closely resembles the duration of a single set of tennis (Chapter 6), further research should consider the influence of ball type over a longer duration. As the physiological response increases over an extended duration in tennis (Chapter 6), but has also been shown to decrease in other wheelchair sports (Sarro et al., 2010), accurate conclusions about the nature of the physiological response should be reserved for further investigation. However, it is plausible to assume that increased physiological demand is likely to be associated with increased duration. Hence, more apparent differences for ball type may be observed during longer matches. In addition, breaks in-play, and during-play, were not recorded and hence were variable in length. The precise nature of these physiological changes should be reserved for further research.

This study revealed no significant differences for court-movement or physiological variables for bout. This suggests that participants covered similar distances and speeds, and experienced equivalent physiological demands across multiple bouts of play. Peak oxygen consumption is lower for exercise testing modes involving reduced active muscle mass (Forbes & Chilibeck, 2007). In the present study, peak $\dot{V}O_2$ was assessed using an arm-crank, as opposed to a wheelchair ergometer. Consequently, peak values, and hence, relative playing intensity, may have been underestimated. However, for all conditions and participants, laboratory measures for HR and $\dot{V}O_2$ during the graded test were used to estimate relative playing intensity. Hence any underestimations would not have confounded comparisons for ball type or bout. Further, while this study reveals lower values for peak $\dot{V}O_2$ than those reported for elite basketball players (Croft et al., 2010), values are consistent with those reported for elite tennis (Croft et al., 2010). Hence, the aerobic fitness level of participants was not a likely explanation for the lack of significance for ball type.

As stated previously, recruitment for studies involving wheelchair sports is challenging due to the small populations involved (Croft et al., 2010), and participation in wheelchair tennis is typically low (Goosey-Tolfrey, 2010). Further, participants with a range of disabilities are often recruited. Disturbed cardiac innervation and / or a disturbed peripheral reflex response are associated with lesions at T5 or above and may have influenced the HR response during match-play in those individuals with SCI. One participant had cerebral palsy, and as such, motor control and hence, rate of skill development, may have been disproportionately affected. This condition is not associated with an abnormal or blunted HR response. However, with physiological responses ~50^{th} percentile, half of all participants achieved higher physiological responses than this participant. Reduced court-movement as a result of a greater proportion of time spent stationary is a possible explanation for this outcome. Players are largely inactive during the serve, and serving times were not standardised. This skill is complex and requires successful ball toss to racket-swing coordination and timing. General observation indicated that some participants were able to coordinate this action effectively, while others needed to repeat the ball toss action. Prolonged inactivity caused by a lack of tennis-specific skills may therefore have contributed to the relatively low exercise intensities observed in the present study. The focus should therefore be on the development of core skills in early phases to ensure that court-movement and thereby, health effects, are maximised.

While there are limitations in HR data collection, HR is an accurate and non-invasive means of reporting exercise intensity for the quantification of physiological demands. Coupled with laboratory measures, HR allows for the prediction of $\%\dot{V}O_{2T}$ and therefore an estimation of absolute $\dot{V}O_2$ during tennis performance. While alternative methods are available for the direct assessment of $\dot{V}O_2$, and these are likely to provide more accurate determinations for intensity, they are cumbersome and thereby inappropriate for competitive sport scenarios. As described previously, players participate in the Open class or Quad division (Section 3.3.2). Hence, it is important to capture data that are representative of the spectrum of players who may choose to play tennis. Therefore, exclusion of individual player data is not justified and collection of HR is appropriate for relevance, accuracy and ease of application.

Comparison in performance variables for play with modified balls is currently limited to three studies involving AB participants (Kachel et al., 2015; Hammond & Smith, 2006; Cooke & Davey, 2005). In all cases, participants had some degree of tennis playing experience. In a study involving young players (~6 to 10 years), the SCB group were older and more experienced than the sample selected to use the LCB (Hammond & Smith, 2006). In earlier work, participants were experienced tennis players but had no experience in using a modified ball (Cooke & Davey, 2005). More recently, players recruited were elite juniors (Kachel et al., 2015). As stated previously, the strength of the present study was that wheelchair basketball players with no experience playing tennis with any type of ball were sampled. Consequently, tennis-specific skill levels were controlled. Chair-propulsion skills were not subject to the same level of control, as a degree of experience was considered favourable to ensure successful completion of 20-min bouts of tennis. However, while participants were skilled in sport-specific chair propulsion, they were unskilled in pushing while holding a racket. Furthermore, as basketball is classified based on degree of physical impairment, there is expected intra-team variance in physical fitness profiles. In the present study, peak values for $\dot{V}O_2$ and peak power output ranged from 1.13 to 2.85 $L.min^{-1}$ and 80 to 230 W, respectively. Hence, not all players were highly conditioned. Sampling of basketball players therefore allows for consideration of performance variables across a range of fitness levels, with good scope for generalisations on novice users and appropriately conditioned beginners.

Chair configurations were not manipulated by the investigators, and players participated in tennis using their own sports wheelchair. Hence, there may have been inter-individual differences in rolling resistance, due to self-selection of tyre type and pressure (Kwarciak et al., 2009). However, all chair tyres were inflated to a level suitable for competitive play. Furthermore, players used the same chair for both conditions, and thereby the same configuration. Instrumented wheels provide additional kinetic information for wheelchair propulsion (Cowan et al., 2008), but are considerably heavier than the DL device used in the present study (4.90 *vs.* 0.01 Kg). The latter should therefore be considered more suitable than alternatives for logging movement during competitive match-play conditions. Also, while DL device accuracy has been questioned (Chapter 4), participants are known to spend a negligible amount of time above the threshold for accuracy (Chapter 5). In this study, participants spent less than 1 % of total time over 2.50 $m \cdot s^{-1}$, which further rationalises the use of the DL, particularly in studies involving low-skill groups operating at relatively low speeds.

As stated previously, average HR was used to determine playing intensity for bouts of tennis. A group of female soccer players covered longer distances at high intensities and sprinted further in international versus domestic matches, with no differences in mean HR response (Andersson et al., 2010). Therefore, mean HR response may not necessarily reflect differences in high-intensity activities. Clearly there are distinct differences between football and tennis, however, this application is of note as tennis is an intermittent sport (Roy et al., 2006) and players are known to perform at relatively high intensities irrespective of rank (Chapter 6). BLa^- data has been reported at fixed percentages of peak $\dot{V}O_2$ to compare wheelchair tennis and basketball playing intensity (Croft et al., 2010). Collection of lactate may therefore be a useful adjunct strategy to support inferences made in future work regarding physiological demands, particularly in studies involving interventions with comparisons between bouts of play.

The present study involved the use of the red LCB. Recent advances have seen developments in ball configurations and design, with a modified green ball now being trialled. This is noteworthy given that the current study reports the red LCB is ineffective in raising physiological cost. Both red and green balls are the same size and diameter as the SCB, but have different bounce and speed characteristics, with the latter bouncing higher than the former (Dyrbus, 2012). It has been proposed that the red ball can sit low after a second bounce, making shot play difficult (Dyrbus, 2012). In contrast, green balls have similar speed characteristics to the SCB and hence, may offer a better success rate for the beginner (Dyrbus, 2012). It is important to note that such propositions are yet to be investigated via an appropriately formulated research design. It is therefore necessary to proceed with caution. However, this is an interesting line of investigation, and further research should consider differences in novice performance when using a range of available ball types. Additional strategies for the elevation of physiological cost during match-play should also be explored to ensure that the many health benefits of tennis are realised for the wheelchair user.

7.6 Conclusions

This study presents data to show that the use of an LCB allows for greater movement and the generation of higher average speeds during tennis match play. While this is case for court-movement, this study shows no difference in the physiological response for separate bouts of play, or between ball types. An LCB is softer and lighter than an SCB, and hence is known to move more slowly through the air (Hammond & Smith, 2006). Therefore, higher court-movement could be linked with increased perceptual ability to reach the ball after an opponent’s shot. Consideration of strategies for increasing the active component of a match are warranted, to facilitate improvements in player performance, but also to allow for increased EE. This is of particular relevance for novice and recreational players who are focused on health-related outcomes. Interestingly, while increased movement activity was noted in the current study, this was not reflected in any increases in the physiological demands of the tennis match-play. Given that the match duration in the current study was standardised to 20-min bouts, longer matches should be the focus for future work. However, this study presents important findings on the impact and potential role of the LCB for player development in tennis.

8

Study 5: Wheelchair tennis skill development, court-movement and physiological cost: effects of organised practice

This chapter has not yet been published.

8.1 Abstract

Purpose: To examine the effects of organised practice on tennis match-play responses and to consider the effects of racket-holding during practice. Examination of the effects and characteristics of practice sessions allows for practical recommendations to be made to encourage skill and confidence development in low-skill players.

Methods: Sixteen AB participants with no wheelchair tennis experience were monitored during repeated bouts of tennis match-play (60-min) interspersed with a single bout of organised practice involving tennis-specific wheelchair mobility drills completed with-tennis racket (R) or without-tennis racket (NR). Graded and peak exercise tests were completed in a controlled laboratory environment. Individual linear HR : $\dot{V}O_2$ relationships were used to estimate on-court $\dot{V}O_2$. A DL was used to record distance and speed.

Results: Significant main effects for match revealed an increase from PRE to POST practice for distance (overall: 34.5 ± 6.9 *vs.* 37.5 ± 6.9 m, $P < 0.05$; forwards: 20.5 ± 6.9 *vs.* 24.2 ± 6.9 m, $P < 0.05$) and speed (peak: 2.22 ± 0.35 *vs.* 2.51 ± 0.35 $m \cdot s^{-1}$, $P < 0.005$; average: 0.58 ± 0.12 *vs.* 0.63 ± 0.11 $m \cdot s^{-1}$, $P < 0.05$). Significant PRE to POST practice increases in self-confidence were observed in 4 out of 5 outcomes ($P < 0.05$). Lower distance and speeds were achieved during R practice with a lower peak physiological response.

Conclusions: Independent of racket-strategy, organised practice increases match-play court-movement and raises self-confidence in tennis-specific mobility and shot-play with no associated increase in mean physiological cost. Changes are desirable and represent enhanced court-mobility. Differences between R and NR practice characteristics provide options for enhancement of tennis skill and optimisation of health outcomes.

8.2 Introduction

The evidence base concerning wheelchair tennis is increasing, with recent studies quantifying court-movement and concomitant physiological cost (Chapters 4 to 7 inclusive; Croft et al., 2010). While tennis activity is intermittent (Roy et al., 2006), HR remains elevated during match-play (Chapter 6). An intense playing environment is most likely caused by repeated pushing in response to ball movement and the limited opportunities for recovery. APT for one game of singles match-play has been found to be ~3-min (2:58 ± 0:33 min, unpublished data), with time between points restricted to a maximum of 20-s (ITF, 2014). Players are permitted to take a 90-s break period to change ends, but this represents a maximum limit and only occurs after every second game (ITF, 2014). Play must be continuous, 'from the time the match starts (when the first service of the match is put in play) until the match finishes' (ITF, 2014), with average match duration noted as 52 ± 9 min (Chapter 6). Therefore, tennis play involves intermittent, high intensity activity over an extended duration. While training across a spectrum of exercise intensities is generally recommended (Croft et al., 2010), specific strategies to optimise training sessions for health- and performance-improvement remain unclear. Off-court aerobic training is advocated for cardiovascular fitness development for tennis players (Roy et al., 2006), with wheelchair exercise, arm-ergometry and circuit resistance training identified as viable modes (Valent et al., 2007). However, a reliance on off-court strategies in isolation is problematic, as training conditions should reflect competitive demands. Players must push the chair whilst holding a racket. This constraint, which is unique to tennis, reduces propulsion speed and acceleration (Goosey-Tolfrey & Moss, 2005) and represents a complex skill challenge (Diaper & Goosey-Tolfrey, 2009; Goosey-Tolfrey & Moss, 2005). As increasing propulsion speed is likely to enable enhanced court-movement and court-positioning (Chapter 6), consideration of R and NR training strategies for organised practice may help to inform player development at all levels. Coaches currently offer training camps for developmental and elite players. Sessions are designed to enhance propulsion skill, and improve sport-specific and health-related attributes. However, movement characteristics and physiological costs of organised practice have not been reported and therefore represent an important area for investigation.

Successful performance in tennis requires adequate court-mobility. Poor movement results in poor positioning, timing and shot execution, leading to errors and reduced rally duration (Dybrus, 2012). Elite tennis players are able to navigate the court at higher speeds, and cover greater distances than low-skill counterparts, as their ability to react and respond to ball movement is more advanced (Chapter 6). As self-confidence is a function of skill-level, elite athletes report higher levels of self-confidence than low-skill counterparts (Neil et al., 2006). Higher confidence levels are associated with positive perceptions of anxiety control, and a positive performance outlook (Hanton et al., 2003).

In contrast, low self-confidence is associated with decreased perceptions of control, problems with focus and concentration, and debilitating effects on performance (Hanton et al., 2003). To ensure that novice players do not become disillusioned with the sport at early stages, consideration of strategies for increasing self-confidence and reducing physical anxiety are merited, particularly for low-skill groups who experience difficulties responding to match-play demands (Chapter 6). Self-confidence in wheelchair tennis is positively correlated with learning and enjoyment motivation (Jeong, 2013). In contrast, physical anxiety is negatively correlated with learning, health-fitness and enjoyment motivation (Jeong, 2013). Investigating the extent to which existing training scenarios stimulate learning and enjoyment is therefore of significant value to stimulate long-term participation in wheelchair tennis and thereby enable health-enhancing effects.

Inexperienced wheelchair users can improve chair propulsion skills in relatively short time periods. Increased ME is associated with the first 12-min of practice (Vegter et al., 2013), and two 60-min practice sessions improve confidence in chair use and problem-solving (Sakakibara et al., 2013b). However, comparatively less is known about the effectiveness of short-term interventions designed to improve propulsion for sporting activity, where the physical environment is more complex and challenging. Using an LCB allows low-skill players to push further and faster around the court (Chapter 7), and improves skill test performance (Hammond & Smith, 2006), which suggests potential for enhancement of court-mobility. However, while increased court-movement has been linked with an increased perceptual ability to reach the ball after an opponent's shot (Chapter 7), no data are available currently to suggest if self-confidence in shot-play and chair propulsion is enhanced when using a modified ball or for any other player development strategies.

A range of tennis-specific drills have been devised to improve propulsion skill and develop tennis court-mobility (Newbery et al., 2010). However, as responses have not yet been measured during organised practice, training effectiveness is unclear. Court-movement and physiological measures obtained during organised practice can be used to identify optimal training session characteristics, and determine how much further and faster players can push during match-play, post-practice both with and without a racket. With comparisons to match-play demands, coaches can use this information to prescribe appropriate training intensities, and structure sessions to optimise health, skill, physiological and performance outcomes. Hence, the purpose of this study was twofold. First, to consider the combined effect of practice and racket-holding on court-movement, physiological responses and self-confidence in match-play. Greater court-movement, heightened physiological responses and higher self-confidence were expected POST (*match*) when compared with PRE (*match*) practice, with greater changes in R (*group*) than NR (*group*). Second, to consider the effect of racket-holding on court-movement and physiological variables during practice, with R (*group*) completing less court-movement with a higher net physiological cost than NR (*group*).

8.3 Methods

8.3.1 Participants

Sixteen healthy AB participants (12 male and 4 female) gave written consent to participate in this study (Section 3.1). Participants had no prior wheelchair propulsion experience, no previous wheelchair tennis playing experience and were recruited through contacts at a UK University.

8.3.2 Experimental procedures

All participants initially underwent physiological profiling in a controlled-laboratory environment. A graded exercise test was completed, with submaximal and peak outcomes reported. On-court activity included two bouts of competitive tennis match-play interspersed with a single bout of organised practice. The practice session included a series of tennis-specific drills designed to enhance court-mobility (Newbery et al., 2010). Drills were developed by leading UK High Performance coaches, and are therefore representative of current wheelchair tennis training programme content.

8.3.3 Physiological profiling

Physical characteristics were recorded (Table 8.1). Exercise modality is an important consideration for assessment of functional capacity in wheelchair users (Goosey Tolfrey, 2013). Considering that arm-crank ergometry is more efficient than wheelchair propulsion (Bhambhani, 2002) and participants in the present study were novice wheelchair users, an electromagnetically braked arm-crank ergometer was deemed suitable for accurate determination of submaximal and peak responses (Section 3.4.1). Participants were seated in a standard chair (without arms) for testing. Once baseline resting data for $\dot{V}O_2$ were obtained, participants completed a 3-min familiarisation stage. HR was monitored using radio telemetry (Section 3.4.2). Four to six 3-min steady-state exercise bouts were completed, followed by consecutive 1-min stages to exhaustion to monitor submaximal responses and for determination of $\dot{V}O_{2peak}$. Initial power output was determined with consideration of the HR response during familiarisation (range: 15 to 20 W). Workload was thereafter increased in 15 to 20 W increments. Feedback was provided to ensure maintenance of desired cadence (75 $rev \cdot min^{-1}$), with the test terminated after three verbal warnings (< 70 $rev \cdot min^{-1}$). Expired air was collected breath-by-breath, and analysed using a calibrated online metabolic cart (Metalyzer 3B, Cortex Medical, Leipzig, Germany). A blood sample extracted from the earlobe was collected in a heparinized capillary tube (20 µL), mixed with 1 mL of hemolysis solution, and analysed to determine whole BLa^- concentration using an analyser (Biosen C-Line Clinic, EKF Diagnostic, Barleben, Germany). BLa^- was recorded at the end of each 3-min stage during graded testing, and immediately after the peak test for determination of peak blood lactate (BLa^-_{peak}) concentration. Differentiated RPE ratings (local, central and overall) were monitored and recorded at equivalent time points. Valid criteria for $\dot{V}O_{2peak}$ were a peak RER value ≥ 1.10, and a peak HR ≥ 95 % of HR_A (200 $b \cdot min^{-1}$ minus chronological age, Lockette & Keyes, 1994). Testing equipment was standardised for all participants and all tests. Mean environmental temperature, atmospheric pressure and relative humidity were recorded and were consistent across all laboratory-based testing (21.6 ± 1.1 °C, 1008 ± 6 mmHg, 30.6 ± 3.5 %).

Table 8.1 Attributes and peak physical characteristics for all participants based on initial physiological profiling

Participants ordered by level of physiological function (ascending order), as indicated by peak oxygen uptake ($\dot{V}O_{2peak}$) in relative units. *Further physiological measures*: laboratory-measured peak HR (HR_L), peak blood lactate concentration (BLa^-_{peak}), respiratory exchange ratio (RER). †Denotes missing value.

Participant	Sex	Age (years)	Body Mass (Kg)	$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	$\dot{V}O_{2peak}$ ($mL \cdot Kg \cdot min^{-1}$)	HR_L ($b \cdot min^{-1}$)	Bla^-_{peak} ($mmol.L^{-1}$)	RER	Peak power output (W)
1	M	38	79.6	3.67	46.1	188	10.6	1.14	163
2	M	20	71.4	3.29	46.1	199	14.5	1.13	158
3	M	25	69.6	3.03	43.5	179	10.1	1.12	141
4	M	21	74.5	2.98	40.0	187	8.8	1.14	146
5	M	25	79.5	3.02	38.0	185	6.8	1.17	150
6	M	24	78.0	2.90	37.2	195	13.0	1.11	118
7	M	22	88.4	3.11	35.2	198	12.6	1.24	163
8	M	25	65.5	2.13	32.5	192	†	1.40	108
9	M	30	76.5	2.41	31.5	187	8.9	1.21	135
10	F	27	60.0	1.87	31.2	176	6.5	1.10	90
11	M	27	95.3	2.73	28.6	181	8.9	1.24	148
12	M	20	74.5	2.04	27.4	202	10.5	1.34	120
13	M	34	92.8	2.49	26.8	171	12.2	1.19	162
14	F	27	68.6	1.77	25.8	186	9.7	1.27	128
15	F	23	74.1	1.81	24.4	194	6.8	1.21	83
16	F	24	74.2	1.57	21.2	173	3.7	1.10	88
Mean		**26**	**76.4**	**2.55**	**33.5**	**187**	**10**	**1.19**	**131**
SD		**5**	**9.4**	**0.63**	**7.8**	**9**	**3**	**0.09**	**28**

8.3.4 On-court activity: participant assignment and groups

Participants were allocated an opponent for tennis match-play based on initial physiological profiling and sex. Individual player numbers were assigned (1 to 16) and two groups (n = 8) were randomly allocated to one of two testing days (Figure 8.1). All participants completed a bout of tennis match-play prior (PRE) to a period of organised practice involving tennis-specific mobility drills. An equal number of participants (male = 6, female = 2) were then randomly allocated to R and NR groups. A further bout of tennis match-play (POST) was completed by all participants following practice. Data analyses were conducted to confirm no significant between-group difference for $\dot{V}O_{2peak}$ (Section 8.3.10). Participants were allocated one of four sports wheelchairs for on-court activity (Invacare TopEnd Pro Tennis). Each chair was identical and players used the same chair for all testing conditions. Wheel size and chair tyre pressure were standardised (wheel diameter: 61.4 cm and 83 $N \cdot cm^2$ respectively) with tyres checked immediately prior to on-court use.

8.3.5 On-court activity: competitive tennis match-play

To allow for accurate inferences to be made to the novice tennis player, match-play characteristics were aligned to likely recreational playing conditions. Users of tennis facilities are expected to make court bookings prior to participation and these are conventionally charged by the hour. Therefore, the likely duration of play for a recreational user would typically be ~60-min. Play would be continuous, would not be formally officiated and would involve random (as opposed to externally enforced) breaks in play. Therefore, 60-min bouts of continuous, competitive tennis activity were completed by each pair, one prior to, and one after a period of organised practice. To ensure competitive playing conditions, players were asked to keep their own score. The standard tennis scoring system was used (ITF, 2014) and explained prior. Players were asked to change ends for their second bout and retrieve their own balls between points. There was no external support or coaching.

Testing was completed on two days using the same two hard courts at an indoor tennis centre. Mean ambient conditions were consistent between tennis activity bouts (environmental temperature: 17.2 ± 0.9 *vs.* 17.5 ± 1.7 °C; atmospheric pressure: 1000 ± 7 *vs.* 999 ± 8 mmHg; relative humidity: 45.5 ± 4.7 *vs.* 46.8 ± 8.1 %) and between testing days (environmental temperature: 18.4 ± 1.2 *vs.* 16.4 ± 0.7 °C; atmospheric pressure: 1002 ± 9 *vs.* 997 ± 5 mmHg; relative humidity: 40.3 ± 1.5 *vs.* 52.0 ± 3.6 %). Court-dimensions were checked prior to play, and ITF regulations confirmed (ITF, 2013). Net height was set to regulation height (92 cm). Play was held in accordance with ITF rules (ITF, 2014). All on-court activity was filmed using previously established procedures (Section 3.3). Match times were recorded using a stopwatch with the start and finish time called by an observer.

Participants completed a 10-min warm-up (propulsion, no racket) prior to the first bout. For each 60-min bout, two new LCB balls were issued and balls were not reused. While LCB's with a red rating have been tested (Chapter 7), performance characteristics of further LCB variants have not been considered. The ITF suggest that the green-rated ball may outperform the improvements associated with the red-rated equivalent (Dyrbus, 2012). Hence, green-rated LCBs were used in the present study. Average mass (g) was recorded for all balls prior to first use using a disc-electronic scale (1035 SSBKDR Platform Electronic Scale, Salter, UK).

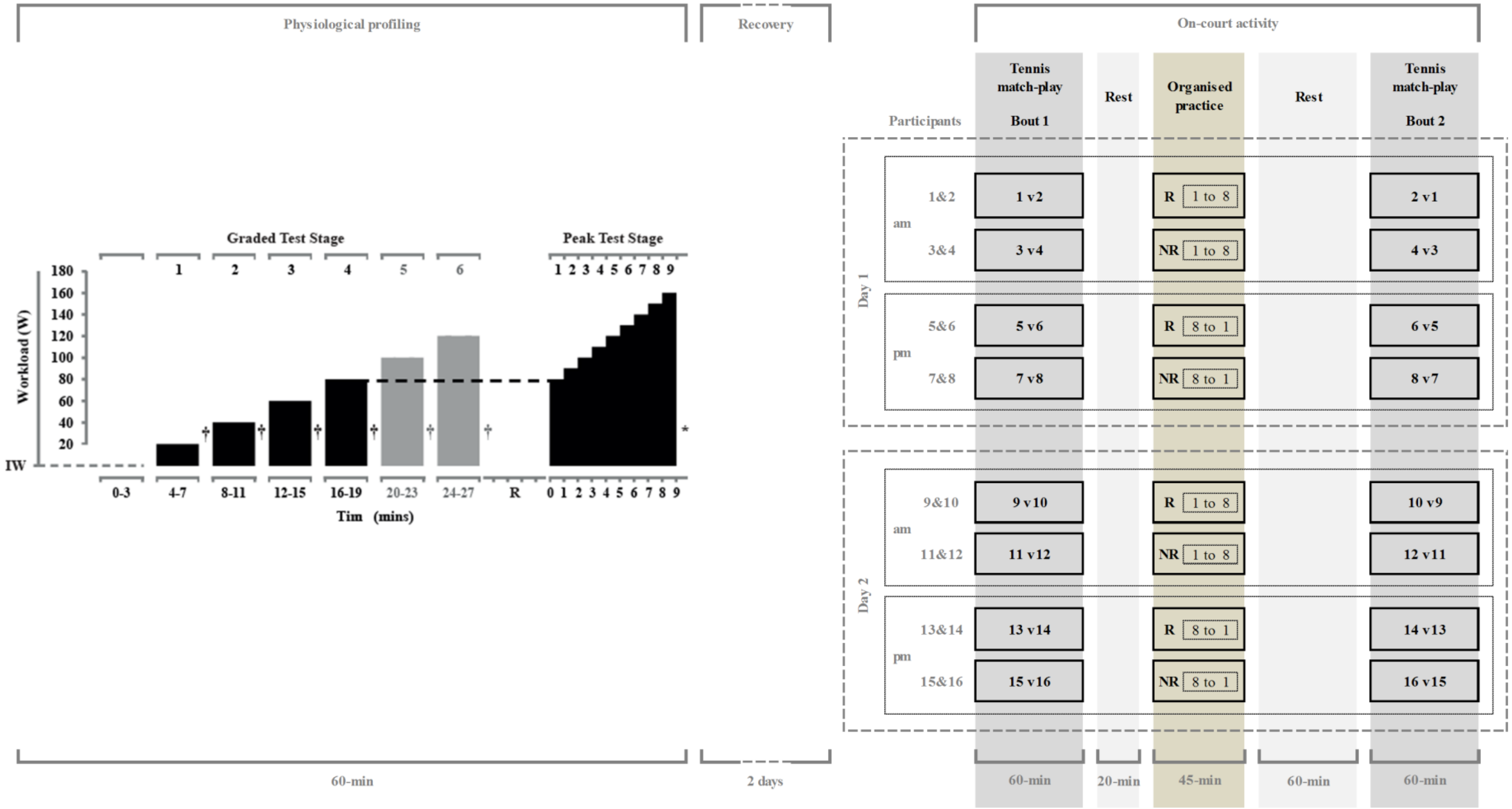


Figure 8.1 Outline of physiological profiling and on-court testing

All tests sequenced chronologically (left to right). *Physiological profiling:* initial workload (IW - grey dashed line) determined during familiarisation. Workload increased above IW in 15 to 20 W increments. Minimum four stages, maximum six completed (black and grey blocks respectively). Peak testing commenced at an equivalent workload to final submaximal stage (black dashed line). 15 to 20 W increments applied at 1-min intervals until volitional exhaustion. †Submaximal and *peak values for HR, $\dot{V}O_2$, BLa^- and RPE recorded. *Tennis match-play:* participant group and number assigned based on physiological profiling and sex. Two 60-min bouts of competitive tennis using an LCB. *Organised practice*: 8 tennis-specific drills completed with (R) or without (NR) a racket in-hand. Drill order randomised within and between groups (i.e. start at drill 1 progressing in order [1 to 8], or start at drill 8 progressing in a reverse sequence [8 to 1])

8.3.6 On-court activity: organised practice

Eight tennis-specific drills, designed for development of wheelchair tennis court-mobility (Newbery et al., 2010), were identified for inclusion (Figure 8.2). Participants completed drills within their groups (i.e. R = 8, NR = 8). Both sides of two tennis courts were used. Drills were completed in sequence (Figure 8.1). For the former, the dominant hand was used. Activity was continuous (3-min). Drills were separated by a 2-min recovery period to allow for explanation of the next drill. Players were instructed to start and stop at the same time. To eliminate an order effect, racket and drill sequences were randomised within- and between-groups (Figure 8.1). Session duration therefore was ~40-min with participants completing ~24-min of activity (i.e. 8 x 3-min).

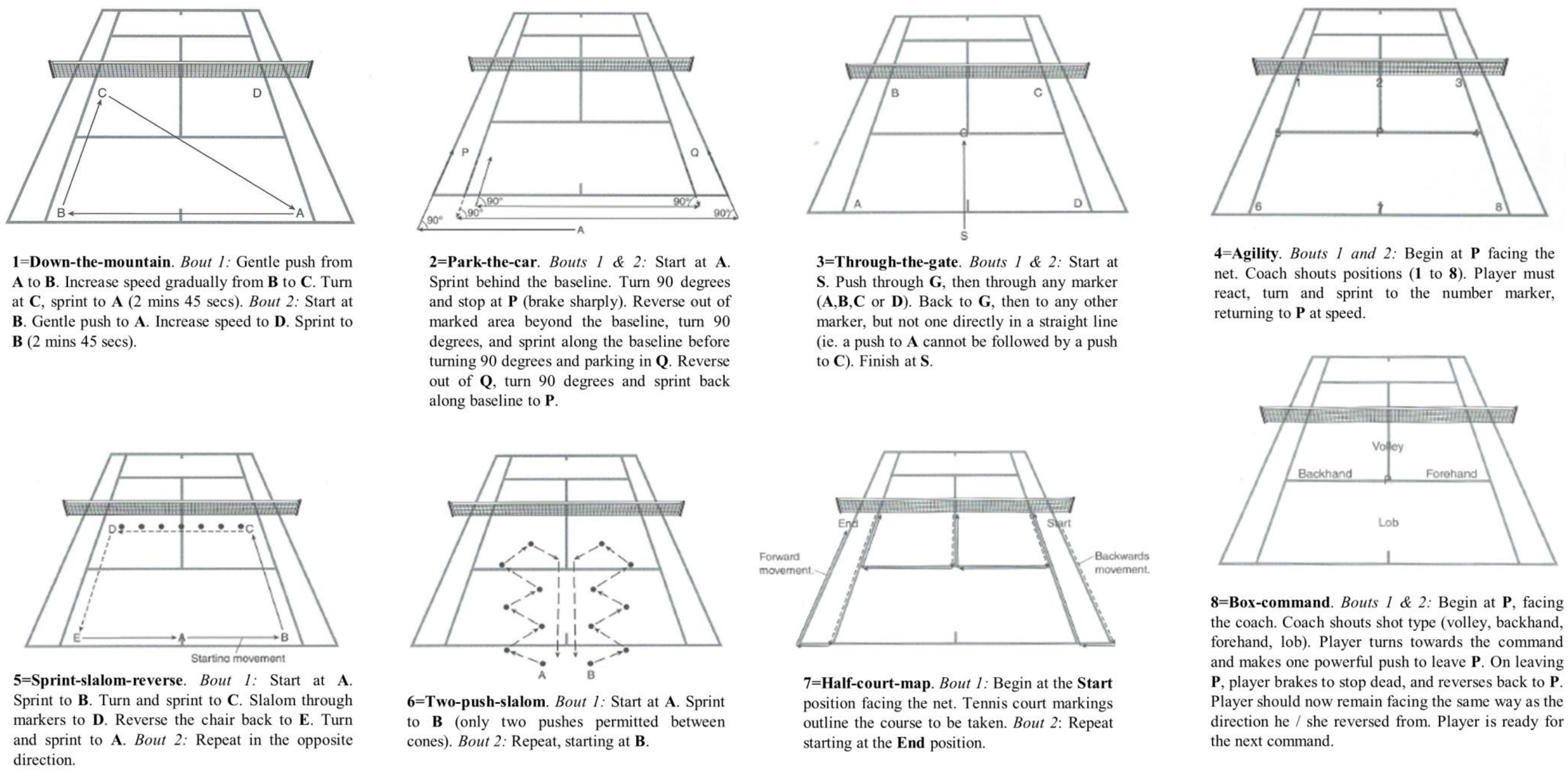


Figure 8.2 Tennis-specific court-mobility drills

Players complete all eight drills once for each condition (with and without racket). One 3-min bout of continuous effort was required for drill completion. A maximum 2-min rest interval was permitted between drills. **Drills**: **1** = down-the-mountain, **2** = park-the-car, **3** = through-the-gate, **4** = sprint-slalom-reverse, **5** = two-push-slalom, **6** = half-court-map, **7** = agility, **8** = box-command (Newbery et al., 2010)

8.3.7 Court-movement variables

Procedures for data capture using the DL have been described in detail previously (Section 3.2). In the present study, one DL was fitted to each wheel. This approach is advocated for the collection of accurate and reliable court-movement data where the testing situation permits (Chapter 4). Values for DLR and DLL were averaged for calculation of distance (overall, forwards, reverse, forwards-to-reverse) and speed (peak, average). The use of mean distance per minute (m) allowed for comparison to previous work (Chapter 6) where between-group comparisons involving variable match duration merited calculation of relative units. Percentage time in speed zones was reported according to previous methodological approaches (Section 5.3.3).

8.3.8 Physiological variables

HR data were recorded continuously during all on-court activity and subsequently averaged over 1-s intervals to align with court-movement variables. HR was expressed as an absolute value and as $\%HR_L$. Peak and minimum HRs were recorded. For estimation of $\dot{V}O_{2T}$ and average oxygen uptake during organised practice ($\dot{V}O_{2P}$), HR and $\dot{V}O_2$ from laboratory testing were regressed against each other using a standard linear model. For ease of reference, $\dot{V}O_{2T}$ and relative exercise intensity during organised practice ($\%\dot{V}O_{2P}$) were calculated using standard formulae (Section 7.3.6). Thereafter, EE was calculated using previously described methods (Section 7.3.6).

8.3.9 Self-confidence

A questionnaire, used previously for determination of post-practice self-confidence in wheelchair tennis propulsion and shot-play (Foulon et al., 2013) was administered by interview immediately after each tennis match-play bout. Five questions were scored on a 7-point Likert scale (Appendix I) with anchors 1 (*not at all confident*) to 7 (*completely confident*). Participants were permitted to ask for clarity if there was confusion regarding the terminology used in the questionnaire.

8.3.10 Data processing and statistical analyses

The SPSS 20.0 statistical package (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Descriptive statistics (mean ± SD) were obtained for all participants. Normality was confirmed by the

Shapiro-Wilk test. Homogeneity of variance was confirmed by Mauchley's and Levene's tests for respective within-participant and between-group measures. Student's *t*-test for independent samples was applied to consider between-group differences in $\dot{V}O_{2peak}$. Average values for logged data from DLR and DLL were used for all court-movement variables. Distance data were collected using a 1-s averaging interval and presented 1-min of play with Grubbs' test (Grubbs, 1969) used to remove significant outliers ($P < 0.05$). HR values were presented as absolute (mean peak, mean minimum and mean average HR) and relative (%HR_{max}, %HR_{min}, %HR_{avg}) playing intensities. To examine the combined effect of organised practice and racket-strategy on match-play, separate 2 x 2 (match-by-group) mixed-measures ANOVAs were used to compare the following dependent variables (*court-movement variables*: overall distance; forwards distance; reverse distance; forwards-to-reverse distance; peak and average speed; *physiological variables*: mean peak, minimum and average HR; %HR_{max}, %HR_{avg} and %HR_{min}; $\dot{V}O_{2T}$ and %$\dot{V}O_{2T}$; *psychological variables*: self-confidence). Due to its appropriateness for ANOVA, partial Eta squared (η^2_p) was calculated to determine ES for ANOVA. Calculations were made by-hand (not in SPSS), as follows:

$$\eta^2_p = \text{sum of squares}_{\text{effect}} / (\text{sum of squares}_{\text{effect}} + \text{sum of squares}_{\text{error}})$$

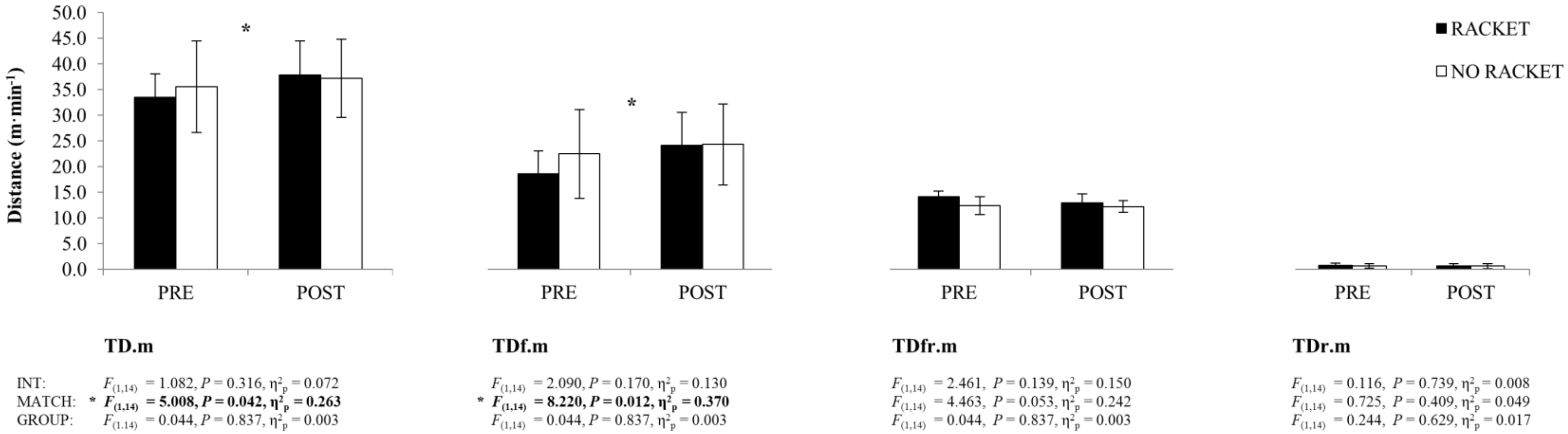
Outcomes were aligned with accepted descriptors for worthwhile effects for η^2_p (large > 0.138, medium > 0.059, small > 0.01; Thomas et al., 1991; Cohen, 1988). Student's *t*-tests for independent samples were applied to examine between-group differences in physiological responses and court-movement variables for R and NR. Due to lack of appropriateness of η^2_p for anything other than ANOVA, Cohen's *d* was calculated to determine ES for between-group comparisons. Accepted descriptors were used (*d*: very large ≥ 1.3, large ≥ 0.8, medium ≥ 0.5, small ≥ 0.2) (Rosenthal, 1996; Thomas et al., 1991; Cohen, 1988). EE was presented in absolute and relative units (kcal and $kcal \cdot min^{-1}$ respectively) with the latter used to determine target duration consistent with an EE of 300 to 350 kcal. Statistical significance was accepted at a level of $P < 0.05$ and 95% CI calculated according to previous methods (Section 4.3.7).

8.4 Results

A non-significant between-group difference in $\dot{V}O_{2peak}$ ($t_{(14)} = -0.492$, $P = 0.630$) indicated that participants were suitably matched for aerobic capacity (R *vs.* NR: 33.0 ± 6.7 *vs.* 33.9 ± 9.2 $ml \cdot kg \cdot min^{-1}$).

8.4.1 Combined effect of practice and racket-strategy on match-play

Large but non-significant interaction effects were observed for TDfr.m ($F_{(1,14)} = 2.461$, $P = 0.139$, $\eta^2_p = 0.150$) and self-confidence when transitioning from pushing to hitting ($F_{(1,14)} = 3.264$, $P = 0.092$, $\eta^2_p = 0.189$). Match-by-group interactions for all other performance variables were not significant (Figures 8.3, 8.4 & 8.5). The main effect for match indicated that independent of racket-strategy, higher overall distances (34.5 ± 6.9 *vs.* 37.5 ± 6.9 m, $F_{(1,14)} = 5.008$, $P = 0.042$), forwards distances (20.5 ± 6.9 *vs.* 24.2 ± 6.9 m, $F_{(1,14)} = 8.220$, $P = 0.012$), peak speeds (2.22 ± 0.35 *vs.* 2.51 ± 0.35 $m \cdot s^{-1}$, $F_{(1,14)} = 11.667$, $P = 0.004$) and average speeds (0.58 ± 0.12 *vs.* 0.63 ± 0.11 $m \cdot s^{-1}$, $F_{(1,14)} = 5.359$, $P = 0.036$) were observed POST practice (Figure 8.3); the effects were large ($\eta^2_p = 0.263$ to 0.455). Physiological variables were not affected by match (Figure 8.4). Relative intensity was consistently low during tennis matches (PRE to POST $\%\dot{V}O_{2T}$: 28.6 ± 9.1 *vs.* 29.0 ± 9.5%). Self-confidence in manoeuvring through a front-hand (Q1) and backhand (Q2) swing, hitting the ball before two bounces (Q4) and returning the ball before two bounces (Q5) was higher for POST *vs*. PRE (Figure 8.5) with large effect sizes ($\eta^2_p = 0.287$ to 0.766). Main effects for group were not significant for any performance variables (Figures 8.3 to 8.5).



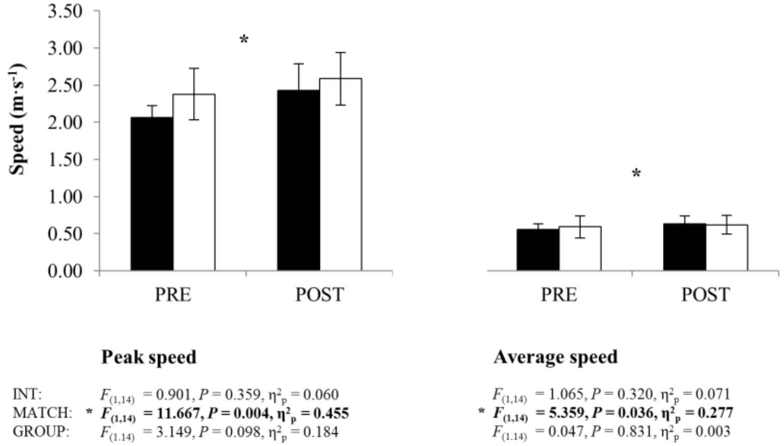


Figure 8.3 Match-by-group interactions of court-movement variables during competitive tennis

Mean values per minute (*distance*) and per second (*speed*). Error bars denote SD. Overall distance (TD.m); forwards (TDf.m), reverse (TDr.m), and forwards-to-reverse counter-movement (TDfr.m) per minute. Values for critical $F_{(\text{df variable, df error})}$, alpha value ($P$) and partial Eta squared (η^2_p) are presented for each interaction (INT) and for both within- (MATCH) and between- (GROUP) effects. Significant findings in bold type ($P < 0.05$). *Significant main effect for MATCH

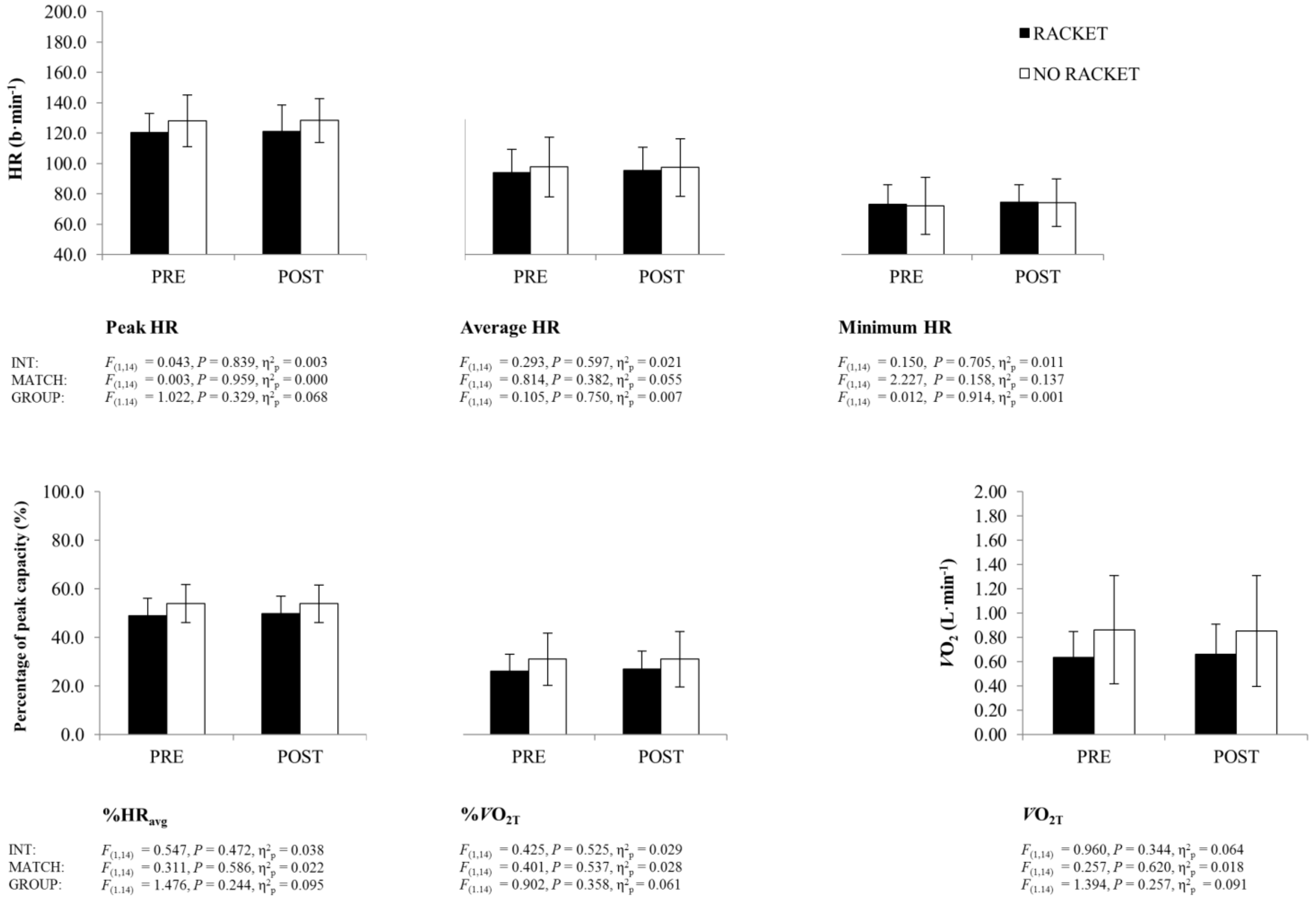
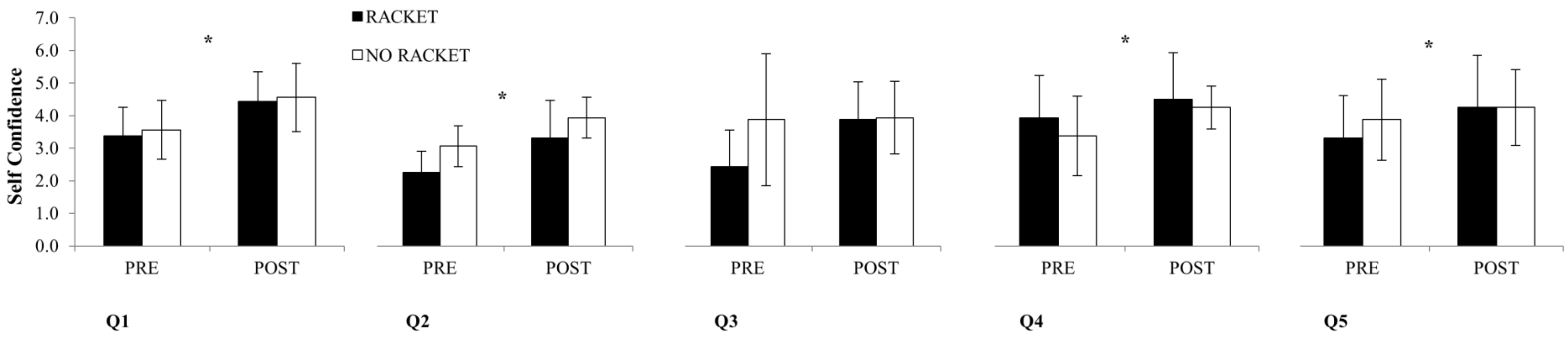


Figure 8.4 Match-by-group interactions of physiological responses during competitive tennis

Peak, average and minimum HR are mean values per minute. Mean average HR as a percentage of HR_L (%HR_{avg}); absolute ($\dot{V}O_{2T}$) and relative (%$\dot{V}O_{2T}$) exercise intensity during tennis match-play. Error bars denote SD. Values for critical $F_{(\text{df variable, df error})}$, alpha value ($P$) and partial Eta squared (η^2_p) are presented for each interaction (INT) and for both within- (MATCH) and between- (GROUP) effects. Significant findings in bold type (P < 0.05). *Significant main effect for MATCH



	Q1	Q2	Q3	Q4	Q5
INT:	$F_{(1,14)}$ = 0.011, P = 0.917, η^2_p = 0.001	$F_{(1,14)}$ = 0.429, P = 0.523, η^2_p = 0.030	$F_{(1,14)}$ = 3.264, P = 0.092, η^2_p = 0.189	$F_{(1,14)}$ = 0.388, P = 0.543, η^2_p = 0.027	$F_{(1,14)}$ = 1.037, P = 0.326, η^2_p = 0.069
MATCH:	* **$F_{(1,14)}$ = 012.395, P = 0.003, η^2_p = 0.470**	* **$F_{(1,14)}$ = 45.762, P = 0.000, η^2_p = 0.766**	$F_{(1,14)}$ = 3.884, P = 0.069, η^2_p = 0.217	* **$F_{(1,14)}$ = 8.211, P = 0.012, η^2_p = 0.370**	* **$F_{(1,14)}$ = 5.644, P = 0.032, η^2_p = 0.287**
GROUP:	$F_{(1,14)}$ = 0.183, P = 0.675, η^2_p = 0.013	$F_{(1,14)}$ = 3.707, P = 0.075, η^2_p = 0.209	$F_{(1,14)}$ = 1.596, P = 0.227, η^2_p = 0.102	$F_{(1,14)}$ = 0.568, P = 0.464, η^2_p = 0.039	$F_{(1,14)}$ = 0.212, P = 0.652, η^2_p = 0.015

Figure 8.5 Match-by-group interaction of self-confidence in tennis-specific wheelchair mobility

Mean values. Error bars denote SD. Questions: *'How confident are you in your ability to: manoeuvre your wheelchair through a front hand swing'* (**Q1**); *'manoeuvre your wheelchair through a back hand swing'* (**Q2**); *'transition the racket hand from pushing to hitting'* (**Q3**); *'hit the ball before two bounces'* (**Q4**); *'return the ball to your opponent within a 2 metre radius'* (**Q5**). For questions 1 to 5 inclusive (**Q1 – Q5**), values for critical $F_{(\text{df variable, df error})}$, alpha value (P) and partial Eta squared (η^2_p) are presented for each interaction (INT) and for both within- (MATCH) and between- (GROUP) effects. Significant findings in bold type (P < 0.05). *Significant main effect for MATCH

8.4.2 Effect of racket-holding on court-movement and physiological variables during practice

Figure 8.6 outlines the difference in performance variables for R and NR. Student’s independent *t*-tests revealed lower court-movement for R, with lower overall (63.8 ± 9.7 *vs.* 82.6 ± 15.1 m), forwards (47.1 ± 9.5 *vs.* 61.3 ± 10.3 m) and reverse distance (5.4 ± 2.2 *vs.* 8.4 ± 3.0 m). R achieved lower peak (2.79 ± 0.39 *vs.* 3.36 ± 0.56 $m \cdot s^{-1}$) and average speeds (1.06 ± 0.16 *vs.* 1.38 ± 0.25 $m \cdot s^{-1}$) and achieved lower relative mean peak exercise intensities than NR (%HR_{max}: 67.5 ± 9.1 *vs.* 78.4 ± 8.8 %). Effect sizes ranged from large to very large (d = 1.19 to 1.48). Large, but non-significant effects were noted for %HR_{avg} ($t_{(14)} = -2.002$, $P = 0.065$, $d = 1.00$), $\dot{V}O_{2P}$ ($t_{(14)} = -1.743$, $P = 0.103$, $d = 0.81$) and %$\dot{V}O_{2P}$ ($t_{(14)} = -1.626$, $P = 0.126$, $d = 0.88$). No other between-group differences in physiological variables were statistically significant and the ES ranged from medium to trivial.

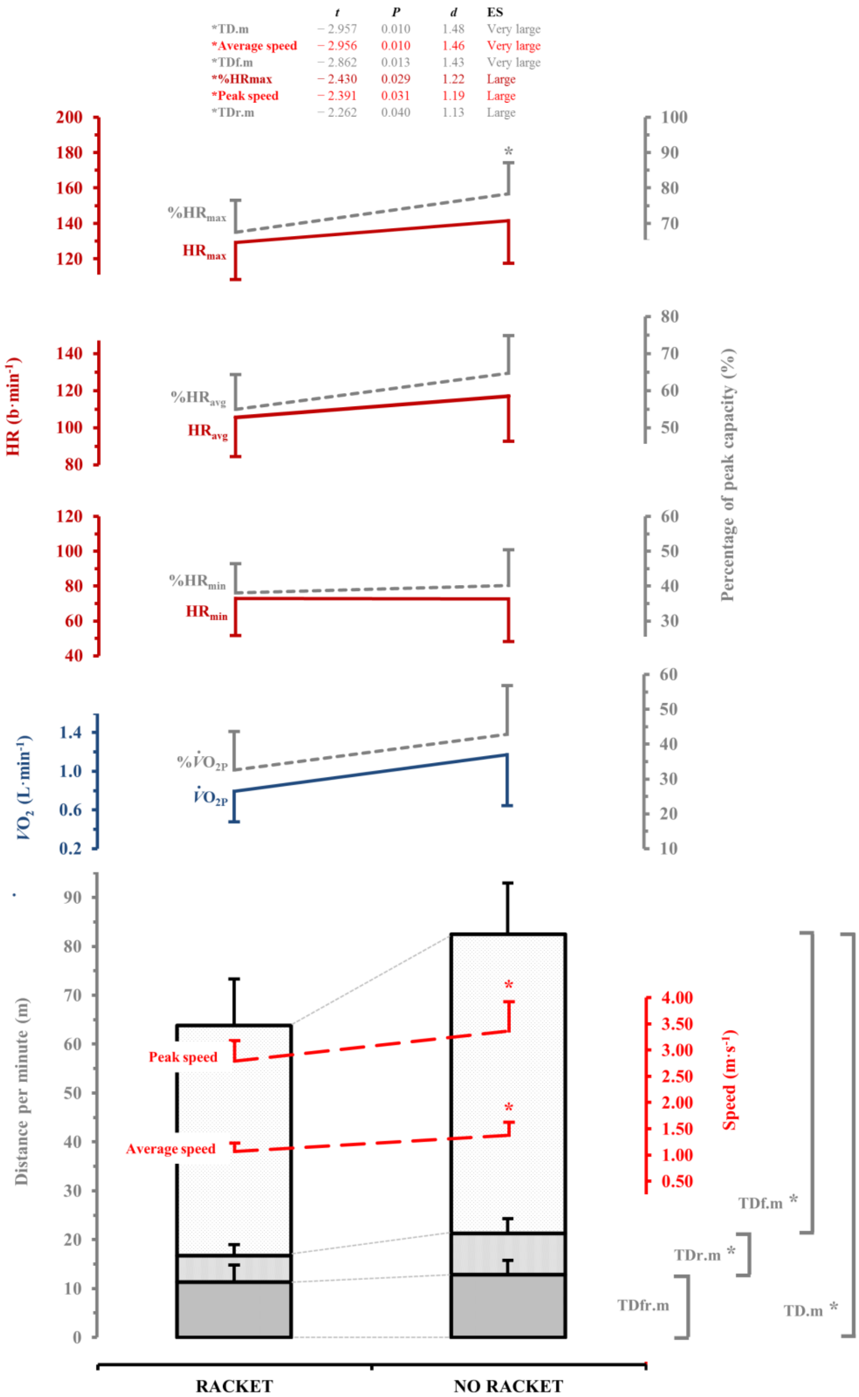


Figure 8.6 Comparison of physiological responses and court-movement variables during organised practice

Mean values. Error bars denote SD. *Dashed line* (percentage of laboratory-measured peak values): mean peak HR as a percentage of HR_L ($\%HR_{max}$), minimum ($\%HR_{min}$) and average ($\%HR_{avg}$) HR; relative exercise intensity during organised practice ($\%\dot{V}O_{2P}$). *Solid line* (physiological variables): mean peak (HR_{max}), minimum (HR_{min}) and average (HR_{avg}) HR; exercise intensity during organised practice ($\dot{V}O_{2P}$). *Stacked data series* (distance): forwards (TDf.m), reverse (TDr.m), and forwards-to-reverse counter-movement (TDfr.m) distance. Overall distance (TD.m) for group indicated by sum total of stacked data series. *Long dashed line* (peak and average speed). *Significant difference between-groups (P < 0.05). T-test statistic (t), alpha level (P) and ES (Cohen's d) presented for significant outcomes in descending order of ES.

While relative EE was also not significantly different between groups (P = 0.098, Table 8.2) a large ES (d = 0.88) showed a tendency for lower EE in R (R *vs.* NR: 95 ± 38 *vs.* 141 ± 63 kcal). Hence, a proportionately higher target activity duration is associated with R (*vs.* NR) for an EE associated with cardiovascular health enhancement (Table 8.2). Figure 8.7 shows R spent more time than NR within one relatively low speed zone (0.5 to 0.99 m·s^{-1}: $t_{(14)}$ = 2.574, P = 0.020, d = 1.29). In contrast, R were significantly less active in two higher speed zones (2.00 to 2.49 m·s^{-1}: $t_{(14)}$ = −2.919, P = 0.011, d = 1.46; 2.50 to 2.99 m·s^{-1}: $t_{(14)}$ = −2.894, P = 0.012, d = 1.45). Time in speed zones 7 and 8 (> 3.00 m·s^{-1}) was negligible, hence there were insufficient data for this analysis.

Table 8.2 EE during organised practice

EE presented in total and relative format as mean (SD) [95% CI]. Activity duration represents duration for completion of drill sequence. Target duration for an EE of 300 to 350 kcal = target EE / relative EE.

			Practice Type						
			R		NR		***t***	***P***	***d***
EE									
	Total	kcal	95 (38)	[64 - 126]	141 (63)	[88 - 194]			
	Relative	kcal·min^{-1}	4.0 (1.6)	[2.7 - 5.3]	5.9 (2.6)	[3.7 - 8.1]	-1.770	0.098	0.88
Duration									
	Activity	min		24					
	Target for EE of 300 to 350 kcal	min	75.8 - 88.4		51.2 - 59.7				

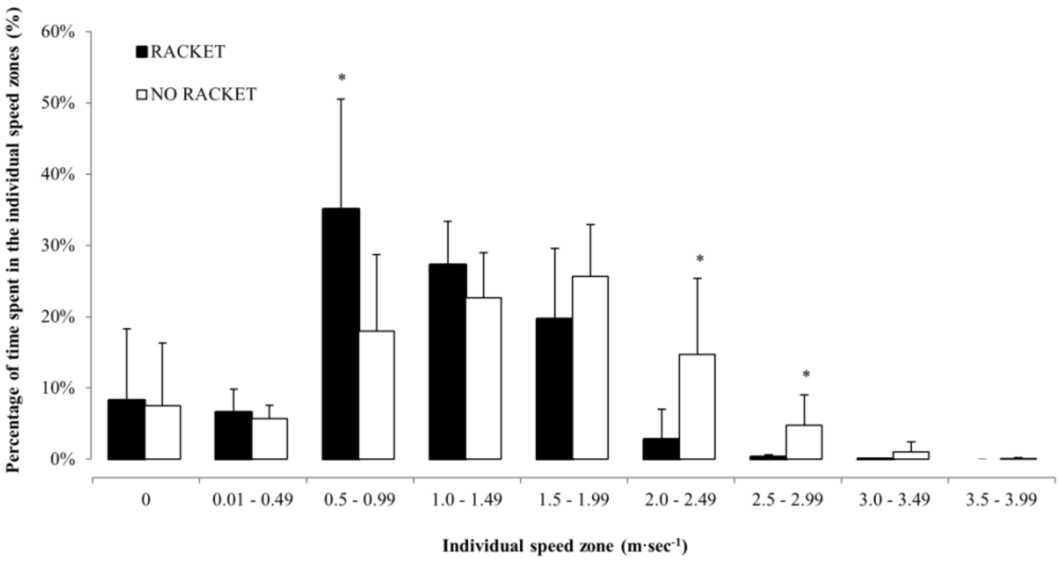


Figure 8.7 Percentage of time spent in individual speed zones for organised practice with and without a racket

*Denotes significant difference for between-group comparisons at each individual speed zone

8.5 Discussion

The purpose of this study was to identify whether match-play performance variables could be enhanced by a short bout of organised practice and determine if racket-strategy during practice was a factor. An additional aim was to consider the effect of racket-holding on performance variables during practice. Investigations into optimal practice conditions are useful in identifying strategies for increasing participation in wheelchair tennis to enable chronic health improvements. This is of particular importance for recreational exercisers who participate in tennis primarily to improve performance, keep physically fit and to socialise (Crespo & Reid, 2007).

8.5.1 Main findings

Significant main effects for group revealed that greater overall (P = 0.042) and forwards (P = 0.012) distances per minute, and higher peak (P = 0.004) and average (P = 0.036) speeds were achieved in tennis match-play post-practice. Consistent with previous findings (Chapter 7), increased court-movement was not associated with a concomitantly higher net physiological cost. While self-confidence in transitioning the racket hand from pushing to hitting was not enhanced (P > 0.05), confidence in wheelchair manoeuvrability and ball-striking were higher after practice (P < 0.05). As significant effects were independent of group (no interaction), racket-strategy has no effect on match-play court-movement and physiological responses. Hence, R or NR practice is likely to enable increases in match-play distance and speed. Such characteristics are desirable for wheelchair tennis performance (Chapter 6). Further analysis of court-movement and physiological responses during practice revealed comparatively lower forwards, reverse and forwards-to-reverse distance, lower peak and average speeds, and a lower percentage time in high speed zones for R (P < 0.05). A lower relative mean peak HR was also attained (P < 0.05). So while practice influences subsequent match-play court-movement per se, NR practice is advantageous for maximising distance, speed exercise intensity and EE. In contrast, R practice may be useful for development of confidence in a key aspect of propulsion skill. Therefore, training mode should be prioritised to ensure agreement with training aims and optimisation of health outcomes.

8.5.2 Impact of short-term practice on match-play performance variables

The ability to push further and faster is a characteristic associated with HIGH (Chapter 6). Hence, considerable interest in strategies for low-skill player-development exists in this area. This study reveals that only a short bout of practice (~24-min) is required to increase court-movement activity during tennis match-play. Novice tennis players in the present study pushed further forwards and in overall terms, and attained higher mean peak and average speeds in match-play, post-practice. Such an outcome is positive, with a likely association between greater court-movement and an enhanced response to ball and opponent movement (Chapters 6 & 7). Interestingly, increased movement activity in the present study was associated with unaltered physiological responses. Match-play with an LCB is associated with similar outcomes, prompting increased court-movement without associated increases in net physiological cost (Chapter 7). One explanation is that practice-induced increases in chair skills are prompting improvements in ME which offset the likely physiological consequences of greater and faster movement activity. This is plausible as increases in ME are caused by changes in propulsion technique (de Groot et al., 2008b), and increases in work per cycle, push time, cycle time (de Groot et al., 2002) and ME (Vegter et al., 2013; de Groot et al., 2002) are associated with practice. Also, lower EE as a consequence of greater ME is associated with experienced wheelchair users when compared with novice and practice (i.e. less skilled) AB groups (Croft et al., 2013). In the early stages, novices are able to better optimise upper body kinematics and dynamics (reduced push frequency and greater work per push) in relatively short periods (~12-min, Vegter et al., 2015). Hence, with higher proportions of energetic yield transferred into purposeful work, higher distances and speeds could realistically be attained with a similar or proportionately lower physiological cost. As previous studies are limited to linear motion on a motorised treadmill, the present study adds considerably to the available literature with consideration of tennis-specific propulsion conditions. Tennis movement patterns are unpredictable with repeated changes of direction and pace. So while an ability to push further and at greater speeds without increases in physiological markers appears to be desirable for optimal performance, further research is required to confirm this notion.

While players have anecdotally stated a preference for the LCB (Chapter 7), no formal means to capture user experiences has been applied previously. A considerable strength of the present study was inclusion of a tool to measure self-confidence which, coupled with court-movement and physiological data, allowed for triangulation of the practice-effect on match-play. As triangulation of methods increases overall confidence in findings and enables understanding of complex interventions (Jones, 2015), it is a favoured technique in sports research, and particularly useful for tennis, which is characterised by complex physiological (Kovacs, 2006), biomechanical (Elliott, 2006), technical and tactical (Reid et al., 2009) elements. Hence, measuring participant views on the extent of learning and skill development is useful in understanding the overall intervention impact. Higher post-practice self-confidence in chair manoeuvrability through both types of ground stroke (front- and back-hand swing) indicates an enhanced perceived aptitude for tennis-specific propulsion. Further, increased confidence in returning the ball before the second bounce, coupled with increases in distance and speed, represent an enhanced ability to assume a strong court position for shot-play. Finally, and interestingly, shot-play is enhanced by practice, with an increased ability to return the ball to an opponent (within a 2-m radius). Given that no drills involved actual ball-to-racket contact, this outcome is noteworthy and suggests that effective practice need not include a ball. Hence in summary, practice-induced changes in court-movement are consistent with player perception of increased mastery in tennis-specific chair propulsion and shot-play. Given that a lack of perceived skill development has been associated with attrition in individual sports including tennis (Molinero et al., 2006), early mastery of technical aspects is critical in ensuring ongoing participation satisfaction and commitment.

Little is known about distance covered using forwards-to-reverse counter-movement or indeed its contribution to performance. However, highly-skilled players are known to cover greater distance using this technique (Chapter 6). Due to a lack of significance, the match-by-group interaction for forwards-to reverse countermovement was not explored. However, a large effect was noted (η^2_p = 0.150) with a tendency for greater post-practice forwards-to-reverse counter-movement in R. Any association made between the effect of R practice and increased forwards-to-reverse movement in post-practice match-play should be cautioned by the relatively low samples in the current study. Nevertheless, consideration of the link between this type of movement and physiological consequences is interesting and worthy of further investigation. A notational profile such as reported by Filipčič et al. (2008), tabulating on-court position and shot outcomes alongside quantification of physiological variables may assist in identifying whether this mode of movement is desirable or associated with wasted energy. However, as distances in this mode are minimal (~13%, Chapter 6), this design is perhaps only of interest for the optimisation of high-level performance.

8.5.3 Characteristics of tennis-specific organised practice: considerations for enhancement of court-mobility

This study revealed lower court-movement activity for R practice with lower distances per minute (overall, forwards and reverse) and lower peak and average speeds. This finding is consistent with previous work indicating that a lower peak velocity is associated with R activity (Goosey-Tolfrey & Moss, 2005). Hence, R appears to restrict court-movement during practice. A lower relative mean peak HR for R also reveals that decreased movement activity is associated with lower peak physiological effort. Hence, completion of tennis-specific court-mobility drills without the constraint of a racket may be useful in optimising conditions for improvements in health. While large effect sizes (d = 0.80 to 1.00) indicated an association between court-movement and increased relative exercise intensity in NR, differences in %HRavg, $\dot{V}O_{2P}$ and %$\dot{V}O_{2P}$ were not significant. So while greater court-movement may have the potential for elevating exercise intensity, further research involving larger samples is required to support this notion.

Comparatively lower EE is associated with experienced wheelchair users in comparison to novice and limited skill (~3 week practice) groups (Croft et al., 2013). Practice leads to improvements in technique which positively influence ME (de Groot et al., 2002). While this confers advantages for sports performance, with higher proportions of energy transferred into purposeful work, participation for health enhancement is driven by a preference for maximisation of EE. Realistically, the net result of increased proficiency in propulsion skill may be a less physiologically challenging activity environment. Dose-response relationships dictate that the magnitude of benefit for any given increase in PA is greater for less active persons (Haskell, 1994). Hence, novices experience greater improvements over shorter time periods than more advanced exercisers. Also, those starting with a less optimal propulsion technique exhibit a faster rate of improvement in gross ME and propulsion technique variables during initial (~12-min) and cumulative (~80-min) bouts of practice (Vegter, 2014). So to maximise EE, strategies for increasing the intensity of the training environment are required to enable positive health outcomes as players develop in their propulsion skill-levels and physical fitness. R training was associated with a greater proportion of time at low speed (zone 2, 0.50 to 0.99 $m \cdot s^{-1}$). This speed is associated with veterans using everyday manual wheelchairs (Tolerico et al., 2007) and is therefore not desirable for maximisation of EE. In contrast, time in high speed zones 5 and 6 (~2.00 to 2.99 $m \cdot s^{-1}$) was lower for R practice. Without a racket, the wheelchair user can make more effective contact with the hand rim, with more effective force production, thereby enabling attainment of higher speeds. The present study estimates that R practice duration would need to be extended to 76-min (minimum) to achieve a target total EE of 300 to 350 kcal. In contrast, < 60–min of NR practice would achieve a similar energetic effect. This is an important consideration given that recreational court-bookings are normally made in one-hour blocks.

The lack of a match-by-group interaction in this study indicates that R practice is not required nor favoured for increased match-play court-movement and confidence (4 out of 5 outcomes). However, a large effect was noted for confidence in transitioning the racket hand from pushing to hitting (η^2_p = 0.189), with a tendency for greater post-practice confidence in R. So while R practice is likely to be a more suitable mode to enable development of this attribute, the lack of a significant difference suggests that this conclusion is tentative currently. Further research involving larger sample sizes is required to confirm the role of R practice in optimising this essential aspect of play. In contrast, it is clear that NR practice offers a more challenging activity environment for the novice player. Hence, novices should undertake practice prior to match-play to maximise tennis-specific court-mobility and self-confidence in chair manoeuvrability. Modalities should be applied with consideration of their performance effects. R practice may be the desirable for developing racket-transitioning skill (from pushing to hitting), but the lack of a significant difference may indicate that this skill is too complex to be enhanced by one single bout of practice and therefore, coaches may need to plan remedial work in this area. NR practice may be employed for maximisation of EE and exposure to a training environment associated with higher speeds and distances for optimisation of health outcomes.

8.5.4 Methodological considerations

DL output can be averaged over any predetermined time interval, with 5-s intervals previously reported for tennis (Chapters 4 to 7 inclusive). Recent findings suggest no mean distance and speed differences for comparisons between 1-s and 5-s averaging intervals (Mason et al., 2014a). However, differences in peak values have been noted, with authors concluding that mean peak speed averaged over 5-s intervals should be interpreted with caution. Increased observation frequency should not be confused with enhanced measurement sensitivity in an instrument which is restricted by its mechanical operation. Irrespective of the averaging interval, the same number of reed switches are triggered and therefore the same volume of data (time stamps) are created. Visual inspection of 1-s data suggests peak speed observations deviate considerably from adjacent values. This raises doubts as to whether such values represent true positives. To address this concern and align with recent research, court-movement data were treated for outliers prior to averaging over 1-s intervals. Such a process is useful in situations where individual data points differ considerably from the normal distribution (Grubbs, 1969).

Even though portable gas analysers are available for collection of expired air during exercise, no direct measures of $\dot{V}O_2$ were taken during on-court activity. While such systems provide stable scores with acceptable agreement with reference measures at low exercise levels, overestimations for $\dot{V}O_2$ are associated with moderate and vigorous exercise (Macfarlane and Wong, 2012). As wheelchair tennis is played at intensities approaching a vigorous level (Chapter 6; Roy et al., 2006), and competitive play is not conducive to invasive monitoring, it is difficult to advocate the use of portable analysers. Hence, laboratory-measured values for HR and $\dot{V}O_2$ were regressed to estimate on-court values. Physiological assessment in controlled laboratory conditions also allowed for the determination of HR_L in preference to HR_A. The former involves direct assessment of peak HR and therefore, more accurate representation of exercise intensity. Where possible, and the appropriate resources are in place, the use of HR_L should be advocated.

Finally, the absence of a control group in this study means that inferences made about the length of practice required to enable increased court-movement are assumptions as opposed to directly assessed aspects. Nevertheless, the lack of a control does not confound the between-group comparisons (i.e. R *vs*. NR), which are central to the purpose of the work.

8.6 Conclusions

Independent of group, tennis court-mobility drills raise self-confidence in chair-mobility and increase overall and forwards distance, and mean peak and average speed during a post-practice bout of match-play. Such characteristics are desirable and represent an enhanced playing ability. Coaches can therefore administer short-term practice sessions for novice players using R or NR drills to equivalent effect, for quick enhancement of tennis match-play court-mobility. Even though drills were completed without a ball in the present study, shot-play confidence is enhanced by practice, most likely due to an increased perceptual ability for wheelchair manoeuvrability. Therefore, ball-to-racket contact is not necessarily required for effective practice. While in general terms, R practice is not required for increased confidence and court-movement, NR practice offers a more stimulating activity environment, with higher peak physiological responses prompted by greater court-movement (distance and speed). These characteristics offer the novice player an ideal opportunity to benefit from an EE associated with optimal health gains. Further work is required to assess the role and importance of R practice in developing competence in transitioning the racket hand from pushing to hitting.

9

General discussion

9.1 Summary of the main findings

Figure 9.1 offers a summary of the main findings within this thesis. These findings from the five experimental studies combine to broaden the knowledge of the sport of wheelchair tennis, particularly with respect to the movement and physiological demands of competitive tennis when played in a wheelchair. It has become apparent that research in this area is important to ensure ongoing participation in a sport which is known to confer positive health effects for those with a physical impairment. Given that PA participation is low in wheelchair users (Ginis et al., 2010b), this is of particular importance. Studies 1 and 2 examined the validity and appropriateness of data logging technologies for wheelchair tennis court-movement quantification. Study 3 profiled match-play characteristics, enabling a greater understanding of the demands of the sport at different playing levels, and drawing distinctions between HIGH and LOW player groups. Finally, experimental studies 4 and 5 examined the effectiveness of interventions to increase court-movement and consider the physiological consequences of such.

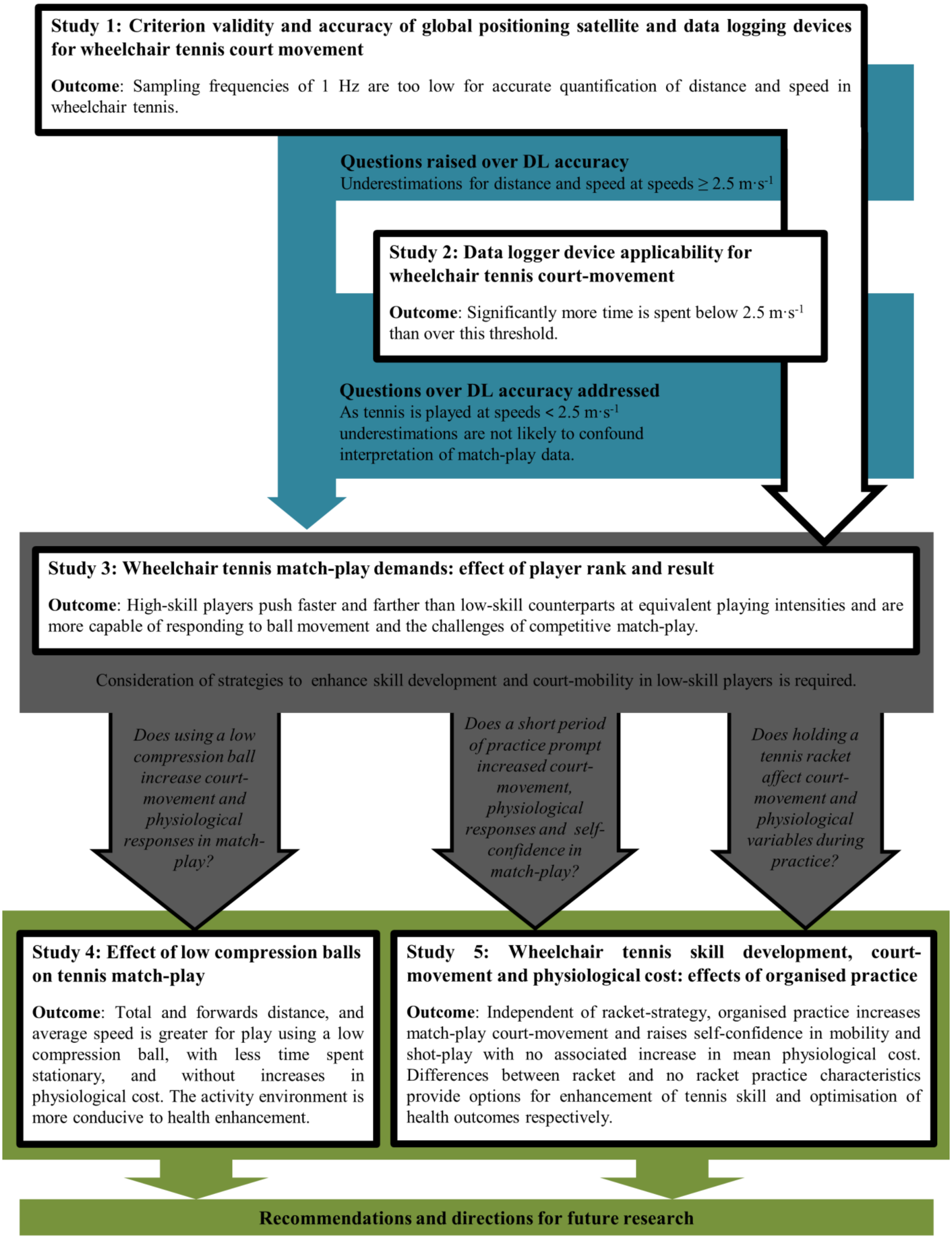


Figure 9.1 Schematic representation of thesis content and outcomes

9.2 Contribution to scientific understanding, practical applications and implications for the sport of wheelchair tennis

9.2.1 Insights into quantification of wheelchair tennis court-movement

This thesis has provided much needed insight into the applicability of the DL for quantification of court-movement for wheelchair tennis. What is clear is that the DL device demonstrates good validity (Chapter 4) with simultaneous testing of two DL devices during fixed-speed, 500 m treadmill testing revealing similar values for distance over repeated trials at speeds consistent with wheelchair tennis match-play (95% CI: 499 to 505 *vs.* 503 to 508 m). TE was low and similar in both devices (TE, CV: 0.3 to 2.1 m, 0.1 to 0.4 %), showing good intra-model reliability (Chapter 4). It is encouraging that general appropriateness for wheelchair tennis court-movement quantification has been confirmed (Chapter 5). However, questions have been raised in this thesis regarding DL accuracy and reliability at high speeds (Chapter 4). This is a notable outcome given that the device has been used in a breadth of wheelchair sports for movement quantification, some of which are commonly associated with higher average and peak speeds than are seen in tennis, with elite wheelchair rugby players reaching peak speeds approaching 4.00 $m \cdot s^{-1}$ (Mason et al., 2014a). However, LOW wheelchair tennis players and skilled wheelchair users with no tennis playing experience spend no time (Chapter 5) and < 1 % of total time (Chapter 7) above the reported threshold for accuracy respectively. Therefore, its use is justified in studies sampling novice and relatively low-skill groups, which are the target population group for recommendations from this thesis.

GPS has been used for the collection of distance and speed in AB team sports (Coutts & Duffield, 2010; Petersen et al., 2009; Edgecomb & Norton, 2006) and therefore offers an alternative to the DL. However, this thesis identifies underestimations for distance and speed in a 1-Hz unit during five out of six tennis-specific drills (Chapter 4). The tennis court is a confined space and players turn frequently. This poses a problem for the GPS which measures the sum of chords in accordance with a predetermined sample rate. Use of a higher sample rate would theoretically enable more accurate determination of court-movement variables in wheelchair court-sports. However, this proposition remains to be proven. Underestimations have been reported for units sampling at 5-Hz in court-sports drills (Duffield et al., 2010) and while preliminary findings indicate that a sample rate of 10-Hz allows for highly accurate distance with only slight underestimations (Castellano et al., 2011), testing was limited to linear motion (15 to 30 m running) and trained male AB athletes. Hence, conclusions on the applicability of high sample rate GPS units for wheelchair tennis movement assessment should be reserved for further study. A further consideration is that many wheelchair tennis events are held indoors. GPS only works outdoors and hence, while greater accuracy may be gained from higher sampling frequencies, the technology does not necessarily offer a practical alternative to the DL. Therefore, at present, and based on the combined evidence offered by this thesis and existing literature, the widespread use of low sampling frequency GPS for court-movement quantification in wheelchair court-sports is not currently advocated.

In contrast to GPS, which operates at a predetermined frequency, DL sample rate is related to reed switch activation. Switches are triggered with wheel rotation and a time stamp is created, with an averaging interval selected for data reporting. While no distance and mean speed differences exist between 1-s and 5-s averaging intervals, 1-s averaging has been considered advantageous for peak speed determination in wheelchair rugby (Mason et al., 2014a). However, decreasing the averaging interval may confound conclusions made around percentage time spent stationary during tennis. Lack of reed switch activation in any one second would be deemed zero movement (0 $m \cdot s^{-1}$). Nevertheless, values of 0 $m \cdot s^{-1}$ could be reported during chair movement. This would be the case if it takes longer than 1-s for the DL pendulum to strike consecutive reed switches. Such movement is likely to be very slow (i.e. coasting) and not within the propulsion phase. Therefore, inferences made about proportions of inactive time and the resultant physiological demand are most likely to be accurate in this thesis. In earlier works (Chapters 4 to 7), a 5-s averaging method was employed. The rationale for this was that no reed switch activation in a 5-s time period is more likely to be consistent with zero chair movement. In contrast, a 1-s averaging method was employed in Chapter 8. This decision was made to align with novel findings as they became available (Mason et al., 2014a). Therefore, comparisons between this and previous works should be treated with caution, with potential for higher estimations of stationary time in more recent work (Chapter 8). It should be noted however, that adjusting the averaging interval will not enhance device sensitivity. So the challenge remains, to find an acceptable averaging interval where DL devices are used for determination of peak speed and time spent stationary within a research design. An acceptable approach would be to remove outliers using a mathematical method, as was completed in Chapter 8 (Grubbs, 1969). Combining no- and low-movement to form a hybrid category is also an option. For example, Mason et al. (2014) stratified all observations < 20% peak speed as 'very low' activity. This may be a useful strategy where researchers are not concerned with quantification of the zero movement aspect.

9.2.2 The requirement for development of skill and court-mobility in novice groups

Enablers for player development in tennis are ongoing passion, persistence, competitiveness, and effort (Crespo & Reid, 2007). Hence, participation must be motivationally stimulating and conducive to player improvement. Chapter 6 of this thesis presents clear distinctions between HIGH and LOW player groups which strongly suggest that the former are more capable of producing purposeful court-movement without altering physiological cost. Hence, there is a requirement for enhancement of skill and competence in LOW, particularly with respect to tennis-specific task-oriented activities, to enable ongoing player development and satisfaction in sporting participation. According to coaching theory, task-based activities are more conducive to enhancing perceived satisfaction than ego-driven activities (Reinboth & Duda, 2006). The former emphasise effortful involvement over outcome, and are focused on personal improvement, while the latter emphasise performance compared to normatively-referenced high ability. Task-oriented tennis activity enhances motivational climate and enjoyment more than ego-driven activity (Crespo & Reid, 2007; Balaguer et al., 1999). Hence, competitive match-play with no training or prior task-based practice, where the only reference point is a more experienced, highly-skilled opponent is likely to be an unsuitable starting point for a novice.

This thesis identifies that HIGH cover greater distances at higher speeds than LOW (Chapter 6), with a likely association between greater court-movement and enhanced court-positioning for shot-play in HIGH. Competence is associated with greater adherence in sports, and is more likely to maintain exercise behaviour than extrinsic motives such as the desire to enhance physical appearance (Ryan et al., 1997). Therefore, to maintain ongoing participation, match-play against an opponent with an equivalent playing standard should be encouraged. From a practical perspective, those responsible for promoting the sport to the public should emphasise the message of recreational, as opposed to highly competitive, tennis play. Further, additional preparation and task-based practice to enhance competence is likely to be very useful, ideally from the very start, when players are new to the sport. Such an intervention is likely to enhance confidence in basic court-mobility and shot-play which is of considerable importance given that addressing low confidence in manual wheelchair use is likely to lead to increased participation (Sakakibara et al., 2013a).

9.2.3 Interventions to enhance participation for novice players

Prior to the completion of this thesis, experimental evidence comparing play using modified compression balls was limited to three studies, with associations made between an LCB and an increased rally speed, lower ball strike, more balls played at the net (Kachel et al., 2015), greater rate of skill development, longer rallies and an extended playing time (Hammond & Smith, 2006; Cooke & Davey, 2005). However, as studies sampled AB individuals (mostly elite or highly experienced) for reference to AB tennis, comparisons to wheelchair users were problematic (Section 8.2). Also, physiological data were not available. Consideration of differences between ball-type for court-movement and resultant physiological demands in the current thesis indicated greater distance and average speeds were associated with the LCB (Chapter 7). Therefore, a case has been made for advocating the LCB for novice play. While increased movement activity would normally be associated with an increased physiological cost, this phenomenon was not observed in experimental investigations. Therefore, while the LCB increases movement activity, additional court-coverage is not sufficient to elevate HR beyond levels associated with play using an SCB. There are many factors that may have contributed to this outcome. For example, if participants found it more difficult to serve with the SCB, this would inevitably mean less time moving the chair, due to the requirement for repeated attempts at service (which involves the chair being stationary). This is an issue in terms of creating an environment which is conducive to health-enhancement as irrespective of ball type, the relative exercise intensity was light (HR: 57 to 63 %; $\dot{V}O_2$: 37 to 45 %, Chapter 7) according to established AB guidelines (ACSM, 2011). Time spent stationary, or at very low activity levels, is a consideration in the degree to which a sport offers potential for health-enhancement. Relatively low exercise intensities (~ 30 to 40 % HR reserve) are insufficient for improvements in propulsion technique and therefore, more effective interventions are required for inactive people with an SCI (van der Scheer et al., 2015b). As stated previously (Section 2.3.2), HR is influenced by lesion level in SCI, with potential for blunted submaximal and peak responses. Nevertheless, exercise intensity can be determined with relative ease and with appropriate accuracy using a simple calculation (200 $b \cdot min^{-1}$ – age, Lockette & Keyes, 1994). Recreational wheelchair tennis players and / or tennis coaches can use this formula to ensure appropriate exercise intensities. This thesis reports that LOW are stationary for longer and spend more time at relatively low speeds (< 1.00 $m \cdot s^{-1}$) than HIGH counterparts (Chapter 5). Faster speeds are associated with greater EE during wheelchair propulsion (Conger et al., 2015) and this is of interest given that an important goal of PA is to maximise EE for chronic health gains. This is of further importance given that wheelchair-specific fitness attributes (i.e. anaerobic work capacity, isometric strength and $\dot{V}O_{2peak}$) of inactive people with SCI are low (van der Scheer et al., 2015b).

A likely mechanism for prolonged stationary periods in wheelchair tennis is that players are focused on technical aspects such as shot-play and the service stroke in developmental phases which yields them less able to respond to ball movement. For repeated success in the service strike, a consistent projection angle is required (Whiteside et al., 2013). Given that shoulder joint kinetics vary according to level and severity of SCI (Reid et al., 2007b) and service velocity is affected by impairment severity (Cavedon et al., 2014), this shot-type is challenging for all wheelchair tennis players, but clearly poses the greatest problem for the novice. Further, competence in wheelchair skills is typically low in the period between discharge and one year after rehabilitation (Fliess-Douer et al., 2013) and more specifically, player ability to hold the racket whilst pushing is not well developed; this is known to be a performance constraint with a negative impact on speed and acceleration (Goosey-Tolfrey & Moss, 2005). Propulsion technique is also mechanically inefficient in the early stages of motor learning (Vegter et al., 2013). It is therefore encouraging that experimental studies in this thesis reveal a strong effect for increased movement activity in the LCB, as coupled with further developments in skill, competence and elevation of the exercise intensity, play using this type of ball is likely to confer favourable effects. Chair skills are not likely to develop through everyday manual propulsion alone (Fliess-Douer et al., 2013) and tennis using an LCB may provide this stimulus. Both red (Chapter 7) and green (Chapter 8) LCB's were used in the present thesis in accordance with ITF stance on use of modified balls when respective study designs were conceptualised. Specific between-ball differences in court-movement and physiological cost have not yet been considered. While study in this area sits outside of the scope of the present thesis, it is a legitimate line of enquiry and is therefore worthy of consideration in further research designs.

While evidence suggests that both wheelchair tennis practice (Barfield et al., 2009) and match-play (Barfield et al., 2009; Abel et al, 2008) conditions are conducive to health enhancement, studies have not used novice wheelchair tennis players. Mixed-sex samples (Barfield et al., 2009) have included wheelchair tennis players, but with high variability in playing experience (up to 20 years) or have targeted highly skilled athletes exclusively (Abel et al., 2008). Therefore, a developing priority in the present thesis was to consider the effects of practice for novice players to determine if a task-based intervention was advantageous for increasing court-movement, and thereby enhancing court-mobility, skill, self-confidence and shot-play. Additionally, practice would hopefully stimulate increases in physiological demands which in turn, enable participants to play at higher exercise intensities and therefore, facilitate desirable health outcomes. Experimental findings from this thesis suggest that only a short bout of pre-practice (~24 min) is desirable for enabling enhanced match-play court mobility, overall and forwards distance, mean peak and average speed, and self-confidence in novice players. These findings are consistent with recent work on the short-term effects of propulsion practice in AB individuals without prior wheelchair experience (Vegter et al., 2015). As these outcomes were independent of practice type, the key message for wheelchair tennis coaches is that players new to the sport undertake some practice prior to taking part in competitive match-play. A short session involving court-mobility drills as used in Chapter 8 would be ideal and could easily be configured into a summer camp or wheelchair tennis taster day. Pre-preparation in this manner will ensure greater competence and court-coverage in match-play without associated increases in physiological cost through appropriate technique development. Interventions that develop skill and confidence without influencing physiological demands are ideal given that lower subjective ratings of pleasure are associated with elevated exercise intensities (i.e. above lactate threshold and the onset of BLa^- accumulation, Ekkekakis et al., 2011).

A considerable strength of this thesis was that further between-group comparisons were made between R and NR practice to examine court-movement and physiological differences between modes. Lower court-movement for R practice resulted in lower peak physiological responses and a less energetic environment (Chapter 8) than NR practice. This outcome supports the notion that the racket is a constraint which impinges on player ability to move around the court, and limits the peak physiological response. That said, an EE of 4.0 (1.6) and 5.9 (2.6) $kcal \cdot min^{-1}$ for R and NR tennis practice respectively (Chapter 8) exceeds the EE associated with manual wheelchair propulsion (~3.3 $kcal \cdot min^{-1}$, McCormick et al., 2016) and therefore both modes afford significant potential for health enhancement. As players continue to play the sport, both R and NR practice is likely to be useful, but for different purposes. Due to a higher peak physiological response during NR practice, this type of session will be useful for developing aerobic fitness, both for health and performance improvements. Further, NR training is associated with a greater percentage time in the faster speed zones (2.00 to 2.99 $m \cdot s^{-1}$, Chapter 8). Greater percentage time in faster speed zones is a characteristic of HIGH (Chapter 6) and is therefore a development priority for LOW. In contrast, R practice may be useful in facilitating mastery of individual racket-holding strategy, which in turn should enable improvements in the specific action of chair propulsion for tennis. However, caution should be noted with this assumption due to the factors outlined in Chapter 8. Nevertheless, in practical terms, neither approach should be ignored nor advocated exclusively. Coaches should therefore ensure that appropriate balances of practice-modes are prescribed into novice development programmes and periodised plans.

9.2.4 Directions for future research: a commentary

The main objective of this thesis was to examine the physiological demands of match-play performance based on court-movement. Hence, measures and performance variables were selected accordingly. However, in the latter stages, it became obvious that considerable value would be added with quantification of psychosocial aspects of participation, and hence, a psychometric tool to measure self-confidence was administered (Foulon et al., 2013). This was of particular interest as the thesis evolved to examine skill-based aspects of performance which were considered to be linked with novice participation and development. While the tool was appropriate to enable a base assessment of self-confidence in court-mobility and shot play, questions were limited to only five aspects, with responses given on a seven point Likert scale using fixed anchors. Also, ambiguous terminology (e.g. 'front-hand swing') may need adjustment for complete understanding. Developing the scope and type of questioning is therefore required in future studies to enable a greater understanding of the important area of tennis-specific self-confidence. Also, questioning should be extended to include enjoyment motivation, which is an important yet under-researched consideration currently. Fun and enjoyment is inextricably linked to participation in young people (Goudas and Biddle, 1993) and has been cited as a key driver for post-SCI sports participation in wheelchair users (Tasiemski et al., 2004). That said, nothing is yet known about the link between enjoyment and ongoing participation in wheelchair tennis and this remains an important area for investigation. A visual analogue scale (VAS) is a popular means to quantify psycho-physiological state with precision, with good validity and reliability reported for mood state (Cella and Perry, 1986), pain (Gallagher et al., 2002) and fatigue (Wolfe, 2004). Inclusion of psychometric assessment into future designs using the VAS would allow for more precise and accurate data identifying the psychosocial drivers behind different types of tennis participation (practice and match-play conditions).

The present thesis involved collection and analysis of court-movement variables. This ensured that studies remained focused and scalable. While outside the scope of the current thesis, an important area for further research is movement aligned to court-position and shot-play. Notational analysis of percentage time in pre-defined court areas and shot type allied to shot outcome (i.e. forehand winner, backhand loser etc.) will add to existing knowledge in defining the characteristics of play and performance. A notational profile of this type has been published for AB tennis (Filipčič et al., 2008), and wheelchair basketball (Goméz et al., 2014) but no equivalent exists for wheelchair tennis. Further, notational profiles have not been used to make distinctions between performance using balls of different properties. This thesis advocates the use of an LCB for novice wheelchair tennis players, with greater court-movement at no additional physiological cost. However, different LCB variants exist, with varying compression ratings [ascending order: red (25%), orange (50%) and green (75%)] (Tennis Australia, 2016). While the green ball is advocated for novice wheelchair players (Dyrbus, 2012), limited work has been completed to explore the differences between ball types and the implications of their use. Consideration of the interplay between court-movement, physiological responses and key notational aspects (i.e. shot type, number of bounces, rally duration etc.) for different ball types would add to the existing knowledge that in general terms, use of an LCB is preferable to an SCB for novice players.

Sex-specific differences in stroke dynamics have recently been reported, with AB males able to generate faster ball and movement speeds, flatter trajectories and more effective first serve and serve-returns than females (Reid et al., 2016). However, such findings are limited to AB elite tennis currently. Therefore, it would be of considerable value to extend the evidence on sex- and format-specific differences in wheelchair tennis in future studies. Where groups have been stratified on this basis, for consideration of percentage time in individual speed-zones (Chapter 5), physiological data were not obtained. Further, previously sampled doubles players were highly skilled and female populations were relatively low. Examination of sex- and format-specific differences in physiological responses and court-movement variables would enable a greater understanding of format-specific energy cost and movement demands. Coupling this with psychometric assessment of self-confidence and enjoyment would inform on the preferred mode, and hence support recommendations for the encouragement of long-term participation. Playing doubles tennis requires collective effort, with players working together on the same team, and greater cohesion, satisfaction and reduced competitiveness are associated with shared tasks that promote interdependence (Evans and Eys, 2015). Therefore, investigations concerned with format-specific comparisons should be considered key priority areas for future study. Due to the lack of available literature in this area, sampling strategy could feasibly be aligned to elite, recreational or novice player groups. However, the priority should be on the latter to enable continuation of work completed to-date exploring optimal characteristics for health, performance and skill development in those who are new to the sport.

The rationale for laboratory-testing modality has been discussed in Chapters 7 and 8. In these instances, the arm-crank ergometer was selected over a wheelchair ergometer due to availability (Chapter 7) and appropriateness for testing AB populations (Chapter 8). Between-mode comparisons have been made previously, with acceptable agreement (Tørhaug et al., 2016) and no differences (Martel et al., 1991; Glaser et al., 1980) reported for peak physiological variables. However, arm ergometry is considered more efficient at submaximal intensities (Sedlock et al., 1990) and therefore, exercise intensity (which is derived from the laboratory-based linear regression of HR and $\dot{V}O_2$) may have been underestimated slightly for match-play in a wheelchair in this thesis. Nevertheless, this will not have confounded between-group comparisons made in either of the experimental chapters. While a novel wheelchair shuttle test does not correlate with $\dot{V}O_{2peak}$ (de Groot et al., 2016a), such tests potentially afford greater applicability to tennis movement dynamics and therefore should be further developed and validated with reference to criterion, laboratory-based measures.

An issue in any research design involving wheelchair sport is the size and constituents of the sample. Populations are typically small and heterogeneous (Valent et al., 2007). Also, considerable inter-individual variability exists in wheelchair users' motor technique due to the varying presence of anterior shoulder pain, which develops from repeated pushing (Sosnoff et al., 2015). As carefully selected AB individuals have no experience of wheelchair propulsion, prior technique is not a confounding factor. Also, AB participants can be more easily matched as are not subject to the inter-individual variability caused by impairment-specific factors. Hence, sampling this group is particularly suitable for studies concerned with the rate and / or magnitude of improvement from baseline. While it is not necessarily a prerequisite, larger sample sizes can typically be secured in designs involving AB individuals, often ensuring greater statistical power. In contrast, the requirement for ecological validity should not be overlooked, with research focusing on real-world environments with appropriate participants (Churton and Keogh, 2013). Due to the inclusive outlook of the ITF, and the lack of a stringent classification system, the range of participants who may choose to play tennis is unrestricted and broad. Studies should therefore seek to recruit wheelchair users, particularly in cases where attitudes, perceptions or responses of those with a physical impairment are implicated. Working with such population groups, sport and exercise scientists should consider the extent to which their interventions impact on the player during performance. Therefore, qualitative studies examining player perceptions of monitoring would therefore be useful in determining what is acceptable and appropriate data collection in a performance setting. In summary, research priorities should therefore be carefully considered prior to recruitment, and matched to outcome requirements.

9.2.5 Summary of research priorities

Due to the limited work in the area of wheelchair tennis, opportunities for further research are broad and far-reaching. Therefore, the following list represents a specific focus of action to take following this thesis. Follow-up studies are presented in priority order:

1. Validation of a tool for assessment of wheelchair tennis enjoyment motivation
2. Wheelchair tennis notational analysis
3. Format- and sex-specific differences in wheelchair tennis

It is likely that the outcomes of follow-up studies 1 and 2 will inform choice of measurement variables in follow-up study 3. With respect to the latter, the intention is to measure court-movement and resultant physiological demands, but also a) include key notational aspects (as identified in follow-up study 2) and b) express the link between match-play format and level of enjoyment. Factoring in sex as an independent variable is desirable as preferences may differ between groups.

9.2.6 Closing statement

This thesis identifies key differences between HIGH and LOW player groups for wheelchair tennis match-play performance variables and therefore advocates the widespread use of LCBs for match-play and a period of pre-practice. As such interventions embed basic court-mobility skills and enhance self-confidence without increasing the physiological load, they are ideal for novice players, for whom early development is vital, to stimulate ongoing participation and therefore facilitate chronic health gains.

10

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11

Appendices

Appendix I

The following questionnaire has been developed to assess task-specific self-efficacy in wheelchair tennis (Foulon et al. 2013).

How confident are you in your ability to:

1. *Manoeuvre your wheelchair through a front hand swing*
2. *Manoeuvre your wheelchair through a back hand swing*
3. *Transition the racket hand from pushing to hitting*
4. *Hit the ball before two bounces*
5. *Return the ball to your opponent within a 2 metre radius*

Participants report on a 7-point Likert scale with anchors of 1 (*not at all confident*) to 7 (*completely confident*).