An Investigation into the Energy Demands of Elite and World Class Tennis Players

Daniel Ellis

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores
University for the degree of Doctor of Philosophy

July 2024

Abstract

Professional tennis is a unique sport in which players travel thousands of miles every year in a continual pursuit of ranking points to increases, stabilise, or improved their world ranking position. The accumulation of points leads to a higher ranking, which in turn grants entry into higher level tournaments offering higher points and increased prize money. In a cyclical manner, a player travels, competes until elimination, then travels to the next tournament. During which the player experiences a variety of playing surfaces, environments, and opposition playing styles. Depending on tournament progression, these periods are interspersed with training blocks of varying duration. Despite literature outlining the technical aspects and performance analysis of tennis, the acute physiological impact of point play and physiological characteristics of players, the nutritional requirements are not well understood. No research has investigated the habitual physical demands experienced by the professional player using field-based measurement tools.

The first study examined the energy expenditure of two world class tennis players (one male, one female) competing at the highest level, the Wimbledon Championships, following a week playing at the Eastbourne International tournament. For the first time, in using the gold standard method in doubly labelled water, the total daily energy expenditure (TDEE) of elite tennis was reported. During analysis, the TDEE for the female player was 3383 $\text{kcal}\cdot\text{d}^{-1}$ during the first week and 3824 $\text{kcal}\cdot\text{d}^{-1}$ during the second. Likewise, the male TDEE was 3712 $\text{kcal}\cdot\text{d}^{-1}$ for the first week and 5520 $\text{kcal}\cdot\text{d}^{-1}$ for the second. During energy expenditure measurement, corresponding match data (points played, shot count, distance covered) show the characteristics of match play were reflective of that previously reported at Grand slam level. The study reported that elite tennis played at the highest level is a high energy demanding sport.

In study 2, the player group was broadened to create a wider understanding of the energy demands highlighted in study 1. In doing so, the doubly labelled water technique was once again employed with female players ranked between 100-200 during WTA grass court tournaments, a junior player during International Tennis Federation J1 and Wimbledon Juniors, and a male doubles player during Wimbledon Championships. The TDEE for the male doubles player was 4586 kcal$\cdot$d^{-1} and lower than that of the male singles player measured during study 1. Although less matches were played by the doubles player, a similar amount of points were played between the two players. One female player was injured on day 1. Data collection continued as an opportunity to investigate the energy requirements of injury and early stages of recuperation from surgery showing Total Daily Energy Expenditure of 2583 kcal$\cdot$d^{-1}. Non-injured adult female participants TDEE were 3396 and 3948 kcal$\cdot$d^{-1}, with the junior player TDEE was 3988 kcal$\cdot$d^{-1}. Even with a lower match count than that reported in study 1, energy expenditure was similar for the uninjured female players as that of the female player in study 1. The energy expenditure data of a wider group of players reflected study 1, finding elite tennis to be a highly energetically demanding sport.

In study 3 the player focus was moved to understanding the energy demands and physiological profile of wheelchair tennis. Wheelchair tennis is reliant solely on the upper body for movement of the chair around the court and simultaneous shot execution, requiring high levels of skill in chair handling and tennis ability. In using the doubly labelled water technique with the world number 1 wheelchair player, energy expenditure was captured during a competitive period of the highest level that included Wimbledon Championships and the British Open. During Wimbledon, TDEE was 3118 kcal$\cdot$d^{-1} and during the British Open was 3368 kcal$\cdot$d^{-1}. During training, TDEE was 3177 kcal·d^{-1}. The physiological profile of the player was also investigated to understand this calibre of athlete. In doing so the aerobic capacity, body composition, sprint capability, and the energy requirements of the world number 1 tennis player were reported.

Study 4 focussed on the emerging need to understand the energy demands during the habitual training of elite tennis players. When considering the high energetic demands of competition, it was clear that a need existed to understand further the chronic energy needs of this population. Therefore, the day-to-day training of the elite player was investigated with no adjustment from established routines. A group of 27 (n = 10 male; n = 17 female) elite tennis players were assessed for resting metabolic rate via gas analysis, total daily energy expenditure, and acute tennis training energy expenditure. Using Actiheart wearable technology, players were analysed over a 2-to-5-day period. Results reflected the outcomes experienced during competition, confirming elite tennis as a high energy demand sport. The measured male TDEE was 4708 ± 583 kcal·d^{-1} and female was 3639 ± 305 kcal·d^{-1}. While a significant difference between male and female players was reported, a relationship between energy expenditure and resting metabolic rate was seen. Nonetheless, a broad spectrum of variability was documented.

This thesis serves to inform the energy demands of elite and world class tennis for the first time. During competition played at the highest level, the technique of doubly labelled water was employed, whereas during training the Actiheart activity monitor method was employed. The presented data now characterises elite tennis as a highly demanding sport in terms of energy expenditure (60 - 90 kcal·kg^{-1} FFM). Additionally, a theme emerged that showed the need for individual analysis.

Acknowledgments

Firstly, I would like to express my deepest gratitude to my Director of Studies, Dr. Tim Donovan. Since meeting during my undergraduate degree at Glyndwr University 10 years ago, Tim has been a constant source of encouragement and support… from cycling to tennis research, Tim's unwavering belief in my abilities have been instrumental in shaping the last 10 years, thank you. I would also like to thank my second supervisor Professor Graeme Close, for his guidance and support during this research. His expertise, patience, and mentorship throughout have been invaluable. I am also thankful to my third supervisor Professor James Morton, for his insightful feedback and constructive criticism, which have greatly enhanced the quality of this work.

I extend my appreciation to the Lawn Tennis Association for supporting this research and express my thanks to all the tennis players who generously contributed their time to the studies, without them this thesis wouldn't exist.

I would like to dedicate this thesis to my family; My wife Louise for her love, encouragement, and understanding during this challenging 10-year journey. My sons Zac and Maxwell, boys.. anything is possible with determination and hard work. My mother Anne for her steadfast support and encouragement. My late father Dudley, whose memory remains a profound source of motivation for me to strive and make him proud. Also, my late Grandmother... a tennis fan who didn't get to see me have a 'proper job'.

Declaration

I declare that the work in this thesis, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own and was carried out in accordance with the regulations of Liverpool John Moores University. Additionally, all attempts have been made to ensure that the work is original, does not, to the best of my knowledge, breach any copyright laws and has not been taken from the work of others, apart from the works that have been fully acknowledged within the text. Moreover, no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Publications

Ellis, D. G., Speakman, J., Hambly, C., Morton, J. P., Close, G. L., Lewindon, D., & Donovan, T. F. (2021). Energy Expenditure of a Male and Female Tennis Player during Association of Tennis Professionals/Women's Tennis Association and Grand Slam Events Measured by Doubly Labelled Water. *Medicine and Science in Sports and Exercise*, *53*(12), 2628-2634.

Ellis, D. G., Speakman, J., Hambly, C., Morton, J. P., Close, G. L., & Donovan, T. F. (2023). An Observational Case Series Measuring the Energy Expenditure of Elite Tennis Players During Competition and Training by Using Doubly Labelled Water. *International Journal of Sports Physiology and Performance*, *18*(5), 547-552.

Ellis, D. G., Speakman, J., Hambly, C., Cockram, A., Morton, J. P., Close, G. L., & Donovan, T. F. (2023). Case-study: Energy expenditure of a world class male wheelchair tennis player during training, Grand Slam and British Open Tournaments Measured by Doubly Labelled Water. *International Journal of Sports Science & Coaching*, *19*(2), 857-863.

Ellis, D. G., Morton, J. P., Close, G. L., & Donovan, T. F. (2024). Energy expenditure of elite male and female professional tennis players during habitual training. *International Journal of Sport Nutrition and Exercise Metabolism, 1*(ahead of print), 1-7.

List of Abbreviations and Acronyms

Abbreviation	**Term**
AB	Able body
ATP	Association of Tennis Professionals
AU	Arbitrary unit
BM	Body mass
BMI	Body mass index
BPM	Beats per minute
CI	Confidence interval
CHO	Carbohydrate
CNS	Central nervous system
CV	Co-efficient of variation
DW	Dry weight
DLW	Doubly labelled water
EA	Energy availability
EE	Energy expenditure
FFM	Fat free mass
G	Grams
H	Hydrogen
HR	Heart rate
HRM	Heart rate monitor
$\mathbf{HR_{max}}$	Maximum heart rate
ICC	Intra class correlation
ISAK	International Society for the Advancement of Kinanthropometry
ITF	International Tennis Federation
Kcal	Kilocalorie
kg	Kilogram
km	Kilometre
L	Litre
LEA	Low energy availability

m Metre
mm Millimetre
m·s Meters per second
MD Match day
mg Milligram
mmol Millimole
O_2 Oxygen
PAL Physical activity level
PCr Phosphocreatine system
P1 Period 1
P2 Period 2
P3 Period 3
RDA Recommended daily allowance.
RER Respiratory exchange ratio
RMR Resting metabolic rate
RPE Rate of perceived exertion.
RPEs Rate of perceived exertion per session
RPI Reciprocal ponderal index
TDEE Total daily energy expenditure
TEF Thermic effect of food
VCO_2 Volume of Carbon Dioxide Produced
VO_2 Volume of Oxygen Consumption
VO_{2max} Maximal Oxygen Consumption
µl Microlitre
WT Wheelchair Tennis
WTA Women’s Tennis Association

List of tables

List of figures

Chapter 1 - General Introduction

1.1 Background

Tennis is a sport played world-wide and spectated by millions of people, with an almost continual schedule of competition throughout the calendar year. The Olympic tennis events and the four Grand Slam tournaments are considered the pinnacle of the sport and are played across grass, clay, and hard-court surfaces. During a Grand Slam schedule, successful players can expect to play seven matches (typically ranging in duration from 1 – 5 h) within a two-week tournament (Kovacs, 2018; Kovacs, 2006). Recovery time between matches is generally 24 – 48 h but is influenced by player schedules (participation in both singles and doubles) as well as delays to the match start times, the result of which could mean participation in multiple matches in a single day.

In considering the intermittent activity profile, tennis is characterised by accelerations, sprints, rapid changes of direction, decelerations, and prolonged rallies, with the maximal recruitment of musculature during shots and strokes (Christmass et al., 2010; Fernandez et al., 2006; Reilly & Palmer, 1995). A diverse range of physical movements involved in the intricacies of ball serving and return mean the physical requirements of tennis span both anaerobic and aerobic energy pathways, relying on the entire energy continuum (Kovacs, 2006). Bouts of match activity are interspersed with recovery periods between points (<20 s), changeovers (90 s) and at the conclusion of each set (120 s), in accordance with rules set by the International Tennis Federation (ITF) (International Tennis Federation, 2019). Depending on the playing surface, player style and sex, the active periods or effective playing time during a match are found to be between 10 – 30% of total match time (Fernandez et al., 2006). The individual characteristics of each playing surface (friction during ball to surface impact affecting ball speed and bounce trajectory) can influence match play and style, impacting the shots played per point, the locomotive demands, and therefore the intensity of active periods (Miller, 2006; Reid et al., 2016; Reid & Duffield, 2014).

Players compete in singles and/or doubles (paired team) matches in both the able body and wheelchair categories. Singles play involves longer rallies and increased court coverage, whereas doubles play sees a greater number of rapid reactions and shorter explosive movement (Martínez-Gallego et al., 2020, 2021; Morgans et al., 1987). However, the wheelchair format differs with less play occurring at the court net, resulting in longer rallies compared with wheelchair singles play. A constant pursuit for ranking points, in a year-round schedule, means players are faced with 50 to +100 matches annually, spread across multiple tournaments, countries, and time zones. Resulting in a cyclical lifestyle of training, travel, and competition with little downtime, dictated by point accrual. Greater points result in superior ranking, better tournaments, and therefore higher financial reward.

At the highest levels of tennis (world top 5), a player may travel with a coach, physiotherapist, doctor, and physical trainer. Based on financial capabilities or perceived priorities, a player within the top 100 world ranking will typically travel with a coach and, occasionally, a physiotherapist or physical trainer. Some players might benefit from support, knowledge, and expertise provided by their national federation or private academies in coaching, sports science, and medicine, which encompasses nutrition. Beyond these resources, coaches or employed physical trainers conduct individual needs analyses to determine player physical and nutritional requirements. However, this process introduces a potential risk of individual biases influencing the interpretation of results and the subsequent delivery of advice.

If a player lacks support or engagement with their national federation nutritionist, they may source external support, or rely on information obtained through personal research (Blogs, podcasts, social media), coach beliefs, or peers. This can inevitably result in confusion or an inappropriate nutritional approach. Currently, a limited amount of research has been conducted to determine the nutritional requirements of elite tennis, making it difficult for the practitioner to make any evidence-based planning. Research to understand macronutrient function and contribution during exercise can help guide recommendations, although the quantity (energy) required by the elite tennis player remains unknown. When considering the competitive and training calendar of an elite tennis player, it becomes clear the need to understand the energy requirements of this population.

From muscle biopsy to global positioning systems, advances in measurement techniques and methods mean the physiological, nutritional, and tactical demands are now equipping support staff with the information needed to develop and progress the athlete towards their competitive potential. Understanding the daily demands of a full-time professional athlete are imperative to successful preparation, performance, and recovery during a competitive schedule. This growth and development within sport science has resulted in many of the physical demands of various professional sports being well understood. Nevertheless, the intricacies specific to tennis render it a challenging sport to study in the field, particularly at the highest levels. Factors that make tennis difficult to study during match play at the elite level include, but are not limited to;

1. Sporting rules meaning activity monitors, are currently not permitted in competition.

2. Data collection is deemed an unwanted interference to the player during match play.

3. As tennis is an individual sport, outside of National federations, few organisations exist that have funding to support such investigations and as such research using credible validated techniques is significantly lacking.

In the laboratory setting, aside from isolated biomechanical analysis (e.g. serve, footwork), tennis in inherently difficult to research due to the inability to recreate the demands of competition within such an environment. Likewise, conducting field-based simulation studies produce limitations due to their inability to truly capture the variability seen within a tennis match. However, developments in player tracking technology (e.g. Hawk-Eye) utilised at the higher levels of competition have begun to quantify the physical locomotive demands experienced during competition and is a continually progressing area. From a nutritional standing, it is imperative to ascertain the demands encountered by elite athletes throughout the ongoing cycle of competitions and training to support both performance and health. This necessitates conducting high-quality research with substantial translational potential. As previously highlighted, the chosen method should align with competition regulations, ensuring minimal disruption and maximum benefit to the athlete.

1.1.2 Aims and objectives

Recently, a focus within sport nutrition research has begun to understand the deleterious effects of low energy availability can have upon an athlete. Subsequently, a range of sports have now been investigated to determine their energy requirements at the highest levels. However, to date no data exists that determines the energy requirement of professional tennis. When considering the continual, almost year-round calendar, that players embark on whilst endlessly chasing ranking points in this nomadic individual sport, it becomes clear that this is a sport that requires the accurate analysis of the nutritional requirements. While tennis activity (match play simulations) itself has been investigated, this does not truly capture the continual demands of competitive match play at the elite level, on-court training drills, gym sessions, prehab exercise and any other habitual activity that a full-time professional tennis players encounter.

Therefore, the over-arching aim of this thesis is to determine the daily energy expenditures experienced during high level competition and daily habitual training in elite (McKay et al., 2022) male and female tennis players.

To achieve this over-arching aim, the thesis is separated into four separate research objectives;

Objective 1. To evaluate the energy expenditure of an elite male and female elite tennis player during high level competition using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition. Determine match play characteristics (distances covered, shot counts) to ensure the demands during data collection are reflective of existing literature.

Objective 2. To evaluate the energy expenditure of a broader range of elite players. Participants to include lower ranked senior female players, junior female player and male doubles players. Data collection will involve high level competitive period that is relative to the player ranking using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition.

Objective 3. To determine the demands and energy expenditure of elite wheelchair tennis. Data collection will profile a world class player by assessing physiological and performance capacities relevant to the sport. Assessment will include internal, and externals loads during match play, in addition to energy expenditure using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition.

Objective 4. To evaluate the training energy expenditures encountered by able body elite tennis players during daily habitual training. Assessment will characterise daily energy requirements, in addition to acute on-court tennis training demands using a method of minimal interference to the participants.

Chapter 2 - Literature Review

2.1.1 Background

The early precursor to tennis of the modern era was Real Tennis, a game played on hard surfaces which became popular with French and British royalty with the first ‘real tennis’ court built at Hampton Court, London which still stands today (ITF, 2019). When ‘real tennis’ was played on grass, it became known as field or long tennis which evolved into today’s ‘lawn tennis’. In 1875 court modifications were made and official rules confirmed before the sport was adopted by what is currently known as the All England Lawn Tennis and Croquet Club, located in Wimbledon, London. In 1968 the open era began, allowing professional and amateur players to compete against each other at Grand Slams. Prior to the open era, only amateur players were permitted to play in established events and grand slams, with no prize money available. Professional players played separate tournaments and majors, namely the Wembley Championship, the US Pro Tennis Championships, and the French Pro Championships. Grass courts continued to be used in most tennis tournaments, including three of the Grand Slams, until the early 1970s, with the Australian Open switching from grass in 1988. Currently, tennis is commonly played on indoor and outdoor hard acrylic, outdoor grass, indoor and outdoor clay, and indoor carpet surfaces.

2.1.2 Competitions

Honours are competed under the ruling of the International Tennis Federation (ITF) from entry level competition for juniors, seniors and wheelchair players, to the major competitions i.e. Grand slams. The ITF oversees the Women's and Men's World Tour series, offering entry and mid-level competitions on a global scale (*ITF*, 2024) Additionally, the ITF manages the Junior World Tennis Tour for players aged 18 and under, as well as the Wheelchair Tennis Tour. The ITF also holds organisational responsibilities for the four Grand Slam tournaments. When progressing from the lower grade ITF tournaments, able body male and female players begin to compete in tournaments run by The Association of Tennis professional (ATP) and Women's Tennis Association (WTA) respectively.

The professional tennis tour operates nearly year-round, featuring tournaments held globally. Players participate continuously, aiming to accumulate ranking points. As players amass more points, their rankings improve, granting them access to higher-tier tournaments with increased prize money. Points achieved through a calendar year then need to be equalled or surpassed the following year to maintain or progress ranking. The 64 tournaments on the ATP calendar currently visit 31 countries in formats with following point values Challenger (50, 75, 100, 125, 175), ATP 250, ATP 500, Masters (1000) or Grand Slam (2000) point format (ATP, 2023). Likewise, the 58 WTA events visited ~30 countries in 2023 and using a similar points format International (280), Premier (470), Premier 5 (900), Premier Mandatory (1000), and Grand Slams (2000) (WTA, 2023). In addition to Olympic events, upon selection, players can represent their country in a team format competition the Billy Jean King Cup (women's) and Davis Cup (men's).

The Olympic tennis events and the four mixed Grand Slam tournaments are considered the pinnacle of the sport, namely (I) Australian Open played on Blue Greenset hard courts, (II) French Open played on red clay courts (III) Wimbledon played on grass courts and (IIII) US Open played on Decoturf hard courts (ITF, 2023). Current day Grand Slams include tennis played by male and female singles, male and female doubles teams, mixed sex doubles teams, and male and female wheelchair singles and male and female doubles teams. Grand Slams also host junior male and female singles, and male and female doubles tennis.

The grand slam surfaces are reflected throughout the professional tennis tour, although manufactured and prepared by various companies. It is widely known that each court surface type can influence game style, point duration and shot count, in addition to the players physical responses (Girard & Millet, 2004; Murias et al., 2007; Sánchez-Pay & Sanz-Rivas, 2021). Court ‘speeds’ are classified by ITF court pace rating (ITF, 2023). A factor primarily influenced by the shock absorption and friction characteristics of the court, subsequently impacting ball bounce height and speed reduction following impact (Miller, 2006). For instance, while grass is categorised as a medium fast and fast-speed surface, elite players subjectively note that the speed of the surface can vary based on the surface preparation leading into the tournament. However, (Miller, 2006) highlights that grass courts produce a lower bounce of the ball, a factor which players may perceive as ‘a fast surface’. Hard court speed can vary depending on the age of the surface, with players reporting newer courts to be abrasive initially, a characteristic that can slow ball speed during bounce. Similarly, the softer and abrasive surface of clay also impacts ball bounce and speed. Therefore, it is understandable that the individual characteristics of each playing surface (friction during ball impact slowing speed and affecting bounce trajectory) can influence match play and style, impacting the ‘work’ durations and the locomotive demands (Brody et al., 2002; Girard & Millet, 2004; Thevenet et al., 2011).

Environmental factors are also varied. Players can experience high temperature, and humidity, that affects the physiological response to exercise (Bergeron, 2003; Périard et al., 2014; Périard & Bergeron, 2014). Exercise in hot environments have seen substrate utilisation shift towards an increased reliance upon carbohydrate relative to oxygen uptake, although attenuated following heat acclimation (Febbraio et al., 1994). A factor that suggests exercise in hot conditions warrants a focus on sufficient carbohydrate intake (Burke, 2001). It is not uncommon for the Australian Open to be played during what could be considered extreme heat (>35 ºC dry bulb). The WTA implemented a heat rule that permits players a 10 min rest period between sets during temperatures >28 ºC wet bulb, in response to The American College of Sport medicine warning of the high risk of heat illness above these temperature (Armstrong et al., 2007). Altitude at some tournament locations (highest being Bogota Colombia, ~2640 m) can also affect ball movement and speed, in addition to the players physiological responses (Girard et al., 2017; Miller, 2006). Although specific “low bounce’ tennis balls have been developed for play at altitude (above 1219 m) (Miller, 2006), players commonly refer to ‘balls hitting the back fence’ at altitude, a reference to the balls appearing to feel lighter. Largely due to the decreased air density at higher elevations results in an increased relative contrast between internal ball pressure and external air pressures. Although it is understood that energy expenditure is elevated (via an increase in resting metabolic rate) at high altitude (3000 m - 5500 m), it is unclear the impact moderate altitude (2000 m - 3000 m) has upon energy expenditure (Stellingwerff et al., 2019).

It is not unusual for the environmental conditions to impact play, delay due to heat rule, or inclement weather on outdoor courts for play to be halted and resumed once conditions have improved. During tournaments, daily ‘order of play’ timetables are issued with a start time (or ‘not before’ start time), opponent and allocated court. Players encounter a challenge when given only an approximate start time, contingent on the completion of preceding matches on their designated court. An accumulation of long matches and/or bad weather can delay the schedule. This can result in late finishes (early hours of the following morning) as some tournaments require matches to be concluded to minimise disruption to the following day’s schedule. In this scenario, a challenge exists when prescribing a pre-match meal at the correct time. The challenge in this scenario is the ability to achieve sufficient energy intake, that is reflective of the played match, in a small window of time prior to sleep.

2.1.3 Game Demands

Not including qualifying rounds (2 or 3 depending on tournament), successful players can expect to complete seven matches of 3 - 5 sets (5 sets only applicable to male players during Grand slams) within a 1 or 2-week tournament with match durations ranging from 1 h to occasionally exceeding 5 h. Depending on the playing surface, player style and gender, actual work durations or effective playing time during a match are found to be between 10 - 30% of total match time (Christmass et al., 1998; Fernandez-Fernandez et al., 2009; Kovacs, 2015; Mendez-Villanueva et al., 2007)

During Grand Slam match analysis, rally durations in women’s singles were seen to be longer (7.1 ± 2.0 s) than men’s (5.2 ± 1.8 s) across all surfaces (O’Donoghue & Ingram, 2001). Average rally durations (Men and Women combined) at the Wimbledon Championships (4.3 ±

1.6 s) have been reported to be significantly shorter than the US Open (5.8 ± 1.9 s), the Australian Open (6.3 ± 1.8 s) and the Roland Garros (7.7 ± 1.7 s) (O'Donoghue & Ingram, 2001). Grass surfaces are classified by ITF as category - 4 medium fast, or 5 - fast (ITF, 2023). The shorter rallies reported for Wimbledon, are reflected in the subjective player reports of Wimbledon Championship courts being 'a fast surface, although slower during the first days of play', presumably due to grass wear with use although no data exists to support these reports. Using Hawk-Eye (Hawk-Eye Innovations Ltd, Basingstoke, UK) player tracking data from the 2012 - 2014 Australian Open, (Reid et al., 2016), found men and women travelled approximately 550 - 575 m per set with women covered 1232 ± 440 m per best of 3 set match and men covered 2110 ± 839 m per best of 5 set match. When using Hawk-eye player tracking data but with a female only focus during 2014 - 2017 Grand Slams, Cui et al., (2018) found distances covered per match are shorter at Wimbledon (1289.28 ± 567.9 m) than the Australian Open (1338.71 ± 571.7 m), the US Open (1423.18 ± 589.1 m) and at the French Open (1452.19 ± 600.2 m). The average shot count per rally during singles match play have been seen to vary between 2.5 - 4.8 depending on surface, sex environment and ball type used but generally fall between 2.5 - 3 (Fernandez et al., 2006, 2009; O'Donoghue & Ingram, 2001).

2.1.4 Anthropometric Characteristics and Game evolution.

Players have become bigger, stronger, and faster athletes, with tennis appearing to have evolved into a power sport build on a foundation of endurance (Fernandez-Fernandez et al., 2009, 2014; Kovacs, 2006). Evident for the tennis spectator when witnessing the evolution of a current elite tennis player's physicality. Observations that were supported by Gale-Watts and Nevill, (2016) when presenting findings on the anthropometric data of successful male Grand Slam players from 1982 to 2011 by using a combination of reciprocal ponderal index (RPI - cm $kg^{-0.333}$) and body mass index (BMI = (kg·m^{-2}). Reciprocal ponderal index is a calculation that incorporates height and weight, providing a measure of linearity and gives an insight into the proportionality of a player's physique. A taller player with increased linearity will have a higher reciprocal ponderal index. While body mass index is considered a marker of adiposity in non-athletic populations, it was used as a proxy for muscle mass in an athletic population. The authors show the muscularity of male elite players have gradually changed to show an increase of BMI and a reduction of RPI, concluding that elite male tennis players have become more power athletes than endurance athletes. Anecdotally the authors provide individual examples of successful players at the time of writing such as Rafael Nadal (BMI = 25.1 kg·m^{-2} and RPI 42.0 cm·kg$^{-0.333}$) and Andy Murray (BMI = 23.2 kg·m^{-2} and RPI 43.5 cm·kg$^{-0.333}$) highlighting their successes have corresponded with an increase in muscularity. Miller, (2006) describes how advances in tennis racket technology has created a lighter racket that can be swung quicker, creating faster, more powerful shots. Potentially a factor involved in the number of aces served by males per match (during Grand Slam, ATP 1000, 500, and 250 tournaments) rising from 4.5 aces in 1991 to 6.7 in 2010 (Filipcic et al., 2015).

No data exists focussing on the evolution of the female tennis player anthropometry, but subjective observations suggest that female players show an increase of muscularity to players of the past (Kuzbud, 2019). Players that won at least one match during the Wimbledon Championships in 2017 were included in a study by Söğüt, (2018) when investigating the impact player stature has on specific match play metrics. Data that also provides an overview of the anthropometirc characteristis of recent male (Table 2.1) and female (Table 2.2) Grand Slam players. It is believed that taller players play a more powerful game, winning more aces, and more points on their first serve, meaning shorter players are required to develop greater court agility (Söğüt, 2019). The impact anthropometry has upon game demands are unknown.

Table 2.1. *Anthropometrics and serve return metrics (mean ± SD) for male players (n = 60) during Wimbledon Championships 2017 taken from Söğüt, (2018).*

Height categories	**>195 cm**	**185 – 195 cm**	**<185 cm**
Age (y)	27.73 ± 4.37	27.30 ± 4.44	29.20 ± 3.96
Height (cm)	198.7 ± 0.03	189.9 ± 0.02	181.6 ± 0.04
Body mass (kg)	90.2 ± 7.90	81.2 ± 5.35	75.8 ± 5.52
BMI (kg·m^2)	22.82 ± 1.64	22.53 ± 1.44	22.97 ± 1.16
Aces per set	4.21 ± 2.33	3.41 ± 1.78	1.81 ± 1.13
1st serve speed (km·h^{-1})	194.40 ± 4.24	186.90 ± 8.63	180.92 ± 10.28
Return points won (%)	34.60 ± 6.08	39.40 ± 8.63	40.12 ± 6.60

Table 2.2. *Anthropometrics and serve return metrics (mean ± SD) for female players (n = 59) during Wimbledon Championships 2017 taken from (Söğüt, 2018).*

Height categories	**>180 cm**	**170 – 180 cm**	**<170 cm**
Age (y)	26.25 ± 4.13	25.08 ± 3.93	27.67 ± 3.87
Height (cm)	182.2 ± 0.02	175.4 ± 0.02	167 ± 0.03
Body mass (kg)	68.77 ± 3.45	64.46 ± 3.97	60.51 ± 3.08
BMI (kg·m^2)	20.72 ± 0.94	20.95 ± 1.35	21.60 ± 1.05
Aces per set	1.82 ± 1.66	1.48 ± 1.07	0.87 ± 0.73
1st serve speed (km·h^{-1})	164.90 ± 7.43	158.25 ± 7.71	153.87± 11.39
Return points won (%)	43.85 ± 5.35	46.25 ± 6.06	50.40 ± 6.99

Brechbuhl et al., (2018) measured the VO_{2max} of 13 females ranked between WTA 132–1211 performed an on-court tennis specific protocol. The VO_{2max} values of 54.9 ± 3.3 $mL·min^{-1}·kg^{-1}$ were seen with a moderate ($r = 0.53$) relationship to competitive ranking, well above the 42 $mL·min^{-1}·kg^{-1}$ that Kovacs, (2006) considers to be a minimum for a female tennis player. Male VO_{2max} data by Banzer et al., (2009) has shown a strong relationship (0.938) between ATP ranking (6 - 97) over 7 y and VO_{2max} (55.0 - 67.4 $mL·min^{-1}·kg^{-1}$) with an average of 61.1 $mL·min^{-1}·kg^{-1}$ across the period. Banzer et al., (2009) concludes that the importance of VO_{2max} to the players performance may be dependent on the players game style. Similarly, to the female data, this is above the Kovacs, (2006) recommendation of >50 $mL·min^{-1}·kg^{-1}$ for male players making the recommendations relevance to an elite population questionable. Although it is questionable if aerobic capacity is a determinant to success in tennis, Baiget et al., (2015) logically conclude that players with higher aerobic capacities play at lower relative intensities. When reviewing existing tennis literature, Ranchordas et al., (2013) collated the participant data across various investigations and methods (gas analysis, heart rate monitoring, match simulations) and can be seen in Table 2.3. However, the participants involved in the studies were of mixed level and not a representation of an elite population.

Table 2.3. *Collated anthropometric and physiological data (mean ± SD) of tennis player participants involved in various investigations that explored the demands of tennis (taken from Ronchordas et al., 2013).*

Sex	Stature (m)	Body mass (kg)	VO_{2max} ($mL·min^{-1}·kg^{-1}$)
Women	1.67 ± .05	59 ± 6	48 ± 3
Men	1.81 ± .09	77 ± 7	53 ± 3

2.1.5 Physiological and metabolic demands

Tennis is a sport of intermittent nature with individual point activity lasting between 5 - 10 s, followed by approximately 10 - 20 s recovery periods between (Fernandez et al., 2006). Tennis is a sport characterised by accelerations and sprints, rapid change of direction and stopping, prolonged rallies, and the maximal recruitment of musculature during shots and strokes. These characteristics suggest a contribution from the complete energy continuum (Christmass et al., 2010; Reilly & Palmer, 1995). Historically, understanding the internal 'load' during official tennis match play has been fraught with difficulty, largely due to the rulings that surround equipment that could be used for live coaching during match play not being permitted. In addition to the intrusive nature of wearing such equipment, or the distracting effect that participation in scientific research may have upon match play. Only recently, have wrist mounted heart rate monitor (HRM) (WTA and ITF matches) and chest mounted HRM (ITF matches) been permitted.

The variability of match durations, playing surfaces, and match play style, are all aspects that have been seen to alter the physiological demands (Girard & Millet, 2004; Martin, et al., 2011). When using a 0 - 10 scale to determine the rate of perceived exertion (RPE), research has found competitive match play to be between 5 - 7 (AU) (Davey et al., 2002; Hornery et al., 2007; Smekal et al., 2001). Mean VO_2 values have been reported as 54.3% and as high as 80.1% of VO_{2max} when measured across a variety of surfaces and conditions but generally fall in a range of 50 - 60% VO_{2max} (Fernandez et al., 2006; Ferrauti et al., 2001; Smekal et al., 2001). Likewise, heart rate data has demonstrated mean values of between 60 - 80% of HR_{max} and in some cases reached over 95%HR_{max} during extended high intensity rallies (Mendez-Villanueva et al., 2007). Such evidence suggests some periods of heightened intensity play are dependant on repeated anaerobic efforts which are supported by a foundation of activity which carries a submaximal aerobic profile (Fernandez et al., 2006). Initial demand for adenosine triphosphate (ATP) is placed on the phosphocreatine (PCr) system. A limited store of PCr within the muscle provides a high-energy phosphate group during the initial ATP requirements of exercise delivering immediate energy but is also depleted rapidly (Mendez-Villanueva et al., 2007). Resynthesis of ATP is initially led by the interaction between phosphocreatine (PCr) and adenosine diphosphate through oxidative pathways. The subsequent contribution of PCr during repeated efforts is dependent on the rate of resynthesis with PCr reductions driving an amplified activation of anaerobic glycolysis with assistance from aerobic glycolysis. An increased aerobic contribution is required with repeated efforts, short recoveries between points, and extended rallies.

The elevated intensities encountered in tennis indicate a preference for the intermittent utilisation of carbohydrate as the primary fuel source, as the rates of fat oxidation fall below the necessary levels to sustain the intensity (Constantin-Teodosiu et al., 2004; Hawley & Leckey, 2015; Romijn et al., 1993). As tennis is an intermittent sport interspersed with periods of high intensity and low intensity a mix of substrates may be required for energy production. At low to moderate intensities, most of the required energy can be provided by a combination of fat from within the muscle (intramuscular triglycerides) and body fat (adipose tissue) and carbohydrate (muscle glycogen and plasma glucose) substrates. As the intensity increases, a greater demand is placed on carbohydrate as the main source of fuel to produce energy. Glycogen is a branched polymer of glucosyl residues, stores of which are relatively small and can be exhausted during prolonged or strenuous exercise (Spriet, 2014). The depletion of muscle glycogen is associated with peripheral fatigue and a reduced capacity to re-synthesise

ATP, with reduced muscle glycogen stores linked with a decrease in muscle function by hampering muscle contraction (Ørtenblad & Nielsen, 2015). As glycogen supplies the majority of energy required during repeated sprints and maximal efforts, indicative of tennis, it is postulated that the depletion of muscle glycogen stores during match play, underpins player fatigue (Hornery et al., 2007). It is widely accepted that during prolonged steady state exercise at a specific intensity, substrate utilisation is generally shifted from carbohydrate oxidation to lipid oxidation. It is also established, that substrate regulation corresponds to the metabolic flux of ATP requirements with glycogen utilised during the early stages of moderate and high intensity exercise through the glycogenolysis pathway (van Loon et al., 2001).

The intermittent (repeatedly from rest or walking, to high intensity) nature of tennis ensures the player does not attain a physiological steady state, implying a continued and repeated reliance on glycogenolysis. Evident in data provided by Ferrauti et al., (2001), displaying an increased metabolic emphasis on glycolytic pathways during tennis compared to steady state running conducted at a matched relative mean intensity. During the early stages of a game, or from a rested position during a change over, the increase of adrenaline, Ca^{2+}, ADP, AMP all contribute to increasing glycolytic flux. Additional increases of adrenaline activate PDH and initiates the conversion of ATP to cAMP, activating phosphorylase kinase (Kjaer et al., 2000). The covalent modification of phosphorylase *b* to its more active form of phosphorylase *a,* is through phosphorylation courtesy of phosphorylase kinase after an increase in the cytosolic level of Ca^{2+} (Brushia & Walsh, 1999). Subsequently, activating glycogen phosphorylase, a key rate-limiting enzyme which is reliant upon P_i and $glycogen_n$ as substrates to produce $glycogen_{n-1}$ and glucose 1-phospate (Chasiotis et al., 1982). The allosteric regulation of glycogen phosphorylase occurs during the attachment of AMP and IMP, competing with ATP or glucose 6-phosphate

(Kjaer et al., 2000; Watt et al., 2001). Therefore, a rise of exercise intensity increases glycogenolysis, due to the increase of ADP, AMP and $P_{i,}$ allosteric regulating glycogen phosphorylase. The intermittent nature of tennis, high intensity bouts to seated rest has been seen to produce repeated increases in catecholamine, subsequently stimulating glycogenolysis and placing a high and repeated reliance on glycogen which may be underestimated by simply considering mean intensity values (Ferrauti et al., 2001).

Since the inception of the muscle biopsy technique by Bergström and Hultman, (1967), glycogen utilisation in a variety of sports, durations and intensities have been investigated. Early work by Saltin and Essen, (1971) found muscle glycogen to be depleted by 20 mmol·kg^{-1} during 30 min of intermittent submaximal cycling for 10s work followed by 20s rest. More recently, Parolin et al., (2013) found muscle glycogen utilization to be 4.04 mmol·kg^{-1} dw·s^{-1} during the initial 6s of a 30s maximal cycling bout. During a 30s maximal sprint running protocol, Cheetham et al., (1986) found a 25% utilisation of muscle glycogen stores. When investigating fibre specific glycogen depletion during 30s sprint running, Greenhaff et al., (1994) found a greater degradation in type II (126.3 ± 15-8 mmol·kg^{-1} dw) than type I (77.0 ± 14-3 mmol·kg^{-1} dw). Whilst exploring sport of an intermittent nature, Saltin, (1973) found soccer players to deplete muscle glycogen stores from 96 mmol·kg^{-1} ww to 32 mmol·kg^{-1} ww by half time and finding just 9 mmol·kg^{-1}ww remaining by full time. Likewise, Bradley et al., (2016) found professional rugby league players to utilise ~40% of muscle glycogen stores during competitive game play.

Following a glycogen depletion protocol and subsequent ~24 h carbohydrate loading phase, Fell et al., (2021) saw no significant reduction in blood glucose but a significant reduction muscle glycogen in participants cycling for 180 min at a fixed intensity at each individual's lactate (La) threshold which equated to 64 ± 3% of VO_{2max}. When considering the data presented by Fell et al., (2021) and the muscle glycogen contribution to high intensity efforts outlined by Romijn et al., (1993) (Figure 2.1) perhaps blood glucose concentration is not a suitable indicator of muscle glycogen levels. Further evidenced by Krustrup et al., (2006), when reporting elevated blood glucose levels throughout a soccer match play despite 50% of the individual muscle fibres being entirely or almost entirely depleted of glycogen following the match. Ferrauti et al., (2001) went on to compare the metabolic and physiological responses to 2 h of tennis match play to that of 2 h steady state continuous running at matched mean intensities (56% VO_{2max} women and 54% VO_{2max} men). The findings showed the contribution of both fat and carbohydrate during both modalities, although a stronger metabolic emphasis for glycolytic and glycogenic activity was seen during tennis match play. Measurements taken through the trials saw significantly higher HR (140 vs 126 $beats{\cdot}min^{-1}$), RER (0.93 vs 0.88), La concentration (1.53 vs 1.01 $mmol{\cdot}L^{-1}$) and blood glucose concentration (5.45 vs 4.34 - $mmol{\cdot}L^{-1}$).

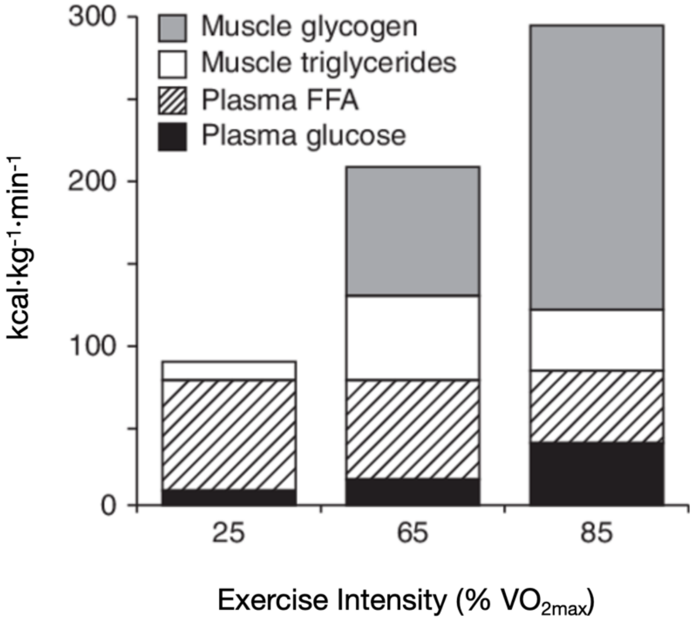


Figure 2.1. *Fuel utilisation in relation the intensity taken from Romijn et al., (1993).*

During glycogenolysis, muscle glycogen provides glucose 6-phosphate, and liver glycogen maintains blood glucose concentrations (Agius, 2015). Therefore, by exogenous CHO maintaining blood glucose concentrations liver glycogen may be spared (Coyle et al., 1986). Several studies have investigated the ergogenic effect of CHO intake during activity and have observed an improvement of stroke quality (Burke & Ekblom, 1984) improved running speed (Ferrauti et al., 1997) serve and return success, and time spend at higher intensities (McRae & Galloway, 2012). During investigations into the supplementation of a 6% CHO drink during 3 h of match play, academy players (18.6 ±1 y) were fed ~8 $g\cdot kg^{-1}\cdot d^{-1}$ CHO, ~2 $g\cdot kg^{-1}\cdot d^{-1}$ protein, 1.58 $g\cdot kg^{-1}\cdot d^{-1}$ fat, a trend for blood glucose to decline was seen although not significant yet CHO intake appeared to maintain blood glucose level compared to the placebo group (Gomes et al., 2013).

If the oxidation of blood glucose is considered the sole fuel source for the central nervous system (CNS) (Nybo, 2003), it logically follows that declining blood glucose levels may impair CNS function, potentially leading to central fatigue. Nybo (2003) found that a reduction in blood glucose during a 180-minute cycling trial was associated with impaired neuromuscular contraction, although this impairment was not observed when euglycemia was maintained. Boyle et al. (1994) report that cerebral glucose uptake begins to decline at blood glucose concentrations of 3.6 $\text{mmol}\cdot\text{L}^{-1}$. Given that brain glycogen stores are small (0.5 - 1.5 g) and undergo continuous turnover, any disruption can negatively impact neuronal function, suggesting that cerebral glucose availability is crucial in preventing central fatigue (Meeusen et al., 2006; Nybo, 2003). Ferrauti et al. (1997) observed blood glucose levels as low as 3.6 $\text{mmol}\cdot\text{L}^{-1}$ in a placebo group (with no energy intake) when play resumed after a break. This is particularly relevant in the context of tennis matches, where athletes experience repeated 90-second seated rest intervals between changeovers (except the first changeover of each set), 120-second rests following the conclusion of a set, and additional toilet and medical breaks as permitted by ITF rules. These breaks, which can sometimes be strategically extended to disrupt play, highlight the importance of maintaining adequate glucose levels to avoid central fatigue (Mueller, 2023).

When analysing players during a professional tournament, Mendez-Villanueva et al., (2007) found, La and ratings of perceved exertion (RPE) values have differed in accordance with return (3.20 ± 1.35 $\text{mmol}\cdot\text{l}^{-1}$, RPE 12 ± 2) or serve (4.61 ± 2.50 $\text{mmol}\cdot\text{l}^{-1}$, RPE 13.4 ± 1.9) during individual game analysis. Additionally, during prolonged competitive rallies La concentrations can be elevated up to 8.6 $\text{mmol}\cdot\text{l}^{-1}$, a finding that also suggests a large energy contribution through anaerobic glycolytic sources (Christmass et al., 1998; Mendez-Villanueva, et al., 2007). Although Fernandez et al., (2006) found lower mean La concentrations of 1.5 - 3.0 mmol·L^{-1} during match play. Christmass et al., (1998) suggest the variability seen in La concentrations historically reported may be due to time of measurement which are restricted by breaks in play and may only be reflective of the activity in minutes leading up to measurement, making comparisons difficult. However, the overall indication from the literature is a high CHO demand and potential depletion.

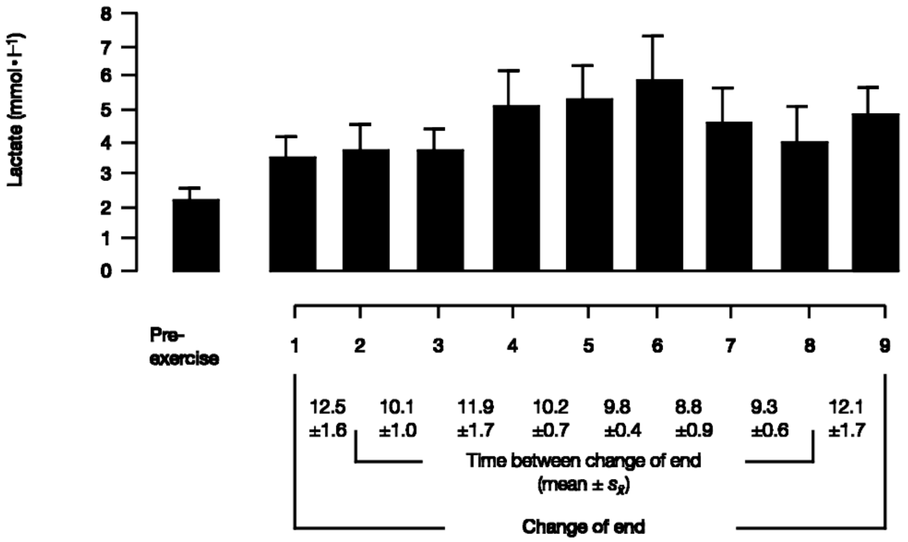


Figure 2.2. *Lactate concentrations at change of end taken from Christmass et al., (1998).*

The individual characteristics of each playing surface (friction during ball impact slowing speed and affecting bounce trajectory) can influence match play and style, impacting the 'work' durations and the locomotive demands (Brody et al., 2002; Girard & Millet, 2004; Martin et al., 2011). When comparing the impact of clay courts to that of hard resin courts, Martin et al., (2011) show that play on clay courts produces in longer rallies (8.5 ± 0.2 vs 5.9 ± 0.5s) and therefore increased effective play time, increased mean HR (154 ± 12 vs. 141 ± 9 b·min^{-1}) and mean La (5.7 ± 1.8 vs. 3.6 ± 1.2 mmol·L^{-1}) during ~56 min match. Likewise, Murias et al.,

(2007) found increased HR on clay courts (143 ± 22 $b \cdot min^{-1}$) compared with hard courts (135 ± 21 $b \cdot min^{-1}$) for nationally ranked players. However, it is questionable if considering mean values provide a clear representation of a sport with such intermittent demands. Murias et al., (2007) also show large differences in peak relative VO_{2max} values during match simulations (93.4% of VO_{2max} on hard courts vs. 75.3% of VO_{2max} on clay courts), indicating higher intensities during shorter periods on hard courts. It is postulated the slower nature of a clay court, allows the player more time to position themselves and therefore more time to prepare the return, resulting in longer rallies and a steadier physiological response. As between point durations are fixed in line with rules, this results in higher total effective playing time on clay (20-30%) when compared to faster hard courts (10-15%) (Fernandez et al., 2006). Fernandez et al., (2006), summarise that during tennis play, the aerobic and anaerobic alactic energy systems are the primary energy pathways utilised. Fast hard courts demand short explosive repeated efforts, resulting in moderate mean intensities (60–70% VO_{2max}) and submaximal with slower courts seeing increased La during lengthy critical rallies. Murias et al., (2007) conclude that the bouts of higher intensity (hard vs clay) and longer relative recoveries see hard surfaces producing a more intermittent response than clay. However, this does not seem to be consistently reflected during other investigations and appears to be highly variable (Fernandez et al., 2006).

2.1.6 Doubles tennis format

The doubles format sees a same sex or mixed sex pairing of two players to form a doubles team. The format shares the same rules of singles tennis with an adjustment to court width (to outer tram line) and occasional variations to scoring formats depending on the competitive event (ITF, 2021). Comparatively from an intensity perspective, a difference in heart rate response has previously been reported between singles and doubles match play, with the latter spending a greater percentage of match time at lower intensities (Morgans et al., 1987). However, accumulative mechanical load measured by accelerometery has been found to be similar between singles and doubles play, though Gentles et al., (2018) suggest the actual activity profile would differ considerably. Although distances during doubles match play have yet to be reported, it would be presumed to be lower than the singles format as found in badminton (Alcock & Cable, 2009). Shots counts per rally have been reported (3.41 ± 2.27) during doubles match play (Martínez-Gallego et al., 2020) and doubles matches generally see a shorter, faster match (Kovalchik & Ingram, 2018)

2.1.7 Wheelchair tennis format

Wheelchair Tennis (WT) is a sport played on the same courts, surfaces and rules set out for able body tennis (AB), with the only exception being that an additional bounce is permitted before the ball is returned. Match formats are best of three sets or two sets and a tiebreaker depending on the competition (the sport is played at the highest levels alongside AB tennis at Grand Slams, the Paralympics and at global events governed by the ITF (International Tennis Federation). Each Paralympic sport has its own classification system to determine the athlete's impairment and the impact it will have on their performance in the sport to ensure success is not determined by the impairment (Tweedy & Vanlandewijck, 2011). In WT players are categorised into either the Open class (an eligible impairment affecting the lower limb/s) or the quad class (an eligible impairment affecting a minimum of three limbs) (ITF, 2023d). Although WT share some of the main characteristics seen in AB, namely being an intermittent, multidirectional sport that requires repeat bursts of high intensity activity (Sindall et al., 2013). Match play involves distinctive physical and technical challenges, different to that of AB, such as multidirectional wheelchair chair propulsion and agility, whilst simultaneously holding a tennis racket and sustaining shot execution (Sánchez-Pay & Sanz-Rivas, 2018).

Wheelchair tennis can be considered a moderate to high intensity sport which is predominantly aerobic in nature with an average intensity of between 69-75% HR^{peak} (Croft et al., 2010; Roy et al., 2006). Roy et al., (2006) additionally profiled the aerobic capacity of skilled WT players, finding (27.10 $ml \cdot kg^{-1} \cdot min^{-1}$). A value lower than that found by Veeger et al., (1991) in wheelchair dependant Paralympians from; track and field VO_{2max} (44.9 $ml \cdot kg^{-1} \cdot min^{-1}$), swimming (39.0 $ml \cdot kg^{-1} \cdot min^{-1}$), basketball (37.9 $ml \cdot kg^{-1} \cdot min^{-1}$), and table tennis (30.7 $ml \cdot kg^{-1} \cdot min^{-1}$). However, an arm crank protocol was used by Roy et al., (2006) as opposed to the treadmill protocol by (Veeger et al., 1991) which have previously seen mixed results when used as a method to determine VO_{2max} in wheelchair dependant participants (Molik et al., 2017; Otto et al., 2019).

The effective playing time seen in WT is between 15-20% of playing time with average shot count to be 3.2 ± 0.5 during Open men's, 3.1 ± 0.8 during Open women's, and 2.5 ± 0.5 during Quads (Mason et al., 2020). During comparison of court surfaces, (Sánchez-Pay & Sanz-Rivas, 2021) found longer points played per on hard court (Hard; 8.86 ± 6.64 s, Clay; 6.97 ± 4.76 s, Grass; 6.33 ± 3.6 s) with greater shot count per point (Hard; 4.50 ± 3.28, Clay; 3.49 ± 2.33, Grass; 3.18 ± 1.76) for top 10 male Open players, values similar to AB. To date no WT doubles match shot count exists. During match play, male Open division players typically cover 2.2 ± 0.8 km and reach peak speeds of 13.8 ± 1 km per set with rallies typically lasting three shots or less (Mason et al., 2020). When considering time spent in speed zones, Sindall et al., (2015) found singles players spend a greater percentage of time at speeds <2.5 $m \cdot s^{-1}$ when compared doubles (90.1 ± 4.4% and 86.6 ± 11.0% respectively) than speeds >2.5 $m \cdot s^{-1}$ (0.4 ± 2.4% and 4.4 ± 6.1%). It is worth highlighting that significant differences in the demands, both physical and movement, were found between high (ITF ranked ≤25) and low (≥350) ranked male player groups (Sindall et al., 2013).

2.1.8 Junior tennis

Junior ITF tournaments are played over the course of a week (with qualification rounds) that comprise of 3 set matches with tie break third set, similar to the senior tennis requirements (ITF, 2023c). High level junior players begin to transition into Junior ITF events at under 14 y by playing Europe wide touraments. The under 16 y juniors generally play globally, including participation (ranking dependant) at the junior Grand Slam, junior Davis Cup and Billie Jean King Cup tournaments. It is observed that u16 y female players start playing lower-level senior ITF tournaments, whereas male junior players start playing senior ITF tournaments at 16 y or later. Junior players training differs to that of seniors in that training takes place around education. Junior players can experience weekly training volumes of 15 - 20 hours (Reid et al., 2013), with 2 - 3 h daily tennis training sessions, 5 - 6 days per week, at their training base following a day's schooling and activity.

Some higher-level player's education schedule must also accommodate additional training sessions during the school day. The busy daily lives of the high performing junior, not only contain education, but also multiple sports, some under 14 y junior players will also coincide their tennis activity with one or more additional sports, prior to fully specialising at under 16 y. To date no data exists exploring the energy demands of a junior tennis player during competition at the highest level. When investigating the energy expenditures of academy junior

(~14 y) players using Actigraph wrist mounted accelerometery during a clay surface training camp, mean daily expenditure was 3959 ± 630 $kcal \cdot d^{-1}$ (Fleming et al., 2022). However, the sex of the participants is unclear. Research employing DLW in other sports revealed that the TDEE for under 18 y male soccer players in an English Premier League academy was 3586 ± 487 $kcal \cdot d^{-1}$, under 15 y players 3029 ± 292 $kcal \cdot d^{-1}$, and under 12/13 y players 2859 ± 265 $kcal \cdot d^{-1}$ during daily training and weekend matches over 14 days (Hannon et al., 2021). When also using DLW in ~17 y elite basketball players, males were reported to expend 4622 ± 681 $kcal \cdot d^{-1}$ and females 4206 ± 788 $kcal \cdot d^{-1}$ (Silva, 2013), measured over 7 days with included weekday training and two weekend competitive games.

2.1.9 Training

Professional tour level tennis players engage in a continuous annual cycle of global competition, or training, at a ratio of 40 - 60% training and 60 - 40% competition, playing between 50 to >100 matches annually (Kovacs, 2018). The time period (days) between tournaments varies and presents the player with a coach-led training opportunity to focus on technical and tactical aspects (Reid et al., 2008).

During pre-season training (usually held during December), daily tennis training volume of elite players has previously been reported at 130.3 ± 41.0 min, with additional 95.5 ± 50.2 min allocated for strength and conditioning (Poignard et al., 2020). Similar total training durations were reported in professional players (n = 12, ATP ranked 500-800) training 17 ± 2.5 $h \cdot wk^{-1}$ (Fernandez-Fernandez et al., 2015). Daily training consists of once or twice daily on-court sessions that comprise of coached drills, point play, physical conditioning, or technical execution of a shot or tactic. Off-court training varies from player to player and the ethos /

approach of their support team, with cultural differences in tennis coaching philosophy evident (Lewit, 2014). The player will engage in resistance training, specific physical robustness exercises, off-court conditioning, and injury prehabilitation.

2.2 Energy expenditure overview

Total daily energy expenditure (TDEE) comprises of energy expenditure during exercise, non-exercise activity thermogenesis, the thermic effect of food and resting metabolic rate (Hills et al., 2014). Measurement can be undertaken directly (measurement of heat transfer) or indirect (measurement of oxygen uptake and carbon dioxide production). Only indirect methods applicable to measurement of an athletic population will be reviewed here.

2.2.1 Resting metabolic rate

Resting metabolic rate (RMR) is the energy that the body needs at complete rest to maintain normal physiological functions. The RMR should be determined by measuring expired gas whilst in a rested supine position for 30 minutes with the athlete in a fasted state. A variety of estimation equations exist based on large scale studies of varying populations, however these can over, or underestimate and results can vary between equations (Hannon et al., 2021; Smith et al., 2018). Fat free mass and RMR have been seen to corelate closely and is the main factor attributed to the variance between individuals (Cunningham, 1980; Stubbs et al., 2018).

2.2.2 Energy expenditure of exercise (EE)

The EE comprises of the energy expended during a given activity which in an athletic population can be the largest component of daily total energy expenditure with endurance athletes expending more than 1000 $\text{kcal}\cdot\text{h}^{-1}$ (Plasqui et al., 2019; Saris et al., 1989). Estimation of EE can be from questionnaires, pedometers, heart rate monitors, indirect calorimetry, actigraphy, accelerometers, or by the doubly labelled water technique which is considered the gold standard (Crouter et al., 2008; Hills et al., 2014; Levine, 2005; Novas et al., 2003; Senatore & Cannataro, 2019; Westerterp, 2017). Each method carries its own challenges and limitations.

2.2.3 Non-exercise activity thermogenesis and thermic effect of food

The energy required for general daily activities e.g., walking, showering, is termed non-exercise thermogenesis (NEAT). The thermic effect of food (TEF) is the energy required to process food consumed into energy. This is difficult to accurately quantify as a sole measurement but is reportedly, between 5 - 10% of calorific intake but is dependent on types of food consumed.

2.2.4 Physical Activity Level (PAL)

Physical activity factors enable a reference index based on average energy expenditures experienced during 24 h. Once Resting Metabolic Rate (RMR) through direct measurement or prediction equations has been determined, the result is multiplied by a ‘physical activity level’ (PAL) value from pertinent research related to a specific activity or lifestyle.

$$\mathrm{PAL} = \mathrm{TDEE}/\mathrm{RMR}$$

The result provides an estimate of daily expenditure to begin formulating dietary intake. A vigorous lifestyle has been defined by a PAL of ~2.4 with the upper limits of expenditure experienced by endurance athletes see values of 4.0 (Westerterp, 2013). Additional research in sport has reported values of 2.6 for female lightweight rowers (Hill & Davies, 2002), 2.5 for male table tennis players during a training camp, and 2.9 for male professional rugby players during an in-season period (Morehen et al., 2016; Sagayama et al., 2017). Research into elite junior basketball players reported a PAL of ~2.8, within a range 2.2 to 3.7 (Silva, 2013). To date the PAL of professional tennis is not understood.

2.3 Measurement of Energy Expenditure in Tennis

2.3.1 Doubly Labelled Water

Doubly labelled water (DLW) is a method considered the ‘gold standard’ (Westerterp, 2017) when measuring total energy expenditure (TDEE) and has been utilised across a range of sports and modalities to capture the TDEE of free-living humans (Hills et al., 2014). The DLW consists of two non-radioactive labelled stable isotopes that are harmless to the participant, deuterium (^2H) and oxygen 18 (^{18}O), to form $^2H_2{}^{18}O$. As both isotopes are eliminated from the body by different means, ^2H leaves as water and ^{18}O leaves as water and carbon dioxide (CO_2). The CO_2 production during substrate use can be calculated by subtracting ^2H elimination from ^{18}O elimination. Isotope enrichments are then converted to EE by using a two-pool model equation and described by Schoeller et al., (1986) as further reviewed by Speakman et al., (2021). By using the method, the participant can continue with their habitual routine without any interference that may occur using any other method.

The method has clear benefits when attempting to understand the TDEE during a tournament by capturing TDEE in its entirety, comprising of the energy expenditure (EE) during match and pre-match practice, NEAT, TEF and RMR. Additionally, it captures the post excess post-exercise oxygen consumption (EPOC) and the subsequent effect of match play recovery on RMR (Kelly et al., 2013), to give a complete overview of the energy demands faced by a tennis player during a period of competition. However, its strengths are also its limitations and while

DLW is considered the gold standard of TDEE measurement of free-living activity, it cannot detect day to day variation or within day variation.

Previous research on high-level male athletes using the DLW method has shown the TDEE of English premier league soccer players (3566 ± 585 kcal·d^{-1}), professional rugby league players (5374 ± 645 kcal·d^{-1}) during training and competition, and professional road cyclists during the Giro d'Italia stage race (6903 ± 764 kcal·d^{-1}) (Anderson et al., 2017; Morehen et al., 2016; Plasqui et al., 2019). Research using DLW in racket sports is sparse, although male badminton players (4686 ± 1180 kcal·d^{-1}) during a training camp have been studied as have male college table tennis players (3695 ± 449 kcal·d^{-1}) during daily training (Sagayama et al., 2017; Watanabe et al., 2008).

To date, female TDEE data measured by DLW is lacking during an in-competition period except for recent analysis of English international soccer players during training and competition (2693 ± 432 kcal·d^{-1}; range: 2105-3507 kcal·d^{-1}) (Morehen et al., 2021). Female training data captured across sports using DLW have shown elite distance runners during training (2826 ± 312 kcal·d^{-1}), elite lightweight rowers during heavy training (3957 ± 1219 kcal·d^{-1}) and elite swimmers during heavy training (5593 ± 496 kcal·d^{-1}) (Hill & Davies, 2002; Schulz et al., 1992; Trappe et al., 1997). A lack of data exists regarding the TDEE in female tennis players using the doubly labelled water (DLW) method. Ndahimana et al., (2017), included female college tennis players when investigating EE prediction equations, finding TDEE to be 2780 ± 430 kcal·d^{-1}. Nevertheless, meaningful comparisons are challenging due to the lack of participant ranking or playing level reported, or any detail surrounding the actual activity recorded. When broadly reviewing existing racket sport literature, currently only badminton training camp data exists using the DLW methodology showing 3239 ± 548 $kcal{\cdot}d^{-1}$ (Watanabe et al., 2008).

2.3.2 Heart rate monitoring

Heart rate monitoring (HRM) via short term telemetry is used widely to measure both intensity and energy expenditure during exercise via chest mounted strap containing an electrode or more recently through wrist watch measurement. As heart rate and oxygen consumption is seen to be linear in nature, HRM is relatively non-invasive approach used to estimate O_2 consumption (Zuntz, 1901). Depending on the exercise intensity, the heart rate measured and therefore the predicted O_2 use, an estimated expenditure varying from 4.69 to 5.05 kcal of consumed O_2 is calculated. A range that considers the estimated oxygen consumption and the respiratory quotient (RQ), the ratio between CO_2 produced and O_2 consumed which varies between 0.70 to 1.00 (McArdle et al., 2006). Using a well-established relationship between RQ, substrate use and therefore caloric equivalent, energy expenditure can be estimated (Zuntz, 1901).

A shortcoming of EE derived from HRM is that during very low and very high intensities the heart rate and O_2 becomes non-linear, or when quick changes (indicative of tennis) are made from low to high intensity and heart rate lag occurs (Achten & Jeukendrup, 2006). During trials at fixed intensities corresponding to 57%, 77% and 90% of maximum heart rate, the correlation coefficient was r^2 0.87 without adjustment for fitness (Keytel et al., 2005). Levine, (2005) state that while it is apparent that HRM can attempt to capture energy expenditure, it could be considered inaccurate due to other variables that may influence heart rate such as stroke volume in a restricted body position or emotion responses that may elevate heart rate. Additionally, between 5-10% of calorific intake is expended through the thermal effect of food and dependant on food types consumed, an additional shortcoming in heart rate monitoring to measure energy expenditure (Westerterp, 2004).

Recent developments in heart rate measurement have involved using wrist mounted straps utilising photoplethysmography optical technology to detects changes in blood volume near the surface of the skin to identify heartbeat and rate (Allen, 2007). Although not currently used at a scientific level within sport, the units are becoming increasing popular with athletes due to the added metrics around sleep, heart rate variability, recovery and exercise stress or strain (Sikka et al., 2019). When comparing three commercially available units, (Hajj-Boutros et al., 2022) found all to have large mean absolute percentage errors when reporting energy expenditure; Apple watch 6 (Apple Inc, Cupertino, CA) (error range 14.9 - 47.8%), Polar Vantage V (Polar Electro Oy, Kempele, Finland) (error range 15.6 - 34.6%), and Fitbit Sense (Fitbit Inc, San Francisco, CA) (error range 17.8 - 45.1%).

Using the HR method, attempts have been made to estimate energy expenditure during tennis play. Novas et al., (2003) found a 20.7% overestimation of energy expenditure measured using heart rate monitoring when compared to gas exchange analysis during adapted match play. It could be argued that the protocol, although aligned to tennis specific durations, was not a true representation of a tennis match. It was noted in the study that HR did not always reflect the energetic cost of exercise reflected in gas exchange data. A limitation to HR collection could be twofold, firstly by HR remaining elevated during periods of rest by emotion / stress, and secondly by not being sensitive enough to detect explosive moments that are lost in HR measurement due to a response lag e.g. a serve (ace) being hit (Fernandez et al., 2006).

2.3.3 Gas analysis

Previous research has estimated energy expenditure during match play using indirect calorimetry however the restrictive nature of such investigations may impact the technical performance, therefore limiting the ecological validity (Brechbuhl et al., 2018). As a non-invasive method, in a clinical environment, indirect calorimetry is considered gold standard to determine EE in resting patients (Delsoglio et al., 2019; Haugen et al., 2007). However, a limitation during dynamic activity may be the restrictive impact that wearing portable metabolic measurement equipment may have upon movements. The potential weight, discomfort and awareness of the worn metabolic devices may influence the type and intensity of play, therefore impacting the EE (Brechbuhl et al., 2018).

Using such approaches, the energy demands of male (Kilit et al., 2016) and female (Novas et al., 2003) players during match play has been reported as 568 ± 59 kcal·h^{-1} and 442 ± 60 kcal·h^{-1} respectively. Nonetheless, it remains to be determined whether such data is reflective of actual competitive tournament match play given the interference that the wearing of portable gas analysis equipment could have on the associated match intensity. Evident when Baiget et al., (2015) conducted a simulated tennis match and found participants not wearing gas analysis equipment won 70% of the sets played. A review paper compared existing research that used HRM and gas analysis during match play and estimated EE to be 30.9 ± 5.5 and 45.3 ± 7.3 kJ·min^{-1} for female and male players respectively (Ranchordas et al., 2013). The estimations were based on an individual tennis match mean intensity of 55% VO_{2max} collated from several research articles on the assumptions of mean body mass, 1 L of O_2 being equivalent to 21 kJ (5 kcal) of energy and a mean gas exchange RQ of 0.9.

2.3.4 Accelerometery and Actigraphy

The introduction of accelerometery has led to EE assessment though alternative sources, with recent advances in accelerometery technology beginning to replace previous assessment methods due to ease and availability.

Although the use of accelerometery within tennis is in its infancy, when using an upper arm mounted metabolic holter (SenseWear, Bodymedia), Senatore and Cannataro, (2019) determined the energy expenditure of a cohort of tennis players in relation to their game style. Conducted on clay surface court, female results showed players categorised as 'striker from baseline' (390 kcal·h^{-1}), 'counter puncher from baseline' (322 kcal·h^{-1}) and 'complete all-court' (275 kcal·h^{-1}) with a mean of 329 kcal·h^{-1} across all groups. Male players were categorised as; 'striker from baseline' (487 kcal·h^{-1}), 'counterpuncher from the baseline' (455 kcal·h^{-1}), 'all-court player' (470 kcal·h^{-1}), 'serve and volleyer '(478 kcal·h^{-1}) and 'attacking player' 525 kcal·h^{-1} with a group mean of 483 kcal·h^{-1}. Although, an interesting factor in this research is the difference that game style has on energy expenditure, the data is lower than the male data (568 ± 59 kcal·h^{-1}) provided by Kilit et al., (2016), and female data (442 ± 60 kcal·h^{-1}) provided by Novas et al., (2003), both via gas analysis. The definitive reason for the variance is hard to attribute, but factors that may contribute are methodology used and the playing surface used (clay vs hard). As a higher total playing time may be seen on clay (20 - 30%), this would logically point to a higher on-court energy expenditure rather than a lower. However, Chapelle et al., (2017) when also using Sensewear devices to investigate physiological impact of court surface during standardised drills, found EE not to be significantly higher on clay court when compared to hard court. In using Actigraph wrist mounted accelerometery, Fleming et al.,

(2022) found the TDEE of junior players (14 ± 1 y) to be 3959 ± 630 kcal·d^{-1} within a range of range 2611 - 5251 kcal·d^{-1} during a 6 day clay court training camp. Although perhaps not representative of a habitual week of a junior tennis player, the data provides an important insight into a heightened period of activity load experienced by the group.

A recent addition to the capture of energy expenditure is through metabolic power, a metric derived from global positioning system (GPS) units (Osgnach et al., 2010). Although their use is currently in its infancy in tennis, the units are used widely across team sports worldwide (Cummin et al., 2013). Work by Di Prampero et al., (2005), suggested the use of measurements of velocity and acceleration to calculate metabolic power. On the basis that the energy cost of accelerated running would equate to that of continual velocity running up an incline, with the initial acceleration known, energy costs can be calculated. However, (Brown et al., 2016), show a significant underestimation during simulated field sport circuits (self-selected speeds, with movement instructions of walk, jog, stride, sprint), and very large (43%) overestimations for walking, with no differences for jogging (7.8%) and running (4.8%). Similarly, Stevens et al., (2015) found an overestimation (6 - 11%) of EE during steady state running at two velocities (7.5km·h^{-1} and 10 km·h^{-1}). While Buchheit et al., (2015) saw a 29% underestimation during soccer specific circuits, and an 85% underestimation during recovery phases. The underestimation of EE was also found by (Oxendale et al., (2017), they conclude that energy expenditure derived using the GPS microtechnology should not be used to determine the energy cost of intermittent exercise.

The "Actiheart" monitor is a chest worn accelerometer and heart rate monitoring combination, that has previously been utilised to determine EE in athletic populations due to its validity against DLW and gas analysis during exercise and everyday activities (Assah et al., 2011; Brage et al., 2015; Crouter et al., 2008; Villars et al., 2012). Actiheart has since been used to measure elite athletes across a variety of sports including lacrosse and basketball (Moon et al., 2021; Santos et al., 2014), horse racing (Wilson et al., 2013), and golf (Kasper et al., 2022). Actiheart differs from Actigraph in that it uses a combination of heart rate monitoring and accelerometery to record with high resolution (heart rate: 128 Hz, acceleration: 32 Hz) an estimation of TDEE on a weekly, daily, hourly or less basis for up to 21 days depending on the selected length of EPOC data points required (Koehler et al., 2013). The device that is mounted to the chest using standard electrocardiogram **(**ECG) electro pad or worn in an identical manner to a HRM when connected to a modified HRM belt (Polar WearLink®+, Cambridge Neurotechnology, Fenstanton, UK) chest strap. It had been suggested that errors may arise due excess movement of the unit during exercise, with a 10^{o} tilt of the unit producing a 3% error (Brage et al., 2006). To address this issue the manufacturer of Actiheart, developed a chest belt to secure the unit in place, resembling the functionality of a Polar WearLink®+ chest mounted HRM strap.

A benefit of the Actiheart system above that of heart rate monitoring per se is the ability of the system to capture the external load during explosive rapid movement (such as a tennis serve) that may not be sufficiently reflected in heart rate response. Furthermore, accelerometery combined with heart rate monitoring also accounts for the increase of heart rate that temperature, dehydration, altitude, and psychological stress may produce (Achten & Jeukendrup, 2006; Cabello Manrique & González-Badillo, 2003). A combination of heart rate monitoring and accelerometery data has been seen to improve estimates of TDEE during physical activity when compared to either method in isolation (Brage et al., 2004). Also providing improved estimation of TDEE during periods of lower intensity physical activity over that of pedometer motion sensors (Thompson et al., 2006).

Additionally, Actiheart can assess TDEE and minute by minute EE, enabling the capture of chronic and acute energy demands (Jagim et al., 2019; Langan-Evans et al., 2020; Wilson et al., 2013). During trials measuring physical activity in free-living adults, there was no significant mean bias reported between Actiheart and DLW following individual calibration ($P = 0.3$) or group calibration ($P = 0.08$) (Assah et al., 2011). However, the mean bias increased when comparing individual (-5.4 ± 5.1 $kJ \cdot kg^{-1} \cdot d^{-1}$) and group calibration (-9.1 ± 8.9 $kJ \cdot kg^{-1} \cdot d^{-1}$). Similar to findings by Villars et al., (2012), reporting mean bias of individual calibration (-4.6 ± 13.1) and group calibration (-7.6 ± 20.2) when compared to DLW. However, this difference was not observed by Santos et al., (2014) in their study comparing DLW to Actiheart in elite junior basketball players (aged 16 y and 17 y). Likewise, they observed no significant mean bias when using step calibration ($P = 0.44$), with better agreement when using group calibration ($P = 0.33$).

Although Actiheart use has not previously been explored with tennis, EE simultaneously measured by gas analysis and Actiheart output in university students during racquetball, reported a small difference of 0.12 $kJ \cdot h^{-1} \cdot kg^{-1}$ (0.03 $kcal \cdot h^{-1} \cdot kg^{-1}$) when using a group calibration method (Crouter et al., 2008). However, Koehler et al., (2013) found a moderate agreement of EE measured by Actiheart and gas analysis data during a high intensity ramp style running activity. Likewise, Nichols et al., (2010) found an EE underestimation for female adolescent cross-country runners attributing the individual efficiency of the running stride as a potential factor. A view also taken by Fudge et al., (2007) when investigating a combined accelerometery and heart rate device to gas exchange data to estimate VO_2. A logical factor when considering cycling power meters can only accurately determine EE once the individual pedalling efficiency is known (Ettema & Lorås, 2009).

2.3.5 Wheelchair tennis expenditure

Previous research has estimated EE for male WT player using HRM during simulated match play to be 301 $kcal \cdot h^{-1}$ (Roy et al., 2006) and when using gas analysis during training 326 $kcal \cdot h^{-1}$ (Abel et al., 2008). However, it is unknown if HR and oxygen uptake was individually calibrated to each wheelchair user as commercially available HRM calculate EE based on oxygen uptake in AB populations (Nightingale et al., 2015; Zuntz, 1901). When calculating the TDEE of wheelchair users, it is questionable if AB prediction equations for RMR / BMR are suitable. Evidenced by (Abel et al., 2003) when reporting the BMR of wheelchair racers and hand bicycle racers when using gas analysis (63.4 ± 12.2 $kcal \cdot h^{-1}$) and when calculated with an equation (74.2 $kcal \cdot h^{-1}$) as recommended by the WHO (World Health Organization, 2003), that considers the anthropometric data, age and sex into of the individual into account. A difference the researchers attribute to the reduced total muscle mass in the lower extremities due to atrophy in wheelchair dependant athletes. A similar finding to Broad et al., (2020) reporting an error range between 9.7 – 21.9% when comparing prediction equations against measured RMR in wheelchair rugby players. Due to the variance of physical function and metabolically active tissue in para-athletes, it is recommended RMR is measured via gas analysis to determine individual needs of para-athletes (Islamoglu & Kenger, 2019). A thought that should be expanded to consider the activity, anthropometric data, age and sex of the individual.

2.4 Current nutritional understanding

To date, no data exists to understand the energy requirements of elite tennis players in competition and training. As previously highlighted, existing data has focused largely on on-court analysis and not captured the habitual daily activity elite players experience during high level competition and/or daily training. The day-to-day training of an elite tennis player involves on court warm ups, tennis drills and point play, strength and conditioning sessions, and supplementary physiotherapy sessions. During competition, the player would engage in pre-match on-court training, warms ups and supplementary physiotherapy exercises, in addition to travel, media and other off court duties. As previously highlighted, match durations are unknown until their completion, which introduces a vast amount of variation into the TDEE of a professional tennis player.

2.4.1 Carbohydrate requirements

Carbohydrate (CHO) is an important fuel source for the brain and provides a key substrate to support both anaerobic and oxidative pathways (Burke et al., 2004). It is well documented that the performance of sustained exercise can be enhanced with a strategy to ensure high CHO availability (Coyle et al., 1983, Coyle et al., 1986). A large body of research also supports the strategy of pre, during and post-performance CHO feeding, to ensure CHO availability and maintain euglycemia (Jeukendrup, 2014). The CHO guidelines proposed by Burke et al., (2015), provide values of 6 - 10 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for moderate to high intensity of 1 - 3 $h{\cdot}d^{-1}$ and 8 - 12 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for moderate to high intensity exercise of 4 - 5 $h{\cdot}d^{-1}$. Ranchordas et al., (2013) recommend male and female tennis players consume 6 - 7 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ during general preparation training, 7 - 8 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ during specific preparation training and 8 - 10 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ during competition. However, the unpredictable nature of tennis means the match could last between 1h and 30 min to over 5 h making accurate recommendations hard.

However, glycogen stores are expendable during sustained or high-intensity exercise (Saltin & Essen, 1971). While findings are mixed, some studies propose that the consumption of exogenous CHO can conserve muscle glycogen stores, sustain blood glucose concentration, and diminish amino acid oxidation (Cermak & Van Loon, 2013; Fell et al., 2021; Kuipers et al., 1987; Vergauwen et al., 1998). When investigating the ergogenic effects of CHO on 4 h of tennis performance, Ferrauti et al., (1997) reported CHO enhanced tennis specific running seeing a lower sprint performance in the placebo group which they postulate was due to degradation muscle glycogen. Additionally, they report CHO ingestion marginally stabilised blood glucose with results of 4.9 ± 0.6 $\text{mmol}\cdot\text{L}^{-1}$ compared to 5.3 ± 0.6 $\text{mmol}\cdot\text{L}^{-1}$ for the placebo and CHO group respectively. A similar finding to Mitchell et al., (1992) when investigating the effects of CHO drink on tennis performance. They also saw no reduction of blood glucose concentrations over 2 x 180 minutes of match play, concluding that tennis match play may not produce a heavy enough metabolic demands to warrant CHO supplementation. However, the research lacks any detail of pre-trial nutritional intake or standardisation instructions which may impact the results.

A similar proposal is made by Ferrauti et al., (1997) by highlighting work by Coyle et al., (1986) found cycling at a fixed intensity of ~72% $\text{VO}_{2\text{max}}$ resulted in significant reduction in blood glucose (to ~2.5 $\text{mmol}\cdot\text{L}^{-1}$) before fatigue at 3 h. Ferrauti et al., (1997) suggest that although tennis is interspersed with high intensity efforts, when considering a tennis match mean intensity of 50 - 60% $\text{VO}_{2\text{max}}$ it may be that tennis is below the intensity to deplete glycogen over 4 h due to a mix of substrates being utilised. It is worth noting that Ferrauti et al., (1997) fed the participants a standardised breakfast and a carbohydrate-rich lunch to simulate typical pre-match conditions (men, 3200 kJ; women, 2500 kJ). Whereas Coyle et al., (1986) instructed the participants to maintain a general diet prior to the trial and arrive at the laboratory following a 16 h fast making a direct comparison difficult due to the difference of pre-trial diet methodology.

In using a muscle biopsy technique, carbohydrate requirements in other sports (soccer, rugby, road cycling) are understood, to date, no research has clearly defined the carbohydrate requirements of tennis. Current recommendations support the intake of carbohydrate during exercise (including intermittent sports) of 1 - 2.5 h to be 30 - 60 $g \cdot h^{-1}$ and exercise of >2.5 h to be 90 $g \cdot h^{-1}$ (Burke et al., 2015). However, making firm recommendations is difficult due to the unpredictability of match duration.

2.4.2 Protein requirements

Proteins are macromolecules that play essential roles in transporting other molecules, supporting the immune system, regulating growth and repair, facilitating movement, and conducting nerve impulses (Widłak, 2013). It was long established that a negative energy balance during exercise results in the oxidation of protein (Calloway & Spector, 1954). Skeletal muscle can oxidise the amino acids alanine, asparagine, aspartate, glutamate, isoleucine, leucine, lysine, and valine (Smith & Rennie, 1996). It is widely considered that an adult requires 0.8 - 0.9 $g \cdot kg^{-1} \cdot d^{-1}$ to fulfil daily protein requirements, a conclusion reached during research based on the nitrogen balance of sedentary individuals (Tarnopolsky, 2004; WHO, 2007). However, it is now understood that athletes have a higher requirement closer to 1.2-1.6 $g \cdot kg^{-}$

$^{1}\cdot d^{-1}$ to maintain a nitrogen balance (Rodriguez et al., 2009). Although for an athlete, maintenance of a nitrogen balance fails to reflect an optimal intake, only a minimum intake (Phillips & Van Loon, 2013). Current data recommends athletes have a daily intake of 1.2 - 2.0 $g\cdot kg^{-1}\cdot d^{-1}$ (Thomas et al., 2016).

2.4.3 Fat requirements

Fat is a crucial constituent of cell membranes and is also essential during the delivery of the fat-soluble vitamin A, D, E and K (Dawson-Hughes et al., 2015; Hickman, 1943). A human is unable to synthesise the essential fatty acids ω-3 and ω-6, therefore consumption is crucial for some metabolic processes (Spector & Kim, 2015). The eicosanoids produced from ω-3 have divergent properties to ω-6 so both should be consumed in balance (Simopoulos, 2007). Fat should contribute to 20 - 35% of total intake (Rodriguez et al., 2009). It has been recommended athlete should not sustain fat intakes below 20% of the total energy intake to maintain the uptake of fat-soluble vitamin (Trumbo et al., 2002). Intake below 20% may compromise the availability of fat-soluble vitamin and ω-3 fatty acids.

2.4.4 Summary

It is well established the role that nutrition can have upon performance and fatigue during exercise (Close et al., 2016; Heaton et al., 2017) and has been postulated to be a cause of central and peripheral fatigue in tennis (Gomes et al., 2014; Hornery et al., 2007). Therefore, it would be logical to presume the player would need to maintain a level of energy intake to be able to sustain the repeated high intensity nature of modern tennis, as negative balance over the course of a tournament may prove detrimental to performance (Loucks, 2004). Although the physical demands of tennis are widely understood, there appears to be a paucity of research to understand the nutritional demands and the energy requirements of a professional tennis player during a tournament schedule. Estimations of match play expenditure made through gas analysis have provided some insight to the energetic demands on-court during simulated match play, but due to the constraints of using such equipment during competitive professional tournaments data is lacking in this area. The accurate assessment of total energy expenditure and total energy intake of tennis players is not well documented. Previous attempts have estimated expenditure from activity logging through questionnaires or heart rate monitoring during game play, but not attempt has been made over the course of a competitive tournament (Juzwiak et al., 2008; Ranchordas et al., 2013).

This literature review was completed during December 2023 using Google Scholar, Openathens, Ebsco, and Science direct databases.

Chapter 3 - General Methods

3.1 General methods

The procedures employed within this thesis are outlined here and refered to within each study.

The four studies presented here, were granted ethical approval by the local Ethics Committee of Liverpool John Moores University in advance of research being conducted. Each participant that volunteered to take part provided written informed consent before each study commenced.

3.1.1 Body mass and height

At the start of each study and at ongoing relevant points (specified in each chapter), the body mass of the participants was collected using Seca weighing scales (Seca model 876, Birmingham, UK). To profile participant anthropometrics, height was measured using a Seca stadiometer (Seca model 217, Birmingham, UK) employing the International Society for the Advancement of Kinanthropometry (ISAK) stretch stature measurement method (Marfell-Jones et al., 2006).

3.1.2 Participants

A total of 35 professional tennis players were recruited for the studies and at no stage did any withdraw. Participants were male (n = 12 able body, n = 1 wheelchair player) and female (n = 22) players. Female (WTA ranking) and male (ATP ranking) career high ranking ranged from top 10 to ~500, and world number 1 wheelchair player (ITF ranking). In accordance with McKay et al., (2022), participants were categorised as elite (n = 29) and world class (n = 6). Elite determined as top 300 in the world or NCAA division1 athlete or competing for national team, exceptional skill level achieved and training maximally. World Class determined as top 20 in the world or Olympic medallist, exceptional skill level achieved and training maximally.

All AB participant characteristics are shown below in Table 3.1. At the request of the participants involved in some chapters, their individual anthropometric data or individual ranking is not reported to maintain anonymity.

Table 3.1 *Summary of participants characteristics from study 1,2 and 3 combined. Data are mean ± SD.*

	n	Age (y)	Height (m)	Weight (kg)	BMI ($kg \cdot m^2$)
Male	12	22.8 ± 3.5	1.87 ± 0.06	79.2 ± 8.1	22.7 ± 1.4
Female	22	23.2 ± 3.9	1.73 ± 0.04	66.4 ± 4.1	22.2 ± 1.2

3.1.3 Maximum aerobic capacity (VO_{2max}) of a wheelchair player (Study 3)

Approximately 7 days prior to TDEE data collection, the participant maximal heart rate (HR_{max}) and VO_{2max} were measured using a Garmin chest mounted heart rate monitor (Garmin HRM Dual, Garmin International, Inc., Olathe, KS, USA) and PNOĒ (ENDO Medical, Palo Alto, CA) gas analyser respectively, during an on-court wheelchair specific multi-stage fitness bleep test protocol (MFT) (Goosey-Tolfrey et al., 2021; Tsekouras et al., 2019). The MFT was conducted using ‘figure of 8 course’ marked by timing gates and cones placed around a hard indoor tennis court (Figure 3.1).

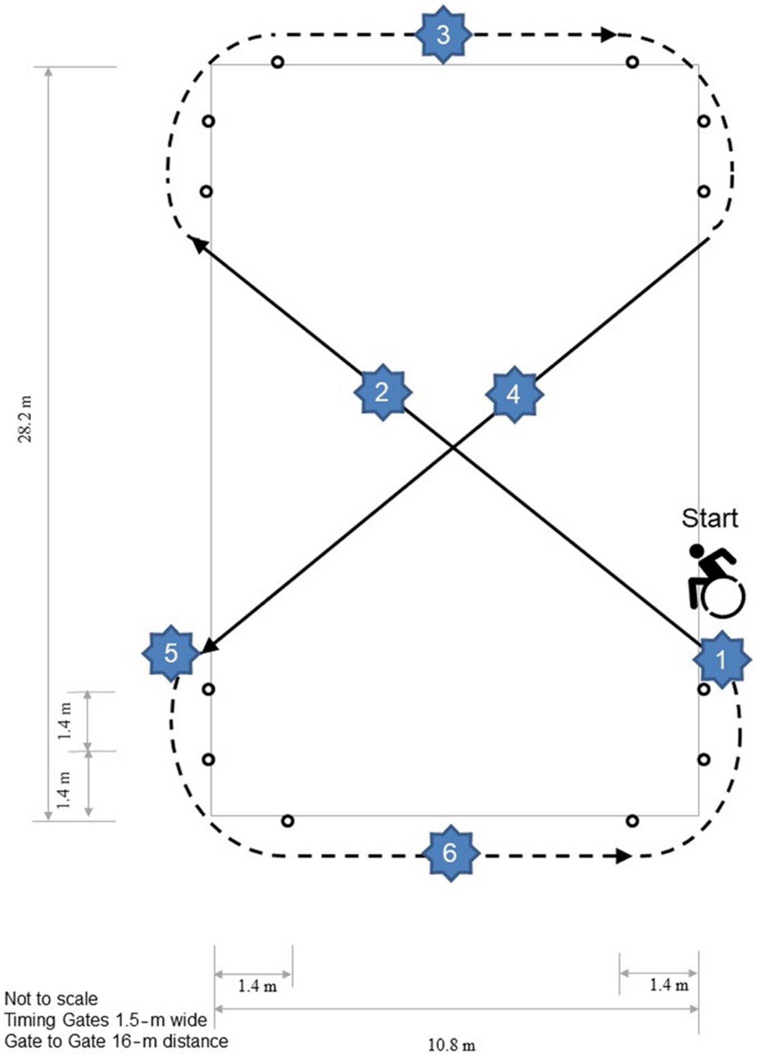


Figure 3.1 *Layout of wheelchair on-court multi-stage fitness test taken from Goosey-Tolfrey et al., (2021)*

Following a starting speed of 1.8 $m \cdot s^{-1}$, each subsequent stage increased by 0.1 $m \cdot s^{-1}$ every 60 s with guidance from audio bleep and verbal encouragement. Once the participant was unable to reach required target on two consecutive occasions the test was terminated. During analysis, VO_{2max} was considered as the highest 30 s oxygen uptake value attained.

3.1.4 Sprint time of a wheelchair player (Study 3)

The 10 m sprint speed was captured using two timing gates placed 10 m apart on an indoor hard surface tennis court (TCi System, Brower Timing Systems, Draper, UT, USA) timed 24 h away from any other testing. The sprint was conducted with tennis racket in hand and initiated immediately behind the first gate and carried through and past the second and recorded as the time to complete 10 m.

3.1.5 Body composition of a wheelchair player (Study 3)

Body composition data are displayed as sum of five upper body skinfold measurements taken from subscapular, tricep, bicep, iliac crest, and abdominal landmarks as outlined by the International Society for the Advancement of Kinanthropometry (Marfell-Jones et al., 2006). Only upper body measurements were taken due to the invasive nature of lower body skinfold measurement for this population. Fat free mass (FFM) was calculated from total body water analysis (^{18}O dilution space) using the doubly labelled water method (Westerterp, 1999).

3.1.6 Resting metabolic rate using doubly labelled water (Study 1 and 2)

Fat free mass was calculated from total body water analysis (^{18}O dilution space) using the doubly labelled water method for further inclusion into the Cunningham equation to predict resting metabolic rate (Cunningham, 1980).

$$\text{Total body water (N)} = [(N_o/1.007) + (N_d/1.043)]/2$$

$$\text{Resting metabolic rate (RMR)} = (500 + 22) \cdot \text{FFM}$$

3.1.7 Measurement of resting metabolic rate using gas analysis (Study 3 and 4)

Resting metabolic rate (RMR) was measured using PNOĒ portable gas analyser. The unit was calibrated using ambient air before use, during 30 min of complete rest in supine position in a darkened room at The National Tennis centre (Roehampton, London), following an overnight fast. Prior exercise, caffeine and alcohol consumption were controlled as per best practise guidelines (Compher et al., 2006). Data from the final 15 min were analysed for lowest coefficient of variation (CV) for VO_2 during a 10 min period and energy expenditure ($kcal \cdot d^{-1}$) calculated (De & Weir, 1949; Roffey et al., 2006). Acceptable CV for VO_2, VCO_2 and RER were 10%, 10% and 5% respectively (Compher et al., 2006). Once RMR was calculated, the participant physical activity level was calculated (Hills et al., 2014).

Physical activity level (PAL) = Total Energy Expenditure / Resting metabolic rate

3.1.8 Quantification of activity loads (Study 1 and 2)

Due to the current federations ruling for no worn coaching devices during competition, daily training and match play loads were assessed using a modified 10-point Borg scale for each session multiplied by the duration of the session to produce RPEs (AU) (Borg, 1982). This was a system the participants had extensive previous experience with.

3.1.9 Quantification of activity loads (Study 1)

Distances covered during match play were collected from Hawk-eye (Hawk-Eye Innovations Ltd, Basingstoke, UK) player tracking data, IBM Slamtracker data (wimbledon.com) and one match from external player tracking software (Hypercode). Match data (points played, shot counts) was sourced from the Lawn Tennis Association performance analysis department following routine tagging using Dartfish analysis software (Dartfish10, London, UK). Training was defined as all on-court training sessions, strength and conditioning sessions, pre-match preparation (away from match court) and match court warm ups.

3.1.10 Quantification of activity loads of a wheelchair player (Study 3)

Activity loads were determined by heart rate (HR) measurement using a chest mounted strap (Garmin HRM Dual, Garmin International, Inc., Olathe, KS, USA) and categorised into three $\%HR_{max}$ zones, <70%, 70 – 85%, >85% (Baiget et al., 2015). The competition and training distances covered were captured by gyroscope (Garmin bike speed sensor 2) (Figure 3.2) placed on the hub of the wheelchair wheel with Bluetooth connection to Garmin bicycle computer (Garmin 520). Data was automatically uploaded on session/match completion and analysed using Trainingpeaks cloud-based software (Peaksware, Colorado, USA).

Figure 3.2 *Garmin bike speed sensor 2.*

3.2 Measurement of training and competition Energy Expenditure Using Doubly Labelled Water (Study 1,2 and 3)

3.2.1 Sample collection

Daily energy expenditure was measured using the doubly labelled water technique. This method has been previously validated on multiple occasions by comparison to simultaneous indirect calorimetry in humans (reviewed in Speakman 1997). Upon arrival at their training venues, the participants were weighed (Seca model 876, Birmingham, UK) before providing a single baseline urine sample into a labelled urine sample collection vessel before sealing. Following collection of a baseline 35ml urine sample to estimate background isotope enrichments, participants self-administered orally a weighed bolus dose (see Figure 3.3) of hydrogen (deuterium ^2H) and oxygen (^{18}O) stable isotopes (Cortecnet, Voisins-Le-Bretonneux, France) in the form of water ($^2H_2{}^{18}O$) (which was witnessed by the lead researcher), and the time of ingestion was recorded. All DLW was prepared by the laboratory of John Speakman and colleagues at The University of Aberdeen.

Each participant was dosed in accordance with their body mass with a bolus of DLW, weighed to four decimal places. Prior to ingestion, a sample of DLW was sent direct from the laboratory to LGC (LGC, Teddington, Middlesex UK) for third party testing of banned substances to ensure no contaminants were present that could place the participant at risk.

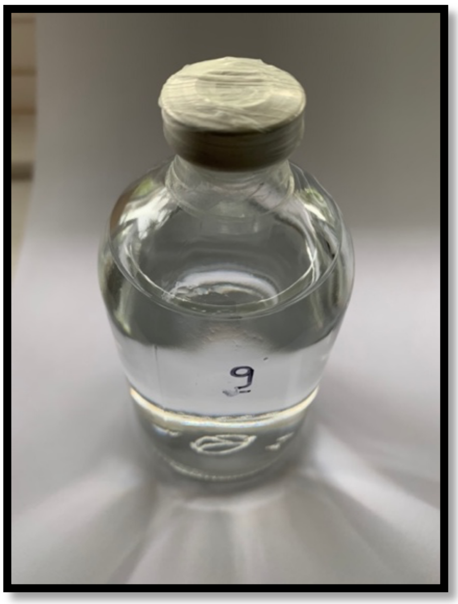


Figure 3.3 *Example of bolus doubly labelled water*

Once administered, to ensure the entire dose had been ingested the glass vessel was refilled with tap water and consumed. The following morning, the participants were weighed and asked to provide a 35 ml sample of the second urine void of the day. Further second void urine samples and body mass were collected daily until day three. This process then continued every 2 – 6 days until completion of data collection. To enable storage at ambient temperature during the field-based collection, the urine samples were then transferred (in triplicate) into 100 µl glass capillaries (Vitrex Medical a/s) before being encapsulated by applying heat to each end of the capillary using a butane gas torch burner (see Figure 3.4). Capillaries were individually labelled and stored into rigid cardboard tubes for protection during transportation.

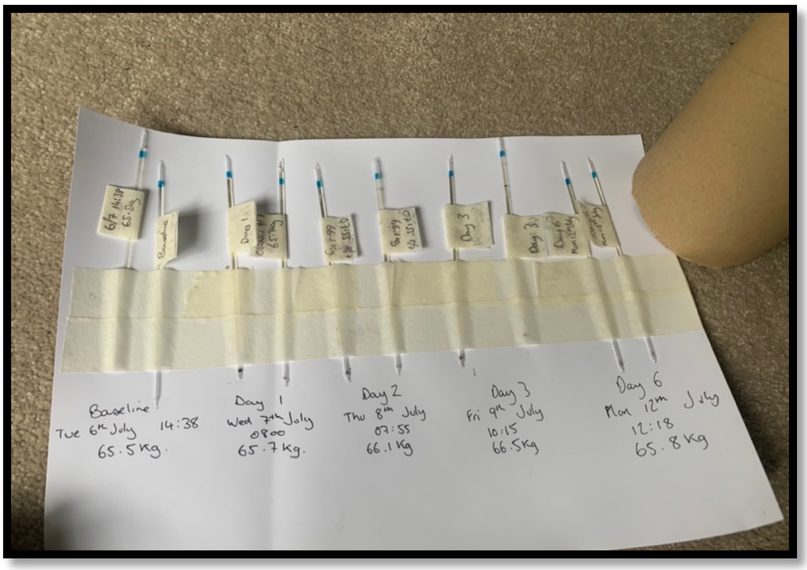


Figure 3.4 *Individual sample capillaries once decanted from urine collection pot.*

3.2.2 Sample analysis

All urine samples were sent for analysis to the laboratory of John Speakman and colleagues at The University of Aberdeen once the study period was completed. Analysis of the isotopic enrichment of urine was performed blind, using a Liquid Isotope Water Analyser (Los Gatos Research, USA) (Berman et al., 2012). Initially the urine was vacuum distilled (Nagy, 1983), and the resulting distillate was used for analysis. Samples were run alongside five laboratory standards for each isotope and international standards to correct delta values to parts per million (ppm). Daily isotope enrichments were $\log_e$ converted and the elimination constants (ko and kd) were calculated by fitting a least squares regression model to the $\log_e$ converted data. The back extrapolated intercept was used to calculate the isotope dilution spaces (No and Nd). A two-pool model, specifically equation A6 from (Schoeller et al., 1986) as modified by (Speakman et al., 2021), was used to calculate rates of CO_2 production.

$$rCO_2 = 0.4554 \cdot N \cdot [(1.007 \cdot k_o) - (1.043 \cdot k_d)] \cdot 22.26$$

$$TDEE\ (MJ/d) = rCO_2 \cdot (1.106 + (3.94/RQ)) \cdot (4.184/10^3)$$

$$Kcal = MJ \cdot 238.85$$

3.3 Measurement of training Energy Expenditure Using Actiheart (Study 4)

Actiheart activity monitors (Actiheart 4; Cambridge Neurotechnology, Fenstanton, UK) were mounted onto a Polar WearLink®+ (Cambridge Neurotechnology, Fenstanton, UK) chest strap (see Figure 3.5) and positioned below the sternum (Brage et al., 2006).

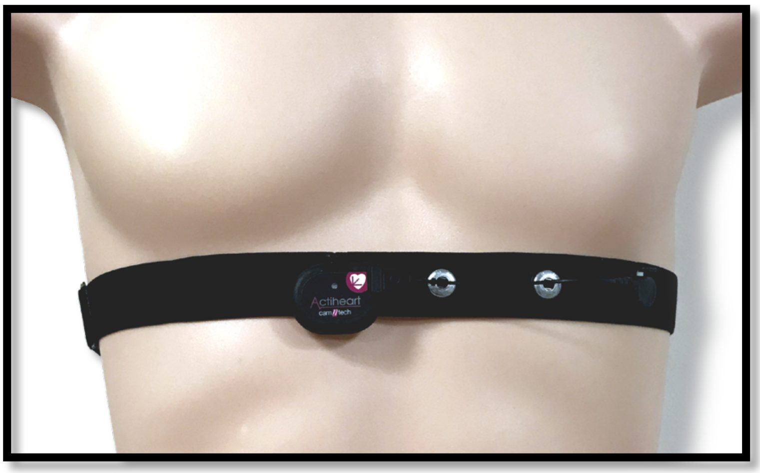


Figure 3.5 *Actiheart chest strap positioning.*

The monitoring period consisted of 2-5 consecutive training days (positioned between tournaments according to player availability) and was conducted at the National Tennis Centre (Roehampton, London). Each monitoring period start, and finish times were selected to allow complete 24 h segments. Participants were asked to wear the Actiheart devices at all times and only removing them during showering.

Immediately following RMR measurement and prior to training, all players were fitted with an Actiheart activity monitor. To prevent inaccurate readings during measurement stemming from high noise levels or a weak signal, a 10 min signal test was carried out while participants wore the device. This test ensured the accurate recording of the R wave for each participant, adhering to the manufacturer's guidelines. All EE data were recorded in 30 s EPOCH length using the group calibration (Group Cal JAP2007) method (Brage et al., 2007), for further calculation using a branch chain prediction equation calculation within Actiheart software (Brage et al., 2004).

Players continued with habitual coach led training with no modifications made for research purposes. Training was defined as all on-court (indoor hard) tennis training sessions and warm-ups. In addition to TDEE, the energy expenditure during individual tennis training sessions were timestamped and analysed for tennis specific EE. Due to the variance of content and inclusion of strength and conditioning sessions, any additional activities were captured within TDEE but were not assessed as part of the specific tennis training evaluation. Following the final day of data collection, the device was connected to the Actiheart software for download and analysis. Each segment was considered in 24 h blocks to determine TDEE. Tennis activity was analysed by highlighting the relevant activity block (see Figure 3.6).

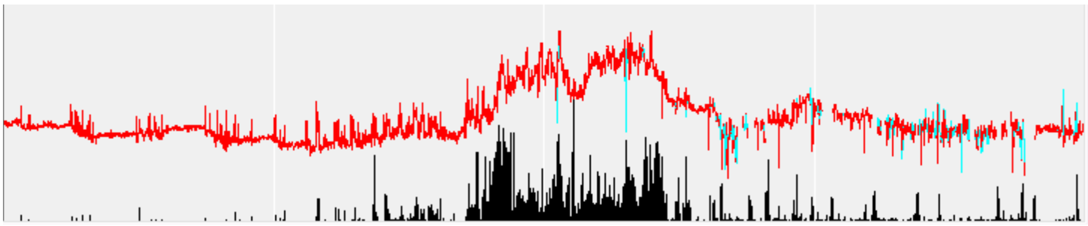


Figure 3.6 *Actiheart activity trace*

Chapter 4 - Energy Expenditure of Elite Male and Female Tennis Players During ATP/WTA and Grand Slam Events

Published in; *Medicine and Science in Sports and Exercise*, *53*(12), 2628-2634.

4.1 Introduction

Although the physical demands of tennis are well documented, the understanding of its energetic demands and associated nutritional requirements is not as advanced. Previous research has estimated energy expenditure during match play using indirect calorimetry; however, the restrictive nature of these investigations limits their ecological validity. Using such approaches, the energy demands during simulated match play have been reported as 568 ± 59 $\text{kcal}\cdot\text{h}^{-1}$ for male players and 442 ± 60 $\text{kcal}\cdot\text{h}^{-1}$ for female players. Nonetheless, it remains uncertain whether these estimates accurately reflect the energy demands of actual competitive tournament play, given the simulated nature of data collection and the potential interference from portable gas analysis equipment.

From a nutritional perspective, it is crucial to assess TDEE rather than just match play energy expenditure. This assessment allows for the development of appropriate nutritional strategies to sustain performance, promote recovery, and support overall health during a typical two-week tournament. The objective was to capture the energy requirements of world-class players during a period that accurately reflects the demands they regularly face, without manipulating or impacting their performance. The DLW method, a non-invasive and gold-standard approach for assessing TDEE in free-living individuals, was employed for this purpose. This method has not yet been applied to elite tennis players over a period comprising a physically demanding training and competitive schedule. The current aim is to quantify the daily energy demands of a world-class male and female tennis player during competition of the highest level.

4.2 Experimental design

Daily energy expenditure was measured using the doubly labelled water technique. Data collection was conducted over a 17 day period (July 2019) (see Figure 4.1) comprising participation in both a WTA/ATP international tournament and the Wimbledon Championships Grand Slam tournament, both were grass court events (see Table 4.2). Sample collection points were positioned to allow for the assessment of energy expenditure during the periods of days 1 – 8 (P1) and 8 – 17 (P2). Throughout data collection, the participants continued with their usual training and preparation with no changes made to their usual competition routines.

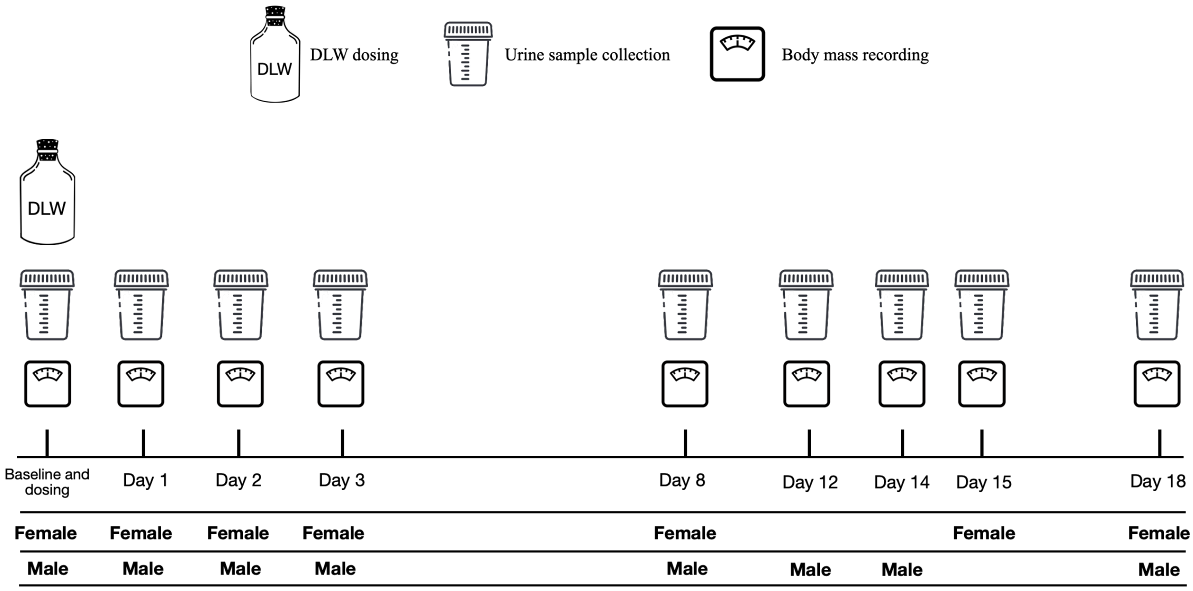


Figure 4.1 Female and male player data collection points showing initial dosing and subsequent sample collection and weight recording.

4.3 Participants

One world class male and female tennis player agreed to take part in this study during 17 days in 2019.

Table 4.1 *Total tournaments and matches played by participants prior to and immediately following analysis period.*

	Tournaments played in 2018	**Total matches in 2018**	**Tournaments played in 2019**	**Total matches in 2019**
Female	37	69	17	52
Male	29	70	30	54

Table 4.1 highlights the tournament and match volume by the participants; during 2018 and 2019 combined, the male and female played a total of 128 and 121 tour level matches respectively.

Table 4.2 *Participant information and analysis period overview*

Player	**Career High Ranking**	**Activity during analysis**	**Total days**	**RMR (kcal·d^{-1})**
Female	WTA Top 10	WTA Eastbourne International (P1) Wimbledon Championships (P2) Supplementary training (throughout)	17 Day 1-8 (P1) Day 8-17 (P2)	1673
Male	ATP Top 15	ATP Eastbourne International (P1) Wimbledon Championships (P2) Supplementary training (throughout)	17 Day 1-8 (P1) Day 8-17 (P2)	1951

All data were displayed for descriptive purposes and therefore are absolute individual values, matches played, points played, total match time, total match distance, total training time , sRPE, shot frequency and EE. Training was defined as all on-court training sessions, strength and conditioning sessions, pre-match preparation (away from match court) and match court warmups.

4.4 Methods

The TDEE was assessed using DLW (see method section 3.2.1 and 3.2.2 for more detail). Fat free mass was calculated using the (^{18}O dilution space) DLW method (section 3.1.6), prior to inclusion into the Cunningham equation to estimate RMR (Cunningham, 1980). Distances covered during match play were collected from Hawk-eye (Hawk-Eye Innovations Ltd, Basingstoke, UK) player tracking data, IBM Slamtracker data (wimbledon.com) and one match from external player tracking software (Hypercode). Match data (points played, shot counts) was sourced from the Lawn Tennis Association performance analysis department following routine tagging using Dartfish analysis software (Dartfish10, London, UK). Daily training and match play loads were assessed using a modified 10-point Borg scale for each session multiplied by the duration of the session to produce RPEs (AU) (Borg, 1982).

4.5 Results

An overview of the training load, match load (and associated match metrics) and daily energy expenditure from the female player for P1 and P2 (Table 4.3) is displayed. Data presented in Figure 4.2 (A, C, E) represent the week comprising participation in the WTA tournament (P1) whereas data presented in Figure 4.2 (B, D, F) represent the period comprising participation in the Wimbledon Grand Slam event (P2). The daily energy expenditure in P2 was approximately

440 kcal·d^{-1} higher than P1, resulting in a PAL level of 2.3 and 2.0, respectively. When expressed relative to FFM, energy expenditure in P1 and P2 corresponded to 63.5 and 71.7 kcal·kg^{-1} FFM, respectively. In P1 the female played 3 matches with a mean duration of 80 ± 13 min (in a range of 74 – 96 min) and covered a mean distance of 856 ± 140 m (in a range of 730 – 1006 m). During P2 the female played 5 matches with a mean duration of 103 ± 30 min (in a range of 70 – 145 min) and covered a mean distance of 1471 ± 449 m (in a range of 1002 – 2141 m).

Table 4.3 *Female player total matches, points, durations, distances and totalo daily energy expenditure (EE) for P1 WTA Eastbourne International grass court tournament, and P2 Wimbledon Championships.*

Period	P1	P2
Matches played	3	5
Points played	362	706
Total match time (min)	241	519
Total match distance (m)	2569	7357
Mean match distance (m)	857 ± 140	1471 ± 449
Total training time (min)	875	795
Total energy expenditure (kcal·d^{-1})	3383	3824

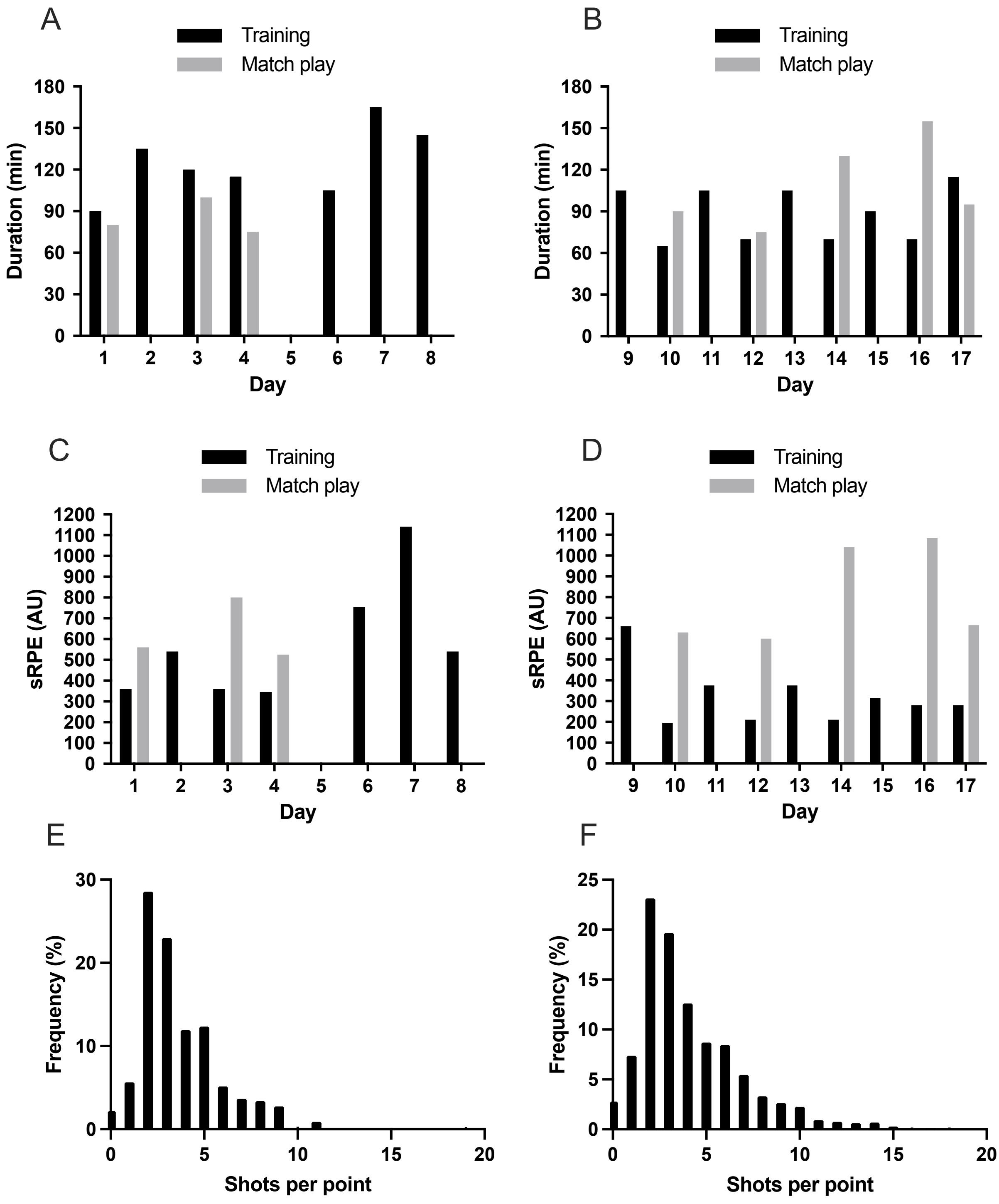


Figure 4.2 *Female player daily durations for P1 (A) and P2 (B), daily RPEs for P1 (C) and P2 (D shots per point frequency for P1 (E) and P2 (F).*

Comparable data for the male player during P1 and P2 (Table 4.4) is displayed. Results show energy expenditure in P2 to be approximately 1800 kcal·d^{-1} higher than P1, thus resulting in a PAL level of 2.8 and 2.2, respectively. When compared to the female player, daily TDEE was comparable in P1 although it was approximately 1700 kcal·d^{-1} higher in P2. When expressed relative to FFM, energy expenditure in P1 and P2 corresponded to 56.3 and 83.7 kcal·kg^{-1} FFM, respectively. In P1 (Figure 4.5 A, C, E) the male played one match (over two days) with a duration of 88 min and covered 1125 m. During P2 (Figure 4.5 B, D, F) the male played 5 matches with a mean duration of 129 ± 55 min (in a range of 90 – 223 min) and covered a mean distance of 2009 ± 1392 m (in a range of 866 – 4175 m). Urine sample collection points and the rate of isotope disappearance can be seen in Figure 4.3 and Figure 4.4.

Table 4.4 *Male player total matches, points, durations, distances, and EE for P1 ATP Queens, and P2 ATP Eastbourne International and Wimbledon Championships.*

Period	P1	P2
Matches played	1 (over 2 days)	5
Points played	133	891
Total match time (min)	88	734
Total match distance (m)	1125	10043
Mean match distance (m)	n/a	2009 ± 1392
Total training time (min)	795	350
Total energy expenditure (kcal·d^{-1})	3712	5520

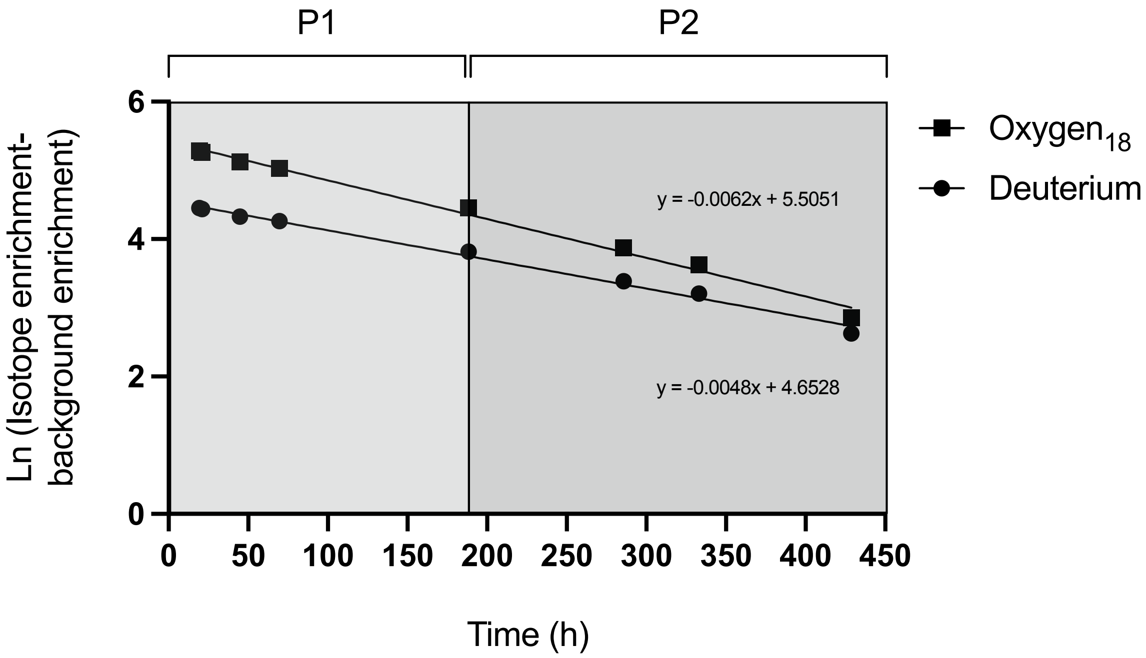


Figure 4.3 *Male rate of isotope disappearance.*

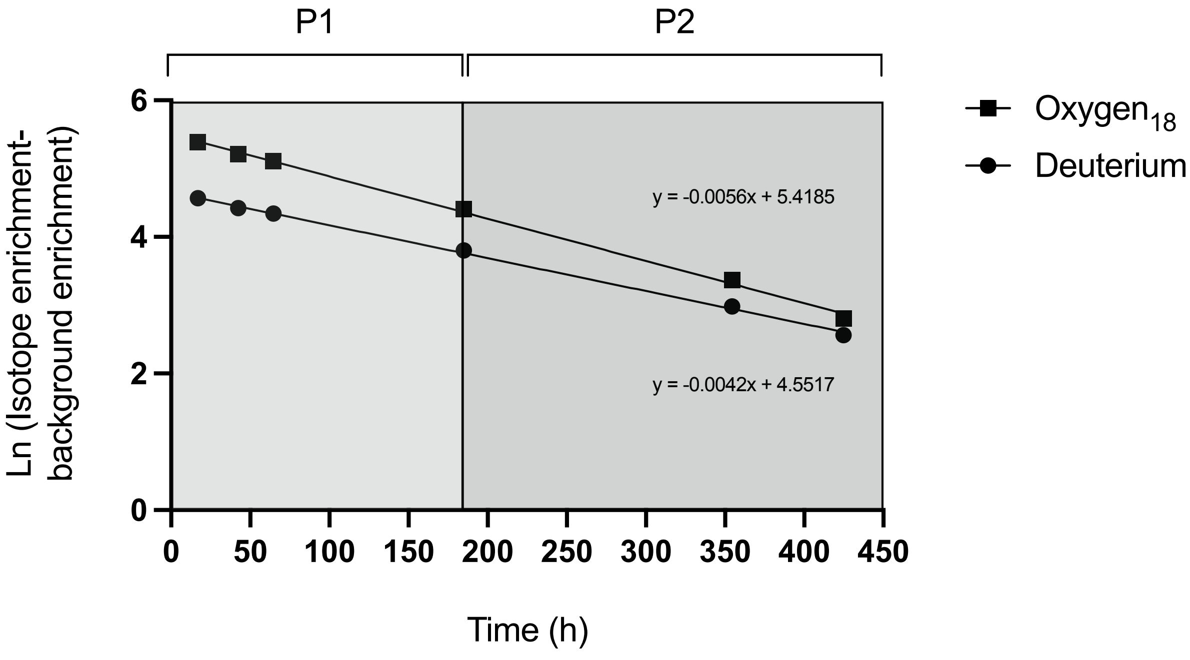


Figure 4.4 *Female rate of isotope disappearance.*

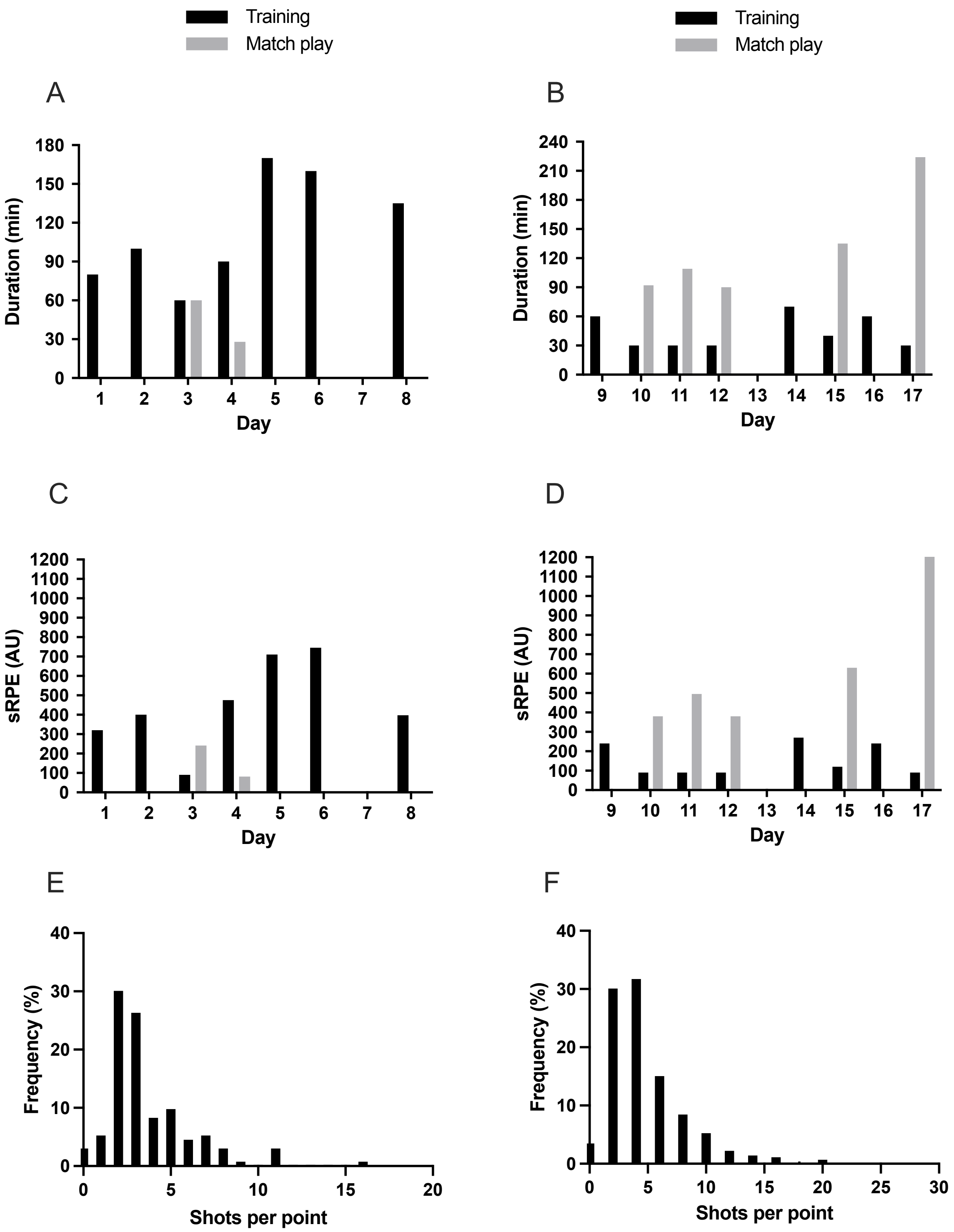


Figure 4.5 *Male player daily training and match durations for P1 (A) and P2 (B), daily training and match RPEs for P1 (C) and P2 (D), shots per point frequency for P1 (E) and P2 (F).*

4.6 Discussion

In using the DLW method, the current research is the first to simultaneously assess the daily energy expenditure of a world class male and female professional tennis player. Importantly, the data collection period comprised a period of the season where both players competed in their respective ATP / WTA tournament as well as the subsequent Wimbledon Championships Grand Slam event. As such, this data provide a platform to establish optimal nutritional strategies for what is considered one of the most physically demanding periods of the annual tennis calendar.

In relation to the female player, a daily TDEE of 3383 kcal·d^{-1} and 3824 kcal·d^{-1} is recorded during P1 and P2 respectively. The increased TDEE of approximately 440 kcal·d^{-1} in P2 is likely explained by greater tournament progression. Indeed, this greater tournament progression resulted in 344 more points won, 278 additional minutes playing time and almost 5 km more distance completed when compared with P1. During P2, the observed mean match distance of 1471 ± 449 m was similar to previous reports from female tennis players during Grand Slam tournaments e.g., Wimbledon (1289 ± 568 m), the Australian Open (1339 ± 572 m), the US Open (1423 ± 589 m) and French Open (1452 ± 600 m) (Cui et al., 2018). Given the similarity in distances covered between previous research and the present case study, it is likely that the current data are therefore representative of a typical grand slam event. In this regard, this DLW data is the first genuine indication of energy expenditure during a Grand Slam week. The daily TDEE of up to 3824 kcal·d^{-1} resulted in a PAL value ranging from 2.0 to 2.3, values that are associated with a 'vigorous lifestyle' (Park, 2019; Westerterp, 2013). Although such PAL values agree favourably with the range (1.71 – 3.4) previously suggested for female athletes (Park, 2019), it is noteworthy that such daily energy expenditure are greater than that reported in elite female distance runners (2826 ± 312 kcal·d^{-1}) during training (Schulz et al., 1992). The current data are similar to those values reported in elite lightweight rowers during heavy training (3957 ± 1219 kcal·d^{-1}) yet remain lower than elite swimmers during heavy training (5593 ± 495 kcal·d-1) (Hill & Davies, 2002; Trappe et al., 1997). The only available previous data on TDEE using DLW that has included female tennis players reported a TDEE of 2780 ± 430 kcal·d^{-1}, however, any comparison is hard to make as participant activity was not recorded, there was no information on the playing standard or ranking of the athletes and it was unclear if the data included actual competition (Ndahimana et al., 2017). When comparing the female TDEE relative to FFM (71.7 kcal·kg^{-1} FFM) to other sports, the current values are higher than elite female distance runners (60.6 kcal·kg^{-1} FFM), similar to badminton (72.2 kcal·kg^{-1} FFM) and lower than elite lightweight rowing (84.4 kcal·kg^{-1} FFM) (Hill & Davies, 2002; Schulz et al., 1992; Watanabe et al., 2008). Whilst this data can be used to inform nutritional guidelines, there remains a requirement to conduct further studies using larger sample sizes and at various phases throughout the season.

The sample collection points for the male player allowed a split in the data analysis in a similar manner to the female athlete, therefore allowing for the calculation of TDEE for P1 (training with one ATP International match) and P2 (training with ATP International and Grand-Slam competition). In this regard, P1 was mainly representative of a training week with little competition (only 88 min). As such, the TDEE reported during P1 (3712 kcal·d^{-1}) was considerably less than P2 (5520 kcal·d^{-1}) which included training and both ATP International and Grand Slam tournament match play. It is therefore apparent that there was a substantial difference in playing demands between P1 and P2 with over six times more points played in

P2. As a consequence, training time during P1 was more than double that in P2. Nonetheless, despite this increase in training time, TDEE in P1 was still 1808 kcal·d^{-1} less than P2 therefore highlighting the major contribution of match play in influencing the daily TDEE of elite players. It is also noteworthy that the mean match duration during P2 was heavily influenced by the participation in a five set Grand Slam match, covering over 40% of the total weekly distance during this single match (4175 m). These daily fluctuations in the activity of professional tennis players emphasise the unique nature of this sport whereby the absolute activity is largely dependent on the 'competitiveness' of the game. This unpredictability of the sport (and associated influence on daily TDEE) therefore necessitates the requirement for a targeted and flexible dietary approach to ensure that energy balance is maintained during the course of a tournament.

To contextualise the TDEE of the male player, it is possible to compare the data to that reported using DLW from other professional sports. It is demonstrated here that the absolute TDEE was higher than English Premier League soccer players (3566 ± 585 kcal·d^{-1}) and similar to professional rugby league players (5374 ± 645 kcal·d^{-1}) during training and competition but lower than professional road cyclists during the Giro d'Italia stage race (6903 ± 764 kcal·d^{-1} using the DLW intercept method) (Anderson et al., 2017; Morehen et al., 2016; Plasqui et al., 2019). Currently no elite level tennis competition data using the DLW methodology exist to which comparisons can be made. The current male data positions tennis as an energetically demanding sport when considering the TDEE relative to FFM (83.7 kcal·kg^{-1} FFM) to other sports, such as rugby league (70.1 kcal·kg^{-1} FFM), English Premier League soccer (54.9 kcal·kg^{-1} FFM). For the male player, PAL values of 2.2 (P1) and 2.8 (P2) were calculated. Although these values do not equal the upper limits of 4.0 reached by endurance athletes (Westerterp, 2013) this data appears to place male tennis players at the upper range when compared to PAL values from other sports (Morehen et al., 2016; Sagayama et al., 2017). These data for the first time propose a valid and accurate TDEE for elite male and female tennis players with a PAL value that may be used to guide future dietary interventions.

The role of energy availability in supporting health and performance is well established (Close et al., 2016; Heaton et al., 2017). In relation to the latter, the effects of CHO have been specifically highlighted in reducing both central and peripheral fatigue during tennis (Gomes et al., 2014; Hornery et al., 2007). Although CHO metabolism was not directly investigated, the DLW data reported here can help to formulate macronutrient guidelines to achieve energy balance during a physically demanding competition period. For example, if protein intake was considered at a fixed amount of 1.8 $g \cdot kg^{-1} \cdot d^{-1}$, fat at a fixed amount of 2 $g \cdot kg^{-1} \cdot d^{-1}$ the remaining caloric intake would be through CHO. For the female player, this would equate to ~6 $g \cdot kg^{-1} \cdot d^{-1}$ for P1 and ~7 $g \cdot kg^{-1} \cdot d^{-1}$ for P2. For the male player, this would equate to ~ 5$g \cdot kg^{-1} \cdot d^{-1}$ for P1 and ~11 $g \cdot kg^{-1} \cdot d^{-1}$ for P2. These values are in line with the CHO guidelines proposed, whereby values of 6 – 10 $g \cdot kg^{-1} \cdot d^{-1}$ for moderate to high intensity of 1 – 3 $h \cdot d^{-1}$ and 8 – 12 $g \cdot kg^{-1} \cdot d^{-1}$ for moderate to high intensity exercise of 4 – 5 $h \cdot d^{-1}$ are suggested Burke et al., (2015). The practicalities at some tennis events mean that the ideal nutrition (macronutrient total, type and timing) is difficult due to poor provision and/or availability. The issues with variable match duration, feeding opportunities and logistical challenges collectively highlight the requirement for bespoke player education programmes to ensure that players can self-monitor, source and administer their own nutrition. The high physical loading and daily TDEE reported here is likely to also induce considerable glycogen depletion, the extent of which remains currently unknown. Such potentially high rates of glycolytic flux coupled with the short turnaround between games (e.g., 1 – 2 days) also demonstrates the requirement to maximise CHO availability in recovery from match play. The energy expenditures reported, and potentially high level of CHO dependency suggest the in-competition feeding strategies typically associated with the endurance athlete (e.g., 30 – 90 g of CHO per hour depending on duration). The CHO cost of match play and the potential ergogenic effects of CHO feeding strategies also represent opportunities for further research.

As with all case-study accounts, the present data are not without limitations that are largely related to collecting data on elite athletes during international competition. To protect athlete confidentiality, age and anthropometrics were not reported, limiting the descriptive data presented. Energy intake was not recorded given the intense demands of a Grand Slam tournament and the invasive nature of such data collection at a time when the athletes needed be fully focussed on competition. A limitation of the DLW technique itself is the inability to report day-to-day variations in TDEE, individual matches or training bouts. For example, it could be presumed the increased duration, distance and RPEs of the male player's final match day will have created a spike of TDEE and increased mean TDEE for the week but are unable to quantify to what degree. Additionally, the reduction in training load that accompanies increased competition demands is likely to lower daily TDEE. Clearly, the requirement to quantify day-to-day variations in both energy intake and energy expenditure is a targeted area for future investigation.

The data presented here has, for the first time, been able to report the energy demands of elite tennis played at the highest level. The relative values for the female (71.7 kcal·kg^{-1} FFM) and male (83.7 kcal·kg^{-1} FFM) player position elite tennis played during WTA/ATP international, and Grand slam tournaments to be energetically demanding. The data now begins to aid the practitioner when formulating nutritional plans for a player of this calibre. However, it emphasises the necessity of expanding the comprehension of the TDEE among professional tennis players to better address the nutritional needs of this population. High daily energy requirements exist and without the support of a nutritionist, a player needs to understand their requirements, when fluctuations may arise and how to adjust their intake appropriately. Future directions should now aim to broaden the understanding of energy expenditure during competition by assessment of other player groups i.e. lower ranked senior players, junior players, and doubles format players.

Chapter 5 - An Observational Case Series Measuring the Energy Expenditure of Elite Tennis Players During Competition and Training Using Doubly Labelled Water

Published in; *International Journal of Sports Physiology and Performance*, *18*(5), 547–552.

5.1 Introduction

The previous chapter provided the first insight into the high energy requirements of world class tennis players during a competitive period which emphasised the demands regularly faced by this group during competition of the highest level. Although it has indicated a benchmark to begin formulation of nutritional plans, it is unclear if these energy expenditures are specific to world class Grand Slam singles players only. To broaden the understanding, there is a requirement to investigate a wider range of players during competition. In using the gold standard DLW technique to negotiate the sport rulings of worn device approval, a broader group of professional tennis players that include lower ranked, junior and doubles players will build on the initial findings. Examining female singles players participating in International WTA tournaments will provide insights into whether the earlier findings were applicable exclusively to the players assessed. Comparison can be also made to the reduced expenditure reported during WTA tournament played during the first period of analysis (P1) by the female player. Incorporating an elite junior player will aid in comprehending whether the daily demands experienced by senior players are mirrored in younger athletes. While there is awareness of the higher explosive yet lower overall intensity distinctions between singles and doubles, there is a lack of research regarding the impact these differences have on energy expenditure (Martínez-Gallego et al., 2020; Morgans et al., 1987). Integrating the demands of a doubles player can facilitate a comparison against the previously reported demands faced by singles players during competition at the highest level of the sport. Therefore, due to the previously high energy expenditures reported, the current aim is to assess the TDEE of a wider group of players during competition to further broaden the understanding of the energy requirements of elite tennis.

5.2 Participants

One male doubles player (MD) ranked ATP top 5, three senior female singles players (FS1, FS2 and FS3) ranked WTA 125 – 375, and one female singles junior player (FSJ) ranked WTA top 350. Table 5.1 highlights the tournament and match volume by the participants during the year of, and prior to, their involvement in the current research.

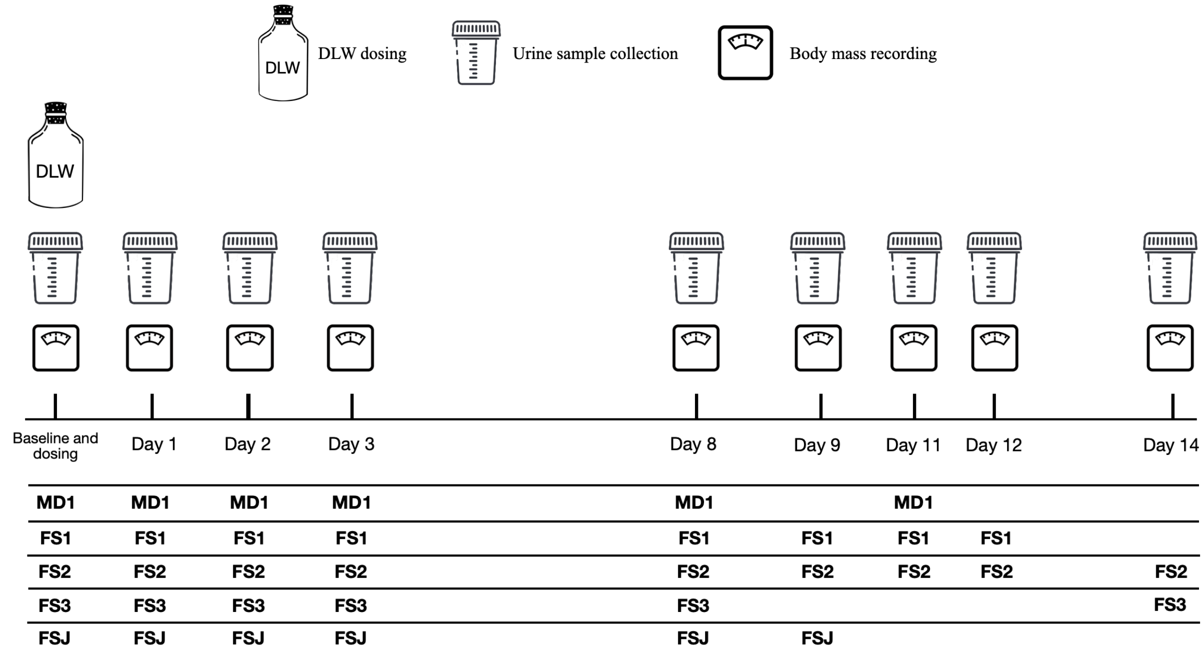
Table 5.1. *Total international tournaments and matches played by participants prior to and immediately following analysis period.*

	Tournaments played in 2018	Total matches in 2018	Tournaments played in 2019	Total matches in 2019
MD	33	86	29	70
FS1	31	59	42	109
FS2	32	71	28	58
FS3	34	75	28	73
FSJ	15	58	13	43

5.3 Experimental design

Daily energy expenditure was measured using the doubly labelled water technique. Data collection was conducted over 9-14 days during periods of competition and training during 2019 (see Figure 5.1). Training was defined as on-court training sessions, strength and conditioning sessions, and pre-match preparation. Competition included the Wimbledon Championships, WTA/ATP international tournaments, Junior and Senior ITF, and Wimbledon

Junior Championships. Throughout data collection, the participants continued with their usual training and preparation. Concerning FS3, the TDEE displayed was from day 3 to day 14 which included one 160 min match on day 3, during which the participant sustained an ankle injury. Data collection continued as a unique opportunity to observe the energy demands of a player following injury. The injury resulted in the complete rupture of the calcaneofibular and anterior talo-fibular ligaments. Surgery was performed 6 days later and involved reconstruction of both ligaments. The affected limb was in a below knee cast and daily movement was quantified by the participant as <45 min per day, requiring the use of crutches throughout the measurement period. Other factors of note were the final match played by MD was split over two days due to failing light, and rain delays were faced by FS1 and FS2 (days 8-9 and 4-5 respectively) resulting in reduced activity.



Baseline and dosing	Day 1	Day 2	Day 3	Day 8	Day 9	Day 11	Day 12	Day 14
MD1	**MD1**	**MD1**	**MD1**	**MD1**		**MD1**		
FS1	**FS1**	**FS1**	**FS1**	**FS1**	**FS1**	**FS1**	**FS1**	
FS2	**FS2**	**FS2**	**FS2**	**FS2**	**FS2**	**FS2**	**FS2**	**FS2**
FS3	**FS3**	**FS3**	**FS3**	**FS3**				**FS3**
FSJ	**FSJ**	**FSJ**	**FSJ**	**FSJ**	**FSJ**			

Figure 5.1 *Data collection points for all participants, showing initial dosing and subsequent sample collection and weight recording.*

5.4 Methods

Daily energy expenditure (kcal·d^{-1}) was measured using DLW, as previously validated by comparison to simultaneous indirect calorimetry in humans (Speakman, 1997). The TDEE was assessed using DLW (see method section 3.2.1 and 3.2.2 for more detail). Fat free mass was calculated using the (^{18}O dilution space) DLW method (section 3.1.6), prior to inclusion into the Cunningham equation to estimate RMR (Cunningham, 1980). Activity loads were captured using a modified 10-point ratings of perceived exertion Borg scale for each session, multiplied by the duration of the session to produce session ratings of perceived exertion (sRPE) (Foster et al., 2001).

$$\text{Total body water (N)} = [(N_o/1.007)+(N_d/1.043)]/2$$

$$\text{Resting metabolic rate (RMR)} = (500+22)\cdot \text{FFM}$$

$$\text{Physical activity level (PAL)} = \text{TDEE/RMR}$$

All data are displayed for descriptive purposes and represent absolute individual values, matches and points played, total match time (min), total training time (min), RPEs (AU), TDEE (kcal·d^{-1}), and TDEE relative to FFM (kcal·kg^{-1} FFM).

5.5 Results

The participant activity loads, PAL, points played, total match and training durations with combined daily mean ± SD are reported in Table 5.2. Daily durations and activity loads are shown in Figure 5.2. Participant's RMR and TDEE ranged between 2049-1568 kcal·d^{-1} and 4586 – 2583 kcal·d^{-1} respectively and are shown in Figure 5.3. Activity energy expenditure (AEE) ranged between 2534 – 840 kcal·d^{-1}. Relative AEE, RMR and TDEE ranged between

48.9 – 14.9 kcal·kg^{-1} FFM, 32.3 – 29.1 kcal·kg^{-1} FFM, and 81.2 – 45.7 kcal·kg^{-1} FFM respectively and are shown in Figure 5.3. The known DLW analytical error (6.03 ± 0.93 %) was within the acceptable range previously reported (Speakman et al., 2021).

Table 5.2. *Participant overview, durations, and activity summary during analysis the period, and individual physical activity level (PAL) recorded.*

Participant	**Age (y)**	**Career high ranking**	**Activity during analysis**	**Total days**	**Surface**	**Total match duration (min)**	**Total training duration (min)**	**Combined Mean ± SD daily durations (min)**	**PAL**
Male doubles (MD)	26	Top 5 ATP Doubles	Wimbledon Championships and training	10	Grass	577	403	98 (± 74)	2.2
Female singles 1 (FS1)	22	Top 125 WTA Singles	WTA International tournament and training	11	Indoor hard and grass	264	1380	149.5 (± 65.7)	2.5
Female singles 2 (FS2)	20	Top 175 WTA Singles	WTA International, ITF tournament and training	14	Indoor hard and grass	270	1540	139.2 (± 83.9)	2.1
Female singles (FSJ)	16	Top 350 WTA Singles	ITF J1, Junior Wimbledon and training	9	Grass	386	795	131.2 (± 66.3)	2.5
Female singles (FS3)	20	Top 375 WTA Singles	ITF tournament and injury	14	Grass	180*	0	n/a	1.5

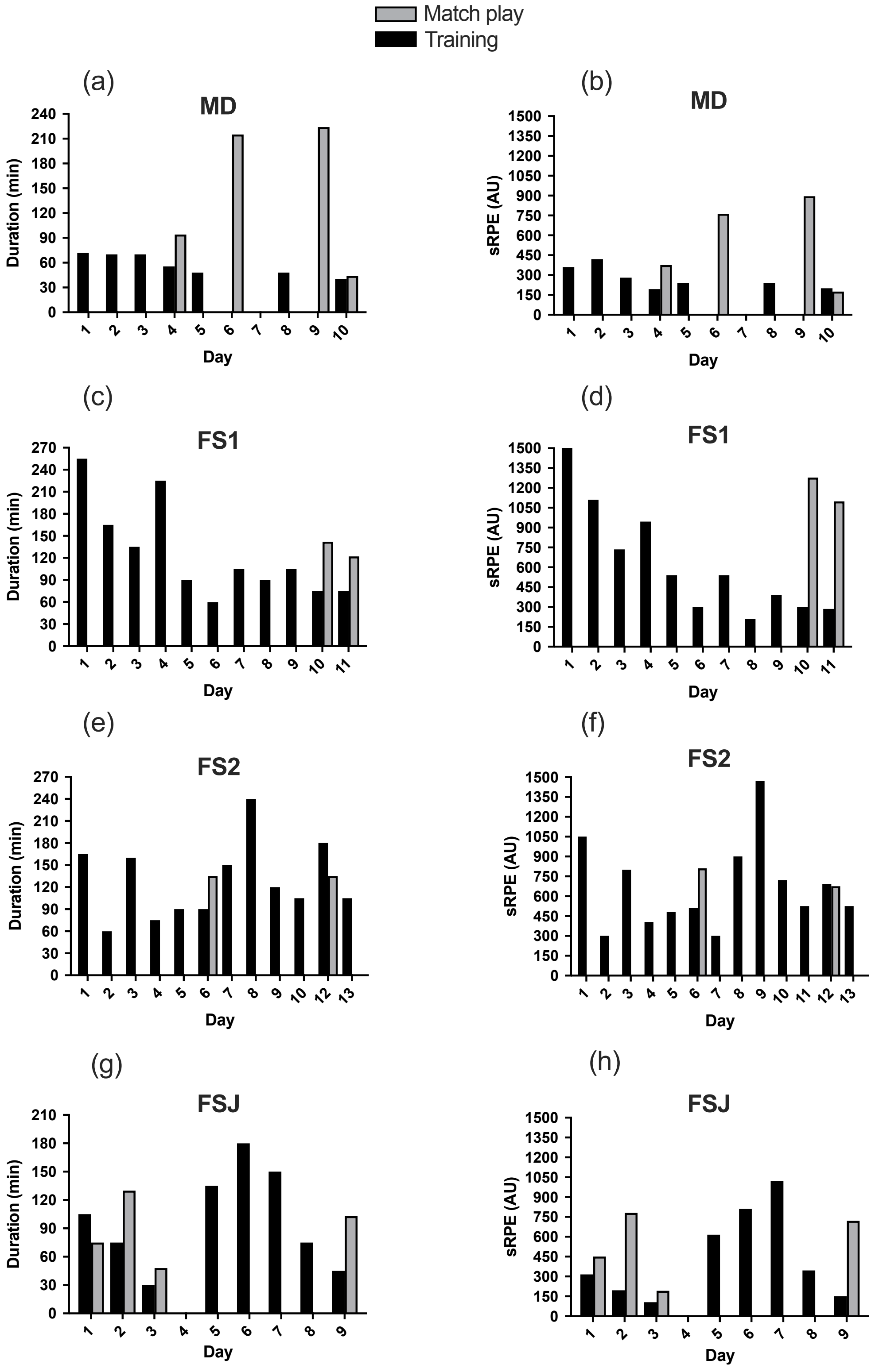


Figure 5.2. *Daily training and match durations, and daily RPEs for MD (A and B), FS1 (C and D), FS2 (E and F) and FSJ (G and H).*

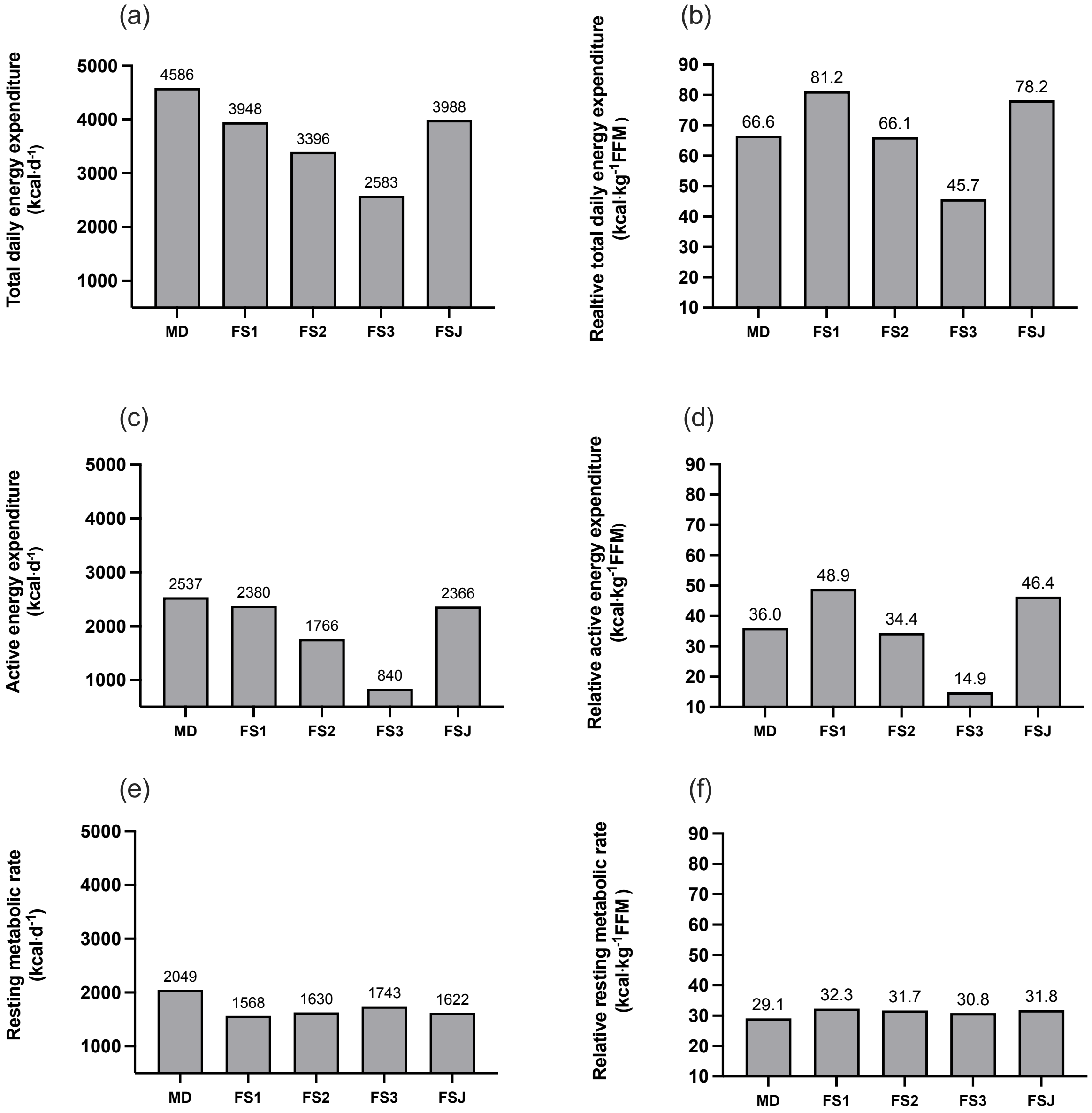


Figure 5.3. *Absolute (kcal·d^{-1}) and relative to fat free mass (kcal·kg^{-1}FFM) values of total daily energy expenditure (TDEE) (A and B), AEE (C and D) and RMR (E and F) are shown for Male Doubles (MD), Female Singles 1 (FS1), Female Singles 2 (FS2), Female Singles 3 (FS3) and Female Singles Junior (FSJ).*

5.6 Discussion

In using the DLW technique in this observational report, the TDEE of tennis players competing at the highest levels of the sport is captured. For the first time, the TDEE assessment of an elite male doubles player, a junior female player and incidentally an injured adult female singles player is reported. Each athlete case is now discussed below.

5.6.1 Men's doubles (MD) player

A daily TDEE of over 4500 kcal and a relative TDEE of 65 kcal·kg^{-1} FFM, was measured over 10 days during the Wimbledon Championships. These values are lower than the previous findings from a male singles player during 10 days of the Wimbledon Championships (5520 kcal·d^{-1}, 83.7 kcal·kg^{-1} FFM), that consisted of 1084 min of training and singles match play combined (daily mean 111 ± 75 min) (Ellis et al., 2021). Although the present athlete played less matches (577 min across 3 matches compared to 734 min across five matches), the points played (891 vs 789), and the combined durations of 980 min were similar (daily mean 98 ± 74 min). Match play intensities, scoring formats and distances covered may differ between singles and doubles, however, it would be speculative to attribute the difference of TDEE to the difference in format (Alcock & Cable, 2009; Kovalchik & Ingram, 2018; Morgans et al., 1987; Senatore & Cannataro, 2019).

5.6.2 Female senior singles players (FS1 and FS2)

The combined durations of match play and training were similar between FS1 and FS2 (mean of 150 min·d^{-1} and 139 min·d^{-1} respectively), although FS1 played more points than FS2 (411 vs 272). Daily TDEE differed by over 700 kcal·d^{-1} with relative values of 81 kcal·kg^{-1} FFM and

66 kcal·kg^{-1} FFM respectively. In addition to points played, a factor that may contribute to these differences include player game style. Evident when Senatore and Cannataro (2019) reported a significant main effect for five different game styles when capturing hourly expenditure.

5.6.3 Injured female senior singles player (FS3)

The player sustained the injury during the latter stages of a match having already played 248 points. As such, activity was limited prior to and following surgery (45 min movement per day). Match play expenditure, the energetic cost of the tissue repair, and general mobility with crutches elevated TDEE by 840 kcal·d^{-1} above RMR producing a PAL value of 1.5. Whilst this data is specific to the individual, it is hoped it can highlight a need to consider energy requirements during a rehabilitation period and not simply reducing intake to achieve RMR requirements in an largely immobile athlete.

5.6.4 Female junior singles player (FSJ)

The mean daily match and training durations were lower than FS1 and similar to FS2 but points played were higher (FSJ; 498, FS1; 411, FS2; 272) with absolute and relative TDEE being comparable to FS1. It is noteworthy that the current data was captured during a summer break from schooling and may not reflect the TDEE experienced during term time (daily education, non-exercise activity, physical education activity, tennis training). The observations reported, highlight a need for further research that quantifies the term time TDEE of high-level junior players, alongside the practical challenges and/or barriers that such a schedule produces for energy intake in this cohort.

5.6.5 Practical applications

The deleterious effects of low energy availability are well documented, and avoidance should be considered a priority when formulating nutritional strategies Burke et al., (2015). The variability of TDEE shown here, suggest that when developing nutritional interventions to achieve sufficient energy intake, it may be prudent to evaluate and assess individual requirements of the player on a case-by-case basis. When considering the TDEE reported here alongside the typical daily duration of activity, this data substantiates previous nutritional guidelines for athletic populations and suggest that daily carbohydrate intakes should likely equate to 6-10 $g \cdot kg^{-1}$ body mass (Logue et al., 2020). In the context of the substantially reduced TDEE of the injured player, CHO intake could be reduced to 3 $g \cdot kg^{-1}$ body mass with protein increased to 2.2 $g \cdot kg^{-1}$ and fat at 1.5 $g \cdot kg^{-1}$ in accordance with research suggesting additional protein intake may retain muscle mass during periods of immobilisation (Milsom et al., 2014). Although future studies with a larger sample size may substantiate these suggestions, the range reported here suggest specific individual assessment would enhance prescription accuracy over the use of mean values derived from wider scale studies. When understanding the lifestyle of a tour level player (travel, accommodation, environment), it is wise to consider the challenges faced (food availability, preference, culture) when achieving energy sufficiency and nutritional education should underpin any strategy.

5.6.6 Conclusion

In considering a limitation of the DLW methodology is the inability to report daily TDEE fluctuations, it is acknowledged that further investigation of acute TDEE variations in professional tennis players would help improve nutritional prescription. Nonetheless, this case series of individual athletes has broadened the understanding of the high energy requirements

(60-90 $\text{kcal}\cdot\text{kg}^{-1}$ FFM) of elite tennis by reporting the TDEE of singles, doubles and junior players in high level competitive environments. The high level of energy demand has once again been observed, suggesting the assessment of other elite tennis formats (wheelchair tennis) in the competitive environment are necessary.

The data presented here now builds on previous results and supports the notion that elite female tennis players with lower world ranking (100 – 400) than previously measured, and junior players have equally high level of energy requirements to that of elite senior players. The current findings have provided a base for educational resource which has since increased both the understanding and ongoing narrative surrounding the energy requirements of the sport from medical, physiotherapy and physical fitness practitioners. A broad multi-disciplinary understanding of the energy demands has enabled the conversion and messaging to be wider than the nutritionist only, further engaging the player to consider their energy requirements as high importance as other aspects of physical preparation routines.

Chapter 6 - Energy Expenditure of an Elite Wheelchair Tennis Player During Training and Competition.

Published in; *International Journal of Sports Science & Coaching*, *19*(2), 857-863.

6.1 Introduction

Participation and interest in para-sports, including wheelchair tennis, are ever growing following the ongoing success and popularity of the Paralympic games (Gold & Gold, 2007). This increase in wheelchair tennis participation and professionalism has also been aided by the increases in prize money (e.g., approximately 40% rise in the total wheelchair tennis prize fund at Wimbledon Championships between 2021-2023). The format is gaining more following and spectators with larger ‘show’ courts hosting matches at Wimbledon Championships (the LTA, 2022). At the highest level of competition, wheelchair tennis demands a significant proficiency not only in tennis skills but also in the adept handling of the wheelchair. The growing professionalism in wheelchair tennis has necessitated an exploration of the format to acquire a more comprehensive and detailed understanding to better support the athletes involved. The demands and energy needs of elite wheelchair tennis now warrant in-depth exploration within an under-researched population. In using the world number 1 wheelchair tennis player, the current aim is to assess the TDEE, and internal / external loads experienced during competition and training, in addition to understanding the physiological profile of such an athlete.

6.2 Participant

A world class male professional WT player competing in the Open category with a career high ranking of World No. 1 volunteered to participate in this study (Table 6.1).

Table 6.1. *Participant information*

Career High ITF Ranking	**Body Mass (kg)**	**Sum of 6 Skinfolds (mm)**	**Resting Metabolic Rate (kcal·d^{-1})**	VO_{2max} **(ml·kg^{-1} min^{-1})**	**HR^{max} (beats·min^{-1})**	**Peak Speed (km·h^{-1})**
World No.1	65.7	58.5	1569	45.3	193	16.34

Table 6.2 *Total international tournaments and matches played by participant prior to and immediately following analysis period.*

Year	Total matches played	Total tournaments
2019	50	19
2020	39	14
2021	74	25

6.3 Experimental design

Daily energy expenditure was measured using the doubly labelled water technique. Data collection was conducted over a 19 day period (July 2021) (see Figure 6.1) comprising participation in both the Wimbledon Championships Grand Slam tournament (grass court) and British Open Wheelchair Championships (outdoor hard court) at Nottingham Tennis Centre, UK. Throughout data collection, the participant continued with their usual training and preparation with no changes made to their usual competition routines. Sample collection was multi-point and positioned to allow for the assessment of energy expenditure during the periods of Wimbledon Championships, during days 1 – 6 (P1), training, during days 6-12 (P2), and British Open, during days 12 – 19 (P3) (Westerterp, 2017).

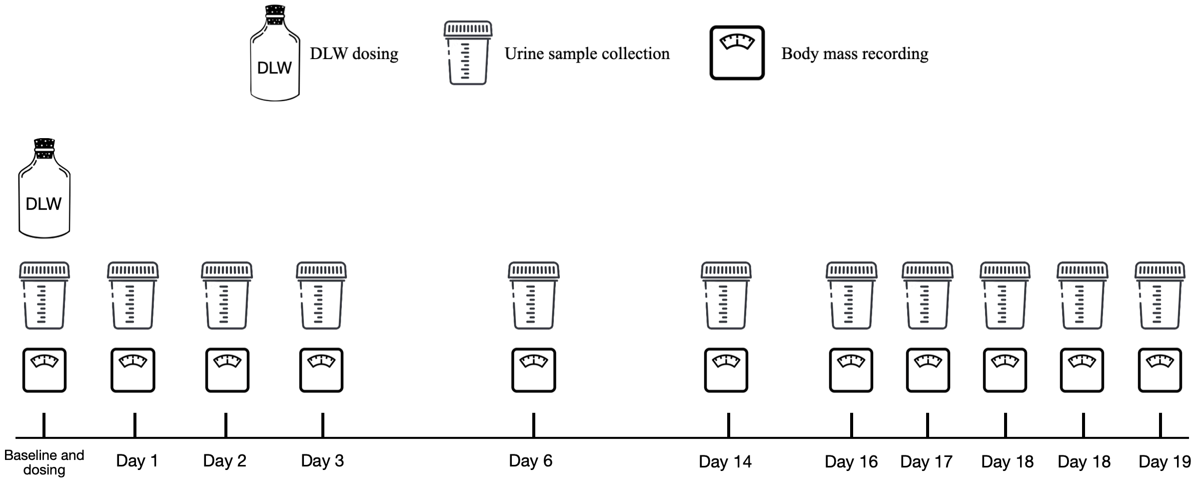


Figure 6.1 *Data collection timeline showing initial dosing and subsequent sample collection and weight recording points.*

6.4 Methods

Daily energy expenditure (kcal·d^{-1}) was measured using DLW, as previously validated by comparison to simultaneous indirect calorimetry in humans (Speakman, 1997). The TDEE was assessed using DLW (see method section 3.2.1 and 3.2.2 for more detail). Fat free mass was calculated using the (^{18}O dilution space) DLW method (section 3.1.6). Heart rate during tennis activity and all on-court distances covered were also captured (section 3.1.12). Approximately 7 days prior to TDEE data collection, body composition using skinfold measurement (section 3.1.5), VO_{2max}, sprint time (10m) and RMR were assessed (see section 3.1.3, 3.1.4 and 3.1.7 respectively).

6.5 Results

Summary data during P1 (Table 6.3), P2 (Table 6.4) and P3 (Table 6.5) and the relative intensities (%HR_{max}) during P1 (Figure 6.2), P2 (Figure 6.3) and P3 (Figure 6.4) are shown. Daily distance (km), duration (min), HR_{max}, HR average, peak %HR_{max}, average % HR_{max}, is shown (Figure 6.5 A-D). The daily energy expenditure increased from 3118 kcal·d^{-1} during P1, to 3177 kcal·d^{-1} during P2, and to 3368 kcal·d^{-1} during P3 (Figure 6.5A), resulting in PAL values of 2.0, 2.0 and 2.2 respectively. When expressed relative to FFM, energy expenditure in P1, P2 and P3 corresponded to 60.3, 61.4 and 65.1 kcal·kg^{-1} FFM, respectively.

In P1, 3 matches were played (one singles and two doubles) with a mean daily duration of 124 ± 20 min (in a range of 117 – 147 min) and covering a mean daily distance of 7.5 ± 0.6 km (7.5 – 8.2 km). During P2, the player had training with no competition, amounting to a mean daily duration of 138 ± 51 min (72 – 192 min) and a mean daily distance of 8.4 ± 2.9 km (4.6 – 11.4 km). During P3, 7 matches were played (4 singles and 3 doubles) with a mean daily duration of 132 ± 61 min (71 – 222 min) and a mean daily distance of 9.5 ± 4.9 km (5.1 – 15.5 km). Shots per rally were 3.5 ± 0.1 during singles match play and 7.5 ± 0.7 during doubles.

Table 6.3 *Activity summary during P1*

Activity	Wimbledon Championships (P1)
Surface	Grass
Total days	5
Singles matches	1
Singles total distance (km)	7.46
Doubles matches	2
Doubles total distance (km)	15.05 (7.52 ± 0.9)
Total (km)	22.51
Total match time (min)	445
Peak speed (km·h^{-1})	16.1 ± 0.6
Total training time (min)	73
Total training distance (km)	3.24
Total energy expenditure (kcal·d^{-1})	3118

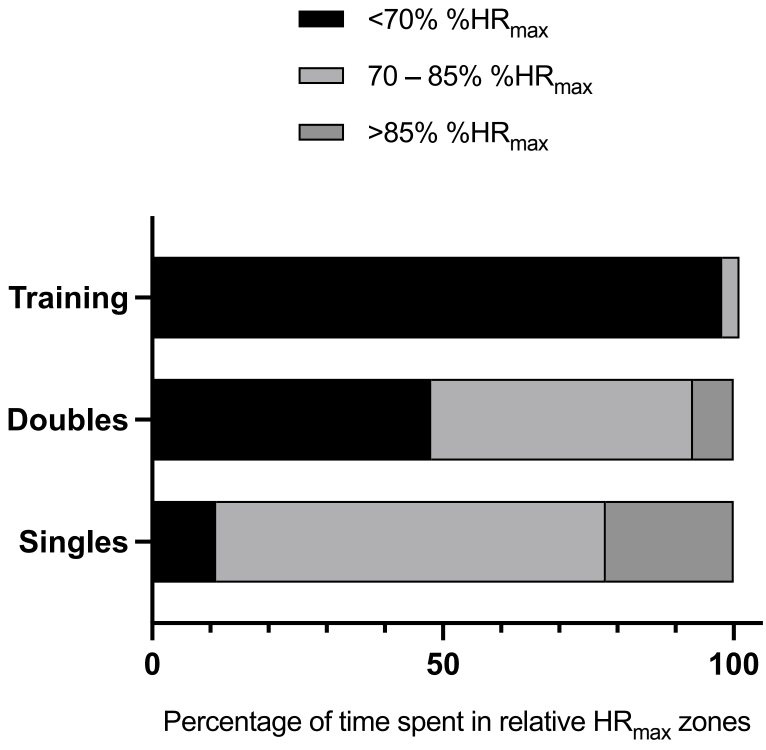


Figure 6.2 *Time spent (% min) in relative HR$_{max}$ zones during P1.*

Table 6.4 *Activity summary during P2*

Activity	Training (P2)
Surface	Outdoor hard
Total days	8
Singles matches	0
Doubles matches	0
Peak speed (km·h^{-1})	15.5 ± 1.2
Total training time (min)	553
Total training distance (km)	33.73
Total energy expenditure (kcal·d^{-1})	3177

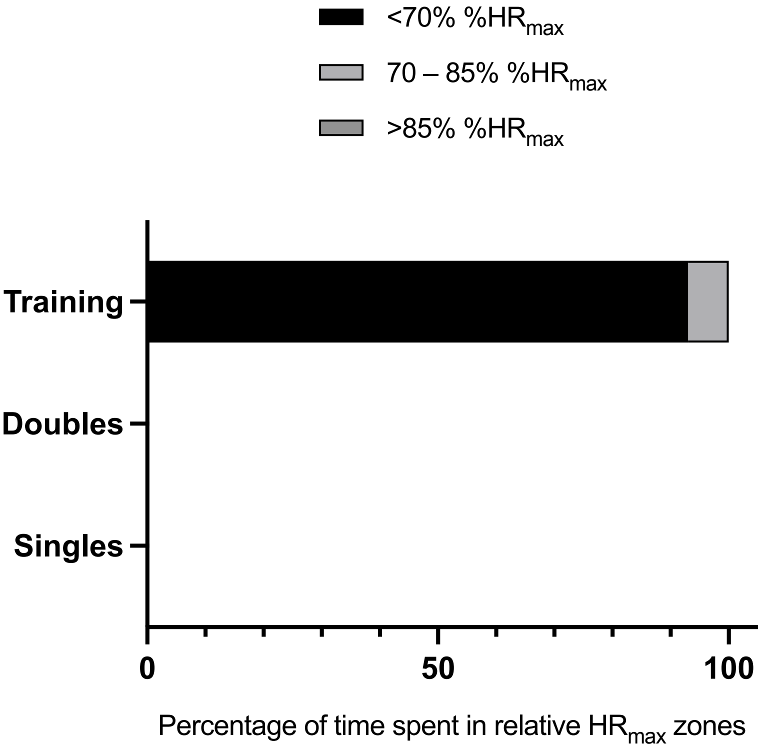


Figure 6.3 *Time spent (% min) in relative HR_{max} zones during P2.*

Table 6.5 *Activity summary during P3*

Activity	British Open Championships (P3)
Surface	Outdoor hard
Total days	5
Singles matches	4
Singles total distance (km)	22.68 (5.67 ± 1.0)
Doubles matches	3
Doubles total distance (km)	28.42 (9.47 ± 1.6)
Total match distance (km)	66.4
Total match time (min)	929
Peak speed ($km \cdot h^{-1}$)	16.2 ± 0.6
Total training time (min)	0
Total training distance (km)	0
Total energy expenditure ($kcal \cdot d^{-1}$)	3368

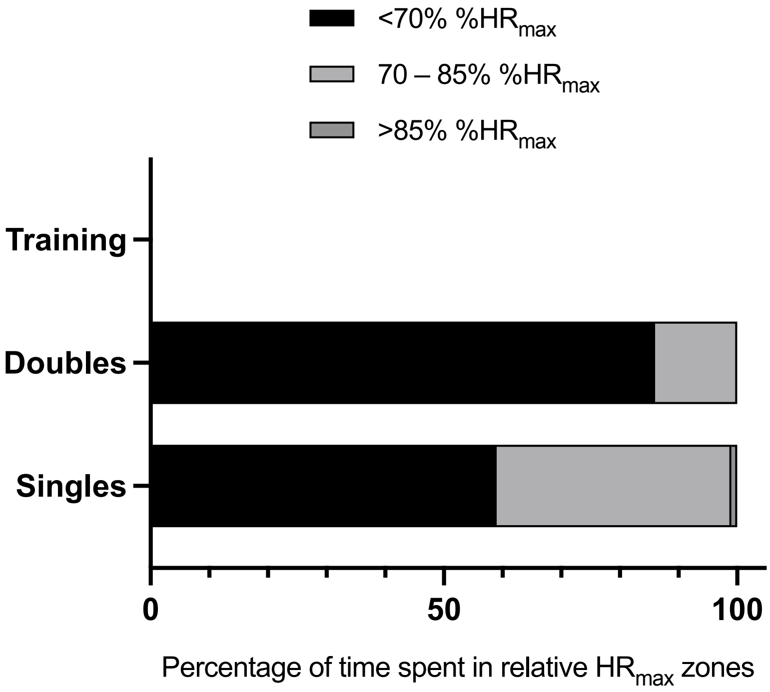


Figure 6.4 *Time spent (% min) in relative HR_{max} zones during P3.*

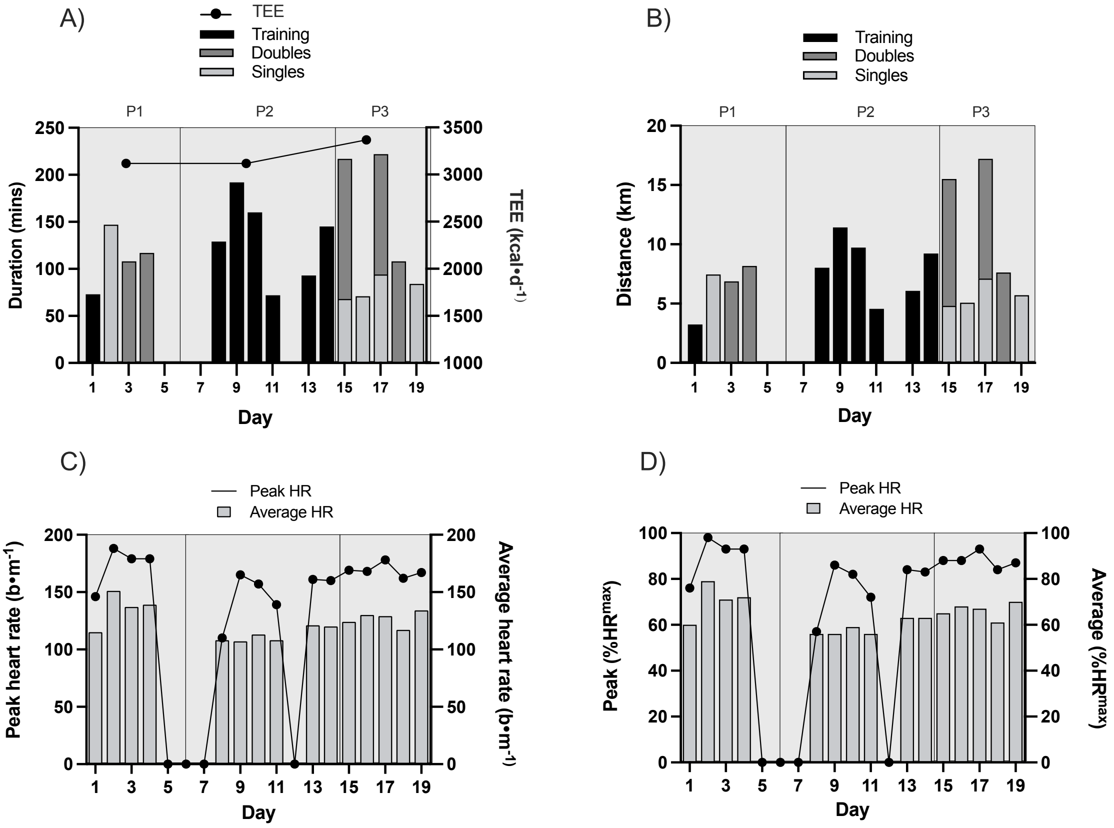


Figure 6.5 *Daily duration (min) and total daily energy expenditure (TDEE) (kcal·d^{-1}) (A), Distance (km) (B), absolute HR$_{peak}$ data (b·m^{-1}) (C) and relative HR data (%HR$_{max}$) (D) are shown.*

6.6 Discussion

We report for the first time the energy demands of a world class elite WT player during training and competition played at the highest level in the male Open category. In doing so, the TDEE during 19 days of training and competition was observed. The data shows a small stepwise increase during each period of collection (P1; 3118 kcal·d^{-1}, to P2; 3177 kcal·d^{-1}, to P3; 3368 kcal·d^{-1}) perhaps logically explained by the increase of duration and distance covered during activity in each period. It should be appreciated that given potential differences in WT match play demands within Quad division, and female Open category, this data is specific to the male Open category.

When compared to the previous data from a male able-bodied player, a lower absolute TDEE during training (3177 vs 3712 kcal·d^{-1}) and competition (3368 vs 5520 kcal·d^{-1}) is reported (Ellis et al., 2021). Currently no DLW data exists that has explored the TDEE of full time paralympic athletes to compare. To contextualise the data shown here, TDEE during P3 is comparable to that of AB English Premier League soccer players (3566 ± 585 kcal·d^{-1}) (Anderson et al., 2017). However, when considering the relative TDEE of 65.1 kcal·kg^{-1} FFM, a value closer to that of AB rugby league players (70.1 kcal·kg^{-1} FFM), than that of English Premier League soccer (54.9 kcal·kg^{-1} FFM) is seen (Anderson et al., 2017; Morehen et al., 2016). Such data highlights the high energy demands of a sport that is dependent on solely the upper body for both propulsion and all technical aspects. This data presented PAL values between 2.0-2.2, values that are associated with a 'vigorous lifestyle' (Westerterp, 2013). When considering the practical application of the data and the variation of physical function across the WT Open category, utilising these PAL values may be prudent when formulating nutritional strategies due to presence of RMR in the PAL calculation. It is worth noting, the data collection during P1 and P3 occurred during a period of strict competitive 'bubbles' designed to eliminate infections during the global Covid-19 pandemic. This may have reduced non-exercise thermogenesis (NEAT) due to travel and activity outside of essential competitive and training being tightly controlled. However, the lack of activity outside training and competition has provided a clearer assessment of the specific TDEE of the sport.

When considering the mean total distances of all matches reported here (singles 6 ± 1.2 km, doubles 8.7 ± 1.6 km) as a per set value, the 2.8 ± 0.5 km is similar to the 2.2 ± 0.8 km per set during analysis of singles match play which included players ranked in the world top 8 (Mason et al., 2020). It is shown here that doubles to have greater distances per set (4.3 ± 0.8) presumably due to the continual circulating movement and position adjustment of both team members. However, peak speeds here (16.2 $k \cdot m^{-1}$) are higher than the 12.2 $k \cdot m^{-1}$ and 13.8 $k \cdot m^{-1}$ previously reported (Mason et al., 2020; Sindall et al., 2013). Reasons for the variance may be due to differences in the methodology used to collect speed data (wheel mounted gyroscope vs data logger), participant rank, and/or competition level. Although limited, research into the accuracy of the Garmin gyroscope wheel sensor did detect a 4.71% error when compared to VBOX 3i RTK GPS system (Siddiqui et al., 2021). Nevertheless, the peak speed recorded on-court, agree with the peak speeds of 16.34 $k \cdot m^{-1}$ recorded during 10m sprint testing using timing gates for this individual. Furthermore, during singles match play, 3.5 ± 0.1 shots per rally were similar to 3.2 ± 0.5 previously found (Mason et al., 2020). Interestingly, the current findings show doubles shots per rally to be 7.5 ± 0.7, higher than 3.41 ± 2.27 found during AB doubles match play (Martínez-Gallego et al., 2020). Although differences of distances covered between AB singles and doubles players has not been investigated it would be presumed to be lower in the AB doubles format than AB singles, as doubles matches generally see a shorter, faster match (Kovalchik & Ingram, 2018).

The mean heart rate during all match play reported here (69 ± 5 $\%HR_{max}$) is similar to 70 ± 9 $\%HR_{max}$ reported during singles match play (Roy et al., 2006). The HR data shown here suggests that singles play was of higher intensity than doubles. It should also be noted that the match intensities during P1 were higher than P3, while a definitive reason is unknown, it is interesting that the two periods were played on different surfaces. Although Wimbledon grass courts are believed to be faster playing surface with lower ball bounce, research has shown grass to increase rolling resistance for the wheelchair user (Koontz et al., 2005; Miller, 2006).

Combined with subjective player feedback reporting that grass is 'a harder surface to push on', this points towards a potential reason for the increased intensity shown. Players report how during the later stages of a grass court tournament, the areas of the court heavily used by AB players (baseline) become worn and flattened. However, the wider areas that wheelchair players find themselves in remain as deeper grass and provide a resistance to wheelchair coasting, meaning more work to maintain movement compared to a hard court surface. An increase of intensity due to surface could be reflected in EE, although difficult to determine due to the non-standardised nature of match play data collection. To determine VO_{2max} of the participant, a wheelchair specific tennis court incremental protocol was used, resulting in 45.3 $ml \cdot kg^{-1} \cdot min^{-1}$. A value higher than values captured in paralympic basketball players (37.9 $ml \cdot kg^{-1} \cdot min^{-1}$) and swimmers (39.0 $ml \cdot kg^{-1} \cdot min^{-1}$), and similar to track and field athletes (44.9 $ml \cdot kg^{-1} \cdot min^{-1}$) (Veeger et al., 1991). The data presented here can begin to benchmark the physical attributes required for WT played at the highest level.

In summary, for the first time the daily TDEE of a world class elite male WT player with a career high of world number one during a 19 day period including training and competition is reported. Additionally, the first TDEE data of any professional para sport athlete captured by the DLW technique during competition is presented. Such data therefore provide a platform to begin the formulation of specific nutritional and training strategies (for on and off the court) and will hopefully stimulate further research into elite Paralympic athletes. The current data is unique due to the participant level, however, it may only be relevant to a small population of players, globally. Therefore, further research is required to understand the requirements of lower-level players. The consideration of the unique and variable physical functionality of a para-athlete mean individual assessment an important factor for this population.

Chapter 7 - Energy Expenditure of Elite Male and Female Professional Tennis Players During Habitual Training

Published in; *International Journal of Sport Nutrition and Exercise Metabolism, 34(3),172-178.*

7.1 Introduction

In analysing the world number one wheelchair tennis player, the findings have further demonstrated the high energy demands across all disciplines of elite tennis played at the highest levels, both by AB and WT players. The data reported has also began to emphasise the high energy expenditures, during training periods between and around competition, but requires investigating further on a larger scale. In using the gold standard DLW technique, it was possible to analyse on a case study basis, the TDEE during competition of the highest level using a method that adhered to the rules of the sport. To this point, competition demands have been highlighted with AB female, male, singles and doubles players in additional to a WT. However, the training periods captured throughout have been between or during tournaments. It is unclear if the training periods captured are reflective of a player's habitual training or reduced due to competition. As elite tennis players engage in a continuous annual cycle of global competition, or training, at a ratio of 40 - 60% training and 60 - 40% competition it appears important to now consider the demands of training to inform the chronic requirements. Explorations now need to profile the continual energy demands during everyday training. By using an efficient and cost-effective method enabling a larger sample group, the findings will help profile the broader energy requirements to support the performance and health of this elite group.

7.2 Participants

Twenty seven (n = 17 female, n = 10 male) professional singles tennis players with ATP/ WTA world ranking (287 ± 187) agreed to participate in this study (see table 7.1). Participants were defined as either Elite (n = 25), or World Class (n = 2) (McKay et al., 2022). The study was approved by the local Ethics Committee of Liverpool John Moores University and the participants provided written informed consent before the study commenced.

Table 7.1. *Participant information*

Sex	Age (y)	Stature (m)	Body mass (kg)
Women	23.8 ± 3.5	1.73 ± 0.04	66.2 ± 4.3
Men	22.3 ± 3.2	1.86 ± 0.06	78.5 ± 8.2

7.3 Experimental design

Players that accessed the National Tennis Centre during the study period were invited to participate with none declining. Using a cohort observational design, players were assessed for resting metabolic rate (RMR), TDEE and tennis training EE.

7.4 Methods

Upon morning arrival at the National Training Centre, the players were weighed (Seca model 876, Birmingham, UK). Following an overnight fast and no vigorous exercise within 14 h of measurement, assessment of RMR was conducted in a darkened room during 30 min of complete rest in a supine position using PNO$\overline{\text{E}}$ portable gas analyser (Tsekouras et al., 2019) calibrated using ambient air before each use (section 3.1.7). Prior exercise, caffeine and alcohol consumption were controlled as per best practise guidelines (Compher et al., 2006). Data from the final 15 min were analysed for lowest coefficient of variation for oxygen uptake (VO_2), carbon dioxide (VCO_2) production and respiratory exchange ratio (RER) during a 10 min period and RMR ($kcal \cdot d^{-1}$) calculated. Collected RMR data was used for individual calibration with Actiheart software (version 4.0.7, Cambridge Neurotechnology, 2020) and used further to calculate physical activity level (PAL) in the following equation (PAL = TDEE/RMR). Immediately following RMR measurement and prior to training, all players were fitted with an Actiheart activity monitor.

The following monitoring period consisted of 2 - 5 consecutive mid-season training days during 2022 - 3 (positioned between tournaments according to player availability) conducted at the National Tennis Centre, UK. Participants were asked to wear the Actiheart devices at all times and only removing them during showering. Players continued with habitual coach led training with no modifications made for research purposes. Training was defined as all on-court (indoor hard) tennis training sessions and warm-ups. In addition to TDEE, the EE during individual tennis training sessions were timestamped and analysed for tennis specific EE. The TDEE on days when players completed either one or two tennis training sessions was also compared. Due to the variance of additional activities captured within TDEE (e.g. resistance, conditioning and physiotherapist led exercise), these were not assessed as part of the specific tennis training evaluation.

Statistical analyses: Data were initially tested for normality using the Shapiro-Wilk's test. Comparisons between male and female groups were performed using non-paired t-test whereby $P \leq 0.05$ was considered as statistical significance. Statistical analyses were completed using GraphPad Prism version 9.5.1, (GraphPad Software, San Diego, California USA). Data are presented as mean ± SD.

7.5 Results

The Actiheart units were worn consistently for between 2 - 5 days, removed only during showering (<5min). A total of 26 days and 33 (1.3 ± 0.5 session·d^{-1}) tennis training sessions were analysed for male players, and a total of 43 days and 58 (1.2 ± 0.4 session·d^{-1}) tennis training sessions were analysed for female players. The RMR of male players was significantly ($t_{24} = 5.6$, $P<0.001$) higher than that of female players (male: 2033 ± 186 kcal·d^{-1}, female: 1624 ± 178 kcal·d^{-1}, 95% CI -557 to -256) and are presented in Figure 7.1A. During the analysis of RMR, no measurement surpassed a <10% coefficient of variation for VO_2 and VCO_2, or <5% for RER, with values of $7.6 \pm 1.8\%$, $8.3 \pm 1.9\%$, and $4.0 \pm 1.2\%$, respectively. Relative RMR was not significantly different ($t_{24} = 1.1$, $P = 0.276$) between groups (male: 26 ± 2.3 kcal·kg^{-1}·d$^{-1,}$ female: 24.8 ± 3.0 kcal·kg^{-1}·d^{-1}, 95% CI -3.6 to 1.1: Figure 7.1B).

The absolute TDEE (male: 4708 ± 583 kcal·d^{-1}, female: 3639 ± 305 kcal·d^{-1}, 95% CI -1283 to -854) of male players were significantly ($t_{66} = 9.9$, $P<0.001$) higher than female and shown in Figure 7.1C. The relative TDEE (male: 58.1 ± 8.3 kcal·kg^{-1}·d^{-1}, female 55.4 ± 5.8 kcal·kg^{-1}·d^{-1}, 95% CI -6.0 to -0.68) of male players were not significantly ($t_{68} = 1.2$, $P = 0.117$) different to female players and shown in Figure 7.1D. Male and female TDEE resulted in a daily PAL value of 2.3 for both groups within a range of 1.6 - 3.0 and 1.6-2.9 respectively.

7.5.1 Absolute tennis training session energy expenditures

Tennis training session EE was significantly higher ($t_{89} = 6.3$, $P<0.001$) for male players (1338 ± 461.7 kcal) compared with female players (885 ± 229.7 kcal) with no significant ($t_{89} = 1.9$, $P = 0.056$) differences in session duration between male (132 ± 41 min) and female (118 ± 30 min: Figures 7.2A and B respectively). When calculated per hour of activity, the absolute tennis training EE for male players was significantly higher (t_{89} = 7.5, P<0.001) than female players per hour (male: 613 ± 137 kcal·h^{-1}, female: 456 ± 63 kcal·h^{-1}, 95% CI -452.5 to -308.6: Figure 7.2C) and per minute (male: 10.2 ± 2.3 kcal·min^{-1}, female: 7.6 ± 1.0 kcal·min^{-1}, 95% CI -3.3 to -1.9).

7.5.2 Relative tennis training session energy expenditures

The relative EE of tennis training for male players was significantly higher (t_{89} = 4.3, P<0.001) than female players per hour (male: 7.9 ± 1.4 kcal·kg^{-1}·h^{-1}, female: 6.9 ± 1.0 kcal·kg^{-1}·h^{-1}, 95% CI -1.6 to -0.6: Figure 7.2D). Relative tennis training EE for male players was significantly higher (t_{89} = 4.3, P<0.001) than female players (male: 17.3 ± 5.5 kcal·kg^{-1}, female: 13.3 ± 3.4 kcal·kg^{-1}, 95% CI -5.8 to -2.1: Figure 7.2E).

7.5.3 Comparison of one and two tennis training sessions per day

The TDEE for days during which two tennis training sessions were completed (7 days), compared to one (19 days), absolute TDEE was not significantly (t_{24} = 0.02, P = 0.982) different for male players (two session: 4574 ± 576 kcal·d^{-1}, one session: 4581 ± 767 kcal·d^{-1}, 95% CI -653.1 to 667.6). The days during which two tennis training session was completed (11 days), compared to one (32 days), absolute TDEE was significantly ($t_{4.7}$ = 41, P<0.001) different for female players (two session: 4012 ± 310 kcal·d^{-1}, one session: 3556 ± 266 kcal·d^{-1}, 95% CI -652.1 to -260.4). Relative TDEE was not significantly ($t_{1.9}$ = 24, P = 0.066) different for male players (two session: 61.8 ± 7.4 kcal·kg^{-1}·d^{-1}, one session: 55.7 ± 7.1 kcal·kg^{-1}·d^{-1}, 95% CI -12.6 to 0.45: Figure 7.1E). Relative TDEE was significantly (t_{41} = 3.1, P = 0.003) female players (two sessions: 59.8 ± 6.7 kcal·kg^{-1}·d^{-1}, one session: 53.9 ± 4.8 kcal·kg^{-1}·d^{-1}, 95% CI -9.6 to -2.1: Figure 7.1F).

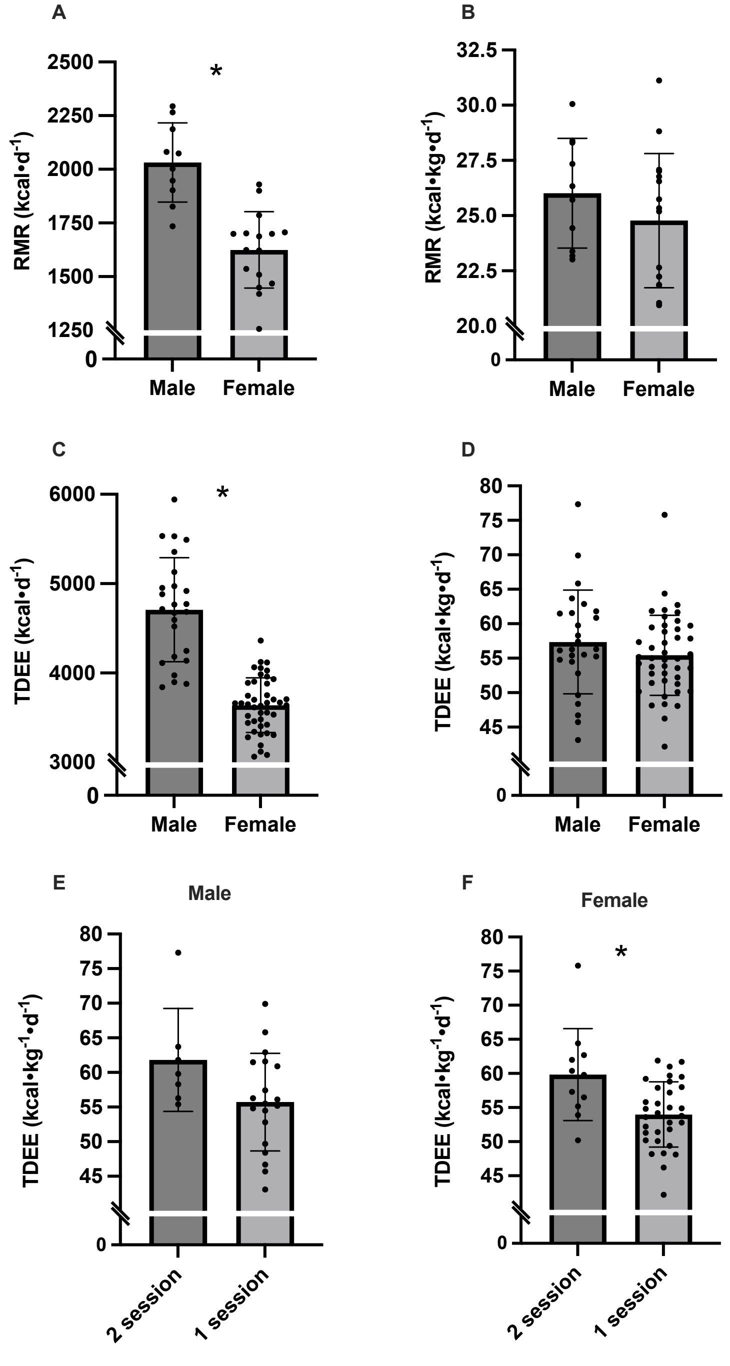


Figure 7.1 *(A) Mean (SD) Resting metabolic rate (RMR) (kcal·d^{-1}), (B) Relative RMR (kcal·kg^{-1}·d^{-1}), (C) Total daily energy expenditure (TDEE) (kcal·d^{-1}), (D) relative TDEE (kcal·kg^{-1}·d^{-1}), (E) relative TDEE comparison of males completing one or two tennis training sessions per day (kcal·kg^{-1}·d^{-1}), (F) TDEE comparison of females completing one or two tennis training sessions per day (kcal·kg^{-1}·d^{-1}). *denotes significant difference between male and female, $P<0.05$. Circles represent individual data points.*

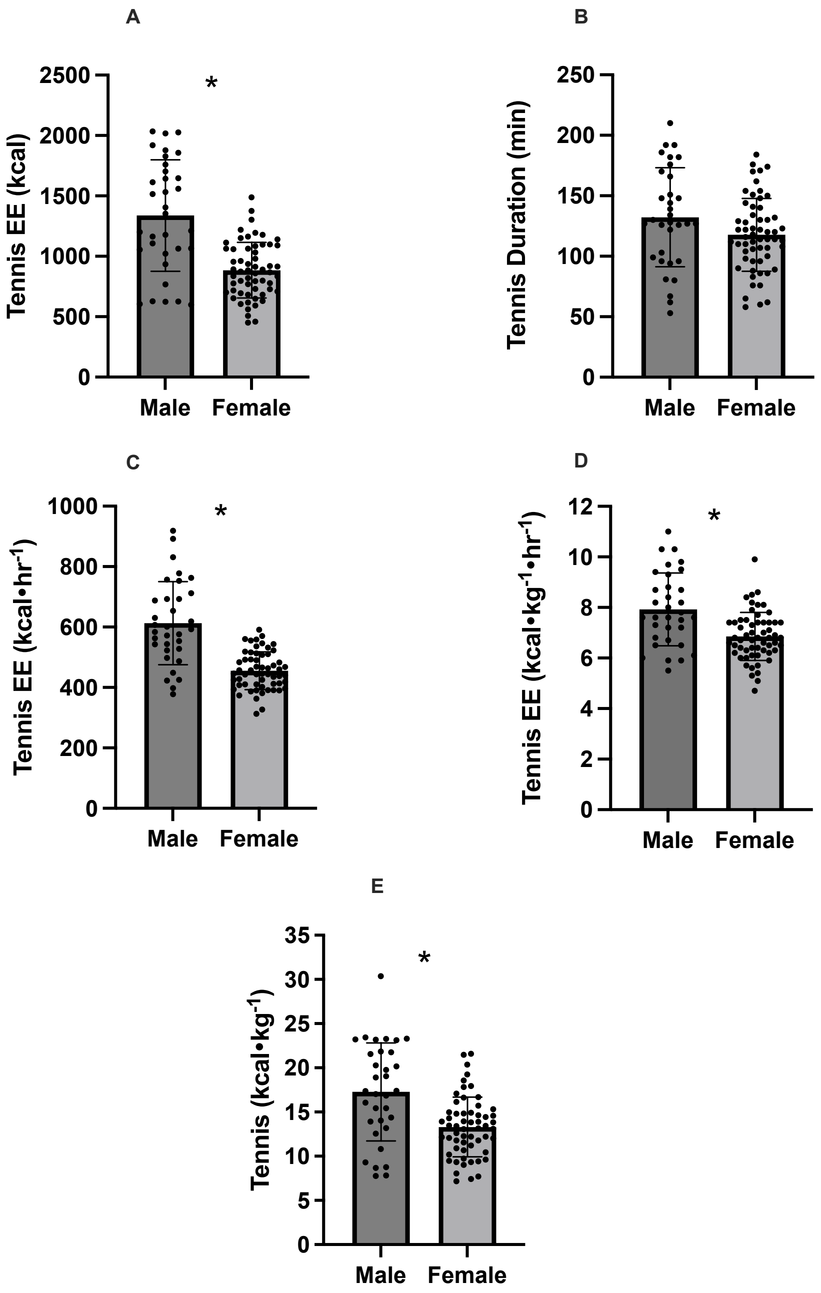


Figure 7.2 *(A) Mean (SD) tennis training session energy expenditure (EE) (kcal), (B) tennis training session duration (min), (C) absolute tennis training session EE (kcal·h*$^{-1}$*), (D) relative tennis training session EE per hour (kcal·kg*$^{-1}$*·h*$^{-1}$*), (E) relative session EE (kcal·kg*$^{-1}$*). *denotes significant difference between male and female, P<0.05. Circles represent individual data points.*

7.5.4 Comparison of current RMR data to other sports

Using one-way ANOVA, comparisons were made between current RMR data and data collated from; Female professional soccer players (Moss et al., 2020), female combat sports (Tortu et al., 2023), female rugby (O'Neill et al., 2022), male trained cyclists (Cocate et al., 2009), male professional soccer players (Carter et al., 2023), male rugby union (Posthumus et al., 2024). Male and female Turkish Olympic athletes from sport athletes; track and field, long distance swimming, modern pentathlon, fencing, karate, taekwondo, boxing, and soccer (Balci et al., 2021). Male and female Brazilian Olympic team from sports; archery, Artistic Swimming, Athletics, Badminton, Beach Volleyball, Boxing, Canoeing, Cycling, Diving, Judo, Karate, Marathon Swimming, Rowing, Sailing, Surfing, Swimming, Taekwondo, Triathlon, Water Polo, Weightlifting and Wrestling (Freire et al., 2021). Male and female NCAA division 3 athletes (Gandhi et al., 2004), male and female elite canoe and rowing (Carlsohn et al., 2011).

In comparison to the current RMR data for females, no differences were observed, except for Turkish Olympic national team members showing lower values and combat sport athletes displaying higher values (see Figure 7.3). Conversely, in comparison to the current RMR data for males, higher values were noted for NCAA athletes, elite canoe and rowing competitors, as well as rugby union players (see Figure 7.4).

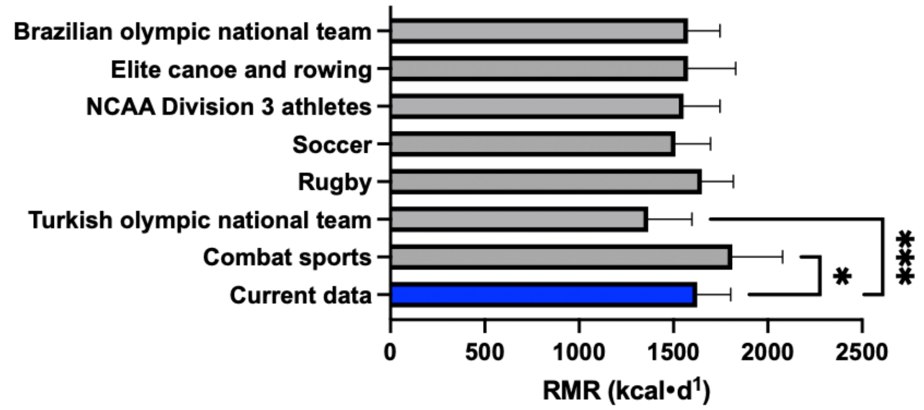


Figure 7.3 *(A) Mean (SD) Resting metabolic rate (RMR) data comparison between current female RMR data and published RMR data from other sports. * denotes significant difference when compared to current data (* (P ≤ 0.05, *** P ≤ 0.001).*

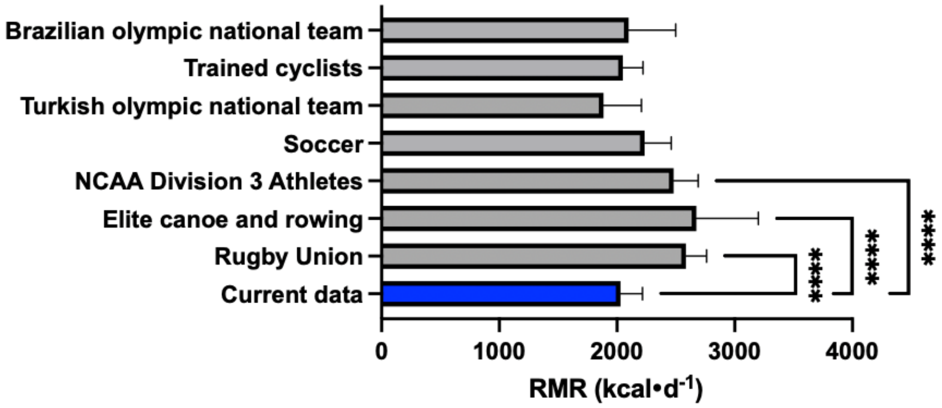


Figure 7.4 *(A) Mean (SD) Resting metabolic rate (RMR) data comparison between current male RMR data and published RMR data from other sports. * denotes significant difference when compared to current data (**** P ≤ 0.0001).*

7.6 Discussion

In using Actiheart activity monitor, the aim of the current research was to assess TDEE and the acute energy demands of tennis training sessions in professional high level and elite tennis players and explore any sex related differences. The data presented here demonstrate that high levels of TDEE is experienced by male and female players during their typical training routines, evident with a PAL of 2.3 associated with a ‘vigorous lifestyle’ (Westerterp, 2013). The data captured here helps inform practitioners working within elite professional tennis when formulating nutritional plans. To address the aims, 27 elite tennis players were recruited to capture the habitual EE regularly experienced by this population using a methodology that would be non-invasive and of no impact to the players during their daily activity. For this reason, the commercially available Actiheart activity monitor provided a data capture method that was of low interference to the habitual training activity of a professional tennis player.

In relation to TDEE, values of ~4700 kcal·d^{-1} and~3600 kcal·d^{-1} for male and female players respectively are reported. Female data that seem comparable to the previous findings of ~3700 kcal·d^{-1} when using doubly labelled water during competition (Ellis et al., 2021, 2023). The similar values demonstrate that competitive and training periods, typical of professional tennis, involve continually high levels of TDEE. Similarly, when considering previous competitive male data (singles ~5500 kcal·d^{-1} and doubles ~4500 kcal·d^{-1}) with male data here (~4700 kcal·d$^{-1).}$ The hourly tennis training EE reported here for female players (456 kcal·h^{-1}) was similar to the 449 kcal·h^{-1} recorded during indirect calorimetry by Novas et al., (2003) and the 443 kcal·h^{-1} collated by Ranchordas et al., (2013). The hourly tennis training EE reported here for male players (613 kcal·h^{-1}) is positioned between the indirect calorimetry values of 568 kcal·h^{-1} previously reported by Kilit et al., (2016) and 649 kcal·h^{-1} data collated by Ranchordas et al., (2013). It is of note that the TDEE reported here sat within a range of 3841 – 5942 kcal·d^{-1} and 3064 – 4362 kcal·d^{-1} for male and female players respectively. Players occasionally participated in two tennis sessions per day, potentially influencing the reported range. On days with two tennis sessions, female players showed a significantly higher absolute TDEE and relative TDEE. While there was no significant difference in male absolute TDEE, relative TDEE increased, although it did not reach statistical significance. Off-court activity (e.g. resistance, conditioning and physiotherapy led exercise) and non-exercise activity could also contribute to the TDEE range seen. However, the broad range is also observed when considering hourly tennis training EE relative to body mass with 4.7 – 9.9 kcal·kg^{-1}·h^{-1} and 5.5 – 11 kcal·kg^{-1}·h^{-1} for male and female respectively.

Although hourly and daily energy expenditures between male and females were significantly different, a PAL value of 2.3 was applicable to both groups. The positive influence that the metabolic requirements of fat-free mass have on RMR are understood (Cunningham, 1980; Stubbs et al., 2018). Although fat-free mass was not captured here, when considering that TDEE appears to be relative to RMR, the sex-related differences in TDEE and EE may be influenced by differences in fat-free mass between groups. Prior research on the sex related differences in the male and female characteristics of competitive tennis play, report no significant difference in point play duration; number of shots played during a point; time between the points; continual shot (rally) pace; and work to rest ratio (Reid et al., 2016). Likewise, distances covered during competitive points were not sex dependent although peak speeds were. While specific to competition only, it indicates that sex-related differences of match play characteristics are small. However, during match play, the time between points and sets are fixed, whereas during training it is determined by the player and/or coach. Therefore, it is unknown how the 'work density' differs between individuals and groups, and perhaps a contributor to the variability seen here. Likewise, although the individual session content was not recorded here, it is a factor that may have influenced the variation of tennis training EE. For example, the increased movement intensity and court coverage seen during point play may increase EE when compared to the isolated practise of a technical shot executed in an almost static position. Nonetheless, with a total of 91 training sessions captured, the data presented provides a clear insight into the high levels of EE experienced by male and female elite tennis players during habitual training.

Observationally, it is apparent that injury free professional tennis players can engage in an almost continual cycle of training or competition 5-6 days per week. Rest or travel occupying the remaining days, with only a short break late in the year prior to resumption of 'pre-season' training during December. Although variable from player-to-player, aside from short periods of rest and recuperation, the endless pursuit for ranking points results in repeated exposure to competitions and subsequently continual high levels of daily EE. Low energy availability is described as a state during which energy intake is not sufficient to support all physiological functions with the prevalence in sport is gradually becoming more widely understood (Logue et al., 2020). Energy availability is calculated as dietary energy intake, minus exercise energy expenditure relative to fat-free mass. Investigations into specific thresholds of energy availability have begun to understand the interchange between energy intake and energy expenditure, and the deleterious effects of low energy availability (Areta et al., 2021). Findings that underscore the importance in educating players of their energy requirements to ensure sufficient energy intake. The current data shows the high energy requirements of a professional tennis player during training and appear to be comparable to competition. Although significant differences were seen between male and female absolute and relative energy expenditures, a

PAL value of 2.3 was applicable for both groups. Therefore, once RMR has been determined, PAL could be used as a guide to begin nutritional prescription. However, given the broad ranges reported it appears that one size does not fit all, therefore, it may be prudent to investigate further the individual player's habitual EE during a variety of typical training days to tailor bespoke plans.

Although CHO requirements were not a focus of this research, the TDEE shown here suggest the suitability of existing recommendations. Specifically, that daily carbohydrate (CHO) intakes should equate to 6 – 10 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for moderate to high intensity of 1 – 3 $h{\cdot}d^{-1}$ and 8 – 12 $g{\cdot}d^{-1}$ for moderate to high intensity exercise of 4 – 5 $h{\cdot}d^{-1}$ (Burke et al., 2015). Accordingly, the TDEE ranges reported here should be reflected in daily CHO requirements with a periodised approach. Based on protein intake at a fixed amount of 1.8 $g{\cdot}kg^{-1}{\cdot}d^{-1}$, and fat at 2 $g{\cdot}kg^{-1}{\cdot}d^{-1}$, with the remaining caloric intake through CHO, the current male and female groups would require 9 $g{\cdot}\ kg^{-1}{\cdot}d^{-1}$ (range 6 - 13 $g{\cdot}kg^{-1}{\cdot}d^{-1}$) and 8 $g{\cdot}\ kg^{-1}{\cdot}d^{-1}$ (range 4 - 12 $g{\cdot}\ kg^{-1}{\cdot}d^{-1}$) respectively. Considering the tennis training durations and EE of both groups, a potentially high level of CHO dependency also lends itself to the on-court feeding strategies typically associated with the endurance athlete (e.g., 30 – 90 g of CHO per hour depending on duration) (Jeukendrup, 2014). The high session EE and TDEE reported here is likely to also induce considerable glycogen depletion, the extent of which remains currently unknown. Such potentially high rates of glycolytic flux coupled with the short turnaround between training sessions also demonstrates the requirement to maximise CHO availability during recovery of daily training.

Collecting ‘real world’ data on elite athletes inherently produces limitations. During analysis, attempting to determine individual tennis session content proved challenging as the philosophy of twenty-seven different coaches varied greatly. Ultimately meaning it was difficult to establish common themes or any standardised on-court or off-court training formats. In this respect, training diaries may have provided clarity when understanding the broad ranges of TDEE reported. Menstrual cycle information, contraception use, or fat-free mass information was captured during analysis and may be considered a limitation. While utilising Actiheart's 'group calibration' is a pragmatic approach when time constraints or broader group analyses are factors, enhancing the accuracy of Actiheart data may be achieved by employing individual calibration when possible (Villars et al., 2012). Further validation of Actiheart for use during tennis activity could be warranted. Nonetheless, a strength of the Actiheart device is in being a non-invasive and practical technique to capture EE with little interference to the athlete while providing data to guide individual requirements. The high energy expenditures shown here now suggest future research should be directed towards understanding the prevalence of low energy availability in elite tennis by investigating energy intake in this population. The present data expands upon prior competitive tournament data, the incorporation of rest days should now be considered in future studies to enhance the comprehension of the requirements for this population beyond training and match days.

Using the largest sample size in existing elite tennis research, the data presented here outlines the high EE of male and female players during habitual training with a PAL value of 2.3 for both groups. The TDEE of male (~ 4700 $\text{kcal}\cdot\text{d}^{-1}$) and female (~3600 $\text{kcal}\cdot\text{d}^{-1}$) players during training builds on previous findings during competition and highlights the continual cycle of high energy demands at the elite level of tennis.

In addition to the competitive energy expenditure data, the current data has added to the player education resources and coaching syllabus content surrounding the energy requirements of training for the professional tennis player. The data reported here has also now began to inform the sport more widely through player support personnel at international governing bodies.

Chapter 8 - General Discussion

8.1 Realisation of the objectives.

Objective 1. To evaluate the energy expenditure of an elite male and female elite tennis player during high level competition using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition. Determine match play characteristics (distances covered, shot counts) to ensure the demands during data collection are reflective of existing literature.

This objective was addressed in Chapter 4. A world-class male and female player were assessed for energy expenditure during Eastbourne WTA/ATP and the Wimbledon Championships using the doubly labelled water method. The complete assessment period was split into two periods to help distinguish between competitions (P1 and P2). In addition to capturing distances covered by the player during the matches, shot counts and session ratings of perceived exertion, the results show the energy expenditures experienced by world class tennis players during competition of the highest calibre. The male player TDEE was ~3700 $kcal \cdot d^{-1}$ during P1 and ~5500 $kcal \cdot d^{-1}$ during P2. The female player TDEE was ~3400 $kcal \cdot d^{-1}$ during P1 and ~3800 $kcal \cdot d^{-1}$ during P2. The results suggested that elite tennis played at the highest level of competition is a highly energetically demanding sport with male and female relative energy expenditures of 83.7 $kcal \cdot kg^{-1}$ FFM and 63.5 $kcal \cdot kg^{-1}$ FFM respectively.

Objective 2. To evaluate the energy expenditure of a broader range of elite players. Participants to include lower ranked senior female players, junior female player and male doubles players. Data collection will involve high level competitive period that is relative to the player ranking using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition.

This objective was addressed in Chapter 5. Senior (n = 3) and junior (n = 1) female players ranked WTA top 125 - 375, and a male (n = 1) doubles player ranked in the world top 5 were assessed for energy expenditure. Assessment took place during competition including WTA International (senior female players) and the Wimbledon Championships (doubles and junior) using the doubly labelled water method. The results displayed high energy expenditures for elite female tennis players (~3400 and ~4000 $\text{kcal}\cdot\text{d}^{-1}$; 66 and 81 $\text{kcal}\cdot\text{kg}^{-1}$ FFM) with lower match counts than players that participated in Chapter 4. The data also showed high energy expenditures for junior female player (~4000 $\text{kcal}\cdot\text{d}^{-1}$; 78.2 $\text{kcal}\cdot\text{kg}^{-1}$ FFM), and the male doubles player (~4600 $\text{kcal}\cdot\text{d}^{-1}$; 67 $\text{kcal}\cdot\text{kg}^{-1}$ FFM) both during competition at the highest level. During the assessment, a senior female player became injured and underwent subsequent surgery and immobilisation. Results show the expenditure during this 14 day period (~2600 $\text{kcal}\cdot\text{d}^{-1}$; 45.7 $\text{kcal}\cdot\text{kg}^{-1}$ FFM) and inform practice of the acute caloric adjustments required during the immediate rehabilitation phase.

Objective 3. To determine the demands and energy expenditure of elite wheelchair tennis. Data collection will profile a world class player by assessing physiological and performance capacities relevant to the sport. Assessment will include internal, and externals loads during match play, in addition to energy expenditure using a methodology that does not interfere with performance, habitual competitive routines, and be permitted during competition.

This objective was addressed in Chapter 6. The World number 1 male wheelchair player underwent physical profiling before assessment of energy expenditure during the Wimbledon Championships (singles and doubles), British Open tournaments (singles and doubles), with a period of training between. Physical profiling included resting metabolic rate, body composition, VO_{2max} and sprint capability to understand the physical attributes of the World number 1 wheelchair tennis player. Energy expenditure was assessed using the doubly labelled water method during three separated periods of continual assessment. Energy expenditure during period 1 (Wimbledon Championships) was ~3100 $kcal \cdot d^{-1}$: 60.3 $kcal \cdot kg^{-1}$ FFM, during period 2 (training) was ~3200 $kcal \cdot d^{-1}$: 61.4 $kcal \cdot kg^{-1}$ FFM, and during period 3 (British Open) was ~3400$kcal \cdot d^{-1}$: 65.1 $kcal \cdot kg^{-1}$ FFM. These data were the first to quantify the physical and energetic demands of elite wheelchair tennis play using the gold standard methodology.

Objective 4. To evaluate the training energy expenditures encountered by able body elite tennis players during daily habitual training. Assessment will characterise daily energy requirements, in addition to acute on-court tennis training demands using a method of minimal interference to the participants.

This objective was addressed in Chapter 7. Senior male (n = 10) and female (n = 17) elite tennis players participated for between 2-5 days during habitual training. Once resting metabolic rate had been measured, players wore chest mounted Actiheart activity monitors continually through the assessment period to determine both daily expenditure and on-court energy expenditures during regular training. Results show that male and female professional tennis players expend ~4700 $kcal \cdot d^{-1}$ and ~3600 $kcal \cdot d^{-1}$ respectively. Absolute male and female on-court energy expenditures were 613 $kcal \cdot h^{-1}$ and 456 ± 63 $kcal \cdot h^{-1}$, with relative energy expenditures on-court being 7.9 ± 1.4 $kcal \cdot kg^{-1} \cdot h^{-1}$, and 6.8 ± 0.9 $kcal \cdot kg^{-1} \cdot h^{-1}$ respectively. The physical activity level (PAL) for both groups was 2.3. These data confirm that the Actiheart monitor is a low interference methodology to determine the energy requirements of tennis players. Moreover, they provide a benchmark for practitioners to begin the prescription of daily nutrition to support performance, recovery, and health.

8.2 General Discussion

Professional tennis is a continual cycle of competition and training with players travelling thousands of miles monthly in the endless pursuit and defence of ranking points. The composition of a professional tennis player's competitive day includes travel from hotel to venue, physiotherapist / trainer led pre match preparation, match warm-ups, match play, and post-match recovery. In this thesis, for the first time, the energetic demands elite players during training and competition periods are reported and position professional tennis as highly energetically demanding sport and lifestyle with competitive energy expenditures between 60-90 $kcal \cdot kg^{-1}$ FFM. When combining the competition expenditure with the habitual training expenditure, it becomes apparent the professional tennis player is continually engaging in high expenditure activity with occasional reductions during rest or travel days. While the numbers of sports that have determined competition and training energy expenditures using DLW is limited, existing literature provides context to the energy expenditures reported here.

8.2.1 Male players during competition

To contextualise the TDEE of the male singles player (Chapter 4), it is possible to compare the data to that reported using DLW from other professional sports. Indeed, it is shown that the absolute TDEE was higher than English Premier League soccer players (3566 ± 585 $kcal \cdot d^{-1}$) and similar to professional rugby league players (5374 ± 645 $kcal \cdot d^{-1}$) during training and competition but lower than professional road cyclists during the Giro d'Italia stage race (6903 ± 764 $kcal \cdot d^{-1}$ using the DLW intercept method) (Morehen et al., 2016; Plasqui et al., 2019).

Currently no elite level tennis competition data using the DLW methodology exist to which comparisons can be made. The male data positions tennis as an energetically demanding sport when considering the TDEE relative to FFM (83.7 kcal·kg^{-1} FFM) to other sports, such as rugby league (70.1 kcal·kg^{-1} FFM), English Premier League soccer (54.9 kcal·kg^{-1} FFM) (Anderson et al., 2017; Morehen et al., 2016) (see Figure 8.1). For the male player in Chapter 4, calculations show PAL values of 2.2 (during P1) and 2.8 (during P2). Although these values do not equal the upper limits of 4.0 reached by endurance athletes (Westerterp, 2013), the increased PAL during week 2 is higher than the 2.5 reported for male tennis table players and equals that of male professional rugby players during an in-season period (Morehen et al., 2016; Sagayama et al., 2017).

The male doubles player data (Chapter 5) resulted in a high daily TDEE of 4586 kcal·d^{-1} and a relative TDEE of 65 kcal·kg^{-1} FFM, as measured over 10 days during the Wimbledon Championships that consisted of 577 min across three matches (last match split over two days due to failing light). These values are lower than the male singles player during 10 days of high-level singles competition that consisted of 734 min across five singles match play. However, the training and match play combined durations (daily mean 98 ± 74 min) were similar between both players, as were points played (891 vs 789). Although match play distances covered between the doubles and singles players cannot be compared here, or against any existing doubles tennis data, it would be presumed to be lower than the singles format as found in other racket sports (Alcock & Cable, 2009). Likewise, from an intensity perspective, a difference in heart rate response has previously been reported between singles and doubles match play, with the latter spending a greater percentage of match time at lower intensities (Gentles et al., 2018; Morgans et al., 1987). The movement and intensity differences are perhaps a key explanation for the variability in expenditures.

When compared to male able-bodied singles player to the male wheelchair tennis player in Chapter 6, a lower absolute TDEE during training (3177 vs 3712 kcal·d^{-1}) and competition (3368 vs 5520 kcal·d^{-1}) is shown (Ellis et al., 2021). However, the data shown here is comparable to that of able body English Premier League soccer players (3566 ± 585 kcal·d^{-1}). Although absolute TDEE of wheelchair player compared to able body doubles player is lower (3368 vs 4586 kcal·d^{-1}), the relative TDEE of 65.1 kcal·kg^{-1} FFM are similar to 66.6 kcal·kg^{-1} FFM. When comparing the relative TDEE of the wheelchair tennis player, a value closer to that of able body rugby league players (70.1 kcal·kg^{-1} FFM), than that of English Premier League soccer (54.9 kcal·kg^{-1} FFM) is shown (Anderson et al., 2017; Morehen et al., 2016). This is the first TDEE data measured using DLW on para-athletes demonstrate the high energy requirements of the wheelchair discipline of the sport in which locomotion around the court is solely dependent on the arms propelling the wheelchair simultaneously to playing tennis. These data will be essential in helping to fuel elite wheelchair players and highlights the importance of using gold standard methodologies in all formats of the game.

8.2.2 Female Singles Players during competition

The female competition expenditure data presented here positions elite female tennis played at the highest levels as a highly energetically demanding sport. The female TDEE data (~3400 to ~4000 kcal·d^{-1}) are similar to those values reported in elite lightweight rowers during heavy training (3957 ± 1219 kcal·d^{-1}) yet remain lower than elite swimmers during heavy training (5593 ± 495 kcal·d^{-1}) (Hill & Davies, 2002; Schulz et al., 1992; Trappe et al., 1997)**.** To date, the only available TDEE data using DLW that has included female tennis players reported a TDEE of 2780 ± 430 kcal·d^{-1}, however, any comparison is hard to make as participant activity was not recorded, there was no information on the playing standard or ranking of the athletes and it was unclear if the data included actual competition (Ndahimana et al., 2017). The relative expenditure (66-82 kcal·kg^{-1} FFM) of the female singles players (Chapter 4 and 5) places relative expenditure higher than the female English national soccer team players (54 kcal·kg^{-1} FFM), elite female distance runners (60.6 kcal·kg^{-1} FFM), badminton (72.2 kcal·kg^{-1} FFM) and similar to elite lightweight rowing (84.4 kcal·kg^{-1} FFM) (Hill & Davies, 2002; Morehen et al., 2016; Watanabe et al., 2008) (see Figure 8.1). Although little data exists investigating the TDEE of female junior athletes using DLW, the relative TDEE of 78.2 kcal·kg^{-1} FFM of the female junior was seen to be higher than 68.7 kcal·kg^{-1} FFM found in elite female basketball academy players (Silva, 2013) (see Figure 8.1).

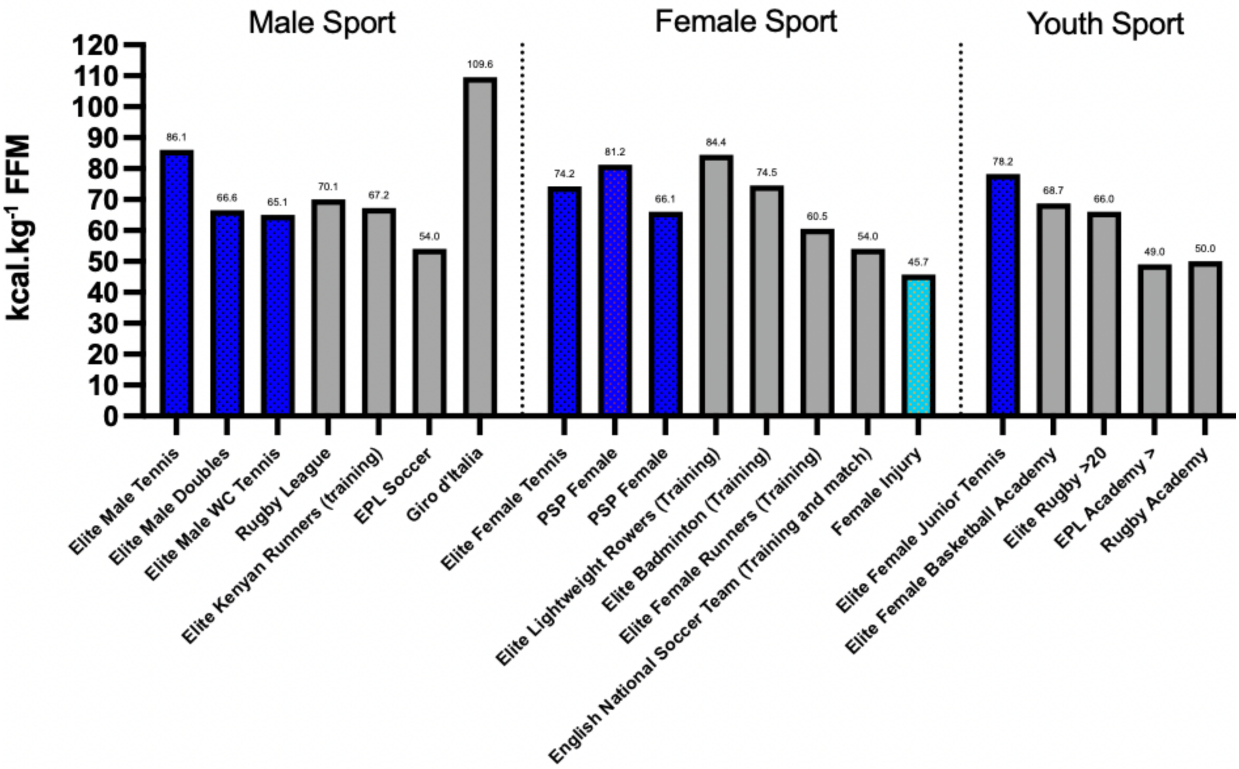


Figure 8.1 *Comparisons of total daily energy expenditure (TDEE) relative to fat free mass (FFM), across a variety of sports and scenarios measured using doubly labelled water (DLW). Blue bars indicate data obtained during this thesis compared to existing literature (grey bars), with light blue highlighting the injured player.*

8.2.3 Male and Female habitual training energy expenditures.

During training periods, a player can spend 1-6 h training daily across 5-6 days per week. When considering the high energy expenditures reported here during competition, it is clear to see the necessity to also assess energy expenditures during training. Daily male and female training energy expenditures of ~4700 kcal·d^{-1} and ~3600 kcal·d^{-1} respectively highlight the requirements of a highly energetically demanding lifestyle. The results presented here should begin to inform educational strategies for players engaging in the continual cycle to support health and performance. Although energy intake was not recorded here, armed with an overview of the energy demands of professional tennis, practitioners can assess intake on an individual basis to prioritise the energy balance, and therefore health and performance of the player they support.

8.3 Limitations and future directions

The current studies are the first to capture the energy demands of elite tennis players during competition at the highest level, and during habitual training. Considering the variability and range reported, further research may develop the understanding further to consider game styles, environments, and surfaces.

8.3.1 Sample size

In using a case study approach within Chapter 4, 5, and 6, a potential limitation exists when considering the small sample size. However, given that the elite population playing at the highest levels is small, the case study approach is the most suitable.

8.3.2 Doubly Labelled Water

The DLW technique is considered the gold standard of energy expenditure measurement during free living activity. The high level of ecological validity that DLW holds, means its ability to measure accurately TDEE while not interfering or influencing daily habits is an ideal methodology when measuring competition of the highest level. The process involves collection and analysing urine samples to determine the reduction of ^{2}H (deuterium) in relation to ^{18}O (oxygen) meaning calculations are made from samples over a series of days or weeks. Despite being the gold standard technique to assess TDEE in free-living conditions, a limitation of the

DLW methodology is the inability to detect day-to-day or within day variations of expenditure. That said, when considering the restrictions around worn devices in competition, DLW poses as not only the best methodology, but the only methodology that can be used at this level to capture TDEE. More broadly, an additional limitation to DLW is the cost (~£1000 per participant), and expertise/equipment required for analysis, putting the methodology out of reach for most outside of scientific research.

8.3.3 Actiheart

Actiheart provided a cost-effective non-invasive method to capture both daily energy expenditure and detect variations in day-to-day and individual session energy expenditures with good agreement to DLW data reported here. The Actiheart software provides an easy-to-use platform for the applied practitioner to quickly inform practise. However, the 'real world' nature of the data provided an issue when attempting to understand the content of sessions outside of tennis. For example, although an activity is recorded as a gym session, it is hard to determine if the session contained off-feet conditioning or resistance exercise. Likewise with tennis sessions, it was very hard to understand the actual session content due to the session goal and coaching philosophy varied greatly between twenty-seven tennis coaches. The devices were calibrated using the 'group' method, as opposed to 'individual' method. This provided an efficient method when analysing an elite population with constraints that surround their time and availability. To individually calibrate the unit would involve a graded step test. The additional time required to individually calibrate for each athlete would have reduced the attractiveness of a low interference method would likely have impacted participation. Findings are mixed regarding the most suitable and accurate calibration (Santos et al., 2014; Villars et al., 2012. However, the use of Actiheart with this population may require further research to determine the most efficient calibration process while maintaining accuracy.

8.3.4 Resting metabolic rate (Gas analysis)

Measurement of resting metabolic rate was conducted using gas analysis following an overnight fast. While participants were instructed to refrain from alcohol, caffeine, and vigorous exercise for 14 hours as per best practise guidelines (Compher et al., 2006), it is understood that prior day exercise would have been variable between individuals and may influence the RMR the following day (Carter et al., 2023). This aspect could be considered a limitation. However, when considering the training regime of elite professional players, requesting players to standardise exercise the day prior to measurement would have limited participation.

8.3.5 Energy Intake

The results presented here have aimed to quantify the energy demands of tennis across disciplines and played at the highest level without disrupting existing competitive routines. Although initially the capturing of energy intake through photo diaries or 24 h recall was considered, it was received poorly from participating players due to any additional stress around competition that remembering to take continual photographs of food may bring. For this reason, energy intake capture was removed from remaining studies. When documenting the habitual training data in Chapter 7, the experience of food diary adherence during applied work. As professional tennis players mostly eat at restaurants or tournament venues, it becomes difficult to accurately determine the ingredient content of the meal. In addition to remembering to take photos and ensuring photo quality for accurate content determination, this method was not considered suitable for inclusion. To understand the prevalence of low-energy availability within this elite population a valid and low interference method of energy intake capture should be employed. A method should consider the variety in culture, availability (restaurants etc.) and therefore food offerings that players experience. As findings reported in this thesis highlight the importance of nutritional education for this group, future directions should investigate the approach and effectiveness of a nutritional educational strategy.

8.3.6 Environments and surfaces

Data collection during competition was largely carried out on grass or hard courts during British summer time. It is unknown if the data derived is applicable to the specific scenarios during data collection or more broadly. Future direction may begin to focus on variable factors evident in tennis such as player game style impact on expenditure and impact of opponent game style and court surface on energy expenditure. Additional considerations include environmental factors such as temperature and humidity. However, given the variability seen within a tennis performance, standardising any other elements of match play would prove difficult, making accurate comparisons difficult to make.

8.4 Practical applications and conclusion

While carbohydrate (CHO) requirements were not a primary focus of this research, the Total Daily Energy Expenditure (TDEE) presented in this study indicates the compatibility with existing recommendations. Specifically, that daily carbohydrate (CHO) intakes should equate to 6 – 10 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for moderate to high intensity exercise of 1 – 3 $h{\cdot}d^{-1}$ and 8 – 12 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for moderate to high intensity exercise of 4 – 5 $h{\cdot}d^{-1}$ (Burke et al., 2015). Accordingly, the TDEE ranges reported here should be reflected in daily CHO requirements with a periodised approach. Based on protein intake at a fixed amount of 1.8 $g{\cdot}kg^{-1}{\cdot}d^{-1}$, and fat at 2 $g{\cdot}kg^{-1}{\cdot}d^{-1}$, with the remaining caloric intake through CHO, the current male and female groups reported here would require ~8 - 10 $g{\cdot}kg^{-1}{\cdot}d^{-1}$. These recommendations fell within a variable range that fluctuated on a daily basis, indicating the necessity to periodise CHO intake in alignment with daily activity levels. Considering the tennis training durations and EE of both male and female groups, a potentially high level of CHO dependency also lends itself to the on-court feeding strategies typically associated with the endurance athlete (e.g., 30 – 90 g of CHO per hour depending on duration) (Jeukendrup, 2014).

Anecdotally, players frequently expressed surprise upon receiving their expenditure data, revealing a lack of awareness regarding their energy requirements, and highlighting the importance of nutritional education for this elite group. Tennis is a nomadic individual sport, players can travel thousands of miles every month, experiencing different cultures and food availability. The player has a reliance on tournament provision, local shops, and hotel food availability. Therefore, it becomes apparent the education of the player, and where relevant, travelling support staff (coaches, physiotherapist, trainer etc.) is of paramount importance to ensure the player is meeting the energy output with sufficient energy input. The impact of any energy mismatch is not just applicable to performance, but for health too. When considering the high and continual energy demands reported here, without due attention, a chronic energy deficit could occur and inadvertently result in the myriad of deleterious effects to performance and health.

The practical applications derived from the findings are;

- Elite tennis players exhibited a continually elevated energy demand, with high energy expenditures reported during both training and competition.
- Considering the challenges that players may face during worldwide travel and food availability, player and support team nutritional education should be paramount to

ensure the player is aware of their energy requirements and how to achieve sufficient intake to avoid inadvertently under fueling.

- Player to player, and day to day variability of energy requirements is evident and supports the need to individually assess the energy requirements on a case-by-case basis using a methodology that is cheap, easy, non-invasive and of little interference to the player. The use of Actiheart is a practical solution for consideration.

Since understanding the benefits that Actiheart can bring to both the player (education of individual needs) and practitioner (individual prescription), use of the unit has become an integral aspect within the assessment processes of the author when working with elite tennis players when determining their individual nutritional requirements. In addition to RMR measurement using gas analysis, the use of Actiheart provides the player with individualised evidence of their needs, which results in greater adherence to subsequent nutritional plans. It is important to note that the data collected during this thesis has been incredibly informative for the sports medicine department of the national federation supporting this Ph.D. A narrative shift can be seen with an emphasis around fuelling and energy balance. Furthermore, the data has provided evidence to support educational delivery to the wider network, within British Tennis and beyond. The enhanced understanding of the energy demands of elite tennis has underscored the significance of nutrition for this population. Participants who took part in these studies have applied their individual results to help support their successes, including winning Grand Slam tournaments.

The novel data presented in this study was the first to profile the energy demands of elite and world class tennis players, both able body and para-athlete, during competition of the highest level. The practical implications of these 'real-world' findings can be promptly applied to inform and guide nutritional practices for players at this level. A comprehensive summary of overall energy intake recommendations was translated into proposed macronutrient guidelines tailored for this specific population. This peer-reviewed published data has highlighted tennis as a high energy-demanding sport, providing practitioners with a newfound understanding of the dietary requirements of elite tennis players.

Chapter 9 - References

Abel, T., Kröner, M., Rojas, V. S., Peters, C., Klose, C., & Platen, P. (2003). Energy expenditure in wheelchair racing and handbiking-a basis for prevention of cardiovascular diseases in those with disabilities. European Journal of Preventive Cardiology, 10(5), 371–376.

Abel, T., Platen, P., Rojas Vega, S., Schneider, S., & Strüder, H. K. (2008). Energy expenditure in ball games for wheelchair users. Spinal Cord, 46(12), 785–790.

Achten, J., & Jeukendrup, A. E. (2006). Heart Rate Monitoring. Sports Medicine, 33(7), 517–538.

Agius, L. (2015). Role of glycogen phosphorylase in liver glycogen metabolism. Molecular Aspects of Medicine, 46, 34–45.

Alcock, A., & Cable, N. T. (2009). A comparison of singles and doubles badminton: heart rate response, player profiles and game characteristics. International Journal of Performance Analysis in Sport, 9(2), 228–237.

Allen, J. (2007). Photoplethysmography and its application in clinical physiological measurement. Physiological Measurement, 28(3). 1-39.

Anderson, L., Orme, P., Naughton, R. J., Close, G. L., Milsom, J., Rydings, D., Boyle, A. O., Michele, R. Di, Louis, J., Hambly, C., Speakman, J. R., Morgans, R., Drust, B., & Morton, J. P. (2017). Energy Intake and Expenditure of Professional Soccer Players of the English Premier League : Evidence of Carbohydrate Periodization. 27(3), 228-238.

Areta, J. L., Taylor, H. L., & Koehler, K. (2021). Low energy availability: history, definition and evidence of its endocrine, metabolic and physiological effects in prospective studies in females and males. European Journal of Applied Physiology, 121(1), 1–21.

Armstrong, L. E., Casa, D. J., Millard-Stafford, M., Moran, D. S., Pyne, S. W., & Roberts, W. O. (2007). Exertional heat illness during training and competition. Medicine and Science in Sports and Exercise, 39(3), 556–572.

Assah, F. K., Ekelund, U., Brage, S., Wright, A., Mbanya, J. C., & Wareham, N. J. (2011). Accuracy and validity of a combined heart rate and motion sensor for the measurement of free-living physical activity energy expenditure in adults in Cameroon. International Journal of Epidemiology, 40(1), 112–120.

Association of tennis professionals. (2023). ATP Tournaments. https://www.atptour.com/en/tournaments

Baiget, E., Fernández-Fernández, J., Iglesias, X., & Rodríguez, F. A. (2015). Tennis play intensity distribution and relation with aerobic fitness in competitive players. PLoS ONE, 10(6).

Balci, A., Badem, E. A., Yılmaz, A. E., Devrim-Lanpir, A., Akınoğlu, B., Kocahan, T., Hasanoğlu, A., Hill, L., Rosemann, T., & Knechtle, B. (2021). Current Predictive Resting Metabolic Rate Equations Are Not Sufficient to Determine Proper Resting Energy Expenditure in Olympic Young Adult National Team Athletes. Frontiers in Physiology, 12 (2), 1–12.

Banzer, W., Thiel, C., Rosenhagen, A., & Vogt, L. (2009). Tennis ranking related to exercise capacity. BMJ Case Reports.

Bergeron, M. F. (2003). Heat cramps: Fluid and electrolyte challenges during tennis in the heat. Journal of Science and Medicine in Sport, 6(1), 19–27.

Bergström, J., & Hultman, E. (1967). A study of the glycogen metabolism during exercise in man. Scandinavian Journal of Clinical and Laboratory Investigation, 19(3), 218–228.

Berman, E. S. F., Fortson, S. L., Snaith, S. P., Gupta, M., Baer, D. S., Chery, I., Blanc, S., Melanson, E. L., Thomson, P. J., & Speakman, J. R. (2012). Direct analysis of δ2H and δ18O in natural and enriched human urine using laser-based, off-axis integrated cavity output spectroscopy. Analytical Chemistry, 84(22), 9768–9773.

Borg, G. A. (1982). Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise, 14(5), 377.

Bradley, W. J., Morehen, J. C., Haigh, J., Clarke, J., Donovan, T. F., Twist, C., Cotton, C., Shepherd, S., Cocks, M., Sharma, A., Impey, S. G., Cooper, R. G., Maclaren, D. P. M., Morton, J. P., & Close, G. L. (2016). Muscle glycogen utilisation during Rugby match play: Effects of pre-game carbohydrate. Journal of Science and Medicine in Sport, 19(12), 1033–1038.

Brage, S., Brage, N., Ekelund, U., Luan, J., Franks, P. W., Froberg, K., & Wareham, N. J. (2006). Effect of combined movement and heart rate monitor placement on physical activity estimates during treadmill locomotion and free-living. European Journal of Applied Physiology, 96(5), 517–524.

Brage, S., Brage, N., Franks, P. W., Ekelund, U., Wong, M. Y., Andersen, L. B., Froberg, K., & Wareham, N. J. (2004). Branched equation modeling of simultaneous accelerometry and heart rate monitoring improves estimate of directly measured physical activity energy expenditure. Journal of Applied Physiology, 96(1), 343–351.

Brage, S., Ekelund, U., Brage, N., Hennings, M. A., Froberg, K., Franks, P. W., & Wareham, N. J. (2007). Hierarchy of individual calibration levels for heart rate and accelerometry to measure physical activity. Journal of Applied Physiology, 103(2), 682–692.

Brage, S., Westgate, K., Franks, P. W., Stegle, O., Wright, A., Ekelund, U., & Wareham, N. J. (2015). Estimation of free-living energy expenditure by heart rate and movement sensing: A doubly-labelled water study. PLoS ONE, 10(9), 1–19.

Brechbuhl, C., Brocherie, F., Millet, G. P., & Schmitt, L. (2018). Effects of Repeated-Sprint Training in Hypoxia on Tennis-Specific Performance in Well-Trained Players. Sports Medicine International Open, 2(5), E123–E132.

Brechbuhl, C., Girard, O., Millet, G. P., & Schmitt, L. (2018). Differences within elite female tennis players during an incremental field test. Medicine and Science in Sports and Exercise, 50(12), 2465–2473.

Broad, E. M., Newsome, L. J., Dew, D. A., & Barfield, J. P. (2020). Measured and predicted resting energy expenditure in wheelchair rugby athletes. Journal of Spinal Cord Medicine, 43(3), 388–397.

Brody, H., Cross, R., & Lindsey, C. (2002). The physics and technology of tennis. Racquet Tech Pub.

Brown, D. M., Dwyer, D. B., Robertson, S. J., & Gastin, P. B. (2016). Metabolic power method: Underestimation of energy expenditure in field-sport movements using a global positioning system tracking system. International Journal of Sports Physiology and Performance, 11(8), 1067–1073.

Brushia, R. J., & Walsh, D. A. (1999). Phosphorylase kinase: the complexity of its regulation is reflected in the complexity of its structure. Frontiers in Bioscience : A Journal and Virtual Library, 4(9), 618-41.

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J. B. (2015). Monitoring locomotor load in soccer: Is metabolic power, powerful? International Journal of Sports Medicine, 36(14), 1149–1155.

Burke, E. R., & Ekblom, B. (1984). Influence of fluid ingestion and dehydration on precision and endurance performance in tennis. Current Sports Medicine Reports, 379–388.

Burke, L. M. (2001). Nutritional needs for exercise in the heat. Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology, 128(4), 735–748.

Burke, L. M., Hawley, J. A., Wong, S. H. S., Jeukendrup, A. E., Burke, L. M., Hawley, J. A., Wong, S. H. S., Asker, E., & Jeukendrup, A. E. (2015). Carbohydrates for training and competition Carbohydrates for training and competition. 0414(10), 37–41.

Cabello Manrique, D., & González-Badillo, J. J. (2003). Analysis of the characteristics of competitive badminton. British Journal of Sports Medicine, 37(1), 62–66.

Calloway, D. H., & Spector, H. (1954). Nitrogen Balanceas Related toCaloric and Protein IntakeinActive Young Men. The American Journal of Clinical Nutrition, 2(6), 405–412.

Carlsohn, A., Scharhag-Rosenberger, F., Cassel, M., & Mayer, F. (2011). Resting metabolic rate in elite rowers and canoeists: Difference between indirect calorimetry and prediction. Annals of Nutrition and Metabolism, 58(3), 239–244.

Carter, J. L., Lee, D. J., Perrin, C. G., Ranchordas, M. K., & Cole, M. (2023). Significant Changes in Resting Metabolic Rate Over a Competitive Match Week Are Accompanied by an Absence of Nutritional Periodization in Male Professional Soccer Players. International Journal of Sport Nutrition and Exercise Metabolism, 33(6), 349–359.

Cermak, N. M., & Van Loon, L. J. C. (2013). The use of carbohydrates during exercise as an ergogenic aid. Sports Medicine, 43(11), 1139–1155.

Chapelle, L., Clarys, P., Meulemans, S., & Aerenhouts, D. (2017). Physiological responses, hitting accuracy and step count of a tennis drill in function of court surface: A randomised cross-over design. International Journal of Performance Analysis in Sport, 17(4), 622–629.

Chasiotis, D., Sahlin, K., & Hultman, E. (1982). Regulation of glycogenolysis in human muscle at rest and during exercise. Journal of Applied Physiology Respiratory Environmental and Exercise Physiology, 53(3), 708–715.

Cheetham, M. E., Boobis, L. H., Brooks, S., & Williams, C. (1986). Human muscle metabolism during sprint running. Journal of Applied Physiology, 61(1), 54–60.

Christmass, M. A., Richmond, S. E., Cable, N. T., Arthur, P. G., & Hartmann, P. E. (1998). Exercise intensity and metabolic response in singles tennis. Journal of Sports Sciences, 16(8), 739–747.

Close, G. L., Hamilton, D. L., Philp, A., Burke, L. M., & Morton, J. P. (2016). New strategies in sport nutrition to increase exercise performance. Free Radical Biology and Medicine, 98, 144–158.

Cocate, P. G., Alfenas, R. de C. G., Pereira, L. G., Marins, J. C. B., Bressan, J., & Cecon, P. R. (2009). Resting metabolic rate of cyclists estimated by mathematical equations and obtained by indirect calorimetry. Revista Brasileira de Medicina Do Esporte, 15, 360–364.

Compher, C., Frankenfield, D., Keim, N., & Roth-Yousey, L. (2006). Best Practice Methods to Apply to Measurement of Resting Metabolic Rate in Adults: A Systematic Review. Journal of the American Dietetic Association, 106(6), 881–903.

Constantin-Teodosiu, D., van Loon, L. J. C., Greenhaff, P. L., Wagenmakers, A. J. M., & Saris, W. H. M. (2004). The effects of increasing exercise intensity on muscle fuel utilisation in humans. The Journal of Physiology, 536(1), 295–304.

Coyle, E. F., Coggan, A. R., Hemmert, M. K., & Ivy, J. L. (1986). Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. Journal of Applied Physiology, 61(1), 165–172.

Croft, L., Dybrus, S., Lenton, J., & Tolfrey-Goosey, V. (2010). A comparison of the physiological demands of wheelchair basketball and wheelchair tennis. International Journal of Sports Physiology and Performance, 5(3), 301–315.

Crouter, S. E., Churilla, J. R., & Bassett, D. R. (2008). Accuracy of the Actiheart for the assessment of energy expenditure in adults. European Journal of Clinical Nutrition, 62(6), 704–711.

Cui, Y., Gómez, M. Á., Gonçalves, B., & Sampaio, J. (2018). Performance profiles of professional female tennis players in grand slams. PLoS ONE, 13(7), 1–18.

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. Sports Medicine, 43, 1025–1042.

Cunningham, J. J. (1980). A reanalysis of the factors influencing basal metabolic rate in normal adults. The American Journal of Clinical Nutrition, 33(11), 2372–2374.

Davey, P. R., Thorpe, R. D., & Williams, C. (2002). Fatigue decreases skilled tennis performance. Journal of Sports Sciences, 20(4), 311–318.

Dawson-Hughes, B., Harris, S. S., Lichtenstein, A. H., Dolnikowski, G., Palermo, N. J., & Rasmussen, H. (2015). Dietary fat increases vitamin D-3 absorption. Journal of the Academy of Nutrition and Dietetics, 115(2), 225–230.

De, J. B., & Weir, V. (1949). New methods for calculating metabolic rate with special reference to protein metabolism. The Journal of Physiology, 109(1–2), 1–9.

Delsoglio, M., Achamrah, N., Berger, M. M., & Pichard, C. (2019). Indirect calorimetry in clinical practice. Journal of Clinical Medicine, 8(9), 1–19.

Di Prampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: A new energetic approach. Journal of Experimental Biology, 208(14), 2809–2816.

Ellis, D. G., Speakman, J., Hambley, C., Morton, J. P., Close, G. L., Lewindon, D., & Donovan, T. F. (2021). Energy Expenditure of a Male and Female Tennis Player during ATP/WTA and Grand Slam Events Measured by Doubly Labelled Water. Medicine and Science in Sports and Exercise. 53(12), 2628-2634

Ellis, D. G., Speakman, J., Hambly, C., Morton, J. P., Close, G. L., & Donovan, T. F. (2023). An Observational Case Series Measuring the Energy Expenditure of Elite Tennis Players During Competition and Training by Using Doubly Labeled Water. International Journal of Sports Physiology and Performance, 18(5), 547–552.

Ettema, G., & Lorås, H. W. (2009). Efficiency in cycling: A review. European Journal of Applied Physiology, 106(1), 1–14.

Febbraio, M., Snow, R., Hargreaves, M., Stathis, C., Martin, I., & Carey, F. (1994). Muscle metab in trained me exercise an climation tress. J Appl Physiol, 76(2), 589–597.

Fell, J. M., Hearris, M. A., Ellis, D. G., Moran, J. E. P., Jevons, E. F. P., Owens, D. J., Strauss, J. A., Cocks, M., Louis, J. B., Shepherd, S. O., & Morton, J. P. (2021). Carbohydrate improves exercise capacity but does not affect subcellular lipid droplet morphology, AMPK and p53 signalling in human skeletal muscle. Journal of Physiology, 599(11), 2823–2849.

Fernandez, J., Mendez-Villanueva, A., & Pluim, B. M. (2006). Intensity of tennis match play. British Journal of Sports Medicine, 40(5), 387–391.

Fernandez-Fernandez, J., Sanz-rivas, D., & Mendez-villanueva, A. (2009). A Review of the Activity Profile and Physiological Demands of Tennis Match Play. Strength & Conditioning Journal, 31(4), 15–26.

Fernandez-Fernandez, J., Sanz-Rivas, D., Sarabia, J. M., & Moya, M. (2015). Preseason training: The effects of a 17-day high-intensity shock microcycle in elite tennis players. Journal of Sports Science and Medicine, 14(4), 783–791.

Fernandez-Fernandez, J., Ulbricht, A., & Ferrauti, A. (2014). Fitness testing of tennis players: How valuable is it. British Journal of Sports Medicine, 48 (1).

Ferrauti, A., Bergeron, M. F., Pluim, B. M., & Weber, K. (2001). Physiological responses in tennis and running with similar oxygen uptake. European Journal of Applied Physiology, 85(1–2), 27–33.

Ferrauti, A., Weber, K., & Strüder, H. K. (1997). Metabolic and ergogenic effects of carbohydrate and caffeine beverages in tennis. Journal of Sports Medicine and Physical Fitness, 37(4), 258–266.

Filipcic, A., Zecic, M., Reid, M., Crespo, M., Panjan, A., & Nejc, S. (2015). Differences in performance indicators of elite tennis players in the period 1991– 2010. Journal of Physical Education and Sport, 15(4), 671–677.

Fleming, J. A., Corr, L. D., Earle, J., Naughton, R. J., & Harper, L. D. (2022). Significant Energy Deficit and Suboptimal Sleep During a Junior Academy Tennis Training Camp. Pediatric Exercise Science, 34(3), 162–167.

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., Doleshal, P., & Dodge, C. (2001). A new approach to monitoring exercise training. The Journal of Strength & Conditioning Research, 15(1), 109–115.

Freire, R., Pereira, G., Alcantara, J. M., Santos, R., Hausen, M., & Itaborahy, A. (2021). New Predictive Resting Metabolic Rate Equations for High-Level Athletes. Medicine & Science in Sports & Exercise, 54(8):1335-1345.

Fudge, B. W., Wilson, J., Easton, C., Irwin, L., Clark, J., Haddow, O., Kayser, B., & Pitsiladis, Y. P. (2007). Estimation of oxygen uptake during fast running using accelerometry and heart rate. Medicine and Science in Sports and Exercise, 39(1), 192–198.

Gale-Watts, A. S., & Nevill, A. M. (2016). From endurance to power athletes: The changing shape of successful male professional tennis players. European Journal of Sport Science, 16(8), 948–954.

Gandhi, M., Aweeka, F., Greenblatt, R. M., & Blaschke, T. F. (2004). Sex differences in resting metabolic rate among athletes. Health (San Francisco), 1, 499–523.

Gentles, J. A., Coniglio, C. L., Mahnken, M. T., Morgan, J. M., Besemer, M. M., & Macdonald, C. J. (2018). The Demands of a Single Elimination College Tennis Tournament. Sport Performance and Science Reports, 1(1), 1–4.

Girard, O., Brocherie, F., & Millet, G. P. (2017). Effects of Altitude/Hypoxia on Single- and Multiple-Sprint Performance: A Comprehensive Review. Sports Medicine, 47(10), 1931–1949.

Girard, O., & Millet, G. P. (2004). Effects of the ground surface on the physiological and technical responses in young tennis players. Science and Racket Sports III, 43–48.

Gold, J. R., & Gold, M. M. (2007). Access for all: the rise of the Paralympic Games. Journal of the Royal Society for the Promotion of Health, 127(3), 133–141.

Gomes, R. V., Capitani, C. D., Ugrinowitsch, C., Zourdos, M. C., Fernandez-Fernandez, J., Mendez-Villanueva, A., & Aoki, M. S. (2013). Does carbohydrate supplementation enhance tennis match play performance? Journal of the International Society of Sports Nutrition, 10(1), 1.

Gomes, R. V., Moreira, A., Coutts, A. J., Capitani, C. D., & Aoki, M. S. (2014). Effect of carbohydrate supplementation on the physiological and perceptual responses to prolonged tennis match play. Journal of Strength and Conditioning Research, 28(3), 735–741.

Goosey-Tolfrey, V. L., de Groot, S., Tolfrey, K., & Paulson, T. A. W. (2021). Criterion Validity of a Field-Based Assessment of Aerobic Capacity in Wheelchair Rugby Athletes. International Journal of Sports Physiology and Performance, 16(9), 1341–1346.

Greenhaff, P. L., Nevill, M. E., Soderlund, K., Bodin, K., Boobis, L. H., Williams, C., & Hultman, E. (1994). The metabolic responses of human type I and II muscle fibres during maximal treadmill sprinting. J Physiol, 478 (1), 149–155.

Hajj-Boutros, G., Landry-Duval, M. A., Comtois, A. S., Gouspillou, G., & Karelis, A. D. (2022). Wrist-worn devices for the measurement of heart rate and energy expenditure: A validation study for the Apple Watch 6, Polar Vantage V and Fitbit Sense. European Journal of Sport Science, 1–13.

Hannon, M. P., Parker, L. J. F., Carney, D. J., McKeown, J., Speakman, J. R., Hambly, C., Drust, B., Unnithan, V. B., Close, G. L., & Morton, J. P. (2021). Energy Requirements of Male Academy Soccer Players from the English Premier League. Medicine and Science in Sports and Exercise, 53, (1). 200-210

Haugen, A. H., Chan, L. N., & Li, F. (2007). Indirect calorimetry: A practical guide for clinicians. Nutrition in Clinical Practice, 22(4), 377–388.

Hawley, J. A., & Leckey, J. J. (2015). Carbohydrate Dependence During Prolonged, Intense Endurance Exercise. Sports Medicine, 45(1), 5–12. https://doi.org/10.1007/s40279-015-0400-1

Heaton, L. E., Davis, J. K., Rawson, E. S., Nuccio, R. P., Witard, O. C., Stein, K. W., Baar, K., Carter, J. M., & Baker, L. B. (2017). Selected In-Season Nutritional Strategies to Enhance Recovery for Team Sport Athletes: A Practical Overview. Sports Medicine, 47(11), 2201–2218.

Hickman, K. (1943). Fat-soluble vitamins. Annual Review of Biochemistry, 12(1), 353–396.

Hill, R. J., & Davies, P. S. W. (2002). Energy intake and energy expenditure in elite lightweight female rowers. Medicine and Science in Sports and Exercise, 34(11), 1823–1829.

Hills, A. P., Mokhtar, N., & Byrne, N. M. (2014). Assessment of Physical Activity and Energy Expenditure: An Overview of Objective Measures. Frontiers in Nutrition, 1.

Hornery, D. J., Farrow, D., Mujika, I., & Young, W. (2007). Fatigue in tennis: mechanisms of fatigue and effect on performance. Sports Medicine (Auckland, N.Z.), 37(3), 199–212.

International Tennis Federation. (2019). ITF Rules of Tennis 2020. 38. http://www.itftennis.com/media/220771/220771.pdf

Islamoglu, A. H., & Kenger, E. B. (2019). Nutrition considerations for athletes with physical disabilities. Current Sports Medicine Reports, 18(7), 270–274.

ITF. (2019). History of Tennis Courts. https://www.itftennis.com/media/2101/surfaces-history-of-tennis-courts.pdf

ITF. (2021). Rules of tennis. https://www.itftennis.com/media/4421/2021-rules-of-tennis-english.pdf

ITF. (2023a). Grand Slam Surfaces. https://www.itftennis.com/en/itf-tours/grand-slam-tournaments

ITF. (2023b). ITF Approved Tennis Balls, Classified Surfaces & Recognised Courts. https://www.itftennis.com/media/4420/2023-technical-booklet.pdf

ITF. (2023c). Rules and regulations. https://www.itftennis.com/en/about-us/governance/rules-and-regulations

ITF. (2023d, January). Wheelchair Tennis Classification Rules. https://www.itftennis.com/media/7271/itf-wheelchair-tennis-classification-rules-2023-final-cleaned.pdf

ITF. (2024). https://www.itftennis.com/en/#

Jagim, A. R., Zabriskie, H., Currier, B., Harty, P. S., Stecker, R., & Kerksick, C. M. (2019). Nutrient Status and perceptions of energy and macronutrient intake in a Group of Collegiate Female Lacrosse Athletes. Journal of the International Society of Sports Nutrition, 16(1).

Jeukendrup, A. (2014). A step towards personalized sports nutrition: Carbohydrate intake during exercise. Sports Medicine, 44(SUPPL.1).

Juzwiak, C. R., Amancio, O. M. S., Vitalle, M. S. S., Pinheiro, M. M., & Szejnfeld, V. L. (2008). Body composition and nutritional profile of male adolescent tennis players. Journal of Sports Sciences, 26(11), 1209–1217.

Kasper, A. M., O'Donnell, A., Langan-Evans, C., Jones, A., Lindsay, A., Murray, A., & Close, G. L. (2022). Assessment of activity energy expenditure during competitive golf: The effects of bag carrying, electric or manual trolleys. European Journal of Sport Science, 1–8.

Kelly, B., King, J. A., Goerlach, J., & Nimmo, M. A. (2013). The impact of high-intensity intermittent exercise on resting metabolic rate in healthy males. European Journal of Applied Physiology, 113(12), 3039–3047.

Keytel, L. R., Goedecke, J. H., Noakes, T. D., Hiiloskorpi, H., Laukkanen, R., van der Merwe, L., & Lambert, E. V. (2005). Prediction of energy expenditure from heart rate monitoring during submaximal exercise. Journal of Sports Sciences, 23(3), 289–297.

Kilit, B., Şenel, Ö., Arslan, E., & Can, S. (2016). Physiological responses and match characteristics in professional tennis players during a one-hour simulated tennis match. Journal of Human Kinetics, 50(2), 83–92.

Kjaer, M., Howlett, K., Langfort, J., Zimmerman-Belsing, T., Lorentsen, J., Bülow, J., Ihlemann, J., Feldt-Rasmussen, U., & Galbo, H. (2000). Adrenaline and glycogenolysis in skeletal muscle during exercise: a study in adrenalectomised humans. The Journal of Physiology, 528(2), 371–378.

Koehler, K., de Marees, M., Braun, H., & Schaenzer, W. (2013). Evaluation of two portable sensors for energy expenditure assessment during high-intensity running. European Journal of Sport Science, 13(1), 31–41.

Koontz, A. M., Cooper, R. A., Boninger, M. L., Yang, Y., Impink, B. G., & Van Der Woude, L. H. V. (2005). A kinetic analysis of manual wheelchair propulsion during start-up on select indoor and outdoor surfaces. Journal of Rehabilitation Research and Development, 42(4), 447–458.

Kovacs, M. (2015). Training the Competitive Athlete. 37(July), 189–198.

Kovacs, M. (2018). The Role of Scheduling and Periodization in Competitive Tennis Players. Tennis Medicine, 679–686.

Kovacs, M. S. (2006). Applied physiology of tennis performance. British Journal of Sports Medicine, 40(5), 381–385.

Kovalchik, S. A., & Ingram, M. (2018). Estimating the duration of professional tennis matches for varying formats. 14(1), 13–23.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjær, M., & Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. Medicine & Science in Sports & Exercise, 38(6), 1165–1174.

Kuipers, H., Keizer, H. A., Brouns, F., & Saris, W. H. M. (1987). Carbohydrate feeding and glycogen synthesis during exercise in man. Pflügers Archiv European Journal of Physiology, 410(6), 652–656.

Langan-Evans, C., Germaine, M., Artukovic, M., Oxborough, D. L., Areta, J. L., Close, G. L., & Morton, J. P. (2020). The psychological and physiological consequences of low energy availability in a male combat sport athlete. Medicine & Science in Sports & Exercise.

Levine, J. A. (2005). Measurement of energy expenditure. Public Health Nutrition, 8(7a), 1123–1132.

Lewit, C. (2014). The secrets of spanish tennis. ITF Coaching and Sport Science Review, 64(22), 9–10.

Logue, D. M., Madigan, S. M., Melin, A., Delahunt, E., Heinen, M., Mc Donnell, S. J., & Corish, C. A. (2020). Low Energy Availability in Athletes 2020: An Updated Narrative Review of Prevalence, Risk, Within-Day Energy Balance, Knowledge, and Impact on Sports Performance. Nutrients 2020, Vol. 12, Page 835, 12(3), 835.

Loucks, A. B. (2004). Energy balance and body composition in sports and exercise. Journal of Sports Sciences, 22(1), 1–14.

LTA. (2022, July 20). Wheelchair tennis to push on after milestone summer. https://www.lta.org.uk/news/wheelchair-tennis-to-push-on-after-milestone-summer

Marfell-Jones, M., Olds, T., Stewart, A., & CARTER, J. E. L. (2006). ISAK: Potchefstroom: International Standards for Anthropometric Assessment.

Martin, C., Thevenet, D., Zouhal, H., Mornet, Y., Delès, R., Crestel, T., Abderrahman, A. Ben, & Prioux, J. (2011). Effects of playing surface (hard and clay courts) on heart rate and blood lactate during tennis matches played by high-level players. The Journal of Strength & Conditioning Research, 25(1), 163–170.

Martin, C., Thevenet, D., Zouhal, H., Mornet, Y., Delès, R., Crestel, T., Ben Abderrahman, A., & Prioux, J. (2011). Effects of Playing Surface (Hard and Clay Courts) on Heart Rate and Blood Lactate During Tennis Matches Played by High-Level Players. The Journal of Strength & Conditioning Research, 25(1).

Martínez-Gallego, R., Crespo, M., Ramón-Llin, J., Micó, S., & Guzmán, J. F. (2020). Men's doubles professional tennis on hard courts: Game structure and point ending characteristics. Journal of Human Sport and Exercise, 15(3), 633–642.

Martínez-Gallego, R., Vives, F., Guzmán, J. F., Ramón-Llin, J., & Crespo, M. (2021). Time structure in men's professional doubles tennis: does team experience allow finishing the points faster? International Journal of Performance Analysis in Sport, 21(2), 215–225.

Mason, B. S., van der Slikke, R. M. A., Hutchinson, M. J., & Goosey-Tolfrey, V. L. (2020). Division, result and score margin alter the physical and technical performance of elite wheelchair tennis players. Journal of Sports Sciences, 38(8), 937–944.

Matt Kuzbud. (2019, June 12). Body types in tennis. https://www.mattspoint.com/blog/body-types-tennis

McArdle, W. D., Katch, F. I., & Katch, V. L. (2006). Essentials of exercise physiology. Lippincott Williams & Wilkins.

McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., & Burke, L. M. (2022). Defining Training and Performance Caliber: A Participant Classification Framework. International Journal of Sports Physiology and Performance, 17(2), 317–331.

McRae, K. A., & Galloway, S. D. R. (2012). Carbohydrate-electrolyte drink ingestion and skill performance during and after 2 hr of indoor tennis match play. International Journal of Sport Nutrition and Exercise Metabolism, 22(1), 38–46.

Mendez-Villanueva, A., Fernandez-Fernandez, J., & Bishop, D. (2007). Exercise-induced homeostatic perturbations provoked by singles tennis match play with reference to development of fatigue. British Journal of Sports Medicine, 41(11), 717–722.

Mendez-Villanueva, A., Fernandez-Fernandez, J., Bishop, D., Fernandez-Garcia, B., & Terrados, N. (2007). Activity patterns, blood lactate concentrations and ratings of perceived exertion during a professional singles tennis tournament. British Journal of Sports Medicine, 41(5), 296–300.

Miller, S. (2006). Modern tennis rackets, balls, and surfaces. British Journal of Sports Medicine, 40(5), 400–405.

Milsom, J., Barreira, P., Burgess, D. J., Iqbal, Z., & Morton, J. P. (2014). Case study: Muscle atrophy and hypertrophy in a premier league soccer player during rehabilitation from ACL injury. International Journal of Sport Nutrition and Exercise Metabolism, 24(5), 543–552.

Mitchell, J. B., Cole, K. J., Grandjean, P. W., & Sobczak, R. J. (1992). The Effect of a Carbohydrate Beverage on Tennis Performance and Fluid Balance During Prolonged Tennis Play. The Journal of Strength & Conditioning Research, 6(2).

Molik, B., Kosmol, A., Morgulec-Adamowicz, N., Lencse-Mucha, J., Mróz, A., Gryko, K., & Marszałek, J. (2017). Comparison of Aerobic Performance Testing Protocols in Elite Male Wheelchair Basketball Players. Journal of Human Kinetics, 60(1), 243–254.

Moon, J. M., Zabriskie, H. A., Harty, P. S., Currier, B. S., Blumkaitis, J. C., Stecker, R. A., Jagim, A., & Kerksick, C. M. (2021). Comparison of Energy Expenditure Observed between Scheduled Activities in Collegiate Team-Sport Female Athletes. Sports, 9(4), 2–12.

Morehen, J. C., Bradley, W. J., Clarke, J., Twist, C., Hambly, C., Speakman, J. R., Morton, J. P., & Close, G. L. (2016). The assessment of total energy expenditure during a 14-day in-season period of professional rugby league players using the doubly labelled water method. International Journal of Sport Nutrition and Exercise Metabolism, 26(5), 464–472.

Morehen, J. C., Rosimus, C., Cavanagh, B. P., Hambly, C., Speakman, J. R., Elliot-Sale, K. J., Hannon, M. P., & Morton, J. P. (2021). Energy Expenditure of Female International Standard Soccer Players. Medicine and Science in Sports and Exercise. 54(5), 769-779.

Morgans, L. F., Jordan, D. L., Baeyens, D. A., & Franciosa, J. A. (1987). Heart rate responses during singles and doubles tennis competition. The Physician and Sportsmedicine, 15(7), 67–74.

Moss, S. L., Randell, R. K., Burgess, D., Ridley, S., ÓCaireallåin, C., Allison, R., & Rollo, I. (2020). Assessment of energy availability and associated risk factors in professional female soccer players. European Journal of Sport Science, 21(6), 861-870

Murias, J. M., Lanatta, D., Arcuri, C. R., & LaiÑo, F. A. (2007). Metabolic and functional responses playing tennis on different surfaces. Journal of Strength and Conditioning Research, 21(1), 112.

Nagy, K. A. (1983). The doubly labeled water (3HH180) method: a guide to its use.

Ndahimana, D., Lee, S. H., Kim, Y. J., Son, H. R., Ishikawa-Takata, K., Park, J., & Kim, E. K. (2017). Accuracy of dietary reference intake predictive equation for estimated energy requirements in female tennis athletes and non-athlete college students: Comparison with the doubly labeled water method. Nutrition Research and Practice, 11(1), 51–56.

Ndahimana, D., Lee, S., Kim, Y., Son, H., Ishikawa-takata, K., Park, J., & Kim, E. (2017). Accuracy of dietary reference intake predictive equation for estimated energy requirements in female tennis athletes and non-athlete college students : comparison with the doubly labeled water method. 11(1), 51–56.

Nichols, J. F., Aralis, H., Merino, S. G., Barrack, M. T., Stalker-Fader, L., & Rauh, M. J. (2010). Utility of the actiheart accelerometer for estimating exercise energy expenditure in female adolescent runners. International Journal of Sport Nutrition and Exercise Metabolism, 20(6), 487–495.

Nightingale, T. E., Walhin, J. P., Thompson, D., & Bilzon, J. L. J. (2015). Predicting physical activity energy expenditure in wheelchair users with a multisensor device. BMJ Open Sport and Exercise Medicine, 1(1), 1–8.

Novas, A. M. P., Rowbottom, D. G., & Jenkins, D. G. (2003). A practical method of estimating energy expenditure during tennis play. Journal of Science and Medicine in Sport, 6(1), 40–50.

O’Donoghue, P., & Ingram, B. (2001). A notational analysis of elite tennis strategy. Journal of Sports Sciences, 19(2), 107–115.

O’Neill, J. E. R. G., Walsh, C. S., McNulty, S. J., Gantly, H. C., Corish, M. E., Crognale, D., & Horner, K. (2022). Resting Metabolic Rate in Female Rugby Players: Differences in Measured Versus Predicted Values. Journal of Strength and Conditioning Research, 36(3), 845–850.

Organization, W. H. (2003). Food-based dietary guidelines in the WHO European Region. Copenhagen: WHO Regional Office for Europe.

Ørtenblad, N., & Nielsen, J. (2015). Muscle glycogen and cell function - Location, location, location. Scandinavian Journal of Medicine and Science in Sports, 25, 34–40.

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & Di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: A new match analysis approach. Medicine and Science in Sports and Exercise, 42(1), 170–178.

Otto, A. K., Reer, R., Holtfreter, B., Riepenhof, H., & Schröder, J. (2019). Physiological responses at the anaerobic threshold and at peak performance during arm crank ergometer diagnostics compared to wheelchair propulsion on a treadmill in elite wheelchair basketball players. Sports Orthopaedics and Traumatology, 35(1), 49–55.

Oxendale, C. L., Highton, J., & Twist, C. (2017). Energy expenditure, metabolic power and high speed activity during linear and multi-directional running. Journal of Science and Medicine in Sport, 20(10), 957–961.

Park, J. (2019). Using physical activity levels to estimate energy requirements of female athletes. Journal of Exercise Nutrition & Biochemistry, 23(4), 1–5.

Parolin, M. L., Chesley, A., Matsos, M. P., Spriet, L. L., Jones, N. L., & George, J. F. (2013). Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise endurance capacity in humans Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise. 890–900.

Périard, J. D., & Bergeron, M. F. (2014). Competitive match-play tennis under heat stress: A challenge for all players. British Journal of Sports Medicine, 48(SUPPL. 1), 2–4.

Périard, J. D., Racinais, S., Knez, W. L., Herrera, C. P., Christian, R. J., & Girard, O. (2014). Coping with heat stress during match-play tennis: Does an individualised hydration regimen enhance performance and recovery. British Journal of Sports Medicine, 48(1), 1–8.

Phillips, S. M., & Van Loon, L. J. C. (2013). Dietary protein for athletes: from requirements to optimum adaptation. Food, Nutrition and Sports Performance III, 29–38.

Plasqui, G., Rietjens, G., Lambriks, L., Wouters, L., & Saris, W. H. M. (2019). Energy Expenditure during Extreme Endurance Exercise: The Giro d'Italia. Medicine and Science in Sports and Exercise, 51(3), 568–574.

Poignard, M., Guilhem, G., de Larochelambert, Q., Montalvan, B., & Bieuzen, F. (2020). The Impact of Recovery Practices Adopted by Professional Tennis Players on Fatigue Markers According to Training Type Clusters. Frontiers in Sports and Active Living, 2(109).

Posthumus, L., Driller, M., Winwood, P., & Gill, N. (2024). The Development of a Resting Metabolic Rate Prediction Equation for Professional Male Rugby Union Players. Nutrients, 16(2), 1–13.

Ranchordas, M. K., Rogerson, D., Ruddock, A., Killer, S. C., & Winter, E. M. (2013). Nutrition for Tennis: Practical recommendations. Journal of Sports Science and Medicine, 12(2), 211–224.

Reid, M., & Duffield, R. (2014). The development of fatigue during match-play tennis. British Journal of Sports Medicine, 48 (1).

Reid, M., Duffield, R., Dawson, B., Baker, J., & Crespo, M. (2008). Quantification of the physiological and performance characteristics of on-court tennis drills. British Journal of Sports Medicine, 42(2), 146–151.

Reid, M. M., Duffield, R., Minett, G. M., Sibte, N., Murphy, A. P., & Baker, J. (2013). Physiological, perceptual, and technical responses to on-court tennis training on hard and clay courts. The Journal of Strength & Conditioning Research, 27(6), 1487–1495.

Reid, M., Morgan, S., & Whiteside, D. (2016). Matchplay characteristics of Grand Slam tennis: implications for training and conditioning. Journal of Sports Sciences, 34(19), 1791–1798.

Reilly, T., & Palmer, J. (1995). Investigation of exercise intensity in male singles lawn tennis. Science and Racket Sports, T. Reilly, M. Hughes, and A. Lees, 10–13.

Rodriguez, N. R., Di Marco, N. M., & Langley, S. (2009). American College of Sports Medicine position stand. Nutrition and athletic performance. Medicine and Science in Sports and Exercise, 41(3), 709–731.

Rodriguez, N. R., DiMarco, N. M., & Langley, S. (2009). Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. Journal of the American Dietetic Association, 109(3), 509–527.

Roffey, D. M., Byrne, N. M., & Hills, A. P. (2006). Day-to-day variance in measurement of resting metabolic rate using ventilated-hood and mouthpiece & nose-clip indirect calorimetry systems. Journal of Parenteral and Enteral Nutrition, 30(5), 426–432.

Romijn, J. A., Coyle, E. F., Sidossis, L. S., Gastaldelli, A., Horowitz, J. F., Endert, E., & Wolfe, R. R. (1993). Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. The American Journal of Physiology, 265(3 Pt 1).

Roy, J. L. P., Menear, K. S., Schmid, M. M. A., Hunter, G. R., & Malone, L. A. (2006). Physiological responses of skilled players during a competitive wheelchair tennis match. Journal of Strength and Conditioning Research, 20(3), 665–671.

Sagayama, H., Hamaguchi, G., Toguchi, M., Ichikawa, M., Yamada, Y., Ebine, N., Higaki, Y., & Tanaka, H. (2017). Energy Requirement Assessment in Japanese Table Tennis Players Using the Doubly Labeled Water Method. International Journal of Sport Nutrition and Exercise Metabolism, 27(5), 421–428.

Saltin, B. (1973). Metabolic fundamentals in exercise. Medicine and Science in Sports, 5(3), 137–146.

Saltin, B., & Essen, B. (1971). Muscle glycogen, lactate, ATP, and CP in intermittent exercise. In Muscle metabolism during exercise (pp. 419–424). Springer.

Sánchez-Pay, A., & Sanz-Rivas, D. (2018). Wheelchair tennis player movement speed: Differences in movement, with and without a racket. ITF Coaching & Sport Science Review , 26(76), 33–36.

Sánchez-Pay, A., & Sanz-Rivas, D. (2021). Physical and technical demand in professional wheelchair tennis on hard, clay and grass surfaces: implication for training. International Journal of Performance Analysis in Sport, 21(4), 463–476.

Santos, D. A., Silva, A. M., Matias, C. N., Magalhães, J. P., Fields, D. A., Minderico, C. S., Ekelund, U., & Sardinha, L. B. (2014). Validity of a combined heart rate and motion sensor for the measurement of free-living energy expenditure in very active individuals. Journal of Science and Medicine in Sport, 17(4), 387–393.

Saris, W., van Erp-Baart*, M., Brouns, F., Westerterp, K., & Hoor, F. (1989). Study on Food Intake and Energy Expenditure During Extreme Sustained Exercise: The Tour de France. International Journal of Sports Medicine, 10(S 1), S26–S31.

Schoeller, D. A., Ravussin, E., Schutz, Y., Acheson, K. J., Baertschi, P., & Jéquier, E. (1986). Energy expenditure by doubly labeled water: Validation in humans and proposed calculation. American Journal of Physiology - Regulatory Integrative and Comparative Physiology, 250(5 (19/5)).

Schoeller, D. A., Ravussin, E., Schutz, Y., Acheson, K. J., Baertschi, P., Jequier, E., & Jéquier, E. (1986). Energy expenditure by doubly labeled water: validation in humans and proposed calculation. American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 250(5), R823–R830.

Schulz, L. O., Alger, S., Harper, I., Wilmore, J. H., & Ravussin, E. (1992). Energy expenditure of elite female runners measured by respiratory chamber and doubly labeled water. Journal of Applied Physiology, 72(1), 23–28.

Senatore, F., & Cannataro, R. (2019). The energy expenditure in the 5 types of modern tennis players. ITF Coaching & Sport Science Review, 27(78), 35–39.

Siddiqui, O., Dibiase, S., Hoang, R., Nguyen, B., Khan, O., & Famiglietti, N. (2021). Evaluating the Accuracy and Reliability of Bicycle GPS Devices. SAE Technical Papers, 2021, 3093–3114.

Sikka, R. S., Baer, M., Raja, A., Stuart, M., & Tompkins, M. (2019). Analytics in sports medicine: implications and responsibilities that accompany the era of big data. Jbjs, 101(3), 276–283.

Silva, A. M. (2013). Total energy expenditure assessment in elite junior basketball players: a validation study using doubly labeled water. Journal of Strength and Conditioning Research, 27(7), 1920–1927.

Simopoulos, A. P. (2007). Omega-3 fatty acids and athletics. Current Sports Medicine Reports, 6(4), 230–236.

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

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 and Performance, 8(1), 28–37.

Smekal, G., Von Duvillard, S. P., Rihacek, C., Pokan, R., Hofmann, P., Baron, R., Tschan, H., & Bachl, N. (2001). A physiological profile of tennis match play. Medicine and Science in Sports and Exercise, 33(6), 999–1005.

Smith, D. R., King, R. F. G. J., Duckworth, L. C., Sutton, L., Preston, T., O'Hara, J. P., & Jones, B. (2018). Energy expenditure of rugby players during a 14-day in-season period, measured using doubly labelled water. European Journal of Applied Physiology, 118(3), 647–656.

Smith, K., & Rennie, M. J. (1996). The measurement of tissue protein turnover. Bailliere's Clinical Endocrinology and Metabolism, 10(4), 469–495.

Söğüt, M. (2018). Stature: Does it really make a difference in match-play outcomes among professional tennis players? International Journal of Performance Analysis in Sport, 18(2), 255–261.

Söğüt, M. (2019). Height- and surface-related variations in match-play outcomes and rankings in professional men's tennis. German Journal of Exercise and Sport Research, 49(3), 332–338.

Speakman, J. R. (1997). Doubly Labelled Water: Theory and Practice. In Theory and Practice. Springer Science & Business Media.

Speakman, J. R., Yamada, Y., Sagayama, H., Berman, E. S. F., Ainslie, P. N., Andersen, L. F., Anderson, L. J., Arab, L., Baddou, I., Bedu-Addo, K., Blaak, E. E., Blanc, S., Bonomi, A. G., Bouten, C. V. C., Bovet, P., Buchowski, M. S., Butte, N. F., Camps, S. G. J. A., Close, G. L., … Wong, W. W. (2021). A standard calculation methodology for human doubly labeled water studies. Cell Reports Medicine, 2(2).

Spector, A. A., & Kim, H.-Y. (2015). Discovery of essential fatty acids. Journal of Lipid Research, 56(1), 11–21.

Spriet, L. L. (2014). New insights into the interaction of carbohydrate and fat metabolism during exercise. Sports Medicine, 44(1), 87–96.

Stellingwerff, T., Peeling, P., Garvican-Lewis, L. A., Hall, R., Koivisto, A. E., Heikura, I. A., & Burke, L. M. (2019). Nutrition and Altitude: Strategies to Enhance Adaptation, Improve

Performance and Maintain Health: A Narrative Review. Sports Medicine, 49(s2), 169–184.

Stevens, T. G. A., De Ruiter, C. J., Van Maurik, D., Van Lierop, C. J. W., Savelsbergh, G. J. P., & Beek, P. J. (2015). Measured and estimated energy cost of constant and shuttle running in soccer players. Medicine and Science in Sports and Exercise, 47(6), 1219–1224.

Stubbs, R. J., Hopkins, M., Finlayson, G. S., Duarte, C., Gibbons, C., & Blundell, J. E. (2018). Potential effects of fat mass and fat-free mass on energy intake in different states of energy balance. European Journal of Clinical Nutrition, 72(5), 698–709.

Tarnopolsky, M. (2004). Protein requirements for endurance athletes. Nutrition, 20(7–8), 662–668.

Thomas, D. T., Burke, L. M., & Erdman, K. A. (2016). Nutrition and Athletic Performance. Medicine and Science in Sports and Exercise, 48(3), 543–568.

Thompson, D., Batterham, A. M., Bock, S., Robson, C., & Stokes, K. (2006). Assessment of low-to-moderate intensity physical activity thermogenesis in young adults using synchronized heart rate and accelerometry with branched-equation modeling. Journal of Nutrition, 136(4), 1037–1042.

Tortu, E., Birol, A., & Aksarı, M. (2023). Evaluation of Different Equations for Resting Metabolic Rate Prediction in Female Combat Sports Athletes. Montenegrin Journal of Sports Science and Medicine, 19(2), 41–48.

Trappe, T. A., Gastaldelli, A., Jozsi, A. C., Troup, J. P., & Wolfe, R. R. (1997). Energy expenditure of swimmers during high volume training. Medicine & Science in Sports & Exercise, 29(7).

Trumbo, P., Schlicker, S., Yates, A. A., & Poos, M. (2002). Dietary reference intakes for energy, carbohydrate, fiber, fat, fatty acids, cholesterol, protein and amino acids.(Commentary). Journal of the American Dietetic Association, 102(11), 1621–1631.

Tsekouras, Y. E., Tambalis, K. D., Sarras, S. E., Antoniou, A. K., Kokkinos, P., & Sidossis, L. S. (2019). Validity and Reliability of the New Portable Metabolic Analyzer PNOE. Frontiers in Sports and Active Living, 1(September), 1–7.

Tweedy, S. M., & Vanlandewijck, Y. C. (2011). International Paralympic Committee position stand--background and scientific principles of classification in Paralympic sport. British Journal of Sports Medicine, 45(4), 259–269.

van Loon, L. J. C., Greenhaff, P. L., Constantin-Teodosiu, D., Saris, W. H. M., & Wagenmakers, A. (2001). The effects of increasing exercise intensity on muscle fuel utilisation in humans. Journal of Physiology, 53 (6), 295–304.

Veeger, H. E. J., Yahmed, M. H., Van Der Woude, L. H. V., & Charpentier, P. (1991). Peak oxygen uptake and maximal power output of olympic wheelchair-dependent athletes. In Medicine and Science in Sports and Exercise (Vol. 23, Issue 10, pp. 1201–1209).

Vergauwen, L., Brouns, F., & Hespel, P. (1998). Carbohydrate supplementation improves stroke performance in tennis. Medicine and Science in Sports and Exercise, 30(8), 1289–1295.

Villars, C., Bergouignan, A., Dugas, J., Antoun, E., Schoeller, D. A., Roth, H., Maingon, A. C., Lefai, E., Blanc, S., & Simon, C. (2012). Validity of combining heart rate and uniaxial acceleration to measure free-living physical activity energy expenditure in young men. Journal of Applied Physiology, 113(11), 1763–1771.

Watanabe, E., Igawa, S., Sato, T., Miyazaki, M., Horiuchi, S., & Seki, K. (2008). 11 Energy expenditure measurement in badminton players during a training camp using doubly-labelled water. Science and Racket Sports IV, 77.

Watt, M. J., Howlett, K. F., Febbraio, M. A., Spriet, L. L., & Hargreaves, M. (2001). Adrenaline increases skeletal muscle glycogenolysis, pyruvate dehydrogenase activation and carbohydrate oxidation during moderate exercise in humans. Journal of Physiology, 534(1), 269–278.

Westerterp, K. R. (1999). Body composition, water turnover and energy turnover assessment with labelled water. Proceedings of the Nutrition Society, 58(4), 945–951.

Westerterp, K. R. (2004). Diet induced thermogenesis. Nutrition and Metabolism, 1, 1–5.

Westerterp, K. R. (2013). Physical activity and physical activity induced energy expenditure in humans: Measurement, determinants, and effects. Frontiers in Physiology, 4, 1–11.

Westerterp, K. R. (2017). Doubly labelled water assessment of energy expenditure: principle, practice, and promise. European Journal of Applied Physiology, 117(7), 1277–1285.

WHO, (2007). Protein and amino acid requirements in human nutrition. World Health Organization Technical Report Series, 935, 1.

Widłak, W. (2013). Protein structure and function. In Molecular biology: not only for bioinformaticians (pp. 15–29). Springer.

Wilson, G., Sparks, S. A., Drust, B., Morton, J. P., & Close, G. L. (2013). Assessment of energy expenditure in elite jockeys during simulated race riding and a working day: Implications for making weight. Applied Physiology, Nutrition and Metabolism, 38(4), 415–420.

WTA. (2023). WTA Tournaments. https://www.wtatennis.com/tournaments

Zuntz, N. (1901). Ueber die Bedeutung der verschiedenen Nährstoffe als Erzeuger der Muskelkraft. Archiv Für Die Gesamte Physiologie Des Menschen Und Der Tiere, 83(10–12), 557–571.

Appendix

Appendix 1.1 Ethical approval study 1, 2 and 3.

Dear Daniel

With reference to your application for Ethical Approval

Ellis, Daniel – PGR - An investigation into the energy expenditure and energy intake of elite professional tennis players during a professional tournament week. (Timothy Donovan/James Morton/Graeme Close)

UREC decision: Approved with provisos.
UREC reference: 19/SPS/031

The University Research Ethics Committee (UREC) has considered the above application by proportionate review. I am pleased to inform you that ethical approval has been granted subject to the provisos listed below. Once the final version of the ethics application with the provisos addressed has been emailed to researchethics@ljmu.ac.uk, the study can commence.

(Please note, UREC will not check that the provisos have been applied in the final version of the ethics application and will not email any further approval notifications to the applicant once the final version of the ethics application has been forwarded to UREC. If the applicant does not want to apply the provisos as stated below, the applicant must notify UREC and resubmit the ethics application for further review)

Amendments made to participants to now include a junior player.

Dear Daniel

Further to the above applications for major amendments which you recently submitted for consideration by the University's Research Ethics Committee. Please accept this email as formal confirmation that REC agreed to approve this application.

Appendix 1.2 Ethical approval for study 4

Dear Daniel

Thank you for registering your study as minimal risk.

Daniel Ellis, PGR - Daily training load and energy requirements of professional tennis players (Timothy Donovan)

UREC reference: 21/SPS/031
Research Governance Assessment: Approved – the study may commence.

Conditions of the favourable opinion
Prior to the start of the study.

- Covid-19. Studies that involve face-to-face activity – you must ensure participant facing documents explain the potential risks of participating in the study which are associated with Covid-19, how the risks will be mitigated and managed.

After ethical review.

- The study is conducted in accordance with the Minimal Ethical Risk Guiding Principles
- You must ensure the information included in the participant facing documents are always current and informed by ongoing risk assessments and any changes to current practices.
- Where any substantive amendments are proposed to the protocol or study procedures further ethical opinion must be sought (https://www.ljmu.ac.uk/ris/research-ethics-and-governance/research-ethics/university-research-ethics-committee-urec/amendments)
- Any adverse reactions/events which take place during the course of the project are reported to the Committee immediately by emailing FullReviewUREC@ljmu.ac.uk
- Any unforeseen ethical issues arising during the course of the project will be reported to the Committee immediately emailing FullReviewUREC@ljmu.ac.uk

Please note that favourable ethics opinion is given for a period of five years. An application for extension of the ethical opinion must be submitted if the project continues after this date.

Appendix 1.3 Thesis publications

Chapter 4

Ellis DG, Speakman J, Hambly C, Morton, J. P., Close, G. L., & Donovan, T. F. (2021). Energy Expenditure of a Male and Female Tennis Player during Association of Tennis Professionals/Women's Tennis Association and Grand Slam Events Measured by Doubly Labeled Water. *Medicine and Science in Sports and Exercise*. *53*(12), 2628-2634. https://doi.org/10.1249/mss.0000000000002745

Chapter 5

Ellis, D. G., Speakman, J., Hambly, C., Morton, J. P., Close, G. L., & Donovan, T. F. (2023). An Observational Case Series Measuring the Energy Expenditure of Elite Tennis Players During Competition and Training by Using Doubly Labeled Water. *International Journal of Sports Physiology and Performance*, *18*(5), 547-552. https://doi.org/10.1123/ijspp.2022-0297

Chapter 6

Ellis, D. G., Speakman, J., Hambly, C., Cockram, A., Morton, J. P., Close, G. L., & Donovan, T. F. (2024). Case-study: Energy expenditure of a world class male wheelchair tennis player during training, Grand Slam and British Open tournaments measured by doubly labelled water. International Journal of Sports Science & Coaching, 19(2), 857-863. https://doi.org/10.1177/17479541231169033

Chapter 7

Ellis, D. G., Morton, J. P., Close, G. L., & Donovan, T. F. (2024). Energy Expenditure of Elite Male and Female Professional Tennis Players During Habitual Training. *International Journal of Sport Nutrition and Exercise Metabolism, 34(3),172-178.* https://doi.org/10.1123/ijsnem.2023-0197