Developing Nutritional Considerations for Elite Squash Players Through a Performance Problems Lens

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A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the Degree of Doctor of Philosophy

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Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.
2. None of the material contained in the thesis has been used in any other submission for an academic award.
3. I am aware of and understand the University's policy on plagiarism and certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged.
4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy.
5. The word count of the thesis is 41,876 (26,758 from publications)
6. This thesis is classed as an 'article-based' submission, meaning all studies arising from this PhD have been published and have been included in the format of the journal they were submitted to as per the Doctoral Schools guidance.

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Thesis Abstract

This PhD programme was a match funded PhD between Sheffield Hallam University, England Squash and the UK Sports Institute. The researcher worked as a performance nutrition practitioner, delivering consultancy services to England Squash while conducting impactful research to create new knowledge and change practice. In collaboration with the coaches and players at England Squash, the researcher undertook a needs analysis to identify four ‘performance problems’: (1) what are players understanding of nutrition; (2) do players have an awareness of their energy expenditure and know how to appropriately fuel and recover effectively from session to session to optimise their health, physical performance and training adaptations?; (3) players generally train twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. Does this give players enough opportunity to optimally recover and rehydrate from one session to the next?; (4) some players have high sweat rates. Are players optimally rehydrated post session when they have limited time in-between training sessions? Consequently, the PhD aimed to answer these ‘performance problems’.

Study one systematically reviewed all the physiological and nutritional literature conducted in squash to ascertain whether any of the ‘performance problems’ identified by the researcher had previously been answered. None of the ‘performance problems’ had been answered and the researcher also found that much of the physiological and nutritional literature is of a low quality and outdated. Thirty-five studies were included in the review. The study utilised the PEDro scale to quantify the methodological quality of the studies with many of the studies conducted in squash shown to have poor (10) or fair (19) methodological quality, and only four conveying good and two conveying excellent methodological quality. This is due to many of the studies conducted in squash being observational in design (32), rather than rather than double blinded crossover design studies.; Only 14/35 studies were conducted using elite or world class players, so it was difficult to translate much of the literature to elite players, due to a lack of validity. Much of the literature may be outdated as the World Squash Federation and Professional Squash Association changed the rules of squash in 2009 and therefore may not be valid due to these rule changes altering the in playing dynamics of squash (Murray et al., 2016). The review also presented some future directions for research to be conducted within squash.

Study two quantified the nutrition knowledge of squash players through the Nutrition for Sport Knowledge Questionnaire (NSKQ) (Trakman et al., 2017). Many of the elite squash players who were funded by England Squash didn’t engage with performance nutrition consultancy services and felt that their knowledge and habits were appropriate. Consequently, the study aimed to screen players to determine whether they could benefit from nutrition support. A greater nutrition knowledge has been shown to lead to superior dietary behaviours (Valliant et al., 2012). Players were shown to have ‘average’ nutrition knowledge, and this led to conversations regarding nutrition support for many

players, as well as whether the non-specific guidelines utilised in the NSKQ were relevant. Players questioned the relevance of the NSKQ and therefore the following two studies aimed to quantify the energetic demands, and hydration demands of elite squash players to critique whether non-specific guidelines were appropriate.

Study three calculated the energy balance of a cohort of elite male squash players throughout a seven-day training microcycle. The study originally aimed to also quantify the energy balance of elite female squash players as well, however due to the cost implications of the methodology utilised, the reference standard doubly labelled water, there wasn't enough funding available. Male players were chosen as that is where the 'performance problem' was perceived to be experienced. Mean daily EE was 4,210 ± 1,017 Kcals throughout the 7-day microcycle, with mean daily EI being 3,389 ± 981 Kcals. This equated to a mean daily negative energy balance of 821 Kcals, with mean EA over the microcycle was 31.68 ± 17.91 $Kcal \cdot kg^{-1}\ FFM \cdot d^{-1}$, indicating reduced EA. Player one was reported to have a mean energy balance of -2,392 $Kcals \cdot d^{-1}$ and mean energy availability of 11 $Kcal \cdot kg^{-1}\ FFM \cdot d^{-1}$. The study highlighted that elite male squash players exhibited a high energy expenditure throughout a training microcycle and may follow poor nutrition strategies such as severe energy restriction, leading to low energy availability and sub optimal carbohydrate intake. These sub optimal nutritional practices may lead to reduced training performance and symptoms of relative energy deficiency in sport. Nutrition support was provided to the cohort of players to optimise their nutrition strategies.

Study four quantified the sweat rates and sweat [Na^+] of elite squash players throughout a training session alongside their hydration practices. The study also aimed to determine whether two hours and thirty minutes was enough time to optimally rehydrate from one training session to the next, as many players would have limited time in-between training sessions. Players were shown to have a mean fluid balance of −1.22 ± 1.22% throughout the training session with a mean sweat rate of 1.11 ± 0.56 $L \cdot h^{-1}$ and a mean sweat [Na^+] of 46 ± 12 $mmol \cdot L^{-1}$. Two hours and thirty minutes was not shown to be enough time to replace the fluid and Na^+ losses experienced from the previous session. Individualised hydration strategies were provided to each player who took part in the study to optimise their hydration strategies, as well as generating conversations with players and coaches regarding the training culture of England Squash and whether two hours and thirty minutes is enough time to optimally refuel and rehydrate from training sessions.

Consequently, this PhD has created new knowledge and changed practices of elite squash players by: (1) systematically reviewing all of the available physiological and nutritional literature conducted within squash, having a positive impact on applied practice by presenting guidance for scientists, coaches, and players, whilst identifying gaps in knowledge to guide researchers on the future directions of research within squash; (2) quantifying the nutrition knowledge of elite squash players, identifying that it may be appropriate for players to consult with a sports nutritionist to increase their sport nutrition knowledge and nutrition habits; (3) calculating the energy balance of elite male squash players throughout a seven-day microcycle, providing the data to inform sport-specific nutritional guidelines while critiquing whether players current nutritional habits are optimal and subsequently providing bespoke nutritional support based on the data; (4) measuring the sweat rates and sweat [Na^+] of players throughout a training session to provide players with individualised hydration strategies to optimise their physical performance.

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Acknowledgments

I'm currently sat in the Sheffield Hallam Collegiate Campus University library writing this. It's 22:30 and I've just finished the last section of my PhD. I've just had a Neapolitan Pizza and I've got a x4 pack of BrewDog Hazy Jane IPA beers. I'm feeling very sentimental as I'm sat in the same spot as when I started University, 10 years ago. Over that 10-year period, I've learned it's crucial to reflect on your experiences; the good, the bad, and the ugly, as a way of processing and making sense of the world. I once read that your twenties are about defining who you are, and who you are not as a person, while establishing your morals, integrity, and what you stand for. To this extent, the past 10 years (my undergraduate, master's, PhD studies alongside my working practice) has acted as the perfect process to do this. On my first day of my PhD, Nigel Mitchell (Nige) told me I would be a completely different person by the end of the process. Never has a truer word been spoken. It's lead me down so many rabbit holes and dead ends that I've lost count. It's taught me that things don't always go your way, but how you reflect and react is crucial. I've developed resilience in abundance, and if you really want something you can go and get it. Family, friends, and a global pandemic (thanks COVID) have all come and gone throughout this process. This is the flow of life. Like anything in high performance, it's a team effort and there's a lot of hard work by many people behind the scenes. Therefore, I want to take the time to acknowledge a few significant individuals along the journey.

Prof. Mayur Ranchordas. (My Director of Studies and Academic Mentor)

I first met Mayur when he delivered a second year University lecture. He breezed into the 200+ lecture theatre in flip flops and shorts and started to talk about his experiences working in elite sport. Mayur spoke about how he had worked for the English Institute of Sport (now the UK Sports Institute) and in elite Premier League football. He shared his experiences of supporting athletes at the Beijing and London Olympic games, as well as the ins and outs of fuelling the elite football player. That's my guy (I told myself). I was desperate to work in elite sport in some capacity. Shortly after, I introduced myself to Mayur and told him my aspirations of following in his footsteps and working in elite sport. Initially, I was met with some scepticism, and he gave me some spiel about how competitive the industry was, but I wasn't having it. I think he could see the passion and stubbornness in my eyes, and he took me under his wing.

I would classify Mayur as one of my closest friends. Over that time, he's become a father, moved up the academic ladder by becoming Chair of Ethics at Sheffield Hallam University, won the prestigious Inspirational Research Supervisor Award, and has recently become a Professor, his ultimate career goal. I'd like to think we've pushed and prodded each other onto better things. I certainly know he has for me. Cheers for taking me under your wing those seven or eight years ago. I wouldn't be doing what I'm doing without your support and guidance.

Nige – The Oracle (My Second Supervisor and Professional Mentor)
I've termed Nige the oracle as everything that he says comes true as if it was written in prophecy. I first met Nige when I was an MSc student. He came in to deliver a guest lecture on sports nutrition. Nige is a Technical Lead Nutritionist at the UK Sports Institute and had been Head of Nutrition at British Cycling and Team Sky Cycling for many years. He spoke about his experiences of working with riders such as Bradley Wiggins and Mark Cavendish and supporting them to Tour De France and Olympic Gold medals. Little did I know that Nige would become the most influential person in my life moving forwards from that day. He has been my professional mentor ever since. If I classify Mayur as one of my closest friends, I would classify Nige as my 2nd dad. My dream from an early age has always been to go to the Olympics and support athletes in their pursuit for greatness. He has unlocked the key to this for me. He saw potential in me when many couldn't. The worst thing in life is wasted talent, and he's squeezed every drop of talent out of me to ensure I am fulfilling mine. He's challenged me to reflect and learn from my experiences, been a sounding board when I've needed it most, and supported me to venture out of my comfort zone and step into the unknown from time to time. There's been a few clutch moments and difficult conversations in my career so far but through Nige's mentorship (and friendship), I've defined my morals, integrity, and what I stand for as an individual. This is undoubtably the greatest achievement of my PhD and it wouldn't be possible without his guidance. The greatest complement I can pay Nige is that in a world where many have their own agendas, I can always trust Nige to have my best interest at heart. Cheers for everything.

Alan and Alison (Other PhD Supervisors)
Sorry that you don't get quite the pep talk that I've given Mayur and Nige. I'm really grateful from the both of you for all the hard work that's gone into my development as an academic and person. The quality of the PhD is in a better place with your input.

Family
Mum and Dad – Thanks for being a sounding board throughout this process. You've supported me emotionally and financially throughout this process. All I can say is that I hope you are proud of what I've achieved so far and continue to achieve in the future.

Tommy T (Bro) – I owe a lot of my desire to reach the top down to you. Our brotherly rivalry has made me into someone that wants to be the best at everything. You've settled down and started a family and I'm looking forward to spending more time being an uncle now that I don't have to spend my weekends finishing off my PhD.

Others to Thanks – Nick Matthew OBE, Rich Chessor, Sam 'Fletch' Fletcher, Dega House Flat, England Squash, Chelsea FC, Aquatics GB, Rus and Dan (because I know you want to be on this).

To the Future

My favourite speech is Matthew McConaughey's 2014 Oscars Speech when he won his Academy Award for Best Actor. He talks about three things he needs in his life: 1) someone to look up to; 2) someone to look forward to; and 3) someone to chase. In the speech, he details that he chases his 'hero', which is him in ten years' time. The premise of the speech is that he's never going to be his 'hero', but that's fine as it gives him someone to 'chase'. I love that speech and probably watch it back more often than I should. I find it amazing how in one of the peak moments of his career, he can deliver a speech with such composure and ease. I suppose that's high performance in a nutshell.

My past experiences blaze a trail for my future. Ten years have passed since Matthew McConaughey delivered that speech and it's also ten years since I started my professional journey. If you would have given me the adventure I've been on over the past ten years, I would have snapped your hand off. BSc, MSc and PhD, while working at the sharp end of elite sport, firstly with England Squash, then at Chelsea FC, and now with Olympic and Paralympic swimmers as part of Aquatics GB. It's not been without its challenges and has taught me some important life lessons: COVID posed the challenge of making me rewrite my PhD a handful of times and caused a lot of stress and strain of whether I could collect any data. Still to this day, my hand in has come down to the last few days!; The Russian invasion of Ukraine caused a financial embargo at Chelsea FC while working there. This caused a lot of anxiety and ambiguity around contracts and my future; Presently, there's a lot of hours spent on the road in my current role which can be difficult to manage at times. Ultimately, when the alarm goes off at 04:00 and you have to make a 4–5-hour journey down to London among a cloud of doubt, there's a choice that you can get out of bed and keep on 'chasing' in the hope it will take you to where you want to go or stay at home and rue your bad luck. Looking back, I'm proud I got out of bed each time to take that drive down. The good outweigh the bad and the ugly. I've had some amazing experiences and met some awesome people along the way. I've always felt like the PhD has been a monkey on my back. The monkeys gone now, and I can enjoy my weekends a bit more easily. Over the past ten years, I've amassed all the knowledge, skills, and experience I need to go on and do what I want to do in the future. However, I'm not content with standing still. It's time to put the skills into practice. My aspirations stretch far beyond what I am currently doing. There ambitious, bold, and challenging. But someone has to do it so it may as well be me. I believe life comes in chapters, one has just passed, and I'm looking forward to start a new one. Here's to the next ten years of 'chasing'. I'm excited to see where I end up. Cheers to everyone who has supported me over the last ten years and here's to the next ten years. Onto the next.

Publications from this PhD

Peer reviewed publications arising from this PhD

Turner, O., Mitchell, N., Ruddock, A., Purvis, A., & Ranchordas, M. (2021). Elite squash players nutrition knowledge and influencing factors. *Journal of the International Society of Sports Nutrition*, *18*(1), 46. https://doi.org/10.1186/s12970-021-00443-3

Turner, O., Mitchell, N., Ruddock, A., Purvis, A., & Ranchordas, M. K. (2023). Fluid Balance, Sodium Losses and Hydration Practices of Elite Squash Players during Training. *Nutrients*, *15*(7), 1749. https://doi.org/10.3390/nu15071749

Turner, O., Mitchell, N., Ruddock, A., Purvis, A., & Ranchordas, M (2024). Physiological and Nutritional Considerations for Elite Squash: A Systematic Review. *Journal of Science in Sport & Exercise*. https://doi.org/10.1007/s42978-024-00313-9

Currently in Peer Review with Journal of Sport Sciences

Doubly Labelled Water Assessment of Elite Male Squash Player's Energy Balance During a Seven Day Training Microcycle

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List of Abbreviations

^{2}H – Deuterium

$^{2}H_2O$ – Deuterium oxide

^{18}O – Oxygen

O_2 – Oxygen

ASSPPT – Aerobic squash-specific physical performance test

a.u. – Auxiliary units

Beats·min – Beats per minute

Breaths·min – Breaths per minute

CI – Confidence interval

CHO – Carbohydrate

cm – Centimeters

COD – Change of direction

CODT – Change of direction test

CV – Coefficient of variation

DIE – Desired initial enrichment

$_{d}$RPE – Differential rating of perceived exertion

DXA - Dual-Energy X-Ray Absorptiometry

EA – Energy availability

EE – Energy expenditure

$EEVO_2$ – Energy expenditure

EI – Energy intake

EPOC – Effective Practice and Organisation of Care

F – Female

FFM – FFM

g·kg·bm – Grams per kilogram of body mass

GB – Great Britain

g·d – Grams per day

h – Hour(s)

H-CHO – High carbohydrate diet

HR – Heart rate

HR_{max} – Heart rate maximum

IAR – Illinois agility run

ICC – Intraclass correlation coefficient

ICT – Incremental Cycle Test

IE – Initial enrichment

IRT – Incremental running test

ISAK - International Society for the Advancement of Kinanthropometry

IST – Incremental squash test

ITT – Incremental treadmill test

K^+ – Potassium

K_2 – Elimination rate of heavy hydrogen (^2H)

K_{18} – Elimination rate of heavy oxygen (^{18}O)

Kcal – Kilocalorie

Kcal·d – Kilocalories per day

Kcal·kg·d – Kilocalories per kilogram per day

Kcal·kg·FFM – Kilocalorie per kilogram of fat free mass

$Kcal \cdot kg^{-1}$ FFM·d – Kilocalorie per kilogram of fat free mass per day

Kcal·h – Kilocalories per hour

Kg – Kilogram

kJ·FFM·d – Kilojoules per fat free mass per day

kJ·h – Kilojoules per hour

kJ·kg·d – Kilojoules per kilogram per day

L - Litre

L·h – Litres per hour

LA^+ = lactate concentration

L-CHO – Low carbohydrate diet

LOA – Limits of agreement

M – Male

m – Meter(s)

mA – milliampere(s)

METs – Metabolic equivalents

mg – Milligram(s)

mg·L·h – Milligrams per litre per hour

min – Minute(s)

MJ·day – Megajoules per day

ml·kg·min – Millilitres per kilogram per minute

mm - Millimeters

mmol·L – Millimole per litre

mol – Molecule

mOsmol·kg – milliosmole per kilogram

MVC – Maximal voluntary contraction

m·s – Meters per second

n – Number

N – Body water volume (mol)

Na^+ – Sodium

[Na^+] – Sweat sodium concentration

NaCl – Sodium chloride

NKQA – Nutrition Knowledge Questionnaire for Athletes

NSP – Non-squash players

NSKQ – Nutrition for Sport Knowledge Questionnaire

One-Way ANOVA – A One-Way Analysis of Variance

PAL – Physical activity level

PAR11 – Point a rally to eleven points

PEDro – Physiotherapy Evidence Database

PgDip – Postgraduate diploma

PhD – Doctor of Philosophy

PLA - Placebo

POS9 – Point on serve to nine points

ppm – Parts per million

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PROSPERO – International Prospective Register of Systematic Reviews

rCO_2 – Rate of carbon dioxide production

RER – Respiratory exchange ratio

RG – Running group

RH – Relative humidity

RMR – Resting metabolic rate

RPE – Rating of perceived exertion

RSA – Repeated sprint ability

s – Seconds

SD – Standard deviation

SENR – Sport and Exercise Nutrition Register

SG – Squash group

SoP – Soccer players

SP – Squash players

sRPE – Session rating of perceived exertion

SSCODT = Squash-specific change of direction test

SSMST – Squash-specific multiple sprint test

SSPT = Squash simulation protocol test

TASS – Talented athlete scholarship scheme

T_e – Time to exhaustion

TEE = Typical error of the estimate

TEE CV% = Typical error of the estimated expressed as coefficient of variation

TEM – Technical error of measurement

TL – Training load

VE – Minute ventilation

VCO_2 – Rate of carbon dioxide production

VO_2 – Rate of oxygen consumption

VO_{2max} – Maximal rate of oxygen consumption

UK – United Kingdom

µL - Microlitre

USA – United States of America

WGBT – Wet globe bulb temperature

y - Years

1.0: Introduction

1.1 Doctoral Philosophy

Science is defined by the Cambridge Dictionary as "obtaining knowledge from the careful study of the structure and behaviour of the physical world, especially by watching, measuring, and doing experiments, and the development of theories to describe the results of these activities" (Cambridge Dictionary, 2024). Scientific research is developed through two philosophical approaches:

(1) Epistemological – The theory of knowledge, relating to methodology, validity and scope, while quantifying the distinction between justified belief and opinion (Allmark & Machaczek, 2018)

(2) Ontological – The study of metaphysics and nature of being (Allmark & Machaczek, 2018)

Research hypotheses can be prescriptive in nature, reaffirming established theories while excluding other scientific possibilities, limiting intellectual curiosity and creativity (Kuhn, 1962). However, scientific research should answer specific questions, utilising the most appropriate tools and strategies available, being hypothesis driven, precise and accurate throughout measurement, while adhering to Systéme International d'Unite's (SI) (Winter & Fowler, 2009).

The researcher had a prior understanding of the sport, having played Squash from the age of eight, competing nationally and internationally throughout their teenage years in various competitions. The researcher competed on the Professional Squash Association tour, achieving a highest world ranking of 355, and in 2017 played in the British Grand Prix, a Professional Squash Association World Tour event. The same year, the researcher then transitioned to becoming a practitioner upon completion of their undergraduate degree (BSc) in Sport & Exercise Science at Sheffield Hallam University, undergoing a work placement as a performance nutritionist with the UK Sports Institute and England Squash, while completing their master's degree (MSc) in Applied Sport & Exercise Science at Sheffield Hallam University. Therefore, this guided the philosophical approach of the PhD programme as they were able to draw on previous experiences and perceptions of Squash.

This PhD programme identified specific 'performance problems' (Coutts, 2016) through a pragmatic philosophical approach. Pragmatists are not committed to a single philosophical system (e.g. epistemological or ontological) and are concerned with creating knowledge that is valid, utilising mixed method research designs to consider what will work best to create valuable data that is useful in the real world (Kaushik & Walsh, 2019). The researcher understood the 'real world' of Squash through being embedded within it, both as a player and practitioner. However, this also meant that they may be predisposed to having a specific bias to the 'performance problems' identified (e.g something they would have useful as a player). Indeed, bias has been reported in pragmatic philosophical approaches. (Florczak, 2022).

Pragmatic philosophical approaches utilise both quantitative explorations combined with the ability to apply contextual knowledge and interpretations of qualitative research. A pragmatic philosophical approach enables a pluralistic approach whereby the researcher could develop 'performance problems' in collaboration with the coaches and players themselves. It enables the development of 'performance problems' and hypothesis without being confined to one specific research paradigm. To this extent, 'performance problems' have been developed from the knowledge and perceptions of the researcher, coaches and players, as well as a systematic literature search (see Section 2.0). This has enabled the PhD programme to cultivate organically based on the literature and what practitioners, coaches, and players value the most.

The PhD programme also utilised a systematic approach through the underpinning of the Applied Research Model for Sports Sciences (ARMSS) (Bishop, 2008). This enabled the PhD programme to be developed in a progressive manner whereby studies have developed new knowledge, layer on layer, with each study building on the knowledge obtained from the previous study (Figure 2). Consequently, a series of robust studies were developed which focused on two stages of the ARMSS, 'defining the problem' (see Section 1.3) and 'describing the problem' (see Section 1.4). These initial stages require the researcher to draw upon their knowledge and understanding of the desired research question(s) but also counsel the collaboration of coaches and athletes (Harper & McCunn, 2017). This has been reported to bridge the gap between research and applied practice, and create richer 'performance problems' (Coutts, 2016).

The PhD programme explored the knowledge and perceptions of coaches and players to develop a series of studies that investigates nutritional considerations for elite squash players through a performance problems lens. Consequently, the main aim of the PhD programme was to develop squash-specific nutritional recommendations for elite squash players to enable sports nutritionists to better advise players to optimise their health and performance.

1.2 'Performance Problems'

Sport science is a multidisciplinary field of practice concerned with the enhancement of human sporting performance (Bishop et al., 2006). Practitioners working in sports science disciplines such as physiology or nutrition are required to translate the best available scientific literature, specific to the individual and environment to optimise their sporting performance (Farquhar et al., 2002). Consequently, the ability to critique the scientific literature and translate it into everyday practice, in a format that is appropriate for a key stakeholder such as an athlete or coach is a crucial part of a practitioner's skill set (Close et al., 2019).

Research from other disciplines suggests that there is a disconnect between science and practice (Lamb et al., 1998), with the translation of science to practice being poor (Colditz et al., 2008). In medical research, research may take 10 to 20 years to be translated into routine medical practice (Sussman et al., 2006). One of the contributors to this lack of translation, and subsequent role scientific innovations have on influencing daily practice may be the way the scientific research question is formulated (Ginexi & Hilton, 2006). As a result, sport science practitioners are encouraged to identify 'performance problems' that they experience while working in the field, with the goal of providing specific performance-based solutions (Cardinale, 2017). It is reported that there is a gap between practitioners and key stakeholders such as the athlete and/or coach (Brink et al., 2018; Malone et al., 2019), and this holistic approach is thought to develop new knowledge, specific to stakeholders, enabling a greater ability to change practice to bridge the gap (Coutts, 2017).

This gap can be bridged through sports science practitioners providing evidence-based practice to athletes and coaches. Evidence based practice is the integration of the practitioner and their expertise, the contemporary research available, and the coaches and athletes' values, with the goal of enhancing sporting performance through the optimisation of the decision-making process throughout specific strategies (Coutts, 2017). The process of developing evidence-based practice can be broken down into five stages (Coutts, 2017):

- Identifying relevant research questions
- Searching and critically evaluating the evidence for its validity, impact, and applicability
- Developing strategies to implement the best available evidence into contemporary practice
- Assessing the effectiveness of new contemporary practices within athletes
- Continuing to reevaluate the evidence and assess current practices within athletes

Evidence-based practice within high performance sport may challenge sporting cultures and belief-based views with scientific data, while involving athletes and coaches into the decision-making process regarding their training and performance (Coutts, 2017). Evidence based practice is designed to improve sporting performance through reducing training errors such as poor training quality or athlete availability due to illness or injury (Coutts, 2017). Evidence suggests that when research questions are formulated multidisciplinary between practitioner(s), coaches, athletes, and other key stakeholders, they have the most impact (Coutts, 2017). Consequently, industry embedded PhD programmes offer the opportunity for practitioners and researchers to embed themselves within a sporting environment under the constraints and pressures of high-performance sport, while working directly with the athletes, coaches, and other key stakeholders. This enables the practitioner or researcher the ability to scope out relevant ‘performance problems’, while also understanding the culture and values of the organisation and the barriers which may limit the translation of traditional research studies (Coutts, 2016; Close et al., 2019). This approach facilitates the development of organic research questions and designing ecologically valid research studies to enhance evidence-based practice and sporting performance.

To this extent, this PhD programme was a match funded PhD between Sheffield Hallam University, England Squash and the UK Sports Institute (formerly the English institute of Sport). The researcher had a prior understanding of the sport, having played Squash from the age of eight, competing nationally and internationally throughout their teenage years in various competitions. The researcher competed on the Professional Squash Association tour, achieving a highest world ranking of 355, and in 2017 played in the British Grand Prix, a Professional Squash Association World Tour event. The same year, the researcher then transitioned to becoming a practitioner upon completion of their undergraduate degree (BSc) in Sport & Exercise Science at Sheffield Hallam University, undergoing a work placement as a performance nutritionist with the UK Sports Institute and England Squash, while completing their master’s degree (MSc) in Applied Sport & Exercise Science at Sheffield Hallam University. The PhD programme, which started in 2019, was a continuation of the work placement undertaken during their master’s degree, with the aim of identifying real world ‘performance problems’ which were experienced in the field, while translating the data collected back to coaches and players to improve their knowledge and understanding of the ‘performance problems’ they were facing. The goal of this was to develop best practice guidelines for England Squash players, taking into consideration contextual factors such as the cultural preferences of the sport, while also challenging these from time to time through the research generated. To best identify the ‘performance problems’, the researcher was also part of the multidisciplinary team, embedded as a performance nutrition practitioner, delivering services to England Squash for their Team England, Academy, Development, and Potential pathway players throughout the duration of the PhD programme. The researcher would primarily class themselves as a practitioner. To this extent, the researcher also worked as a performance nutritionist for an elite Premier League football team on a consultancy basis during their third year of the PhD programme, as well as currently working as a performance nutritionist at Aquatics GB (formerly British Swimming) and the UK Sports Institute, working with Olympic and Paralympic swimmers. This exposure to different sporting environments enabled for a richer critique of the culture of squash, questioning the status quo, much of which is detailed in the synthesis section (see section 6).

1.2 Sports Nutrition & 'Performance Problems'

Sports nutrition is in its junior years as a scientific discipline in comparison to other health-based sciences such as medicine and physiotherapy (Close et al., 2019). Seminal studies in the 1960's quantified the role of muscle glycogen and carbohydrate availability on exercise capacity and performance (Bergström & Hultman, 1966*a*; Bergström & Hultman, 1966*b*; Bergström et al., 1967; Hermansen et al., 1967), paving the way for a multitude of sports nutrition research. In the early 1990's, there were less than 100 peer reviewed journal articles published per year in sports nutrition (Jonvik et al., 2022). This contrasts with the present day, whereby approximately 3500 peer reviewed journal articles were published in 2021 (Jonvik et al., 2022). Knowledge and understanding have been established around the effects of various nutrients and ergogenic aids to modulate sports performance, augment training adaptations, facilitate recovery from exercise, optimise immune function, and enhance body composition (Kerksick et al., 2018). It is now common practice to see sports dietitians and performance nutritionists employed by professional sports teams, national governing bodies or as private consultants to some of the world's greatest athletes to optimise their sporting performance. The industry is also becoming more formalised with professional associations such as the British Dietetics Association creating the Sport & Exercise Nutrition Register to create a standard level of working practice and regulate the industry.

Some of the key determinants of sports performance from a nutrition perspective are considered to be (1) do individuals consume enough energy to account for their energy expenditure; (2) is the macronutrient distribution optimal given the individuals training load; (3) what is the micronutrient status of the individual; (4) is the individual sufficiently euhydrated at the commencement of exercise to optimise their performance; (5) do individuals have the required nutrition knowledge and skills to be able to apply appropriate strategies to optimise their performance.

Performance nutrition practitioners will utilise evidence-based practice to ensure that athletes' nutrition knowledge, skills and behaviours are appropriate to carry out optimal nutrition strategies, depending on their sport and requirements of an individual. With the growing field of sports nutrition and the development of the role of the performance nutrition practitioner, there is sometimes a conflict between the working worlds of the 'fast' practitioner and the 'slow' researcher as there isn't the evidence base to draw from (Close et al., 2019). 'Performance problems' need to be answered to help athletes and coaches win a world championship, or to obtain an Olympic or Paralympic medal, and there isn't the time or opportunity to conduct perfectly detailed randomised controlled trials or wait for a body of research to be conducted so that a meta-analyses or position statement can be formulated on a specific subject (Coutts, 2016). To this extent, as detailed in the 'Performance Problems' section (see section 1.1), the PhD aimed to create a body of research to solve some of the 'performance problems' experienced within elite squash while working in the field.

Bishop (2008) developed an Applied Research Model for Sport Sciences, citing 8 stages: (1) defining the problem; (2) descriptive research, or as I will term it, 'describing the problem'; (3) predictors of performance (regression studies); (4) Experimental testing of procedures; (5) determinants of key performance indicators; (6) intervention studies; (7) barriers to uptake; and (8) implementation in a sports setting (effectiveness trials). The PhD programme aimed to utilise the Applied Research Model for Sport Sciences to answer the 'performance problems' experienced. However, due to the lack of research conducted within elite squash, as discussed in the subsequent sections, the researcher never created new knowledge past stage two, focusing on 'defining the problem' and 'conducting descriptive research'.

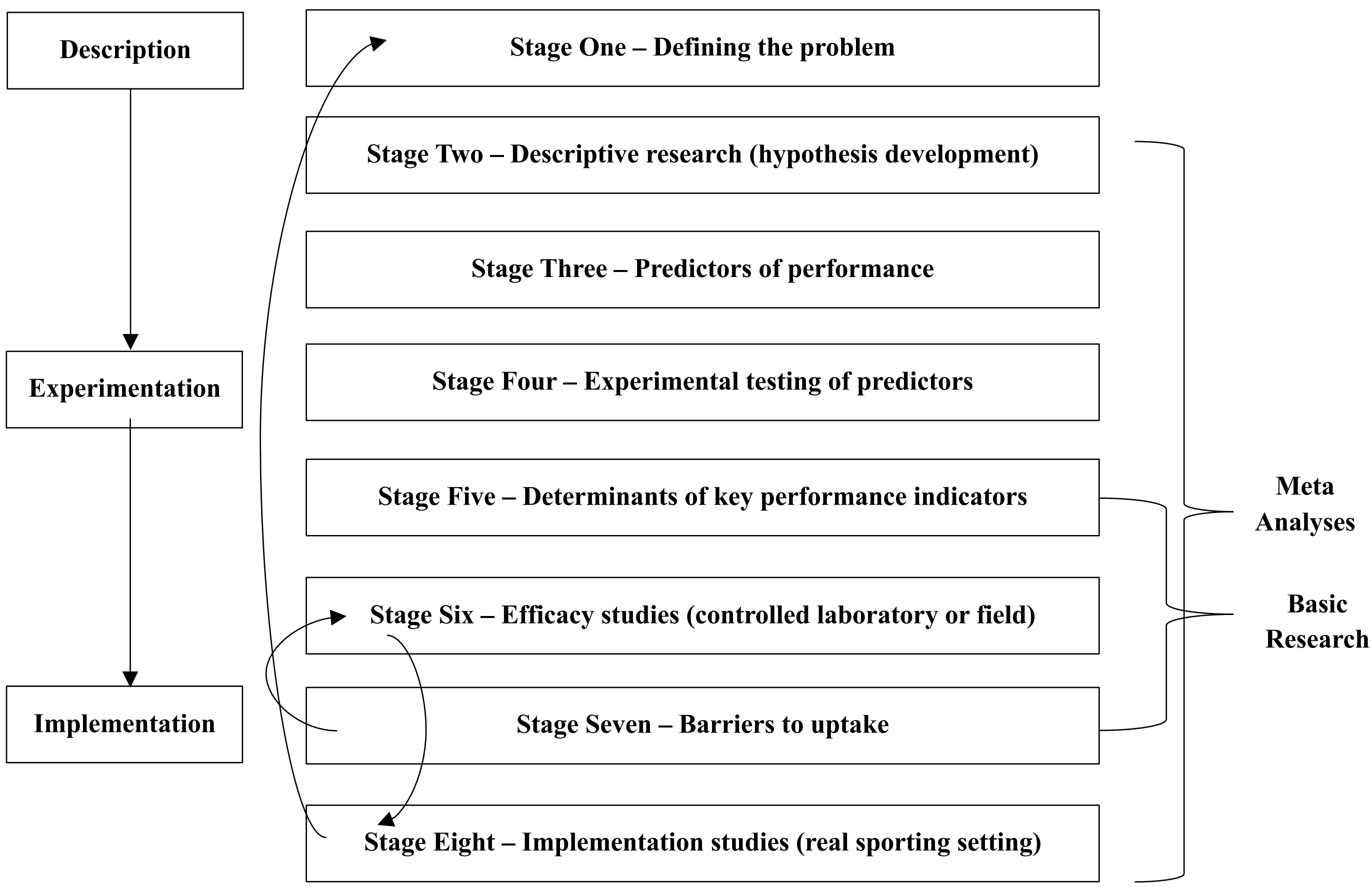

Figure 1. The Applied Research Model for Sports Sciences (adapted from Bishop, 2008)

1.3 Defining the 'Performance Problem'

The first step of integrating evidence-based practice within sport nutrition research is to define the 'performance problem(s)'. The researcher was in a fortunate position having already had prior knowledge of the sport through competing at an international level and working with many of England Squash's elite players and coaches throughout their work placement prior to the PhD programme. However, it was crucial that upon initially enrolling on the PhD programme, the researcher discussed issues they had witnessed with the players and coaches, as well as obtaining feedback from them on the 'performance problem(s)' they felt they were experiencing.

In the initial months of the PhD programme, the researcher conducted a needs analysis in collaboration with the coaches and players. The researcher spent time in the performance environment observing the practices of players throughout training and competition. The researcher also provided nutrition services to many of the players during this needs analysis phase which stimulated conversations between the researcher, players and coaches regarding any 'performance problems'. Consequently, 'performance problems' were able to develop organically and some of the following 'performance problems' were identified by the researcher, coaches, and players:

1) England Squash have never had a full-time nutritionist working in the sport, and there seemed to be some ambiguity regarding the impact nutrition can have on performance. Therefore, what were players understanding of nutrition?

2) Anecdotally, players were seen to have high training loads with much of this training performed at a high intensity. As a result, did players know their energy expenditure and how to fuel and recover effectively from session to session to optimise their health, physical performance and training adaptations?

3) Due to high training loads anecdotally experienced and cultural preferences of the sport, squash players generally trained twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. Did this give players enough opportunity to optimally recover and rehydrate from one session to the next or should coaches and players reconsider their training schedules and periodisation to facilitate greater recovery to maximise their training response?

4) Anecdotally, some players were shown to have high sweat rates. This was so apparent that one player had to change their t-shirt, socks and shoes after each break in training due to their high sweat rates, to prevent excess sweat on the court floor. This player's sweat rate was later

quantified to have a sweat rate of 2.12 $L{\cdot}h^{-1}$ (player one data; see section 5.3). A ‘performance problem’ was how do ensure squash players which high sweat rates are optimally hydrated when they have high training loads and limited time in-between training sessions?

Once the ‘performance problems’ were defined, it is crucial that the researcher understood the scientific principles which relate to the ‘performance problems’ (Bishop, 2008). These principles can be split into two parts:

1) Non-specific technical knowledge of the researcher – This relates to the researcher’s underlying knowledge of the basic biochemistry (McConell, 2022), physiology (McCardle et al., 2014) and contemporary nutrition guidelines (Kerksick et al., 2018). To this extent, the researcher had a BSc in Sport and Exercise Science, an MSc in Applied Sport & Exercise Science, a PgDip in Sports Nutrition as well as two years working as a performance nutritionist in the field prior to starting the PhD programme. The researcher acknowledges that their non-specific technical knowledge was still limited at the beginning of the PhD programme but through the experience of undertaking the PhD, combined with various practitioner roles previously described, this has increased immensely.

2) Squash-specific knowledge to apply to players and coaches – Examples of these include knowing how much energy players expend to advise a player on their nutritional intake; how much sweat sodium is lost during a match to advise a player on their hydration strategy. While the researcher had significant contextual understanding of the sport through competing and working as a performance nutrition practitioner within it, the researcher was only aware of a handful of peer reviewed journal articles and therefore making it difficult to apply evidence-based practice.

Study one aimed to review all the physiological and nutritional research utilising a systematic approach, to ascertain whether any of the ‘performance problems’ had previous been answered in the scientific literature.

Study One – Physiological and Nutritional Considerations for Elite Squash: A Systematic Review

Study one of the PhD programme was to review all of the available physiological and nutritional literature conducted within squash utilising a systematic approach, with the aim of obtaining a greater understanding of the squash-specific physiological and nutritional demands of the sport. An aim of the study was also to guide other practitioners, coaches, and players on how best to interpret the contemporary data and identify gaps in the literature to guide researchers on the future directions within squash. Previous research had provided a review of the performance requirements of squash (Jones et al., 2018), but this was the first study to systematically review the physiological and nutritional literature within squash. A systematic approach was utilised as this is highest level of evidence among scientific literature and therefore, systematic reviews are seen as an effective way to communicate the best evidence quickly, enhancing evidence-based practice (Wallace et al., 2022). The systematic review outlined that the current research within squash had focussed on a variety of areas such as the physiological demands of squash to match play, the training load during a two-week microcycle, and the effects of carbohydrate and creatine supplementation on squash-specific performance.

Squash was shown to be a high intensity intermittent sport which places high demands on aerobic metabolism during match play, as conveyed by performing at a high % VO_{2max} and HR_{max} (Girard et al., 2007). Similarly, elite squash match play places a demand on players due to the high energy expenditures experienced during match play (Girard et al., 2007). Despite this, no research has ever quantified the energy expenditures of elite squash players throughout a training microcycle and therefore it is difficult to provide evidence based nutritional recommendations to players. This is unlike other sports whereby this data has been quantified such as in tennis (Ellis et al., 2021) and soccer (Anderson et al., 2017) to create sport-specific nutritional guidelines (Ranchordas et al., 2013; Collins et al., 2021), enabling practitioners to provide evidence-based recommendations to athletes. Many of the studies conducted in squash had poor (10) or fair (19) methodological quality as quantified through the Physiotherapy Evidence Database (PEDro) scale (Pedro, 2022). The PEDro scale is commonly used across physiotherapy, health, medical research, and sport (Elkins et al., 2013) and has exhibited ‘excellent’ inter-rater reliability for clinical trials (intraclass correlation coefficient [ICC] = 0.91) (Gonzalez et al., 2018). The PEDro scale has also been shown to assess a reasonable breadth of methodological quality, displaying no redundant items amongst the 11 PEDro scale items (de Morton et al., 2009). Thirty-two of the studies identified were observational studies. As discussed in the ‘sports nutrition and performance problems section’ (see section 1.2), it is difficult to conduct perfectly detailed randomised controlled trials with high scientific rigour when working in the field, due to the training periodisation of athletes and performance goals that assume priority over anything else. Only 14/35 studies were conducted on elite or world class players and therefore the validity of extrapolating much of the data and translating it to elite squash players was questionable as they may not be valid in elite populations (Currell & Jeukendrup, 2008), such as the aerobic energy costs of recreational squash players during match play (Montpetit et al., 1987). Another key consideration was that much of the key literature to provide physiological and nutritional recommendations were out of date. In 2009, the World Squash Federation and Professional Squash Association standardised the rules for professional players, changing the scoring system from 9 point-on serve (POS9) to 11 point-a-rally (PAR11), while also lowering the tin line from 48.3 cm to 43.2 cm. This had been reported to alter the physical demands and shot characteristics of squash, reducing the duration of rallies (pre rule changes = 15.0 ± 5 s; post rule changes = 13.2 ± 16 s), while increasing the number of shots per rally (pre rule changes = 11 ± 16; post rule changes = 13 ± 19) (Murray et al., 2016). An interpretation of this data could be that players have changed their shot strategies to become more attacking because of the lowered tin height, as conveyed by the shorter rally durations. To this extent, only 17/35 studies reviewed were published during or after the 2009 rule change, making it difficult to provide evidence-based recommendations as much of the evidence may have altered.

Study one was the first review to synthesise the physiological and nutritional research conducted in squash, utilising a systematic approach. It highlighted that current research within squash had focussed on a variety of areas such as the physiological demands of squash to match play, the training load during a two-week microcycle, the sweat [Na^+] rates of elite players (conducted afterwards as part of this PhD programme), the nutritional knowledge of elite players (conducted afterwards as part of this PhD programme) and the effects of carbohydrate, and creatine supplementation on squash-specific performance. The study also proposed many future directions to advance research and evidence-based practice within squash, enabling for sport-specific recovery and nutritional guidelines to be created. At the time of conducting the systematic review, none of the ‘performance problems’ identified could be answered from the scientific literature, so this guided the research aims of the PhD programme.

1.4 Describing the ‘Performance Problem’

The second step of integrating evidence-based practice within sport nutrition research is to describe the ‘performance problem(s)’. From the systematic review, some data proved useful such as the quantification of the energetic demands of elite male squash players during simulated match play (Girard et al., 2007). This outlined that squash players expended 1179 ± 148 $Kcal{\cdot}h^{-1}$, mean heart rate of 92 ± 3 % heart rate maximum, mean blood lactate concentrations of 8.3 ± 3.4 $mmol{\cdot}L^{-1}$ and mean respiratory exchange ratio of 0.94 ± 0.04 during simulated match play (Girard et al., 2007). This fed the narrative that squash players have high training loads and energy expenditures and therefore there is a high demand on nutrition to ensure that players are appropriately fuelled.

James et al., (2021) quantified the training load of elite Malaysian squash players across a variety of internal (i.e. psychophysiological) and external demands (i.e. musculoskeletal). While this data was useful, it was apparent that training prescription was different in comparison to England Squash elite and potential pathway players. For example, Malaysian players trained for a mean duration of 605 minutes per week, whereas anecdotally the researcher was witnessing players train for more than that duration per week. This was later quantified in study three (see section 4) whereby players were shown to train for a mean duration of 915 ± 92 minutes. Consequently, while this data was useful, it wasn't representative of the cohort of players at England Squash.

Research into the dietary habits of elite Spanish squash players via a food consumption frequency questionnaire (Ventura-Comes et al., 2019) displayed that players nutritional practices were suboptimal, under consuming carbohydrate rich foods such as bread, potatoes, pasta, and rice in comparison to non-specific carbohydrate guidelines (Burke et al., 2011). Questions were raised on whether players lack the knowledge to carry out appropriate nutritional behaviours or whether non-specific guidelines were appropriate for elite squash players. However, food frequency questionnaires had been shown to display poor validity and reliability (Thompson & Subar, 2017) and therefore more valid and reliable methods to quantify dietary intake such as weighed food diaries, Snap 'N' Send and 24-h dietary recall (Bingham et al., 1994; Costello et al., 2017) needed to be employed when quantifying the dietary habits of elite squash players.

As a result, three research questions were formulated to describe the performance problems experienced within England Squash and key nutritional performance determinants:

1) What is the nutrition knowledge of elite squash players?

2) What are the energy expenditures of elite squash players and are their nutritional habits optimal in relation to their energy expenditure?

3) What is the sweat [Na^+] rates of elite squash players and are their hydration strategies optimal in relation to their sweat [Na^+] rates?

Study Two – Elite Squash Players Nutrition Knowledge and Influencing Factors

England Squash were going through a transitional phase within their Team England and Academy players. Players such as three-time world champion Nick Matthew and 2018 Commonwealth Games medallist James Willstrop had either retired or were transitioning into the final stages of their careers and there was a crop of new generational talent coming through. Many of these players had either never had any nutrition support before or this had been limited to a one-off generic presentation at some stage during their junior development. As squash had limited nutrition resource in the past, there was also no prominent nutrition culture within the sport and after conversations with players and coaches, it became apparent that there was an ambiguity around optimal nutritional practices within the sport. This coupled with the fact that there were no squash-specific nutritional guidelines to provide evidence-based practice. Consequently, a starting point was to quantify the nutrition knowledge of elite squash players as well as the factors which influence players nutrition knowledge.

The main aim of this study was to outline whether players required nutritional support to increase their nutrition knowledge and subsequent dietary behaviours to support the general health and physical performance. A greater nutrition knowledge has been shown to lead to superior dietary behaviours (Valliant et al., 2012). As there was no prominent nutrition culture within England Squash, many players felt they didn't require nutrition support and that their behaviours were optimal. Therefore, quantifying players nutrition knowledge was used as a tool to screen players on who may require nutrition support, while acknowledging that greater nutrition knowledge does not solely translate to more optimal dietary habits (Birkenhead & Slater, 2015). The study also asked players what research they would like to be conducted in squash in the future. The aim of this was to ensure that research was undertaken specific to player's needs, involving them in the process as previously discussed in the 'Performance Problems' section (see section 1.1). The study included all of England Squash's elite players as well as their podium potential players, while recruiting players from the Professional Squash Association to increase the richness of data.

Elite squash players were shown to have average nutrition knowledge (56 ± 12 %), while players were shown to value quantifying the energetic demands throughout a training period as the research they would like to see undertaken in the future. This facilitated conversations around developing an 'England Squash Performance Nutrition Education Framework' to increase players nutrition knowledge alongside one-to-one consultancy work with many of the elite players, with the goal optimising their performance. Many of the players also felt that their nutrition knowledge was appropriate, but that the non-specific nutrition guidelines which were included in the NSKQ, the tool utilised to quantify nutrition knowledge was not appropriate for squash players. Therefore, there was a desire to create squash-specific nutritional guidelines by calculating the energy expenditures of elite squash players over a training microcycle, while quantifying the energy intake of players to determine whether their nutritional behaviours were optimal in relation to their training load.

Study Three – Doubly Labelled Water Assessment of Elite Male-Squash Player's Energy Balance During a Seven-Day Training Microcycle

In practice, the researcher was observing large training demands, coupled with the fact that there are no squash-specific guidelines to provide evidence-based recommendations to players. During the researchers work placement with England Squash and the UK Sports Institute, the researcher provided nutrition services to an elite player who was diagnosed with chronic fatigue syndrome, thought to be due to training consistently with low energy availability (Logue et al., 2018), because of their large training demands and suboptimal energy intake. Players surveyed in study two, 'Elite Squash Players Nutrition Knowledge & Influencing Factors' also highlighted that there was a desire to quantify the energetic demands throughout a training period as the research they would like to see undertaken in the future. Therefore, this study aimed to calculate the energy balance of elite male squash players throughout a seven-day training microcycle. This provided data to create squash-specific nutritional recommendations for elite male squash players while quantifying whether their current practices are optimal in relation to their training load. The study utilised the doubly labelled water method, the first of its kind within squash. The researcher had originally planned to quantify the energy balance of elite female squash players as well, however, due to funding and the cost implications of the doubly labelled water method, there was only enough funding for one cohort of players (i.e. three male players). The 'performance problem' was seen to be predominantly problematic in male players whereby anecdotally, training loads seem to be greater in comparison to female players.

Study Four – Fluid Balance, Sodium Losses and Hydration Practices of Elite Squash Players During Training

Another performance problem was that due to the large training demands anecdotally experienced and cultural preferences of the sport, squash players generally train twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. Some players displayed high sweat rates and therefore a question stimulated in collaboration with the players and coaches was whether this short recovery period in-between sessions gives players the opportunity to optimally rehydrate from one session to the next. Consequently, the aim of this study was to create individualised hydration strategies for each England Squash elite player, specific to their sweat rate and sweat [Na^+]. By increasing knowledge and understanding of each players individualised hydration strategy, this was thought to optimise hydration practices. The aim was to also critique whether 2 hours 30 minutes is an appropriate recovery time to rehydrate post session, and that this data may influence coaches' decisions around training schedules and periodisation, such as not programming two intense sessions in close proximity whereby sweat rate may be higher.

1.5 Aims of the PhD

Following the 'performance problems' approach detailed previously, the overarching aim of the PhD programme was to develop squash-specific nutritional recommendations for elite squash players to enable sports nutritionists to better advise players to optimise their health and performance. To address these aims, the following research aims were developed:

1) To systematically review the current physiological and nutritional literature within squash to determine the quality of literature and identify gaps where knowledge was required (see section 2.0).

2) To quantify the nutritional knowledge of elite squash players to help provide an indication of whether players require nutrition support and education to increase their nutrition knowledge and improve food choices to support high training and match demands, as well as a general healthy lifestyle (see section 3.0).

3) To concurrently quantify energy expenditure and energy intake among a cohort of elite male squash players throughout a 7-day training microcycle. This data can be used to create specific nutritional recommendations for the sport so that sports nutritionists can better advise players to optimise their health and performance

4) To quantify the sweat rates and sweat [Na^+] of elite squash players throughout a training session alongside their hydration practices, to provide players, coaches, and practitioners with information to optimise players' hydration strategies during training (see section 5.0).

The literature review and consequently systematic review were completed as the first stage of the PhD programme. This then guided what research needed to be conducted to answer the 'performance problems'. Studies two and four were completed prior to the systematic review being completed and written for publication. Consequently, these are included in the systematic review.

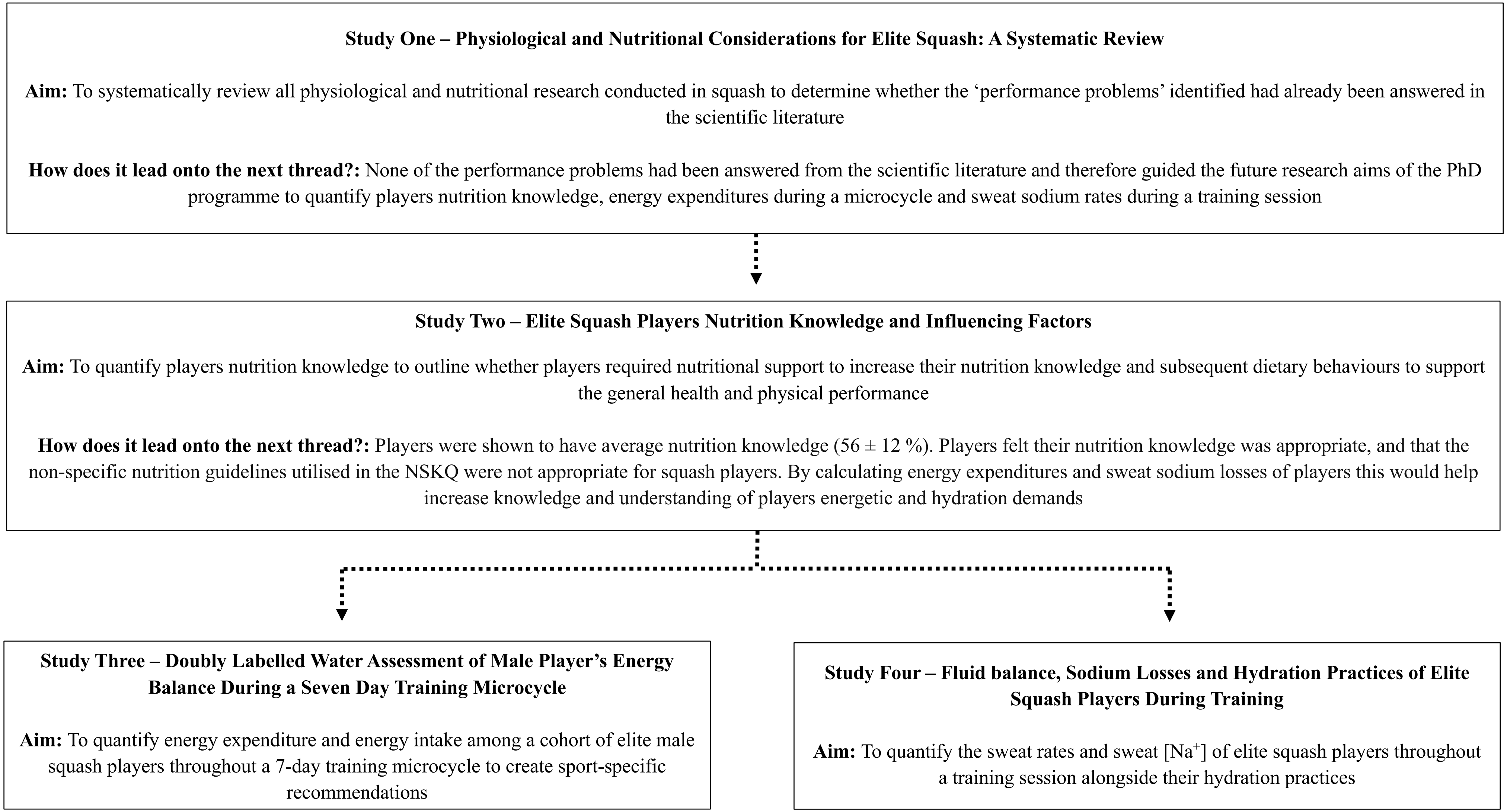

Figure 2. Schematic detailing the golden thread of the PhD programme

2.0: Study One – Physiological and Nutritional Considerations for Elite Squash: A Systematic Review

2.1 Why is there no Literature Review in this Thesis?

PhD thesis traditionally contain a review of the literature before presenting research outputs (Holbrook et al., 2007). However, due to the first research output of this PhD programme being a systematic review, it seems impractical to provide a review of the literature within squash, and then systematically review it in this study. Therefore, this thesis will not contain a traditional literature review and reviewers are asked to consider the systematic review as the review of the literature. Section 2.3 (Justification of Methodology) outlines why a systematic review was chosen to be conducted rather than a traditional literature review.

2.2 Study Summary & the Golden Thread

As referenced in 'Defining the Performance Problem' (see 'section 1.3), after discussions with players and coaches, and identifying four 'performance problems', the first stage of the PhD programme was to review the available literature regarding physiology and nutrition within squash. The aim of the study was to obtain a greater understanding of the squash-specific physiological and nutritional research which had previously been conducted within the sport. Therefore, this study utilised a systematic review methodological approach (Higgins, 2020) to synthesise all the previous physiological and nutritional literature which had been conducted in squash. The aim was to identify whether the 'performance problems' could be solved from the available literature. The study also aimed to collate all the previous research conducted and provide a critique of the literature to guide practitioners, coaches, and players on how best to interpret the contemporary data, while identifying gaps in the literature to guide researchers on the future directions within squash.

2.3 Justification of Methodology

As discussed in 'Performance Problems'' (see section 1.1), practitioners aim to provide evidence-based practice to athletes and coaches. Practitioners may not have the time to critically appraise primary studies and therefore review articles play a key role in identifying and synthesising the literature relevant to a specific research question or topic (Palmatier et al., 2018). According to Palmatier et al., (2018), review articles aim to:

- Outline the scope of a specific research question or topic
- Provide definitions within it to avoid any ambiguity or inconsistencies
- Provide an integrated, synthesised overview of the current state of knowledge of a specific research question or topic
- Identify limitations and contradictions within the literature

- Critique previous methodological approaches
- Provide a theoretical framework on the literature to develop individuals understanding of it
- Identify gaps in the literature whereby future research should focus

It is difficult for a research paper to cover all these aims (Palmatier et al., 2018). However, a research article should aim to achieve three significant goals:

1) The research question or topic needs to be appropriate for a review paper in that there is enough previous literature to be able to appropriately critique and synthesise the research question or topic

2) The review must use appropriate analysis techniques from a breadth of literature in a fascinating writing style

3) The review must provide new insights based on the critique and synthesis of the literature

There are a variety of different review formats to review the literature within a specific research question or topic, such as but not exclusive to: a systematic review; literature or narrative review; critical review; meta-analysis; mapping review; rapid review; scoping review; and umbrella review (Grant and Booth, 2008). The study utilised a systematic review to systematically review all the physiological and nutritional literature conducted within squash. Systematic reviews are seen as the highest level of evidence among scientific literature and therefore, systematic reviews are seen as an effective way to communicate the best evidence quickly, enhancing evidence-based practice (Wallace et al., 2022). Systematic reviews provide a precise summary of the literature regarding a specific research question or topic, through a clearly formulated methodological process (Higgins, 2020). This contrasts with a literature or narrative review which reviews literature in an unsystematic method, increasing the risk of researcher bias (Cipriani & Geddes, 2003). Systematic reviews undergo a rigorous search strategy to identify appropriate literature, increasing external validity (Moosapour et al., 2021). Due to the methodological process undertaken, researchers can critique and discuss the generalisability of findings within the literature such as the demographics, characteristics or inventions utilised (Mulrow, 1994; Nasser et al., 2012). In this study, this could be whether research on amateur squash players is appropriate to generalise in an elite context.

Part of the systematic review process is to critically appraise the methodological quality of the literature (Higgins, 2020). There are a variety of tools to quantify the methodological quality such as the Cochrane risk of bias tool for randomised trials (Higgins et al., 2011), the Physiotherapy Evidence

Database (PEDro) scale (Pedro, 2022), and the Effective Practice and Organisation of Care (EPOC) Group (EPOC, 2024). By reporting the methodological quality of the literature, it increases the accuracy and internal validity of the review (Higgins, 2020). Systematic reviews also require more than one reviewer to critique the methodological quality and extract the data from the literature, increasing the reliability of the review (Belur et al., 2018). A systematic review also has a detailed and predefined protocol, promoting transparency throughout the review process (Higgins, 2020). This protocol includes a review question, search strategy, eligibility criteria, tools utilised in the study and methods relating to statistical analysis (Higgins, 2020). The detailed and predefined protocol acts as a road map for authors to ensure that they complete the review with high scientific rigour, as outlined previously in this section (e.g. assessment of methodological quality). Researchers are required to register their systematic reviews on databases such as PROSPERO or PRISMA (Strauss & Moher, 2010). Registering the systematic review protocol minimises bias as it enables individuals to review the reported methods alongside what was originally planned during the registration process (Moosapour et al., 2021). This reduces the subjectivity of reviewers in the review process, increasing objectivity (Moosapour et al., 2021). Registering the systematic review also helps to avoid duplications of reviews (Booth et al., 2011*a*; Booth et al., 2011*b*; Beyer & Wright, 2011).

The study utilised the Physiotherapy Evidence Database (PEDro) scale to quantify the methodological quality of studies (Pedro, 2022). The PEDro scale is commonly used across physiotherapy, health, medical research, and sport (Elkins et al., 2013). The PEDro scale has exhibited ‘excellent’ inter-rater reliability for clinical trials (intraclass correlation coefficient [ICC] = 0.91) (Gonzalez et al., 2018). The PEDro scale has also been shown to assess a reasonable breadth of methodological quality, displaying no redundant items amongst the 11 PEDro scale items (de Morton et al., 2009).

2.4 Physiological and Nutritional Considerations for Elite Squash Players: A Systematic Review

2.4.1 Abstract

Purpose: To systematically review all physiological and nutritional research conducted in squash to guide practitioners on how best to interpret the data, while identifying gaps in the literature to guide researchers on the future directions of research within squash.

Methods: Following PRISMA guidelines, studies investigating an aspect of physiology or nutrition within squash were identified using scientific databases CINAHL, MEDLINE, PUBMED, and SPORTDiscus, from March 2022 to October 2023.

Results: Of the 1208 studies identified, 35 met the inclusion criteria across a variety of physiological and nutritional topics such as the physiological demands of squash, anthropometric characteristics of squash players, the physiological characteristics of squash players, squash-specific performance tests, the training demands of squash, the nutritional requirements of squash, the hydration demands of squash, the nutrition knowledge of squash players, and nutritional supplements for squash players. Ten studies had poor methodological quality, 19 fair, four good, and two excellent. Seventeen out of 35 studies included were undertaken post the 2009 rule change, and 14 studies were conducted on either elite or world class players. Twenty-nine of the studies involved male players, with 15 involving female players.

Conclusion: Much of the physiological and nutritional literature is of a low quality and outdated. We present future research focuses throughout the review such as quantifying the game characteristics of male and female players, the energy expenditures during a training and competition microcycle, and the efficacy of certain nutritional supplements with an aim to create sport specific guidelines and advance evidence-based practice within squash.

2.4.2 Introduction

Squash is classified as one of four major racket sports along with badminton, tennis, and table-tennis (Lees, 2003). It was first played at Harrow school in 1865, originating from a combination of the traditional racket sports; real tennis, and racquets (World Squash Federation, 2022*a*). Squash is unique to other major racket sports as players compete in the same area of the court, with the simplest ruling being that the ball must be struck before bouncing twice and hit the front wall, landing above the tin line (bottom out of court line) and below the front wall and side wall lines (World Squash Federation, 2022*b*). Squash has 123 national squash federations and 50,000 courts worldwide (World Squash Federation, 2022*c*). Squash is currently included in the Pan-American Games, Asian Games, Pacific Games, Commonwealth Games, and World Games programmes (World Squash Federation, 2022*c*). It has also featured as a showcase sport in the 2018 Youth Olympic Games and has recently gained inclusion into the Los Angeles 2028 Summer Olympic Games programme (Olympics, 2023). The Professional Squash Association is the global governing body for men's and women's professional squash around the world. It has over 1,400 registered players and runs more than 600 competitions around the world each year (Professional Squash Association, 2022). At elite level, squash is a high intensity intermittent sport which requires a blend of physical, technical, psychological, and tactical capabilities (Jones et al., 2018). Elite male matches are reported to last a mean match duration of 54 minutes, with players covering a mean distance of 1848 m throughout a match (Murray et al., 2016). Squash is characterised by sport-specific movements which are highly dynamic and acyclic in nature such as 3-6 metre sprints, lunges, and changes of direction (Vučković et al., 2003).

Elite male squash has been reported to elicit a mean energy expenditure of 4933 ± 620 $kJ \cdot h^{-1}$, mean heart rate of 92 ± 3 % of heart rate maximum (HR_{max}) and mean respiratory exchange ratio (RER) of 0.94 ± 0.06 (Girard et al., 2007), demonstrating the high intensity nature of the sport. However, in 2009, the World Squash Federation and Professional Squash Association standardised the rules for professional players, changing the scoring system from 9 point-on serve (POS9) to 11 point-a-rally (PAR11), while also lowering the tin line from 48.3 cm to 43.2 cm. This has been reported to alter the physical demands and shot characteristics of the sport, reducing the duration of rallies (pre rule changes = 15.0 ± 5s; post rule changes = 13.2 ± 16 s), while increasing the number of shots per rally (pre rule changes = 11 ± 16; post rule changes = 13 ± 19) (Murray et al., 2016). An interpretation of this data could be that players have changed their shot strategies to become more attacking because of the lowered tin height, as conveyed by the shorter rally durations. It can be debated that much of the research undertaken in squash is outdated due to these rule changes. Consequently, the purpose of this review was to evaluate the current physiological and nutritional literature regarding squash. This investigation will contribute to the current knowledge of squash by synthesising literature and have a positive impact on applied practice by presenting guidance for scientists, coaches, and players, whilst identifying gaps in knowledge to guide researchers on the future directions of research within squash.

2.4.3 Methods

2.4.3.1 Protocol and Registration

This review was conducted in accordance with the contemporary guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Page et al., 2021) and was prospectively registered on the Registry of Systematic Reviews & Meta-Analyses (registration number 1328) (Registry of Systematic Reviews & Meta-Analyses, 2022).

2.4.3.2 Eligibility Criteria

Original research such as randomised control trials, observational and cross-sectional studies using squash players which are published in peer reviewed journals were included in the review. Excluded items included abstracts, conference posters, review articles and unpublished theses. All 'standards' of squash performance (e.g. beginner, recreational, collegiate, national, elite and world class etc.) were included. Only studies written in English were included. Studies were required to investigate an aspect of nutrition (e.g. nutrition knowledge, dietary analysis, effects of a nutritional substance on squash performance) or physiology (e.g. energetic demands, training load, performance test, physiological profiling etc.) relating to squash. The underpinning biochemical and physiological demands of squash inform nutritional recommendations, hence why these two subject areas were combined in this review.

2.4.3.3 Search Strategy

Studies that investigated an aspect of nutrition or physiology relating to squash were identified through the following databases: CINAHL (EBSCO), MEDLINE (EBSCO), PUBMED, and SPORTDiscus (EBSCO). A literature search was conducted every month, upon inception (March 2022) until the end date (October 2023), to retrieve newly published articles. A search strategy was conducted with a combination of the terms ("squash sport[MeSH Terms]") AND ("squash[Title]") being searched for. Additionally, citation chaining (where another source cites another source) was also performed after the literature search using identified studies to discover other relevant research articles. After conducting the search strategy, duplicate studies were removed using Refworks bibliography software (ProQuest). Two independent reviewers (OT and NM) assessed studies for their title, abstract and descriptors to determine eligibility. The full text of studies which satisfied the inclusion criteria were reviewed before being selected. If there were any disagreements in this process, a third reviewer (MR) was conferred with (Figure 3).

2.4.3.4 Data Extraction

Data extraction was conducted by the first author (OT) into an Excel (V 16.58, Microsoft) data extraction form. Extracted information included but not exclusive of; (1) participant and study characteristics (authors, age, sex, stature, body mass, sample size, playing standard); (2) type of intervention (randomised control trial, observational, cross-sectional); (3) measurement of intervention (test procedure, frequency, duration etc.); (4) means and standard deviations (SDs) for outcome measures of the intervention (e.g. nutrition knowledge score, energy expenditure, RER, time etc.).

2.4.3.5 Assessment of Methodological Quality

The PEDro scale was used to assess the methodological quality of studies (Pedro, 2022). The scale rates the quality of clinical trials (Cashin & McAuley, 2019) and is commonly used across physiotherapy, health, medical research, and sport (Elkins et al., 2013). The scale has been shown to be a valid and reliable tool to distinguish between studies with low and high methodological quality (Cashin & McAuley, 2019). Although the scale was originally intended for physiotherapy and clinical trials, it is considered comparable to other methodological quality scales (Cashin & McAuley, 2019). The scale consists of 11 items, assessing external validity (item 1), internal validity (items 2 to 9), and statistical reporting (items 10 and 11). Each item is rated 1 or 0 (yes or no), depending on whether the criterion is satisfied in the study (Elkins et al., 2013). Items 2-11 scores are collated to provide a score between 0 to 10. Studies with a greater methodological quality have a higher score. Scores of less than 4 are considered 'poor', 5-6 are considered 'fair', 6-8 are considered 'good' and 9-10 are considered 'excellent' (Foley et al., 2006). The PEDro scale has exhibited 'excellent' inter-rater reliability for clinical trials (intraclass correlation coefficient [ICC] = 0.91) (Gonzalez et al., 2018). The assessment of methodological quality was conducted by two reviewers (OT and NM). A third reviewer (MR) was conferred with if there were any disagreements.

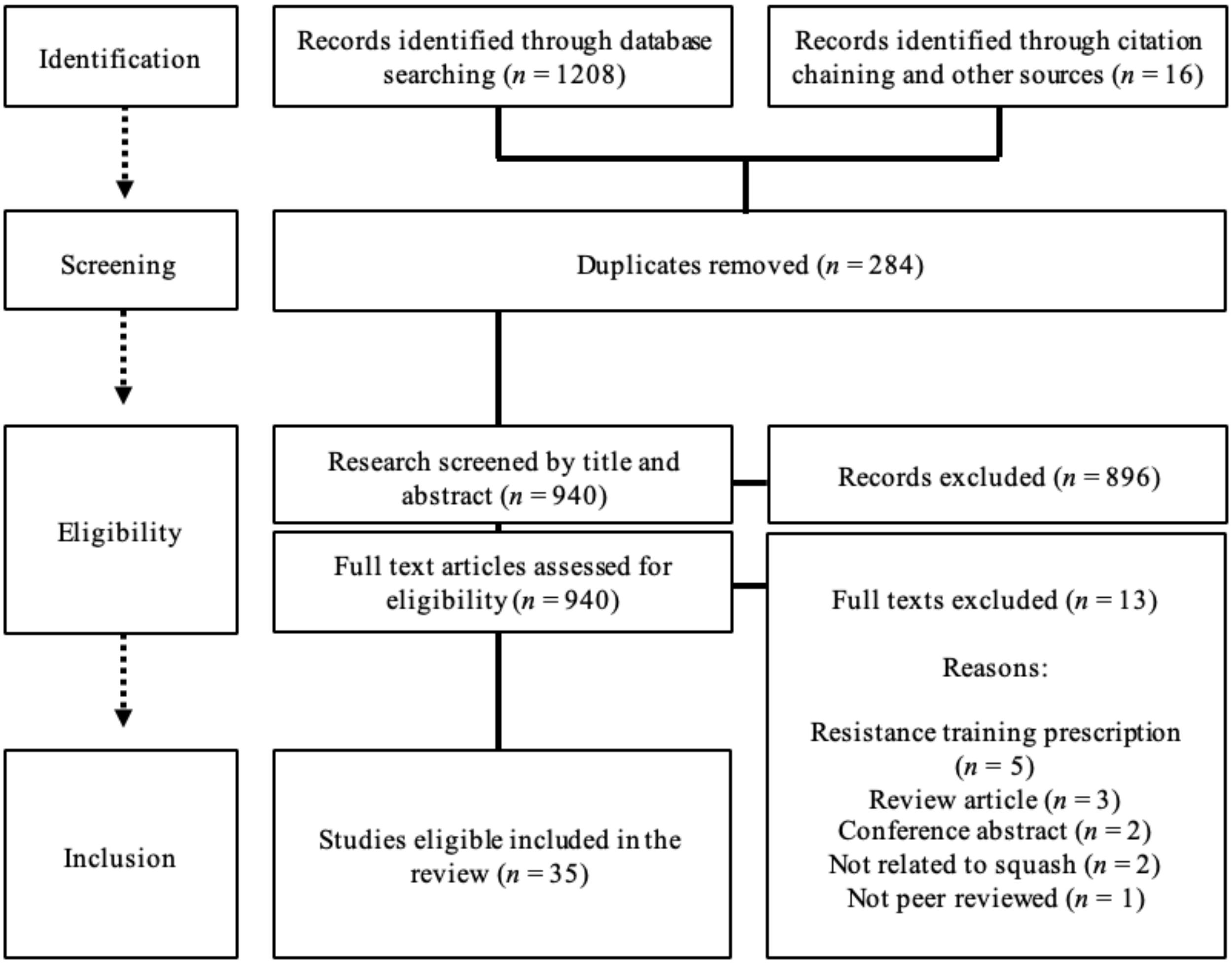

Figure 3. PRISMA flow chart displaying the study selection process

2.4.4 Results

Overall, 35 studies were considered to have met the inclusion criteria and were included in the review (see Figure 3). Table 1 displays the study characteristics, aims, methodology, results, key findings and PEDro quality rating of the reviewed studies. Many of the studies conducted in squash had poor (10) or fair (19) methodological quality, with only four being considered good and two being considered excellent. Only 14/35 studies were conducted on elite or world class players. Twenty-nine of the studies involved male players, with 15 studies involving female players, while four studies did not specify the sex of the player(s). Overall, 78% of the players included in studies were male, while 22% were female. Studies which did not include the sex of the player(s) were not included in the percentage calculation. Only 17/35 studies reviewed were published during or after the 2009 rule change.

Table 1. Study characteristics, aims, methodology, results, key findings and PEDro quality rating

Reference (Country)	Participant Standard Tier	n (sex)	Age (Years)	Study Aim(s)	Methods	Results	Key Finding(s)	PEDro Quality Rating
Beaudin et al., (1978) (Canada)	2	10 (M)	29.4	Quantify whether squash is an appropriate exercise to promote and/or maintain cardiovascular fitness Assess blood lactate levels post squash	45-minute squash match	↑ Blood lactate HR_{max} = 185 ± 12.5 beats·min^{-1} Mean HR = 155 ± 8.2 beats.min^{-1}	Squash exhibits heart rate responses which elicit aerobic training effects Squash does not produce high blood lactate concentrations	**3/10 = Poor**
Blanksby et al., (1973) (Australia)	1-3	Sedentary = 25 (M) active = 25 (M) "A" grade = 25 (M)	Sedentary = <40 active = <40 "A" grade = N/A	Quantify the physiological strain of squash at different playing standards using heart rate	30-minute squash match	↓ HR among middle aged active players ↔ HR between sedentary and "A" grade players	Middle aged active and "A" grade players work within tolerable limits while playing squash Middle aged sedentary players exposed themselves to a high world load and therefore players should begin slowly and allow for ample recovery time in between rallies	**2/10 = Poor**
Blanksby et al., (1980)	1-3	Sedentary = 9 (M);	Sedentary = 44.8	To quantify the alterations in blood pressure and rectal temperature	30-minute squash match	↑ Rectal temperature		**2/10 = Poor**

(Australia)		active = 9 (M) “A” grade = 9 (M)	active = 44.2 “A” grade = 25.8	experienced by sedentary, active and "A"-grade male squash players during a simulated match play.		↑ Systolic blood pressure ↓ Diastolic blood pressure	Despite squash requiring individuals to exercise at a vigorous intensity, rectal temperatures did not reach dangerous levels (37 °C to 39 °C) Blood pressure increased and anyone with already elevated blood pressure should seek medical advice before playing squash	
Bottoms et al., (2006) (Scotland)	2-3	16 (M)	31 ± 6	To quantify the effects of carbohydrate ingestion on skill maintenance following short duration exercise simulating the demands of squash play in squash players	Participants participated in three trials (familiarisation, CHO trial, and PLA trial) Players completed a reaction test, maximal voluntary activation fatigue test, squash skill test, and on court shuttle running and ghosting tests	↔ Skill maintenance ↑ Visual reaction time ↔ Maximal voluntary contraction pre and post exercise	Carbohydrate ingestion during squash may maintain skill levels after fatiguing exercise due to elevated blood glucose levels	**10/10 = Excellent**
Brady et al., (1989) (Ireland)	2	10 (M)	49	Quantify players heart rate and metabolic response during a competitive squash match and during a ITT to compare whether metabolic changes ensued during these exercise bouts	There were two testing sessions: Competitive squash match and ITT; phlebotomy and assessment of heart rate were performed immediately pre-exercise, immediately post-exercise (<1 min), 5 minutes post-exercise, and 30 minutes post-exercise	↑ Mean HR post-match ↑ Plasma noradrenaline post-match ↑ Plasma LA^+ immediately post-match ↑ Blood glucose post-match ↓ Plasma potassium post-match ↑ Serum free fatty acids post-match	Individuals with coronary heart disease should not partake in squash	**4/10 = Fair**

						↔ Plasma adrenaline ↔ Haematocrit		
Brigden et al., (1992) (England)	2	4 (M) 1 (F)	30	Quantify blood pressure changes while partaking in squash	Squash match (time not specified)	↑ Systolic blood pressure ↑ Mean HR	Participating in squash may be a risk for individuals with pre-existing diseases	**3/10 = Poor**
Chin et al., (1995) (Hong Kong)	4	10 (Not specified)	20.7 ± 2.5	To quantify the physiological profiles of elite squash players and provide baseline data for coaches, players, and practitioners to compare against	A battery of tests including: body composition test (skinfolds); pulmonary function test; continuous running test; squash-specific field test; muscular strength test (isokinetic dynamometer); and flexibility test (sit and reach test)	Stature = 172.6 ± 4.3 cm Body mass = 67.7 ± 6.9 kg Body fat % = 7.4 ± 3.4 % VO_{2max} = 61.7 ± 3.4 $ml \cdot kg^{-1} \cdot min^{-1}$ Alactic power index = 15.5 ± 1.8 $W \cdot kg^{-1}$ Sit and reach test = 38.5 ± 6.2 cm	Players have a low body fat %, average flexibility, and high aerobic and anaerobic capabilities	**3/10 = Poor**
Girard et al., (2005) (France)	3-5	7 (M)	24.9 ± 4.1	Develop a squash-specific fitness test; Compare physiological responses recorded during the IST with an ITT	Two testing sessions: ITT whereby participants completed an incremental treadmill test to exhaustion and field testing whereby participants completed a IST	↑ in VO_{2max} IST vs. ITT ↑ in competition ranking correlated with Te in ST (r = -0.96; p<0.001)	The ST allowed for higher maximal values to be achieved The ranking of players strongly correlated with Te of the IST	**6/10 = Good**
Girard et al., (2007) (France)	3-5	7 (M)	24.9 ± 4.1	Quantify the energetic demands of elite male squash simulated match play	Two testing sessions: Squash-specific fitness test to quantify VO_{2max} and a best of three squash match simulating	Mean $EEVO_2$ = 4,933 ± 620 $kJ \cdot h^{-1}$ Mean VO_2 = 54.4 ± 4.8 $ml \cdot min^{-1} \cdot kg^{-1}$ Mean HR = 177 ± 10 $beats \cdot min^{-1}$	Elite male squash is largely a high intensity aerobic activity, while placing high demands on the anaerobic energy systems Coaches should aim to control the various energetic pathways to optimise the	**4/10 = Fair**

						Mean RER = 0.94 ± 0.06 Mean LA^+ = 8.3 ± 3.4 $mmol \cdot L^{-1}$	prescription of a conditioning session	
Girard et al., (2010) (France)	2	10 (M)	32.2 ± 7.3	Quantify the alterations of neuromuscular function after simulated squash match play	Players completed a 1-hour simulated squash match play against another player. Post squash match neuromuscular test sessions occurred (maximal voluntary contractions and electromyographic signals)	↓ MVC post squash match ↓ Peak torque post squash match	1-hour simulated squash match play induces central fatigue as well as an alteration in excitation contraction coupling Training neural factors (increased reflex excitability), structural (hypertrophy) and biochemical may delay central fatigue and increase fatigue resistance	**4/10 = Fair**
Gouttebarge et al., (2013) (Netherlands)	4	6 (F)	31 ± 8	Develop a squash specific fitness test that encompasses the physiological demands and quantify it's face and convergent validity	Two testing sessions: TT whereby participants completed an incremental treadmill test to exhaustion and field testing whereby participants completed a ST	↑ VO_{2max} TT vs. ST ↑ HR_{max} ST vs. TT ↔ LA^+	The ST had a good level of validity in comparison to the TT The ST may be preferable for practitioners as it requires minimal equipment	**4/10 = Fair**
James et al., (2019) (Malaysia)	4	6 (M) 2 (F)	20.3 ± 2.1	Validate and quantify the retest reliability of a squash-specific exercise test which calculates a maximal performance score as well as physiological markers such as VO2max, lactate thresholds and oxygen cost in a squash-specific context	Three testing sessions: TT whereby participants completed an incremental treadmill test to exhaustion and a field testing whereby participants completed a ST in two separate trials to assess reliability of the ST	↑ VO_{2max} TT vs. ST ↑ HR_{max} ST vs. TT ↑ LA^+ TT vs. ST ↑ RPE TT vs. ST	The ST is suitable to quantify squash specific performance, alongside physiological assessments such as HR, LA^+, and VO_2 to quantify adaptations to training	**6/10 = Good**
James et al., (2021*a*) (Malaysia)	4	11 (M) 4 (F)	20 ± 3	Quantify the training intensities and loads of group, ghosting, feeding, matchplay and conditioning sessions across a 2-week in-season microcycle	During a two week in season period, players wore 100-Hz triaxial accelerometer/global positioning system and heart rate monitor during on court (group, feeding,	Time >90% maximum HR: ↓ Feeding ↔ Among other sessions Relative playerload: ↑ Conditioning	Group sessions provide the highest training loads and have a key role within the training process Findings of the study help facilitate planning or	**4/10 = Fair**

					ghosting and match play) and off-court (conditioning) sessions	↔ Ghosting and matchplay Highest playerload: ↑ Conditioning ↑ Group (in comparison to other on court sessions) RPE: ↑ Group	adjustment of frequency, volume and intensity of sessions to reach the desired physiological result	
James et al., (2021*b*) (Malaysia)	4	11 (M) 4 (F)	19.1 ± 2.5	Investigate the relationships between training load approaches in elite squash players, during a 2-week microcycle	Throughout 134 on-court sessions and 32 off-court 'conditioning' sessions among players: External load (playerload) was captured using a tri-axial accelerometer Internal load was quantified via HR, sRPE and dRPE-Legs; dRPE-Breathing Heart rate was utilised to quantify Banister's, Edward's and TEAM TRIMPs	Playerload was 'moderately correlated' with: TRIMP-Bannister TRIMP-Edwards Moderate correlation between s RPE and Playerload Association of sRPE was 'large' with TRIMP-Banister Association of sRPE was 'very large' with TRIMP-Edwards Association of sRPE was 'moderate' with TRIMP-TEAM sRPE-Legs and dRPE-Breathing had nearly perfect correlations with sRPE and each other	Quantifying the internal and external load of elite players is recommended to understand the physical demands of squash Isolating an individual squash training session and interpreting the data from it may underestimate or overestimate the physical stress a player is enduring	**4/10 = Fair**

James et al., (2022) (Malaysia)	4	21 (M) 10 (F)	Males = 20 ± 4 Females = 18 ± 5	Quantify the physiological attributes of elite squash players and determine which characteristics correlate with squash performance	Participants completed: ASSPPT; RSA; CODT; 5m sprint test; squat jump; countermovement jump; anthropometric profiling	Higher ranked players performed significantly better on: ↑ ASSPPT final lap ↑ 4 $mM \cdot L^{-1}$ lap of ASSPPT ↑ COD ASPPT 'very large' correlation with: 4 $mM \cdot L^{-1}$ lap of ASSPPT ASSPPT 'large' correlations with: COD RSA Sum-of-7 skinfolds VO_{2max}	Quantifying players RSA, COD, body composition and cardiovascular fitness are pertinent when profiling elite squash players	**4/10 = Fair**
Kingsley et al., (2006) (Wales)	2	8 (M)	16.2 ± 0.8	Develop a squash simulation protocol which replicates the physiological demands of elite junior squash	Participants completed: A squash match against a player of a similar standard; IST; SSPT	Between squash match and SSP: ↔ HR_{max} ↔ Mean HR ↔ RPE ↑ LA^{+} post-match in SSPT	The SSPT mirrored the physiological demands of an elite junior squash match and is a suitable field-based test to quantify physiological responses to elite junior squash The SSP can be applied to quantify the efficacy of interventions such as ergogenic aids	**5/10 = Fair**
Lombard et al., (2014) (South Africa)	2	10 (M)	23.4 ± 3.5	Determine the relationship between players physiological characteristics and their squash performance and club ranking	Participants completed: Static stork stand balance test; Dynamic star excursion stand balance test; Illinois agility test; Standard ruler drop	Correlation between ranking and performance in the star excursion stand balance test	Some physiological characteristics may be more essential than for optimal squash performance	**4/10 = Fair**

					response time test; 10m acceleration test			
Lynch et al., (1992) (Ireland)	2	10 (M)	52	Are the physiological and metabolic responses of squash exaggerated or accentuated when squash matches are performed in close proximity	Players underwent three matches in 36 hours	↑ Mean HR post-match ↔ Plasma noradrenaline post-match ↑ Plasma LA^+ immediately post-match ↓ Plasma K^+ post-match ↑ Serum free fatty acids post-match	Squash has several physiological risk factors which could contribute to an underlying coronary heart disease and sudden cardiac death	**4/10 = Fair**
MacGowan et al., (1994)	2	12 (Not specified)	24	Effects of several fluid replacement strategies post-match play on metabolic responses	Each player played 5 games of squash and then consumed: No fluid replacement; 500 ml distilled water; 500 ml weak electrolyte solution; 500 ml glucose solution; 500 ml glucose/electrolyte 'sports' drink Metabolic responses assessed 5-, 15-, 30-, and 60-minutes post exercise: Lactate; free fatty acids; glucose; potassium; sodium; urine osmolarity	↑ blood glucose levels when consuming 500 ml glucose solution & 500 ml glucose/electrolyte 'sports' drink	Fluid replacements may increase blood glucose levels but not electrolyte levels	**6/10 = Good**
Madjumdar et al., (2009) (India)	2	33 (M) 9 (F)	15-19 years old	Quantify the physiological demands of squash through heart rate and lactate during matchplay	Four on court drill sessions (ghosting, court run, shuttle run, box sprint) and one matchplay session were monitored with blood lactate levels being taken	Between sexes: ↔ HR ↔ Blood LA^+ Blood LA^+: ↓ Matchplay in comparison to other sessions	Higher blood LA^+ in on court drills suggest they may not be appropriate to optimise training adaptations for matchplay	**4/10 = Fair**
Micklewright and	1-3	11 (M) 10 (F)	M = 20.4 ± 3	Develop a reliable and valid squash specific incremental test (SSIT)	Players underwent an ITT before completing a IST	Positive intraclass correlation between two SSIT and time to fatigue	The IST can be used to quantify the maximal aerobic capacity of squash players	**4/10 = Fair**

Papapdopoulou (2008) (England)			F = 22.1 ± 5.7	Create a conversion table to estimate $VO2_{max}$ from the SSIT time to fatigue	test twice, separated by at least 72 hours between tests	Positive correlation between SSIT performance and VO_{2max} Regression equations found the IST to be a valid and reliable tool to quantify VO_{2max}		
Montpetit et al., (1987) (Canada)	2	16 (M)	27.1 ± 5.2	Quantify the aerobic energy costs of recreational squash	EE was collected during three separate occasions using the Douglas Bag Technique	EE = 600 $Kcal \cdot h^{-1}$ Squash played at 57 % of VO_{2max}	Thirty minutes of squash would be appropriate as an exercise session to develop and maintain fitness due to the intensity level and energy expenditure of squash	**3/10 = Poor**
Raman et al., (2014) (New Zealand)	2-3	9 (M)	24 ± 8	Quantify whether a high carbohydrate diet prior to a simulated squash match altered physical performance	Players completed a simulated squash match on two separate occasions after consuming either a high CHO or calorie matched low CHO diet	High CHO trial: ↑ RER ↑ Time to completion ↑ Blood glucose ↑ LA^{+}	High CHO prior to simulated squash match increases carbohydrate oxidation rate and maintenance of higher blood glucose levels. This is associated with optimised physical performance	**8/10 = Good**
Romer et al., (2001) (England)	3	9 (M)	21.3 ± 0.3	Quantify the effects of creatine monohydrate supplementation on high intensity, intermittent exercise performance in competitive squash players	Players underwent a ghosting protocol in a double blinded crossover design whereby they consumed either creatine monohydrate or maltodextrin with a 4-week washout period in-between	Creatine Monohydrate: ↑ Mean set sprint time	Creatine Monohydrate supplementation improves squash-specific exercise performance in squash players	**10/10 = Excellent**
Rosimus (2018) (England)	4	1 (F)	19	Case study quantifying the effect of a nutritional intervention on body composition, vitamin D status and physical performance	Player underwent a 6 week moderate energy restricted diet (70-78% of 2300 Kcals)	After 6-week intervention: ↓ Sum of 8 skinfolds ↑ Lean mass to fat mass ratio ↑ 25-hydroxyvitamin D3 ↑ Ferritin ↑ Eosinophils	A structured dietary calorie restricted intervention in conjunction with a strength and conditioning programme is an appropriate way to optimise body composition and physical performance	**2/10 = Poor**

						↑ Triglycerides ↑ Reactive strength index ↑ On court repeated speed	characteristics of an elite squash player	
Steininger & Wodick (1987) (Germany)	2	7 (M) 6 (F)	Junior players	Quantify the anaerobic threshold and VO2max during a laboratory-based test and a squash-specific field test	Participants completed an IST test before undergoing an ITT	Low correlation between ranking and ITT High correlation between ranking and IST	Physiological characteristics obtained from field-based tests are more valid for estimating squash specific fitness in comparison to laboratory based tests	**3/10 = Poor**
Turner et al., (2021) (England)	3-5	37 (M) 40 (F)	24 ± 5	Assess the nutrition knowledge of elite squash players Investigate the factors which may influence an elite squash players nutrition knowledge Assess the association between age and world ranking on nutrition knowledge Quantify whether players standard of relevant education and main source of nutrition knowledge influence nutrition knowledge	Quantify players nutrition knowledge via the NSKQ alongside additional questions to determine influencing factors	Nutrition knowledge: Players had average nutrition knowledge (56 ± 12 %) ↔ M vs. F Influencing factors: ↔ World ranking and NSKQ score ↔ Age and NSKQ score ↑ Relevant undergraduate degree ↑ Nutrition information from a registered nutritionist	Elite squash players should aim to increase their nutrition knowledge by consulting with a sports nutritionist	**4/10 = Fair**
Turner et al., (2023) (England)	4-5	7 (M) 7 (F)	25 ± 5 (M) 25 ± 4 (F)	Quantify the fluid balance and sweat $[Na^+]$ of elite squash players during a training session alongside their hydration practices	Players fluid balance was taken during a training session Hydration practices (fluid and sodium intake) were calculated via a self-reported food diary until the players next session	Mean fluid balance = – 1.22 ± 1.22% Mean sweat rate = 1.11 ± 0.56 $L \cdot h^{-1}$ Mean sweat $[Na^+]$ = 46 ± 12 $mmol \cdot L^{-1}$ ↑ Males sweat rate in comparison to females	There is variability in players hydration demands and the data highlights the need to quantify and individualise players hydration strategies as well as training prescription to ensure players can optimally rehydrate	**4/10 = Fair**

					Sweat $[Na^+]$ was quantified post session through Pilocarpine Iontophoresis Players perceived seat rate and sweat $[Na^+]$ concentration were taken during sweat $[Na^+]$ collection	↑ Increased rehydration practices when have 21 hrs 30 mins in comparison to 2 hrs 30 mins		
Ventura-Comes (2018) (Spain)	3-4	International: 10 (M) 4 (F) National: 20 (M) 8 (F)	International: 25 ± 6.2 National: 35.6 ± 14.2	Quantify the consumption of nutritional supplements by national and international level squash players	Players were sent a validated telematic survey to quantify their nutritional supplement consumption	↑ Supplementation in international players ↑ Advice regarding supplementation in international players	International level players show a higher level of supplementation in comparison to national level players	**3/10 = Poor**
Ventura-Comes (2019) (Spain)	3-4	International: 10 (M) 4 (F) National: 20 (M) 8 (F)	International: 25 ± 6.2 National: 35.6 ± 14.2	Quantify the dietary habits of national and international squash players via a validated food frequency questionnaire	Players completed a validated food frequency questionnaire with differences being compared between national and international players	International players: ↑ Bread ↑ Nuts No differences in: ↔ Meat ↔ Fish ↔ Fruit ↔ Vegetables ↔ Pulses ↔ Potato ↔ Pasta ↔ Rice ↔ Soft drinks ↔ Sweets ↔ Snacks	National and international players may over consume protein and under consume carbohydrates Players do not obtain their nutrition advice from a sport dietitian	**3/10 = Poor**
Wilkinson et al., (2009*a*) (England)	2	8 squash players (not specified)	30 ± 11.2	Examine the validity of an IST by determining the endurance capability and VO_{2max} of trained squash players in comparison to distance runners using an IST and ITT protocol	SG and RG underwent the ITT and IST in a counterbalanced order, separated by at least 48 hours	Comparisons between SG vs. RG in IST: ↑ SG time to exhaustion ↔ VO_{2max}	The ST is a valid means to assess VO_{2max} of squash players	**5/10 = Fair**

		8 runners (not specified)				↔ HR_{max} Comparisons between SG vs. RG in ITT: ↑ RG time to exhaustion ↑ RG VO_{2max} ↔ HR_{max}		
Wilkinson et al., (2009*b*) (England)	2	8 (not specified)	29.6 ± 9.4	Examine the reproducibility of assessments from a squash-specific fitness test	Participants performed a IST twice, separated by at least 7 days	Time: LOA = 14; TEM = 27 VO_{2max}: LOA = 0.2; TEM = 2.4 HR_{max}: LOA -2; TEM = 2 Economy: LOA = -3.9; TEM = 1.6	The ST produces reproducible assessments for the assessment of endurance capabilities in squash players	**4/10 = Fair**
Wilkinson et al., (2009*b*) (England)	2	10 squash players (M) 10 non-squash players (M)	Squash players = 23 ± 4 Non-squash players = 24 ± 3)	Examine the validity of a squash-specific test designed to assess change-of-direction speed	SP and NSP underwent two trials of the SSCODT and two trials of the IAR. Each trial was separated by at least 24 hours	Performance results: ↔ in time to completion between SP and NSP in IAR ↑ SP in SSCODT Reproducibility of performance in ST among SSCODT: TEM = 0.13 s CI = 0.09 – 0.21 s	The SSCODT is a valid and reliable field-based assessment for squash players which produces more accurate assessments when compared to an equivalent nonspecific field test	**4/10 = Fair**
Wilkinson et al., (2010) (England)	2	8 squash players (M) 8 soccer players (M)	Squash players = 25 ± 5 Soccer players = 22 ± 3	Examine the validity and reproducibility of a squash-specific test designed to assess multiple sprint ability	SP and SoP underwent two trials of the SSMST and two trials of the BST. Each trial was separated by at least 24 hours	Performance results: ↔ in time to completion between SP and SoP in BST ↑ SP in ST Reproducibility of performance in ST among SqP: TEM = 6 s CI = 4 – 13 s ICC r = 0.97	The ST is a valid and reliable field-based assessment for squash players to assess multiple sprint ability	**5/10 = Fair**

Wilkinson et al., (2012) (England)	3-5	20 (M) 11 (F)	M = 26 ± 2 F = 25 ± 2	Compare performance on a battery of fitness tests among elite-standard squash players on different tiers of a national performance program (senior, transition, and TASS) Investigate possible relationships among test scores and player rank in such players Identify fitness factors that relate to squash-specific multiple-sprint ability in this standard of player	During one session, players completed a battery of fitness tests; countermovement jump, drop jump, squash-specific test of change-of-direction (COD), squash-specific test of multiple-sprint (SSMST), and multistage fitness test (MFT)	Countermovement jump height: ↔ Between senior vs. transition players ↑ Male vs. female Squash-specific change of direction speed: ↑ Senior vs. TASS (i.e. faster) ↔ Senior vs. transition players ↑ Male vs. female Squash-specific multiple sprint ability: ↑ Senior vs. transition ↑ Senior vs. TASS ↔ Transition vs. TASS players ↑ Male vs. female Fastest multiple sprint: ↑ Senior vs. transition ↑ Senior vs. TASS ↔ Between transition vs. TASS players ↑ Male vs. female Endurance fitness: ↔ Senior vs. transition vs. TASS players ↑ Male vs. female Correlations between test score and player rank:	Lower-body- explosive capabilities and multiple-sprint ability are important performance variables for elite squash ability	**4/10 = Fair**

						↑ Fastest sprint in SSMST with increased world ranking		

Reference (Country)	Participant Standard Tier	n (sex)	Age (Years)	Study Aim(s)	Methods	Results	Key Finding(s)	PEDro Quality Rating
Beaudin et al., (1978) (Canada)	2	10 (M)	29.4	Quantify whether squash is an appropriate exercise to promote and/or maintain cardiovascular fitness Assess blood lactate levels post squash	45-minute squash match	↑ Blood lactate HR_{max} = 185 ± 12.5 $beats \cdot min^{-1}$ Mean HR = 155 ± 8.2 $beats.min^{-1}$	Squash exhibits heart rate responses which elicit aerobic training effects Squash does not produce high blood lactate concentrations	**3/10 = Poor**
Blanksby et al., (1973) (Australia)	1-3	Sedentary = 25 (M) active = 25 (M) “A” grade = 25 (M)	Sedentary = <40 active = <40 “A” grade = N/A	Quantify the physiological strain of squash at different playing standards using heart rate	30-minute squash match	↓ HR among middle aged active players ↔ HR between sedentary and “A” grade players	Middle aged active and “A” grade players work within tolerable limits while playing squash Middle aged sedentary players exposed themselves to a high world load and therefore players should begin slowly and allow for ample recovery time in between rallies	**2/10 = Poor**
Blanksby et al., (1980) (Australia)	1-3	Sedentary = 9 (M); active = 9 (M) “A” grade = 9 (M)	Sedentary = 44.8 active = 44.2 “A” grade = 25.8	To quantify the alterations in blood pressure and rectal temperature experienced by sedentary, active and "A"-grade male squash players during a simulated match play.	30-minute squash match	↑ Rectal temperature ↑ Systolic blood pressure ↓ Diastolic blood pressure	Despite squash requiring individuals to exercise at a vigorous intensity, rectal temperatures did not reach dangerous levels Blood pressure was elevated and anyone with already elevated blood pressure should seek medical advice before playing squash	**2/10 = Poor**

Bottoms et al., (2006) (Scotland)	2-3	16 (M)	31 ± 6	To quantify the effects of carbohydrate ingestion on skill maintenance following short duration exercise simulating the demands of squash play in squash players	Participants participated in three trials (familiarisation, CHO trial, and PLA trial) Players completed a reaction test, maximal voluntary activation fatigue test, squash skill test, and on court shuttle running and ghosting tests	↔ Skill maintenance ↑ Visual reaction time ↔ Maximal voluntary contraction pre and post exercise	Carbohydrate ingestion during squash may maintain skill levels after fatiguing exercise due to elevated blood glucose levels	**10/10 = Excellent**
Brady et al., (1989) (Ireland)	2	10 (M)	49	Quantify players heart rate and metabolic response during a competitive squash match and during a ITT to compare whether metabolic changes ensued during these exercise bouts	There were two testing sessions: Competitive squash match and ITT; phlebotomy and assessment of heart rate were performed immediately pre-exercise, immediately post-exercise (<1 min), 5 minutes post-exercise, and 30 minutes post-exercise	↑ Mean HR post-match ↑ Plasma noradrenaline post-match ↑ Plasma LA^+ immediately post-match ↑ Blood glucose post-match ↓ Plasma potassium post-match ↑ Serum free fatty acids post-match ↔ Plasma adrenaline ↔ Haematocrit	Individuals with coronary heart disease should not partake in squash	**4/10 = Fair**
Brigden et al., (1992) (England)	2	4 (M) 1 (F)	30	Quantify blood pressure changes while partaking in squash	Squash match (time not specified)	↑ Systolic blood pressure ↑ Mean HR	Participating in squash may be a risk for individuals with pre-existing diseases	**3/10 = Poor**
Chin et al., (1995) (Hong Kong)	4	10 (Not specified)	20.7 ± 2.5	To quantify the physiological profiles of elite squash players and provide baseline data for coaches, players, and practitioners to compare against	A battery of tests including: body composition test (skinfolds); pulmonary function test; continuous running test; squash-	Stature = 172.6 ± 4.3 cm Body mass = 67.7 ± 6.9 kg	Players have a low body fat %, average flexibility, and high aerobic and anaerobic capabilities	**3/10 = Poor**

				specific field test; muscular strength test (isokinetic dynamometer); and flexibility test (sit and reach test)	Body fat % = 7.4 ± 3.4 % VO_{2max} = 61.7 ± 3.4 $ml \cdot kg^{-1} \cdot min^{-1}$ Alactic power index = 15.5 ± 1.8 $W \cdot kg^{-1}$ Sit and reach test = 38.5 ± 6.2 cm		
Girard et al., (2005) (France)	3-5	7 (M)	24.9 ± 4.1	Develop a squash-specific fitness test; Compare physiological responses recorded during the IST with an ITT	Two testing sessions: ITT whereby participants completed an incremental treadmill test to exhaustion and field testing whereby participants completed a IST	↑ in VO_{2max} IST vs. ITT ↑ in competition ranking correlated with Te in ST (r = -0.96; p<0.001)	The ST allowed for higher maximal values to be achieved The ranking of players strongly correlated with Te of the IST	**6/10 = Good**
Girard et al., (2007) (France)	3-5	7 (M)	24.9 ± 4.1	Quantify the energetic demands of elite male squash simulated match play	Two testing sessions: Squash-specific fitness test to quantify VO_{2max} and a best of three squash match simulating	Mean $EEVO_2$ = 4,933 ± 620 $kJ \cdot h^{-1}$ Mean VO_2 = 54.4 ± 4.8 $ml \cdot min^{-1} \cdot kg^{-1}$ Mean HR = 177 ± 10 $beats \cdot min^{-1}$ Mean RER = 0.94 ± 0.06 Mean LA^+ = 8.3 ± 3.4 $mmol \cdot L^{-1}$	Elite male squash is largely a high intensity aerobic activity, while placing high demands on the anaerobic energy systems Coaches should aim to control the various energetic pathways to optimise the prescription of a conditioning session	**4/10 = Fair**
Girard et al., (2010) (France)	2	10 (M)	32.2 ± 7.3	Quantify the alterations of neuromuscular function after simulated squash match play	Players completed a 1-hour simulated squash match play against another player. Post squash match neuromuscular test sessions occurred (maximal voluntary contractions and electromyographic signals)	↓ MVC post squash match ↓ Peak torque post squash match	1-hour simulated squash match play induces central fatigue as well as an alteration in excitation contraction coupling Training neural factors (increased reflex excitability),	**4/10 = Fair**

							structural (hypertrophy) and biochemical may delay central fatigue and increase fatigue resistance	
Gouttebarge et al., (2013) (Netherlands)	4	6 (F)	31 ± 8	Develop a squash specific fitness test that encompasses the physiological demands and quantify it's face and convergent validity	Two testing sessions: TT whereby participants completed an incremental treadmill test to exhaustion and field testing whereby participants completed a ST	↑ VO_{2max} TT vs. ST ↑ HR_{max} ST vs. TT ↔ LA^+	The ST had a good level of validity in comparison to the TT The ST may be preferable for practitioners as it requires minimal equipment	**4/10 = Fair**
James et al., (2019) (Malaysia)	4	6 (M) 2 (F)	20.3 ± 2.1	Validate and quantify the retest reliability of a squash-specific exercise test which calculates a maximal performance score as well as physiological markers such as VO2max, lactate thresholds and oxygen cost in a squash-specific context	Three testing sessions: TT whereby participants completed an incremental treadmill test to exhaustion and a field testing whereby participants completed a ST in two separate trials to assess reliability of the ST	↑ VO_{2max} TT vs. ST ↑ HR_{max} ST vs. TT ↑ LA^+ TT vs. ST ↑ RPE TT vs. ST	The ST is suitable to quantify squash specific performance, alongside physiological assessments such as HR, LA^+, and VO_2 to quantify adaptations to training	**6/10 = Good**
James et al., (2021*a*) (Malaysia)	4	11 (M) 4 (F)	20 ± 3	Quantify the training intensities and loads of group, ghosting, feeding, matchplay and conditioning sessions across a 2-week in-season microcycle	During a two week in season period, players wore 100-Hz triaxial accelerometer/global positioning system and heart rate monitor during on court (group, feeding, ghosting and match play) and off-court (conditioning) sessions	Time >90% maximum HR: ↓ Feeding ↔ Among other sessions Relative playerload: ↑ Conditioning ↔ Ghosting and matchplay Highest playerload: ↑ Conditioning ↑ Group (in comparison to other on court sessions) RPE: ↑ Group	Group sessions provide the highest training loads and have a key role within the training process Findings of the study help facilitate planning or adjustment of frequency, volume and intensity of sessions to reach the desired physiological result	**4/10 = Fair**

James et al., (2021*b*) (Malaysia)	4	11 (M) 4 (F)	19.1 ± 2.5	Investigate the relationships between training load approaches in elite squash players, during a 2-week microcycle	Throughout 134 on-court sessions and 32 off-court 'conditioning' sessions among players: External load (playerload) was captured using a tri-axial accelerometer Internal load was quantified via HR, sRPE and dRPE-Legs; dRPE-Breathing Heart rate was utilised to quantify Banister's, Edward's and TEAM TRIMPs	Playerload was 'moderately correlated' with: TRIMP-Bannister TRIMP-Edwards Moderate correlation between s RPE and Playerload Association of sRPE was 'large' with TRIMP-Banister Association of sRPE was 'very large' with TRIMP-Edwards Association of sRPE was 'moderate' with TRIMP-TEAM sRPE-Legs and dRPE-Breathing had nearly perfect correlations with sRPE and each other	Quantifying the internal and external load of elite players is recommended to understand the physical demands of squash Isolating an individual squash training session and interpreting the data from it may underestimate or overestimate the physical stress a player is enduring	**4/10 = Fair**
James et al., (2022) (Malaysia)	4	21 (M) 10 (F)	Males = 20 ± 4 Females = 18 ± 5	Quantify the physiological attributes of elite squash players and determine which characteristics correlate with squash performance	Participants completed: ASSPPT; RSA; COD; 5m sprint test; squat jump; countermovement jump; anthropometric profiling	Higher ranked players performed significantly better on: ↑ ASSPPT final lap ↑ 4 $mM \cdot L^{-1}$ lap of ASSPPT ↑ COD ASPPT 'very large' correlation with: 4 $mM \cdot L^{-1}$ lap of ASSPPT	Quantifying players RSA, COD, body composition and cardiovascular fitness are pertinent when profiling elite squash players	**4/10 = Fair**

						ASSPPT ‘large’ correlations with: COD RSA Sum-of-7 skinfolds VO_{2max}		
Kingsley et al., (2006) (Wales)	2	8 (M)	16.2 ± 0.8	Develop a squash simulation protocol which replicates the physiological demands of elite junior squash	Participants completed: A squash match against a player of a similar standard; IST; SSPT	Between squash match and SSP: ↔ HR_{max} ↔ Mean HR ↔ RPE ↑ LA^+ post-match in SSPT	The SSPT mirrored the physiological demands of an elite junior squash match and is a suitable field-based test to quantify physiological responses to elite junior squash The SSP can be applied to quantify the efficacy of interventions such as ergogenic aids	**5/10 = Fair**
Lombard et al., (2014) (South Africa)	2	10 (M)	23.4 ± 3.5	Determine the relationship between players physiological characteristics and their squash performance and club ranking	Participants completed: Static stork stand balance test; Dynamic star excursion stand balance test; Illinois agility test; Standard ruler drop response time test; 10m acceleration test	Correlation between ranking and performance in the star excursion stand balance test	Some physiological characteristics may be more essential than for optimal squash performance	**4/10 = Fair**
Lynch et al., (1992) (Ireland)	2	10 (M)	52	Are the physiological and metabolic responses of squash exaggerated or accentuated when squash matches are performed in close proximity	Players underwent three matches in 36 hours	↑ Mean HR post-match ↔ Plasma noradrenaline post-match ↑ Plasma LA^+ immediately post-match ↓ Plasma K^+ post-match ↑ Serum free fatty acids post-match	Squash has several physiological risk factors which could contribute to an underlying coronary heart disease and sudden cardiac death	**4/10 = Fair**
MacGowan et al., (1994)	2	12 (Not specified)	24	Effects of several fluid replacement strategies post-match play on metabolic responses	Each player played 5 games of squash and then consumed:	↑ blood glucose levels when consuming 500 ml glucose solution & 500 ml	Fluid replacements may increase blood glucose levels but not electrolyte levels	**6/10 = Good**

					No fluid replacement; 500 ml distilled water; 500 ml weak electrolyte solution; 500 ml glucose solution; 500 ml glucose/electrolyte 'sports' drink Metabolic responses assessed 5-, 15-, 30-, and 60-minutes post exercise: Lactate; free fatty acids; glucose; potassium; sodium; urine osmolarity	glucose/electrolyte 'sports' drink		
Madjumdar et al., (2009) (India)	2	33 (M) 9 (F)	15-19 years old	Quantify the physiological demands of squash through heart rate and lactate during matchplay	Four on court drill sessions (ghosting, court run, shuttle run, box sprint) and one matchplay session were monitored with blood lactate levels being taken	Between sexes: ↔ HR ↔ Blood LA^+ Blood LA^+: ↓ Matchplay in comparison to other sessions	Higher blood LA^+ in on court drills suggest they may not be appropriate to optimise training adaptations for matchplay	**4/10 = Fair**
Micklewright and Papapdopoulou (2008) (England)	1-3	11 (M) 10 (F)	M = 20.4 ± 3 F = 22.1 ± 5.7	Develop a reliable and valid squash specific incremental test (SSIT) Create a conversion table to estimate $VO2_{max}$ from the SSIT time to fatigue	Players underwent an ITT before completing a IST test twice, separated by at least 72 hours between tests	Positive intraclass correlation between two SSIT and time to fatigue Positive correlation between SSIT performance and VO_{2max} Regression equations found the IST to be a valid and reliable tool to quantify VO_{2max}	The IST can be used to quantify the maximal aerobic capacity of squash players	**4/10 = Fair**
Montpetit et al., (1987) (Canada)	2	16 (M)	27.1 ± 5.2	Quantify the aerobic energy costs of recreational squash	EE was collected during three separate occasions using the Douglas Bag Technique	EE = 600 $Kcal \cdot h^{-1}$ Squash played at 57 % of VO_{2max}	Thirty minutes of squash would be appropriate as an exercise session to develop and maintain fitness due to	**3/10 = Poor**

							the intensity level and energy expenditure of squash	
Raman et al., (2014) (New Zealand)	2-3	9 (M)	24 ± 8	Quantify whether a high carbohydrate diet prior to a simulated squash match altered physical performance	Players completed a simulated squash match on two separate occasions after consuming either a high CHO or calorie matched low CHO diet	High CHO trial: ↑ RER ↑ Time to completion ↑ Blood glucose ↑ LA^{+}	High CHO prior to simulated squash match increases carbohydrate oxidation rate and maintenance of higher blood glucose levels. This is associated with optimised physical performance	**8/10 = Good**
Romer et al., (2001) (England)	3	9 (M)	21.3 ± 0.3	Quantify the effects of creatine monohydrate supplementation on high intensity, intermittent exercise performance in competitive squash players	Players underwent a ghosting protocol in a double blinded crossover design whereby they consumed either creatine monohydrate or maltodextrin with a 4-week washout period in-between	Creatine Monohydrate: ↑ Mean set sprint time	Creatine Monohydrate supplementation improves squash-specific exercise performance in squash players	**10/10 = Excellent**
Rosimus (2018) (England)	4	1 (F)	19	Case study quantifying the effect of a nutritional intervention on body composition, vitamin D status and physical performance	Player underwent a 6 week moderate energy restricted diet (70-78% of 2300 Kcals)	After 6-week intervention: ↓ Sum of 8 skinfolds ↑ Lean mass to fat mass ratio ↑ 25-hydroxyvitamin D3 ↑ Ferritin ↑ Eosinophils ↑ Triglycerides ↑ Reactive strength index ↑ On court repeated speed	A structured dietary calorie restricted intervention in conjunction with a strength and conditioning programme is an appropriate way to optimise body composition and physical performance characteristics of an elite squash player	**2/10 = Poor**
Steininger & Wodick (1987) (Germany)	2	7 (M) 6 (F)	Junior players	Quantify the anaerobic threshold and VO2max during a laboratory-based test and a squash-specific field test	Participants completed an IST test before undergoing an ITT	Low correlation between ranking and ITT High correlation between ranking and IST	Physiological characteristics obtained from field-based tests are more valid for estimating squash specific fitness in comparison to laboratory based tests	**3/10 = Poor**
Turner et al., (2021)	3-5	37 (M)	24 ± 5	Assess the nutrition knowledge of elite squash players	Quantify players nutrition knowledge via the NSKQ	Nutrition knowledge:	Elite squash players should aim to increase their nutrition	**4/10 = Fair**

(England)		40 (F)		Investigate the factors which may influence an elite squash players nutrition knowledge Assess the association between age and world ranking on nutrition knowledge Quantify whether players standard of relevant education and main source of nutrition knowledge influence nutrition knowledge	alongside additional questions to determine influencing factors	Players had average nutrition knowledge (56 ± 12 %) ↔ M vs. F Influencing factors: ↔ World ranking and NSKQ score ↔ Age and NSKQ score ↑ Relevant undergraduate degree ↑ Nutrition information from a registered nutritionist	knowledge by consulting with a sports nutritionist	
Turner et al., (2023) (England)	4-5	7 (M) 7 (F)	25 ± 5 (M) 25 ± 4 (F)	Quantify the fluid balance and sweat [Na$^+$] of elite squash players during a training session alongside their hydration practices	Players fluid balance was taken during a training session Hydration practices (fluid and sodium intake) were calculated via a self-reported food diary until the players next session Sweat [Na$^+$] was quantified post session through Pilocarpine Iontophoresis Players perceived seat rate and sweat [Na$^+$] concentration were taken during sweat [Na$^+$] collection	Mean fluid balance = – 1.22 ± 1.22% Mean sweat rate = 1.11 ± 0.56 L·h^{-1} Mean sweat [Na$^+$] = 46 ± 12 mmol·L^{-1} ↑ Males sweat rate in comparison to females ↑ Increased rehydration practices when have 21 hrs 30 mins in comparison to 2 hrs 30 mins	There is variability in players hydration demands and the data highlights the need to quantify and individualise players hydration strategies as well as training prescription to ensure players can optimally rehydrate	**4/10 = Fair**
Ventura-Comes (2018) (Spain)	3-4	International: 10 (M) 4 (F)	International: 25 ± 6.2 National:	Quantify the consumption of nutritional supplements by national and international level squash players	Players were sent a validated telematic survey to quantify their nutritional supplement consumption	↑ Supplementation in international players ↑ Advice regarding supplementation in international players	International level players show a higher level of supplementation in comparison to national level players	**3/10 = Poor**

		National: 20 (M) 8 (F)	35.6 ± 14.2					
Ventura-Comes (2019) (Spain)	3-4	International: 10 (M) 4 (F) National: 20 (M) 8 (F)	International: 25 ± 6.2 National: 35.6 ± 14.2	Quantify the dietary habits of national and international squash players via a validated food frequency questionnaire	Players completed a validated food frequency questionnaire with differences being compared between national and international players	International players: ↑ Bread ↑ Nuts No differences in: ↔ Meat ↔ Fish ↔ Fruit ↔ Vegetables ↔ Pulses ↔ Potato ↔ Pasta ↔ Rice ↔ Soft drinks ↔ Sweets ↔ Snacks	National and international players may over consume protein and under consume carbohydrates Players do not obtain their nutrition advice from a sport dietitian	**3/10 = Poor**
Wilkinson et al., (2009*a*) (England)	2	8 squash players (not specified) 8 runners (not specified)	30 ± 11.2	Examine the validity of an IST by determining the endurance capability and VO_{2max} of trained squash players in comparison to distance runners using an IST and ITT protocol	SG and RG underwent the ITT and IST in a counterbalanced order, separated by at least 48 hours	Comparisons between SG vs. RG in IST: ↑ SG time to exhaustion ↔ VO_{2max} ↔ HR_{max} Comparisons between SG vs. RG in ITT: ↑ RG time to exhaustion ↑ RG VO_{2max} ↔ HR_{max}	The ST is a valid means to assess VO_{2max} of squash players	**5/10 = Fair**
Wilkinson et al., (2009*b*) (England)	2	8 (not specified)	29.6 ± 9.4	Examine the reproducibility of assessments from a squash-specific fitness test	Participants performed a IST twice, separated by at least 7 days	Time: LOA = 14; TEM = 27 VO_{2max}: LOA = 0.2; TEM = 2.4 HR_{max}: LOA -2; TEM = 2 Economy: LOA = -3.9; TEM = 1.6	The ST produces reproducible assessments for the assessment of endurance capabilities in squash players	**4/10 = Fair**

Wilkinson et al., (2009*b*) (England)	2	10 squash players (M) 10 non-squash players (not specified)	Squash players = 23 ± 4 Non-squash players = 24 ± 3)	Examine the validity of a squash-specific test designed to assess change-of-direction speed	SP and NSP underwent two trials of the SSCODT and two trials of the IAR. Each trial was separated by at least 24 hours	Performance results: ↔ in time to completion between SP and NSP in IAR ↑ SP in SSCODT Reproducibility of performance in ST among SSCODT: TEM = 0.13 s CI = 0.09 – 0.21 s	The SSCODT is a valid and reliable field-based assessment for squash players which produces more accurate assessments when compared to an equivalent nonspecific field test	**4/10 = Fair**
Wilkinson et al., (2010) (England)	2	8 squash players (M) 8 soccer players (M)	Squash players = 25 ± 5 Soccer players = 22 ± 3	Examine the validity and reproducibility of a squash-specific test designed to assess multiple sprint ability	SP and SoP underwent two trials of the SSMST and two trials of the BST. Each trial was separated by at least 24 hours	Performance results: ↔ in time to completion between SP and SoP in BST ↑ SP in ST Reproducibility of performance in ST among SqP: TEM = 6 s CI = 4 – 13 s ICC r = 0.97	The ST is a valid and reliable field-based assessment for squash players to assess multiple sprint ability	**5/10 = Fair**
Wilkinson et al., (2012) (England)	3-5	20 (M) 11 (F)	M = 26 ± 2 F = 25 ± 2	Compare performance on a battery of fitness tests among elite-standard squash players on different tiers of a national performance program (senior, transition, and TASS) Investigate possible relationships among test scores and player rank in such players Identify fitness factors that relate to squash-specific multiple-sprint ability in this standard of player	During one session, players completed a battery of fitness tests; countermovement jump, drop jump, squash-specific test of change-of-direction (COD), squash-specific test of multiple-sprint (SSMST), and multistage fitness test (MFT)	Countermovement jump height: ↔ Between senior vs. transition players ↑ Male vs. female Squash-specific change of direction speed: ↑ Senior vs. TASS (i.e. faster) ↔ Senior vs. transition players ↑ Male vs. female	Lower-body- explosive capabilities and multiple-sprint ability are important performance variables for elite squash ability	**4/10 = Fair**

Squash-specific multiple sprint ability:
↑ Senior vs. transition
↑ Senior vs. TASS
↔ Transition vs. TASS players
↑ Male vs. female

Fastest multiple sprint:
↑ Senior vs. transition
↑ Senior vs. TASS
↔ Between transition vs. TASS players
↑ Male vs. female

Endurance fitness:
↔ Senior vs. transition vs. TASS players
↑ Male vs. female

Correlations between test score and player rank:
↑ Fastest sprint in SSMST with increased world ranking

↑ indicates significant increase ($p < 0.05$); ↓ indicates significant decrease ($p < 0.05$); ↔ indicates no significant differences ($p > 0.05$). Participant standard tier (McKay et al., 2022) = Tier 0 = sedentary; Tier 1 = Recreationally active; Tier 2 = Trained/developmental; Tier 3 = Highly trained/national level; Tier 4 = Elite/international level; Tier 5 = World class; HR = Heart rate; HR_{max} = Heart rate maximum; CHO = Carbohydrate; PLA = Placebo; VO_{2max} = Maximal rate of oxygen consumption; ITT = Incremental treadmill test; IST = Incremental squash test; Te = Time to exhaustion; $EEVO_2$ = Energy expenditure; VO_2 = rate of oxygen consumption; RER = Respiratory exchange ratio; MVC = Maximal voluntary contraction; LA^+ = lactate concentration; RPE = Rating of perceived exertion; sRPE = Session rating of perceived exertion; dRPE = differential rating of perceived exertion; ASSPPT = Aerobic squash-specific physical performance test; RSA = Repeated sprint ability; COD = Change of direction; CODT = Change of direction test; SSPT = Squash simulation protocol test; K^+ = Potassium; NSKQ = Nutrition for Sport Knowledge Questionnaire; $[Na^+]$ = Sweat sodium concentration; SG = Squash group; RG = Running group; LOA = Limits of agreement; TEM = Technical error of measurement; SP = Squash players; NSP = Non-squash players; SSCODT = Squash-specific change of direction test; IAR = Illinois agility run; CI = Confidence interval; ICC = Intraclass correlation coefficient; SoP = Soccer players; SSMST = Squash-specific multiple sprint test TASS = Talented athlete scholarship scheme

2.4.4.1 Physiological Demands of Squash

Thirteen studies have quantified a physiological demand of squash, with four studies published during or after the 2009 rule change and four studies including either elite or world class players. Research has quantified the physiological demands of junior squash players through heart rate and blood lactate concentrations during match play (Majumdar et al., 2009). In recreational players, the energetic demands (Montpetit et al., 1987), heart rate response (Blanksby et al., 1973; Beaudin et al., 1978;; Blanksby et al., 1980; Montpetit et al., 1987; Lynch et al., 1992; Bottoms et al., 2006), blood lactate concentrations (Beaudin et al., 1978), blood pressure response (Blanksby et al., 1980; Brigden et al., 1992), and rectal temperature during squash match play (Blanksby et al., 1980) have been quantified, as well as the metabolic responses (Brady et al., 1989; Lynch et al., 1992) and alterations of neuromuscular function post squash match play (Girard et al., 2008). In elite players, a game analysis quantifying the physiological responses during match play among male players has been undertaken (Girard et al., 2007).

2.4.4.2 Anthropometric Characteristics of Squash Players

Twenty-six studies included an anthropometric characteristic (Table 2), with 12 studies published after the 2009 rule change, as well as 13 including either elite (tier 4) or world class (tier 5) players.

Table 2. Anthropometric Characteristics of Squash Players

Reference (Country)	Participant standard tier	*n* (sex)	Age (years)	Stature (cm)	Body mass (kg)	Body fat (%)	Method of body fat % calculation
Beaudin et al., (1978) (Canada)	2	10 (M)	29.4		77.4	10.3	Not disclosed
Bottoms et al., (2006) (Scotland)	3	16 (M)	31 ± 6	178 ± 2	80.1 ± 12		
Chin et al., (1995) (Hong Kong)	4	10 (Not specified)	20.7 ± 2.5	172 ± 4.3	67.7 ± 6.9	7.4 ± 3.4	Sum of three skinfold thickness
Girard et al., (2005) (France)	3-5	7 (M)	24.9 ± 4.1	177 ± 5.9	72.1 ± 6.1		
Girard et al., (2007) (France)	3-5	7 (M)	24.9 ± 4.1	177 ± 5.9	72.1 ± 6.1		
Girard et al., (2010) (France)	2	10 (M)	32.2 ± 7.3	179 ± 4.5	74.2 ± 5.5		
Gouttebarge et al., (2013) (Netherlands)	4	6 (F)	31 ± 8	170 ± 8.3	59.5 ± 5.7		
James et al., (2019) (Malaysia)	4	6 (M) 2 (F)	20.3 ± 2.1	171 ± 7	64.7 ± 6.3		
James et al., (2021) (Malaysia)	4	11 (M) 4 (F)	M = 20 ± 3 F = 19 ± 1	M = 172 ± 8 F = 158 ± 4	M = 66 ± 5 F = 52 ± 5		
James et al., (2022) (Malaysia)	4	21 (M) 10 (F)	M = 20 ± 4 F = 18 ± 5	M = 173 ± 6 F = 160 ± 4	M = 65 ± 6 F = 55.7 ± 5	M = 9 ± 2 F = 19 ± 5	Sum of 7 Skinfolds thickness
Kingsley et al., (2006) (Wales)	2	8 (M)	16.2 ± 0.8	176 ± 6	61.3 ± 6		

MacGowan et al., (1994) (Ireland)	Not specified	12 (Not specified)	24	178	77.5		
Madjumdar et al., (2009) (India)	2	33 (M) 9 (F)	M = 18 ± 2 F = 16 ± 1	M = 168 ± 6 F = 165 ± 6	M = 57.9 ± 8 F = 61.6 ± 5.3	M = 15.1 ± 7.9 F = 25.9 ± 6.5	Sum of 4 skinfolds thickness
Micklewright and Papapdopoulou (2008) (England)	1-3	11 (M) 10 (F)	M = 20.4 ± 3 F = 22.1 ± 5.7	M = 179 ± 4 F = 166 ± 10	M = 73.8 ± 7.5 F = 60.3 ± 5.5		
Montpetit et al., (1987) (Canada)	1	16 (M)	27 ± 5		70.5 ± 8.2		
Raman et al., (2014) (New Zealand)	2-3	9 (M)	24 ± 8	180 ± 1	76.9 ± 6.8		
Romer et al., (2001) (England)	3	9 (M)	21.3 ± 0.3	177 ± 4	73.3 ± 3.3	15.2 ± 1.4	Sum of 4 skinfolds thickness
Rosimus (2018) (England)	4	1 (F)	19	178	80.9	22	Sum of 8 skinfolds thickness
Turner et al., (2023) (England)	4 & 5	7 (M) 7 (F)	M = 25 ± 5 F = 25 ± 4	M = 184 ± 2 F = 169 ± 7	M = 78.9 ± 7.3 F = 63.7 ± 8.6		
Ventura-Comes (2018) (Spain)	4 (I) and 3 (N)	Tier 4 = 10 (M); 4 (F) Tier 3 = 20 (M); 8 (F)	Tier 4 = 25 ± 6.2 Tier 3 = 35.6 ± 14.2	Tier 4 = 180 ± 1 Tier 3 = 170 ± 1	Tier 4 = 72.1 ± 10.1 Tier 3 = 68.3 ± 11.4		
Ventura-Comes (2019) (Spain)	4 (I) & 3 (N)	Tier 4 = 10 (M); 4 (F) Tier 3 = 20 (M); 8 (F)	Tier 4 = 25 ± 6.2 Tier 3 = 35.6 ± 14.2	Tier 4 = 178 ± 1 Tier 3 = 173 ± 1	Tier 4 = 72.1 ± 10.1 Tier 3 = 68.3 ± 11.4		
Wilkinson et al., (2009) (England)	2	8 (not specified)	30 ± 11	180 ± 4	81.3 ± 10.2		
Wilkinson et al., (2009) (England)	2	8 (not specified)	30 ± 9	177 ± 5	69.4 ± 6.7		
Wilkinson et al., (2009) (England)	2	10 (M)	23 ± 4	180 ± 5	79.7 ± 5.3		

Wilkinson et al., (2010) (England)	2	8 (M)	25 ± 5	177 ± 4	72.8 ± 7.8
Wilkinson et al., (2012) (England)	3-5	Senior = 7 (M); 5 (F) Transitional = 3 (M); 4 (F) TASS = 9 (M); 3 (F)	Senior (M) = 26 ± 2 Senior (F) = 25 ± 2 Transitional (M) = 22 ± 1 Transitional (F) = 21 ± 1 TASS (M) = 20 ± 1 TASS (F) = 20 ± 1		Senior (M) = 79.5 ± 6 Senior (F) = 62.5 ± 3.1 Transitional (M) = 69.9 ± 2.8 Transitional (F) = 58.4 ± 1.7 TASS (M) = 69.5 ± 6.8 TASS (F) = 66.2 ± 9.1

Participant standard tier (McKay et al., 2022) = Tier 0 = sedentary; Tier 1 = Recreationally active; Tier 2 = Trained/Developmental; Tier 3 = Highly Trained/National Level; Tier 4 = Elite/International Level; Tier 5 = World Class; TASS = Talented Athlete Scholarship Scheme

2.4.4.3 Physiological Characteristics of Squash Players

Nineteen studies have quantified a physiological characteristic of squash players (Table 3), with nine of these studies being published after the 2009 rule change, and six of the studies including either elite (tier 4) or world class (tier 5) players.

Table 3. Physiological Characteristics of Squash Players

			Aerobic Characteristics				Anaerobic Characteristics	
Reference (Country)	**Participant standard**	***n* (sex)**	**VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)**	**Maximum heart rate ($beats \cdot min^{-1}$)**	**Lactate Threshold (% VO_{2max})**	**Test method**	**SSCODT (s)**	**SSMST (s)**
Beaudin et al., (1978) (Canada)	2	10 (M)	45	185 ± 13		ICT		
Bottoms et al., (2006) (Scotland)	3	16 (M)	62.9	188 ± 8		ITT		
Chin et al., (1995) (Hong Kong)	3	10 (Not specified)	61.7 ± 3.4	191 ± 7	80.1 ± 4.9	ITT		
Girard et al., (2005) (France)	3-5	7 (M)	ITT = 54.9 ± 2.5 IST = 63.6 ± 3.0	ITT = 195 ± 9 IST = 193 ± 8	ITT = 92 ± 5.6 IST = 90.5 ± 3.5	ITT IST		
Girard et al., (2007) (France)	3-5	7 (M)	63.6 ± 3	193 ± 8		IST		
Gouttebarge et al., (2013) (Netherlands)	4	6 (F)	ITT = 49.1 ± 5.2 IST = 48.9 ± 5.3	ITT = 185 ± 14 IST = 187 ± 16		ITT IST		
James et al., (2019) (Malaysia)	4	6 (M) 2 (F)	ITT = 48.8 ± 5 IST = 46.2 ± 4.1	ITT = 195 ± 7 IST = 200 ± 7		ITT IST		
James et al., (2022) (Malaysia)	4	21 (M) 10 (F)	47.7 ± 5.3			IST	M = 9.21 ± 0.57 F = 10.46 ± 0.68	M = 221.0 ± 11.0 F = 250.6 ± 12.6
Kingsley et al., (2006) (Wales)	2	8 (M)		198 ± 9		IST		

Madjumdar et al., (2009) (India)	2	33 (M) 9 (F)	M = 55.3 ± 4 F = 46.2 ± 4	M = 189 ± 7 F = 190 ± 12	ITT		
Micklewright and Papapdopoulou (2008) (England)	1-3	11 (M) 10 (F)	(M) = 58.2 ± 6.7 (F) = 42.1 ± 6.3		ITT		
Montpetit et al., (1987) (Canada)	1	16 (M)	55 ± 6	186 ± 8			
Romer et al., (2001) (England)	3	9 (M)	61.9 ± 2.1				
Steininger & Wodick (1987) (Germany)	2	7 (M) 6 (F)	58.5 ± 8.1	195 ± 6	ITT		
Wilkinson et al., (2009*a*) (England)	2	8 (not specified)	ITT = 49.6 ± 7.3 IST = 52.2 ± 7.1	ITT = 191 ± 13 IST = 190 ± 7	ITT IST		
Wilkinson et al., (2009*b*) (England)	2	8 (not specified)	50.8 ± 6.5	189 ± 10	IST		
Wilkinson et al., (2009*c*) (England)	2	8 (not specified)				10.90 ± 0.44	
Wilkinson et al., (2010) (England)	2	8 (M)	56.8 ± 5.5		Not specified		232 ± 32
Wilkinson et al., (2012) (England)	3-5	Senior = 7 (M); 5 (F) Transitional = 3 (M); 4 (F) TASS = 9 (M); 3 (F)	Senior (M) = 56.2 ± 2.1 Senior (F) = 49.3 ± 3.2 Transitional (M) = 59.4 ± 2.9 Transitional (F) = 49.3 ± 3.3 TASS (M) = 55.3 ± 5.3 TASS (F) = 48.3 ± 3.8		IRT	Senior (M) = 8.8 ± 0.44 Senior (F) = 9.02 ± 0.32 Transitional (M) = 9.15 ± 0.57 Transitional (F) = 9.34 ± 1.03 TASS (M) = 9.35 ± 0.64 TASS (F) = 10.45 ± 0.55	Senior (M) = 203 ± 9 Senior (F) = 213 ± 6 Transitional (M) = 213 ± 3 Transitional (F) = 235 ± 19 TASS (M) = 219 ± 14 TASS (F) = 245 ± 13

Participant standard tier (McKay et al., 2022) = Tier 0 = Sedentary; Tier 1 = Recreationally active; Tier 2 = Trained/Developmental; Tier 3 = Highly Trained/National Level; Tier 4 = Elite/International Level; Tier 5 = World Class; TASS = Talented Athlete Scholarship Scheme; ICT = Incremental Cycle Test; ITT = Incremental Treadmill Test; IST = Incremental Squash Test; IRT = Incremental Running Test; SSCODT = Squash-Specific Change of Direction Test; SSMST = Squash-Specific Multiple-Sprint Test; TASS = Talented Athlete Scholarship Scheme

2.4.4.4 Squash-Specific Performance Tests

Table 4 outlines the characteristics of the squash-specific performance tests. Ten studies have created squash-specific performance tests to quantify a variety of physiological and technical capabilities such as change of direction speed (Wilkinson et al., 2009*c*), multiple sprint ability (Wilkinson et al., 2010), and players endurance capacity (Steininger & Wodick, 1987; Chin et al., 1995; Girard et al., 2005; Kingsley et al., 2006; Micklewright & Papapdopoulou, 2008; Wilkinson et al., 2009*a*; Gouttebarge et al.,2013; James et al., 2019).

Table 4. Characteristics of Squash-Specific Performance Tests

Reference (Country)	Participant Tier Standard	*n* (sex)	Test Capability Measure	Reliability and Validity Data	Technical Requirement to Test?	Test Overview
Chin et al., (1995) (Hong Kong)	4	10 (not specified)	Endurance capacity	No	Graded squash test whereby player must 'ghost' to an area of the court (when a corresponding lightbulb flashes) and perform a squash swing to hit a static squash ball	The IST's utilisation should be used with caution as it hasn't been validated
Girard et al., (2005) (France)	5	7 (M)	Endurance capacity	IST Intra-rater reliability Time to exhaustion = 1085 ± 267 v 1099 ± 195 s (*p* = >0.05); CV = 0.9% HR_{max} =192.2 ± 4.5 v 187.5 ± 6.1 beats · min^{-1} (*p* = >0.05); CV = 1.8% IST vs. ITT VO_2 = 57.6 ± 3.9 vs. 50.5 ± 4.3 ml·kg·min^{-1} (*p* = <0.01)	Graded incremental test whereby the player must 'ghost' to one of six areas on the court denoted by audio and visual feedback in a random order	Players were able to attain a greater VO_2 in the IST in comparison to the ITT, potentially due to the squash specific technical demands of the squash test making it potentially more appropriate than a non-specific endurance capacity test The test requires squash specific movements such as 'ghosting' over marked areas The random order of the IST may make the test more squash specific as the player is having to react to a stimulus. However, squash players utilise many visual cues to anticipate an opponent's shot and

						therefore fixed visual cues may be negligible The IST was shown to have good intra-rater reliability
Gouttebarge et al., (2013) (Netherlands)	4	6 (F)	Endurance capacity	(IST vs. ITT) VO_{2max} = 48.9 ± 5.3 ml·kg·min^{-1} vs. 49.1 ± 5.2 ml·kg·min^{-1}; r = 0.9 (p = <0.05) HR_{max} = 187 ± 16 beats·min^{-1} vs. 185 ± 14 beats·min^{-1}; r = 0.99 (p = <0.01)	Graded incremental test whereby the player must 'ghost' to one of six areas on the court denoted by audio feedback in a fixed order	The IST is shown to have a good level of validity in comparison to ITT The test requires squash specific movements such as 'ghosting' over marked areas
James et al., (2019) (Malaysia)	4	6 (M) 2 (F)	Endurance capacity	IST vs. ITT VO_2 = 46.2 ± 4.1 ml·kg·min^{-1} vs. 48.8 ± 5 ml·kg·min^{-1} Mean bias = 2.5 ml·kg·min^{-1} TEE = 3.3 ml·kg·min^{-1} TEE (CV%) = 7 LOA = -3.5:8.6 ml·kg·min^{-1} r = 0.79 d = 0.56 IST Intra-rater reliability VO_2 = 47.7 ± 5.4 ml·kg·min^{-1} vs. 46.2 ± 6.8 ml·kg·min^{-1} Mean bias = 1 ml·kg·min^{-1} TEE = 1.5 ml·kg·min^{-1} TEE (CV%) = 3.2 LOA = -3.2:5.1 ml·kg·min^{-1} r = 0.95 d = 0.25	Graded incremental test whereby the player must move to one of six areas on the court denoted by audio feedback in a fixed order	The IST is a modification of Gouttebarge et al., (2013). Squash-specific 'ghosting' and movements (e.g. running backwards to the centre of the court) were removed from the IST as well as increasing shuttle distances by ~10% to account for this The IST good intra-rater reliability and good agreement between the IST and ITT in performance and physiological markers. The IST is therefore an appropriate tool to determine squash-specific endurance capacity
Kingsley et al., (2006) (Wales)	2	8 (M)	Endurance capacity	No	Graded incremental test whereby the player must ghost to one of eight areas on the court denoted by audio feedback in a fixed order	The IST's utilisation should be used with caution as it hasn't been validated

Micklewright & Papapdopoulou (2008) (England)	1-3	11 (M) 10 (F)	Endurance capacity	IST validity with ITT *r* = 0.92 (*p* <0.001) IST Intra-rater reliability Time = 569 ± 139 s vs. 478 ± 107 s; *r* = 0.99 (*p* = 0.001) CV = 2.7% LOA = 2.7-3.9	Graded incremental test whereby the player must run towards and place a foot in one of four areas (front right, front left, back right, back left) on the court denoted by audio feedback in a random order. Players were required to hold a racket to increase specificity	IST had good validity in comparison to ITT IST had good intra-rater reliability Caution to be applied as IST did not directly measure VO_2 with a regression analysis being used to calculate this May not be specific to elite squash players as the IST was validated in novice to national level players
Steininger & Wodick, (1987) (Germany)	2	7 (M) 6 (F)	Endurance capacity	No	Graded squash test whereby player must ghost to are of the court (when corresponding lightbulb flashes) and perform a squash swing to hit a static squash ball	The IST's utilisation should be used with caution as it hasn't been validated
Wilkinson et al., (2009*a*); Wilkinson et al., (2009*b*) (England)	2	8 (not specified)	Endurance capacity	IST validity vs. ITT RER = 1.23 ± 0.8 vs. 1.31 ± 0.1 (*p* = 0.15); post-test L^{+} = 9.0 ± 1.3 $mmol \cdot L^{-1}$ vs. 9.8 ± 2.4 $mmol \cdot L^{-1}$ (*p* = 0.25); final VO_2 increase = 1.02 ± 0.8 $ml \cdot kg \cdot min^{-1}$ vs. 0.71 ± 0.7 $ml \cdot kg \cdot min^{-1}$ (*p* = 0.43) IST Intra-rater reliability	Graded incremental test whereby the player must ghost to one of six areas on the court denoted by audio feedback in a random order	IST had good validity in comparison to ITT IST had good intra-rater reliability The random order of the IST makes it more squash specific as the player is having to react to a stimulus May not be specific to elite squash players as the IST was validated in recreational level players

				Time = 692 ± 148 vs. 715 ± 168 s; LOA = 14 ± 62 s; TE = 27 ± 4 % VO_{2max} = 50.8 ± 6.5 ml·kg·min^{-1} vs. 51.2 ± 6.9 ml·kg·min^{-1}; LOA = 0.2 ± 5.1 ml·kg·min^{-1}; TE = 2.4 ± 4.7 %		
Wilkinson et al., (2009*c*) (England)	2	8 (not specified)	Change of direction speed	SSCODT Intra-rater reliability TEM = 0.13 s CI = 0.09 s – 0.21 s Correlations between SSCODT and IAR $r = 0.77$, $p < .01$	Time trial test whereby player has to perform lateral movements over short distances to mimic the squash-specific movement patterns	SSCODT had good intra-rater reliability and correlated with IAR SSCODT test discriminated between squash and non-squash players suggesting its squash-specific nature May not be specific to elite squash players as the SSCODT was validated in recreational level players
Wilkinson et al., (2010) (England)	2	8 (M)	Multiple sprint ability	TEM = 6 s CI = 4 – 13 s ICC r = 0.97	Time trial test whereby player has to perform lateral movements over short distances to mimic the squash-specific movement patterns	SSMST had good intra-rater reliability and correlated with Bakers Test SSMST test discriminated between squash and non-squash players suggesting its squash-specific nature May not be specific to elite squash players as the SSMST was validated in recreational level players

Standard tier (McKay et al., 2022) = Tier 0 = sedentary; Tier 1 = Recreationally active; Tier 2 = Trained/developmental; Tier 3 = Highly trained/national level; Tier 4 = Elite/international level; Tier 5 = World class; 'Ghost' or 'ghosting' = Technical squash term whereby player performs a squash swimming shot without hitting a ball; HR_{max} = Heart rate maximum; VO_{2max} = Maximal rate of oxygen consumption; ITT = Incremental treadmill test; IST = Incremental squash test; VO_2 = rate of oxygen consumption; RER = Respiratory exchange ratio; LA^+ = lactate concentration; LOA = Limits of agreement; TEM = Technical error of measurement; TEE = Typical error of the estimate; TEE CV% = Typical error of the estimated expressed as coefficient of variation; SSCODT = Squash-specific change of direction test; IAR = Illinois agility run; CI = Confidence interval; ICC = Intraclass correlation coefficient; SSMST = Squash-specific multiple sprint test

2.4.4.5 Training Demands of Squash

Two studies have quantified the training demands of squash players. Research has quantified the training intensities and training loads of elite squash players during a 2-week in-season microcycle (James et al., 2021*a*) and investigated the relationships between training load approaches in elite squash players, during a 2-week microcycle (James et al., 2021*b*). Table 4 conveys the training loads of different squash sessions as reported by James et al., (2021*a*).

2.4.4.6 Nutritional Requirements of Squash

Four studies have measured a nutritional requirement of squash. Research has quantified the energy expenditure and respiratory exchange ratio of elite match play in male players (Girard et al., 2007), whether a high carbohydrate diet prior to a simulated squash match altered physical performance (Raman et al., 2014), the effect of a nutritional intervention on body composition, vitamin D status and physical performance in an elite female player (Rosimus, 2018), and the dietary habits of national and international squash players via a validated food frequency questionnaire (Ventura-Comes et al., 2019).

2.4.4.7 Hydration Demands of Squash

Two studies have quantified a hydration demand of squash. Previous research has quantified the of several fluid replacement strategies post-match play on metabolic responses (Macgowan et al., 1994) and the fluid balance, sweat [Na^+] and hydration practices of elite players during a training session (Turner et al., 2023).

2.4.4.8 Nutrition Knowledge of Squash Players

One study has quantified the nutrition knowledge of squash players, with Turner et al., (2021) quantifying the nutrition knowledge of elite players via the Nutrition for Sport Knowledge Questionnaire (Trakman et al., 2017; Trakman et al., 2019).

2.4.4.9 Nutritional Supplements for Squash

Three studies have quantified a nutritional supplement for squash. Research has quantified the effects of a carbohydrate containing fluid on squash-specific skill maintenance (Bottoms et al., 2006), the results of creatine monohydrate supplementation on squash-specific performance (Romer et al., 2001), the supplementation consumption of international level Spanish squash players (Ventura-Comes et al., 2018), and the supplementation knowledge of elite squash players (Turner et al., 2021).

2.4.5 Discussion

The aim of this review was to evaluate the current physiological and nutritional literature regarding squash to guide practitioners, coaches, and players on how best to interpret the contemporary data, while identifying gaps in the literature to guide researchers on the future directions within squash. To our knowledge, this is the first systematic review to examine the physiological and nutritional literature within squash.

The main findings were (1) there are 35 studies which met the inclusion criteria across a diversity of topics such as the physiological demands of squash, anthropometric characteristics of squash players, the physiological characteristics of squash players, squash-specific performance tests, the training demands of squash, the nutritional requirements of squash, the hydration demands of squash, the nutrition knowledge of squash players, and nutritional supplements for squash players; (2) many of the studies conducted in squash have poor (10) or fair (19) methodological quality, with only four conveying good and two conveying excellent methodological quality. This is due to many of the studies conducted in squash being observational in design (32), rather than rather than double blinded crossover design studies; (3) only 14/35 studies were conducted using elite or world class players; (4) 17/35 studies reviewed are published during or after the 2009 rule change. Consequently, this section will critically appraise the contemporary physiological and nutritional literature within squash.

2.4.5.1 Physiological Demands of Squash

Girard et al., (2007) quantified the physiological responses during match play in elite male squash players. They reported a mean VO_2 of 54.4 ± 4.8 $ml \cdot kg^{-1} \cdot min^{-1}$ or 92 ± 3 % of VO_{2max} and mean heart rate of 177 ± 10 $beats \cdot min^{-1}$ or 92 ± 3% HR_{max} during match play. They also reported a mean minute ventilation (VE) of 102.6 ± 12.1 $L \cdot min^{-1}$, a breathing frequency of 47.9 ± 4.8 $breaths \cdot min^{-1}$ and mean blood lactate value of 8.3 ± 3.4 $mmol \cdot L^{-1}$. Players spent 24 ± 9% and 69 ± 18% above >90% of their VO_{2max} and HR_{max} respectively, while spending 14 ± 23% and 32 ± 25% above >95% of their VO_{2max} and heart rate maximum respectively. This data conveys that a high demand is placed on aerobic metabolism with some contribution from anaerobic glycolysis during match play, as exhibited through high blood lactate concentrations, an oxygen uptake response near VO_{2max}, and heart rate response near HR_{max}.

Much of the literature conducted on the physiological demands of squash match play is not relevant to elite players as it has been undertaken in junior (Majumdar et al., 2009), or recreational players (Blanksby et al., 1973; Beaudin et al., 1978; Blanksby et al., 1980; Montpetit et al., 1987; Brady et al., 1989; Lynch et al., 1992; Girard et al., 2010). For example, Montpetit et al., (1987) reported a mean heart rate of 147 ± 18 beats $\cdot min^{-1}$ (72 ± 13% heart rate maximum) during match play, considerably less than Girard et al., (2007). This may be due to the disparity in playing levels between the players, and inability for recreational athletes to maintain high workloads for extended periods of time due to a lower lactate threshold (Joyner & Coyle, 2008).

Murray et al., (2016) reported that the rule changes in 2009 have altered the physical demands of elite squash. Consequently, players, coaches and conditioning coaches should interpret the data with caution as it may be outdated due to rule changes. This rule change may affect the physiological demands of match play and therefore practitioners should consider this when proposing training prescription.

Future research should aim to quantify the physiological responses during match play in elite players with the altered rule changes to determine whether rule changes have affected the physiological responses during match play. Girard et al., (2007) only quantified the physiological responses of elite male players, and the physiological responses during match play of elite female players have never been quantified. Therefore, future research should also quantify the physiological responses during match play of elite female players to compare differences between male players and develop exercise prescription guidance specific to elite female players.

Future research should also aim to quantify muscle and blood metabolites in elite squash match play among male and female players. Squash matches can last >90 minutes, with high intensity intermittent exercise lasting around this duration being shown to completely deplete muscle glycogen stores in individual muscle fibers, reducing high intensity performance (Krustrup et al., 2006). Quantifying the muscle and blood metabolites in elite squash match play among male and female players would enable the ability to make specific nutritional recommendations based on the substrate utilisation during match play. Future research should also aim to quantify the locomotor demands of elite squash, such as the total distance covered and amount of high intensity movements, accelerations and decelerations. This data would help provide information on how to better condition players to the demands of elite squash.

Professional squash matches are played in a variety of different environmental conditions such as hot and humid environments as well as at altitude (Professional Squash Association, 2024). These environmental conditions may alter the physiological demands and ball velocity and therefore future research should aim to quantify whether any differences are experienced in a variety of different environmental conditions.

2.4.5.2 Anthropometrical Characteristics of Squash Players

Anthropometrical characteristics (stature, body mass, body fat %) can quantify an individual's body composition (Wang et al., 2001). Body composition is a key performance variable (Ackland et al., 2012), and low amounts of fat mass alongside an appropriate amount of lean mass may be beneficial for players to execute squash-specific movements, and move efficiently around the court (Cronin et al., 2003).

There appears to be diversity in the anthropometrical characteristics of elite squash players. Turner et al., (2023) quantified the stature and body mass of elite or world class English players, reporting a mean stature of 184 ± 2 cm and body mass of 78.9 ± 7.3 kg among male players, and a mean stature of 169 ± 7 cm and body mass of 63.7 ± 8.6 kg among female players. In comparison, elite Malaysian squash players were shown to be smaller and lighter, with James et al., (2022) reporting a mean stature and body mass of 173 ± 6 cm and 65 ± 6 kg among male players, and a mean stature and body mass of 160 ± 4 cm and 55.7 ± 5 kg among female players. Players from different regions may have physical differences due to their geographic ancestry which could influence performance, in combination with differences in playing styles and/or playing standard.

Quantifying the stature and body mass of an individual only portrays a small aspect of body composition in comparison to multi component models (Wang et al., 2001). To date, six studies have quantified the body fat % of squash players. Elite players appear to have a lower body fat % than sub-elite players. Chin et al., (1995) reported elite Hong Kong players to have a body fat % of 7.4 ± 3.4 %, in comparison to Romer et al., (2001) who found sub-elite players to have a body fat % of 15.2 ± 1.4 %.
Elite female squash players have been shown to have a greater body fat percentage (19 ± 5 %) in comparison to elite male players (9 ± 2 %) (James et al., 2022). This is consistent with epidemiological studies which have shown the female sex to have to have a greater amount of adipose tissue, equating to approximately 10 % more body fat than male counterparts (Karastergiou et al., 2012), due to the female sex hormone oestrogen (Okura et al., 2003).

All six studies which provided a methodology to how they have quantified body fat % (see Table 2) have utilised the skinfolds thickness method (Kasper et al., 2021). However, there were differences in the number of sites taken for skinfold thickness, and therefore caution should be applied when comparing between studies (Martin et al., 1985). Another limitation of skinfold thickness is that by converting the data into a doubly indirect method such as a body fat %, it adds a layer of complexity (Kasper et al., 2021). There are over 100 formulae for converting sum of skinfold thickness to body fat % (Kasper et al., 2021), which are often created in varying populations and protocols (Kasper et al., 2021). Therefore, it is hard to make comparisons between studies, as no study presented the formulae utilised to convert their data.

Future research should aim to quantify the anthropometrical characteristics of elite male and female squash players, among a variety of different ethnicities. This would quantify the body composition of elite squash players and whether there are any differences between sexes and ethnicities. If body fat % is of interest, then Dual-Energy X-Ray Absorptiometry (DXA) is a valid and reliable tool (Nana et al., 2015; Kasper et al., 2021), provided that the methodology follows a standardised protocol (Nana et al., 2016). If sum of eight skinfolds is of interest, then skinfolds callipers are a valid and reliable tool (Kasper et al., 2021).

2.4.5.3 Physiological Characteristics of Squash Players

Elite squash matches are variable in length and are reported to have a mean match duration of 59 ± 20 minutes, ranging from 39 minutes to 89 minutes (Jones et al., 2018). However, anecdotally, matches can be considerably shorter (<25 minutes) and longer (>100 minutes) depending on the playing conditions, playing styles of the players, and tactics employed. Elite squash players are reported to have a VO_{2max} ranging from 46.2 $ml·kg^{-1}·min^{-1}$ to 63.6 $ml·kg^{-1}·min^{-1}$ (Table 3). Some of the data presented should be interpreted with caution however, as some studies did not differentiate data between sexes (Chin et al., 1995; James et al., 2019; James et al., 2022), with Wilkinson et al., (2012) reporting that elite male players outperformed elite female players in all physiological characteristics. Research has shown that VO_{2max} is not correlated with world ranking (Chin et al., 1995; Wilkinson et al., 2012; James et al., 2022). Consequently, elite squash players may be required to have a developed aerobic system at a threshold level to ensure that their performance isn't inhibited, enabling them to sustain long match durations (Jones et al., 2018), and optimise recovery from one rally to the next (Tomlin & Wegner, 2001). However, this isn't a differential physiological characteristic at elite level. Squash is a high intensity intermittent sport whereby elite male match play is performed at a mean VO_2 of 54.4 ± 4.8 $ml·kg^{-1}·min^{-1}$ or 92 ± 3 % of VO_{2max}. Consequently, a high lactate threshold is required to ensure players can sustain high intensity exercise for a continued period (Girard et al., 2007). Girard et al., (2005) reported elite male players to have a lactate threshold of 92 ± 5.6 % of VO_{2max}. This is greater than data previously conveyed by Chin et al., (1995) who reported a lactate threshold of 80.1 ± 4.9 % among players. This ~10 % difference in lactate threshold could be due to differences in playing ability (tier 3 vs tier 4-5) or an indication of how squash has become more glycolytic and requires players to perform at an intensity closer to their VO_{2max} for longer periods of match play.

More recently, high intensity and high intensity intermittent characteristics have also been quantified among elite players to mimic the demands of match play (Girard et al., 2007). Wilkinson et al., (2012) reported that among male and female players, squash-specific multiple-sprint ability (SSMST), fastest sprint from the SSMST and change of direction speed correlated with a players world ranking. Consequently, the ability to produce high amounts of force and translate this into squash specific movements for extended periods of time is a key performance indicator for elite male and female squash players (Wilkinson et al., 2012).

Future research should aim to quantify the physiological characteristics of elite squash players. It is difficult to compare between studies as they have been performed on players of differing standard and a variety of tests (e.g. incremental treadmill test or incremental squash test) to quantify variables. Data collected is also based on relatively sporadic samples, often with the same players from a select group of countries (e.g. England, Malaysia). Therefore, future research should also aim to quantify the physiological characteristics from a variety of different samples of players. This would enable a richer analysis of the physiological characteristics of elite players and determine how different playing standards and styles influence the physiological characteristics of players. Murray et al., (2016) reported that the intensity of match play is increasing, however, much of the data collected is prior to the 2009 rule change (e.g. lactate threshold; Girard et al., 2005) and key data is missing such as the lactate threshold of elite female players.

2.4.5.4 Squash-Specific Performance Tests

Sport-specific tests increase construct validity (Currell & Jeukendrup, 2008) and as a result, research has focused on creating squash-specific performance tests to quantify a variety of squash-specific physiological and technical capabilities. Three studies creating a squash-specific endurance test did not report any data regarding the validity, reliability, and/or sensitivity of the performance tests (Steininger & Wodick, 1987; Chin et al., 1995; Kingsley et al., 2006), and as a result, their utilisation should be used with caution. All studies which have reported validity, reliability and/or sensitivity data reported high sensitivity and reproducibility (Girard et al., 2005; Micklewright & Papapdopoulou, 2008; Wilkinson et al., 2009*a*; Wilkinson et al., 2009*c*, Wilkinson et al., 2010; Gouttebarge et al., 2013; James et al., 2019).

Wilkinson et al., (2009*c*) developed a squash-specific change of direction speed test (SSCODT) to quantify players change of direction speed. The SSCODT included no straight-line sprints but rather a variety of lateral movements over short distances to mimic the squash-specific movement patterns exhibited in squash (Vučković et al., 2003) and therefore may be more appropriate to utilise in a testing battery than a non-specific field-based change of direction test, such as the Illinois agility run (IAR). The study was performed by recreational male squash players and to determine its ability to screen elite male and female squash players change of direction speed, future research should aim to quantify whether similar results are observed in elite male and female players.

Wilkinson et al., (2010) devised a squash-specific multiple sprint test (SSMST) to quantify players repeated sprint ability. The SSMST mimicked the squash-specific movement patterns exhibited in squash (Vučković et al., 2003) with no straight lines, consisting of short, dynamic lateral movements and therefore may be more appropriate than a non-specific field-based test such as the Baker's sprint test. The SSMST produced higher physiological responses in comparison to the Baker's sprint test, however, blood lactate concentrations are lower than exhibited during match play (Girard et al., 2007 = 8.3 ± 3.4 mmol·L^{-1}). This could be due to Wilkinson et al., (2010) testing recreational squash players. As previously discussed (see section 4.1), recreational players may not be able to reach the high intensities observed in elite squash. Consequently, future research should aim to quantify whether similar results are observed in an elite male and female population.

Five squash-specific endurance tests have been developed and validated (Girard et al., 2005; Micklewright & Papapdopoulou, 2008; Wilkinson et al., 2009*a*; Gouttebarge et al., 2013; James et al., 2019). Three squash-specific endurance tests were conducted on elite or world class players and therefore may be more valid to use with an elite population (Girard et al., 2005; Gouttebarge et al., 2013; James et al., 2019). Girard et al., (2005) utilised audio and visual feedback, displaying where to move throughout the test. This is in contrast to other tests, which have used just audio feedback (Gouttebarge et al., 2013; James et al., 2019). While squash players respond to both audio and visual cues during match play, it could be debated that responding to visual cues in a fixed position during an incremental test is questionable and doesn't enhance the squash-specificity of the test (Micklewright & Papapdopoulou, 2008). Rather, during match play, players respond to cues such as body positions of the opponent, and the direction of travel of the ball. The squash-specific endurance test designed by Girard et al., (2005) also requires specialist computer software to project images onto a wall using a projector, making it difficult for the administration of the test in the field as it requires specialist equipment (James et al., 2019). There are also some variations in the requirement for 'ghosting' strokes (Technical squash term whereby player performs a squash swimming shot without hitting a ball) and squash-specific movements between the three tests. Girard et al., (2005) and Gouttebarge et al., (2013) included squash-specific 'ghosting' strokes in their tests, whereas James et al., (2019) did not. James et al., (2019) collected pilot data prior to data collection and found squash-specific 'ghosting' strokes were shown to exhibit high levels of variation at maximal stages, while limiting some players ability to achieve a maximal effort due to possessing a slower stroke speed (James et al., 2019). Girard et al., (2005) and Gouttebarge et al., (2013) also required players to complete squash-specific movements throughout the test, similar to how players would move during match play (such as backward running when moving back to the centre of the court). James et al., (2019) excluded the requirement for squash-specific movements, as from the pilot data collected, players were not able to maintain the intensity of the later test stages when performing squash-specific movements, despite not reaching maximal fatigue. This is most likely due to the reductions in speed when running backwards.

Consequently, James et al., (2019) squash-specific endurance test may be the most appropriate squash-specific endurance to quantify endurance capabilities of elite squash players. The test is validated in elite players, is easy to utilise in the field, and has undergone rigorous pilot testing to ensure that a true VO_{2max} value has been achieved, rather than due to squash-specific movements confounding the result.

2.4.5.5 Training Demands of Squash

James et al., (2021*a*) reported that group sessions were the longest in duration (79 ± 12 min) in comparison to feeding (55 ± 15 min), ghosting (35 ± 15 min), match play (46 ± 17 min), and conditioning sessions (37 ± 9 min) throughout a two-week microcycle in elite squash players. Group sessions were shown to elicit the greatest sRPE (5793 ± 1477 a.u.) and most high intensity movements (189 ± 88 >3.5 $m \cdot s^{-1}$), playing a key role in preparing players for competition due to their likely effect on aerobic fitness (James et al., 2021*a*). Group sessions may have elicited the greatest sRPE and most high intensity movements due to the duration of group sessions in comparison to other sessions, enabling for more load to and movements to occur. For example, match play sessions were shown to have a greater mean heart rate (Match play = 81 ± 6 % HR_{max} vs group = 76 ± 5 % HR_{max}) and greater time > 90% heart rate maximum (Match play = 10 ± 10 min vs group = 7 ± 10 min) but were shorter in duration. To this extent, conditioning sessions were shown to have the greatest RPE (77 ± 16 a.u.) and player load (519 ± 153 a.u.) but were only 37 ± 9 minutes in duration. James et al., (2021*b*) reported that there was minimal agreement between internal and external load metrics during the two-week microcycle and collecting the data in isolation (i.e. just internal) may underestimate or overestimate the amount of stress a player is feeling. Consequently, it is important to collect a variety of internal and external load metrics to determine the amount of stress a player is undergoing throughout a microcycle, rather than in isolation. Different cohorts of elite squash players may also train differently (e.g. greater duration in match play sessions), altering the training load. Future research should aim to quantify the training load of various cohorts of elite squash players throughout a microcycle to compare differences between them.

2.4.5.6 Competition Demands of Squash

No current research has quantified the competition demands of squash. Elite squash matches during competition are played in proximity (~8-48 hours in-between matches), with players required to potentially compete in 1-6 matches in as many days during PSA World Series events. Research in tennis (Ellis et al., 2021; Ellis et al., 2023*a*; Ellis et al., 2023*b*), soccer (Anderson et al., 2019; Anderson et al., 2019; Brinkmans et al., 2019; Morehen et al., 2022), and rugby league (Morehen et al., 2016) has quantified the player load during competition. Future research should aim to quantify

the cumulative player load during elite squash competition to determine the internal and external load players experience.
Squash match play has been shown to alter neuromuscular function in recreational players through the development of peripheral fatigue (Girard et al., 2010), with peripheral fatigue potentially reducing physical performance in subsequent matches (Kirkendall, 1990). Therefore, future research should aim to quantify whether there are any alterations in neuromuscular function after elite squash match play in male and female players. Peripheral fatigue may not be as prevalent post-match play in elite players, due to the training players undertake to condition their body to the rigours of competition (Girard et al., 2010; Gibson et al., 2019; James et al., 2021*a*). Research in soccer has also quantified the muscle damage, inflammatory, immune and performance responses following matches in proximity (Mohr et al., 2016) to create specific physiological (Nédélec et al., 2013) and nutritional recovery strategies (Ranchordas et al., 2017). Future research should aim to do the same in elite male and female squash players during competition so specific physiological and nutritional recovery strategies can be devised and determine whether logistical changes, such as the duration of time in-between matches needs to be altered by the World Squash Federation and Professional Squash Association to ensure high quality matches throughout competitions.

2.4.5.7 Nutritional Requirements of Squash

Girard et al., (2007) quantified the energy requirements during match play in elite male squash players. They reported a mean energy expenditure of 4,933 ± 620 $kJ \cdot h^{-1}$ and RER of 0.94 ± 0.06. This is considerably more than recreational squash players who exhibited an energy expenditure of 2,850 $kJ \cdot h^{-1}$ during match play (Montpetit et al., 1987). As previously discussed (see section 4.1), recreational players may not be able to reach the high intensities observed in elite squash. Similarly, elite male tennis players were shown to expend significantly less (2,718 ± 438 $kJ \cdot h^{-1}$) during match play (Ranchordas et al., 2013). This could be due to the increased intensity during match play in squash and differences in total playing time between squash (70 ± 5 %; Girard et al., 2007) and tennis (20-30 %; Smekal et al., 2001). Consequently, nutritional strategies should be individualised to the demands of squash, as generic nutritional guidelines may not be relevant due to differences in energy requirements.

Future research should aim to quantify the energy expenditures of elite squash players throughout a training microcycle to create specific nutritional guidelines during training, as had been done in other racket (Ranchordas et al., 2013) and high intensity intermittent sports (Collins et al., 2021). As previously highlighted by Turner et al., (2021), players dietary intakes should also be reported alongside energy expenditure to quantify whether players current dietary habits are optimal. This has been previously conducted in other racket (Sagayama et al., 2017; Ellis et al., 2021; Ellis et al., 2023*a*; Ellis et al., 2023*b*) and high intensity intermittent sports (Ebine et al., 2002; Silva et al., 2013;

Morehen et al., 2016; Costello et al., 2018; Smith et al., 2018; Anderson et al., 2019; Anderson et al., 2019; Brinkmans et al., 2019; Costello et al., 2019; Hannon et al., 2021; Morehen et al., 2022; Dasa et al., 2023). Similarly, the energy expenditures during a competition period should be quantified to create specific nutritional guidelines during competition (Ranchordas et al., 2013; Collins et al., 2021).

Raman et al., (2014) explored whether a high carbohydrate diet prior to a simulated squash match altered physical performance in recreational to national standard players. Players consumed either a high carbohydrate diet (H-CHO) (11.1 $g \cdot kg^{-1}$) or a calorie matched low carbohydrate diet (L-CHO) (2.1 $g \cdot kg^{-1}$) 48 hours prior to a simulated squash match. They reported that players completed five games of a simulated match in a significantly faster time (2340 ± 189 s) in the H-CHO condition in comparison to the L-CHO condition (2416 ± 128 s). Respiratory exchange ratio (0.80 vs. 0.76), blood glucose and blood lactate concentrations were also significantly higher in the H-CHO condition in comparison to the L-CHO condition. Consequently, consuming a high carbohydrate diet prior to may increase physical performance during squash due to increased carbohydrate oxidation rates and higher blood glucose concentrations.

Rosimus (2018) quantified the effects of a 6-week nutritional intervention on body composition, vitamin D status and physical performance on an elite female squash player. Preintervention energy intake was estimate at 2,511 ± 568 $Kcal \cdot d^{-1}$ with carbohydrate, protein and fat intake being approximately 365 ± 121 $g \cdot d^{-1}$, 114 ± 29.5 $g \cdot d^{-1}$, and 86 ± 7.4 $g \cdot d^{-1}$ respectively. During the intervention, dietary assessment revealed a daily energy intake of 1,501 ± 150 $Kcal \cdot d^{-1}$, with a carbohydrate, protein, and fat intake of approximately 169 ± 35 $g \cdot d^{-1}$, 82 ± 40.9 $g \cdot d^{-1}$, and 55 ± 23.2 $g \cdot d^{-1}$ respectively. The intervention targeted a structured energy restriction of 500-700 $Kcal \cdot d^{-1}$ so may not be representative of a players optimal energy intake to fuel and recover appropriately from training session to session. The player achieved a body mass loss of 2.9 kg (80.9 kg to 78 kg) during the intervention and saw a reduction in sum of eight skinfolds (127 mm to 107 mm) and increase in lean mass (61.8 kg to 63.5 kg). The players squash-specific physiological characteristics improved with an increase in reactive strength index (3.10 to 3.25) and a reduction in the time to complete both an on-court speed (9.15 s to 8.62 s) and repeated on-court speed tests (206 s to 194 s). Consequently, the study highlights that a gradual energy deficit can optimise body composition and physical performance in an elite squash player.

Ventura-Comes et al., (2019) reported the dietary habits of national level Spanish squash players. They reported that players may under consume carbohydrate rich foods such as bread, pasta, rice, and potatoes in comparison to contemporary guidelines (Burke et al., 2011). The data collected by Ventura-Comes (2019) was quantified via a food frequency questionnaire and as previously suggested by Turner et al., (2021), this should be interpreted with caution as food frequency questionnaires have been conveyed to display poor validity and reliability (Thompson & Subar, 2017) in comparison to other methods such as 24-h dietary recall, snap 'N' send method and weighed food diaries (Bingham et al., 1994; Costello et al., 2017). Contemporary carbohydrate guidelines may not be appropriate for elite squash players and quantifying the energy expenditures of elite squash players throughout a training microcycle would help determine whether they are appropriate. Players dietary habits should also be quantified using more valid and reliable techniques such as weighed food diaries or snap 'N' send (Bingham et al., 1994; Costello et al., 2017). This would also determine the macronutrient and micronutrient intake of elite squash players, which to date has not been quantified.

2.4.5.8 Hydration Demands of Squash

MacGowan et al., (1994) quantified the effects of consuming either: no fluid replacement; 500 ml of water; an electrolyte solution; a glucose solution; or a glucose/electrolyte 'sports' drink post-match play among recreational players on metabolic responses such as lactate, free fatty acids, glucose, potassium, sodium, and plasma osmolality. They found that the glucose containing drinks significantly elevated blood glucose levels but did not influence potassium or sodium levels, stating that there is no benefit to consuming a fluid replacement other than water during short intense sports such as squash. A key limitation of this study is that they did not report the fluid balance during the squash match, or whether players consumed any electrolytes during the squash match. Sweat rates and sweat [Na^+] are highly individualised (Barnes et al., 2019) and all the players recorded may have had low sweat [Na^+] rates, with this not being quantified.

Turner et al., (2023) quantified the fluid balance and sweat [Na^+] of elite squash players during a training session, alongside their hydration practices. They found that elite squash players had a mean fluid balance of −1.22 ± 1.22 % throughout the session, exhibiting a mean sweat rate of 1.11 ± 0.56 $L \cdot h^{-1}$ and a mean sweat [Na^+] of 46 ± 12 $mmol \cdot L^{-1}$. Male players were shown to have significantly higher sweat rates than female players, hypothesised to be due to the female sex hormones estrogen and progesterone (Giersch et al., 2020; Rodriguez-Giustiniani et al., 2022). Seven players had 21 hrs 30 mins until their next training session whereas the other seven players had 2 hrs 30 mins until their next training session. There was a significant difference in fluid and sodium intake post session between the two groups, with the players who had 21 hrs 30 mins until their next training session able to optimally rehydrate in comparison to players who had 2 hrs 30 mins until their next training session, who were not able to. Turner et al., (2023) concluded that sweat rates and sweat [Na^+] are highly variable and there is a need to individualise players hydration strategy alongside training prescription to ensure players optimally rehydrate. As suggested by Turner et al., (2023), future research should aim to quantify the sweat rates of elite squash players during hot conditions to compare differences to moderate environmental conditions (temperature = 17–24 $^{\circ}$C; humidity 40–

60%). Elite players compete in hot environments such as the 2022 Professional Squash Association World Championships, which was held outdoors in Cairo, Egypt (Professional Squash Association, 2023). This would help players determine whether differing hydration strategies are appropriate when competing in hot and humid environmental conditions. Future research should also aim to quantify the sweat rates of players during match play. Research has shown that elite squash match play may be performed at a higher intensity to training sessions (Girard et al., 2007; Gibson et al., 2019; James et al., 2021), with exercise intensity being an intraindividual factor in individuals sweat rates (Baker, 2017). Previous research has quantified the thermoregulatory responses of recreational players, whereby players core increased from 37 °C to 39 °C during 39 minutes of match play (Blanksby et al., 1980). Due to the hot and humid environmental conditions elite squash players compete in, future research should also aim to quantify the thermoregulatory responses of elite squash such as core temperature. Anecdotally, many elite squash matches at the 2022 Professional Squash Association World Championships in Cairo whereby temperature exceeded 30 °C lasted a longer than 60 minutes, and this may put athletes at risk of heat stress unless appropriate interventions are applied (Périard et al., 2021). Other sports such as soccer have drinks and cooling breaks, and it may be appropriate for squash to implement strategies such as these if severe thermoregulatory demands are experienced.

2.4.5.9 Nutrition Knowledge of Squash Players

Turner et al., (2021) reported that elite squash players had 'average' nutrition knowledge as defined via the Nutrition for Sport Knowledge Questionnaire [Trakman et al., 2017; Trakman et al., 2019). There were no significant differences in nutrition knowledge between sexes. Age and world ranking were shown to have a weak positive effect on nutrition knowledge. It was reported that older players may have more time to accumulate knowledge and understanding of nutrition, while players who had a higher world ranking may be able to pay for a nutrition consultant or may have an optimised performance due to more appropriate dietary habits due to greater nutrition knowledge (Turner et al., 2021). Players who had a relevant undergraduate degree had better nutrition knowledge than those who had no relevant education, as many may have studied a nutrition module as part of their course (Turner et al., 2021). Players who consulted with a sports nutritionist were shown to have better nutrition knowledge than those who obtained nutrition information from the internet or a sport scientist, with the authors concluding that players should consult with a sports nutritionist to increase their nutrition knowledge (Turner et al., 2021).

Future research should quantify the effectiveness of a nutrition education intervention at increasing the nutrition knowledge of elite squash players (Tam et al., 2019). Future research should also quantify the dietary habits of elite squash players to determine whether a greater nutrition knowledge translates to more optimal dietary habits (Spronk et al., 2014).

2.4.5.10 Nutritional Supplements for Squash Players

Supplements may be beneficial for a squash player to correct nutritional deficiencies, augment training adaptations, and optimise performance during competition (Maughan et al., 2018). Current research within squash regarding supplements has quantified the effects of a carbohydrate containing fluid on squash-specific skill maintenance (Bottoms et al., 2006), the results of creatine monohydrate supplementation on squash-specific performance (Romer et al., 2001), the supplementation consumption of international level Spanish squash players (Ventura-Comes et al., 2018), and the supplementation knowledge of elite squash players (Turner et al., 2021). Turner et al. (2021) reported elite squash players had poor supplementation knowledge via the Nutrition for Sport Knowledge Questionnaire (Trakman et al., 2017; Trakman et al., 2019). Despite this, research suggests that squash players do consume supplements, with Ventura-Comes et al., (2018) reporting 100 % of international level Spanish squash players consumed some form of supplement when surveyed. Players were shown to consume supplements with lower efficacy such as flax seed oil, glutamine, and branch chain amino acids in comparison to ones which have a higher efficacy such as beta-alanine, creatine, and sodium bicarbonate (Maughan et al., 2018).

Bottoms et al., (2006) quantified the effects of a 6.4 % carbohydrate drink solution on skill maintenance, cognitive function, and maximal voluntary contraction fatigue test, pre and post a squash-specific fatigue protocol in recreational squash players. Carbohydrate supplementation during exercise has been reported to delay the onset of fatigue through sparing muscle glycogen stores, prevent hypoglycemia, and reduce the impairment of excitation contraction coupling during exercise (Rollo et al., 2020). They reported that a 6.4 % carbohydrate drink had no significant effect on skill maintenance, although significantly more shots landed in the scoring zone during the skill test. Carbohydrate ingestion also had a significant effect on visual reaction time. Consequently, carbohydrate ingestion may help maintain skill level and reaction times during squash.

Romer et al., (2001) reported that a creatine monohydrate supplementation protocol of x4 servings of 0.075 $g.kg^{-1}$ for x5 days increased squash-specific high intensity intermittent performance. During a squash-specific ghosting protocol, creatine monohydrate supplementation significantly increased mean set sprint time in comparison to a control group (maltodextrin) by 3.2 ± 0.8 % ($p = 0.004$). A potential limitation of the study is that Romer et al., (2001) did not use a validated squash-specific performance test and therefore it is difficult to ascertain whether improvements in mean set sprint time were due to a familiarization effect (Currell & Jeukendrup, 2008).

As previously discussed by Turner et al., (2021), future research should aim to quantify the efficacy of supplements on squash-specific performance to create consensus for an appropriate supplementation protocol for squash players similar to other racket (Ranchrodas et al., 2013) and high intensity intermittent sports (Collins et al., 2021). Beta-alanine, sodium bicarbonate, caffeine, and nitrate supplementation may be beneficial for elite squash players either acutely or chronically throughout training and/or competition (Maughan et al., 2018).

2.4.6 Conclusions

This is the first systematic review to synthesise the physiological and nutritional research conducted in the sport of squash. Current research within squash has focussed on a variety of areas such as the physiological demands of squash to match play, the training load during a two-week microcycle, the sweat [Na^+] rates of elite players, the nutritional knowledge of elite players and the effects of carbohydrate and creatine supplementation on squash-specific performance. Squash is a high intensity intermittent sport which places high demands on aerobic metabolism during match play, as conveyed by performing at a high % of VO_{2max} and HR_{max}. Similarly, elite squash match play places a high nutritional demand on players due to the high energy expenditures experienced during match play. Consequently, generic nutritional guidelines may not be relevant as energy expenditures were shown to differ in comparison to other racket sports.

Many of the studies conducted in squash had poor (10) or fair (19) methodological quality and only 14/35 studies are conducted on elite or world class players. Therefore, it is hard for practitioners and coaches to make accurate recommendations to optimise training, fuelling and recovery as much of the scientific literature is based on recreational players and poor methodology (e.g. unblinded, no control group etc.). Much of the key literature to provide physiological and nutritional recommendations is lacking or out of date (pre 2009 rule change). The 2009 rule change is also reported to have changed the physical demands of the sport (Murray et al., 2016), and to this extent 17/35 studies reviewed are published during or after the 2009 rule change.

The present study proposes many future directions to advance research and evidence-based practice within squash such as quantifying the physiological demands of elite female match play, muscle and blood metabolites during match play and calculating the energy expenditures and dietary intakes of players during a training microcycle and competition period. This research would enable sport-specific recovery and nutritional guidelines to be created such as in other racket sports (Ranchordas et al., 2013) and high intermittent sports (Nédélec et al., 2013; Ranchordas et al., 2017; Collins et al., 2021). This would help guide practitioners, coaches, and players to optimise training, fuelling and recovery which can ultimately improve performance.

3.0: Study Two – Elite Squash Players Nutrition Knowledge and Influencing Factors

3.1 Study Summary and the Golden Thread

After conducting a systematic review on the available physiological and nutritional literature within squash, none of the 'performance problems' outlined by the researcher had been solved. The first performance problem was that England Squash had never had a full-time nutritionist working in the sport, and there seemed to be some ambiguity regarding the impact nutrition can have on performance. The researcher was experiencing players to exhibit high training loads, with the systematic review outlining that squash is a high intensity intermittent sport with players expending 1179 ± 148 $Kcal \cdot h^{-1}$, mean heart rate of 92 ± 3 % heart rate maximum, mean blood lactate concentrations of 8.3 ± 3.4 $mmol \cdot L^{-1}$ and mean respiratory exchange ratio of 0.94 ± 0.04 during simulated match play (Girard et al., 2007). England Squash were going through a 'transitional phase' at an elite level and many of these players had either never had any nutritional support before or this had been limited to a one-off generic presentation at some stage during their junior development. When engaging with players around nutritional support, their knowledge and understanding of nutrition seemed limited. Consequently, a starting point was to quantify the nutritional knowledge of elite squash players as well as the factors which influence players nutritional knowledge. The main aim of this study was to outline whether players required nutritional support to increase their nutrition knowledge and subsequent dietary behaviours to support the general health and physical performance. A greater nutritional knowledge has been shown to lead to superior dietary behaviours (Valliant et al., 2012). As there was no prominent nutrition culture within England Squash, some of the players didn't feel they required nutritional support and felt that their behaviours were optimal. Therefore, quantifying players nutritional knowledge was used as a tool to screen players on who may require nutrition support, while acknowledging that greater nutrition knowledge does not solely translate to more optimal dietary habits (Birkenhead & Slater, 2015).

3.2 Justification of Methodology

3.2.1 Nutrition Knowledge Questionnaires

There are a variety of studies quantifying athletes' nutrition knowledge (Trakman et al., 2016). Many of these studies employ self-developed questionnaires, of which lack appropriate validation (Trakman et al., 2016), or non-specific nutrition knowledge questionnaires such as the general nutrition knowledge questionnaire (Parmenter & Wardle, 1999) which lack validity in an athletic population (Trakman et al., 2016). Valid and reliable questionnaires are assessed for seven components:

1) Face validity (Allen et al., 2023) – Does the questionnaire measure the intended measure

2) Content validity (Haynes et al., 1995) – Does the questionnaire cover the content domain of interest

3) Item discrimination (Panjaitan et al., 2018) – Comparing between two cohorts of individuals to assess the success of the questionnaire

4) Internal consistency reliability (Revicki, 2014) – Do the items in the questionnaire all measure the same concept

5) Construct validity (Colliver et al., 2012) – The extent a questionnaire assesses the concept is it supposed to measure

6) External reliability (Murad et al., 2018) – The extent to which a questionnaire produces similar results in the same conditions at a different time point

7) Item analysis (Ferketich, 1991) – A statistical analysis to test the overall performance of the questionnaire and individual questions to recognise which questions may be too easy or difficult and therefore not appropriate

Trakman et al., (2016) reported that the maximum sports nutrition questionnaire validation score was three out of the seven components. Many of the sport nutrition questionnaires employed in studies also had issues with construct validity as many of the questions asked where based on old nutritional guidelines rather than contemporary guidelines (Trakman et al., 2017). They also have limited cultural applicability and are typically only measured in one cohort of athletes (e.g. track and field). Therefore, this limits the ability of a questionnaire to be utilised across a variety of different sporting context, cultures, and standards of athletes, limiting the comparison between different cohorts (Trakman et al., 2017). At the time of data collection, there were two sport nutrition knowledge questionnaires which had been developed and validated in the literature (Furber et al., 2017; Trakman et al., 2017).

3.2.1.1 The Nutrition Knowledge Questionnaire for Athletes (NKQA)

The Nutrition Knowledge Questionnaire for Athletes (NKQA) (Furber et al., 2017) is an 85-question questionnaire with six sub-sections regarding (1) carbohydrate; (2) protein; (3) fat; (4) general nutrition; (5) fluid; and (6) sports nutrition. The NKQA used five of the recommended validation methods listed above, excluding face validity and item analysis. The NKQA conveyed good item discrimination, content, and construct validity with nutrition trained individuals who were qualified sports nutritionist or undertaking a postgraduate qualification (NUT) scoring significantly higher in comparison to matched educational level, non-nutrition individuals such as professionals or postgraduate students (NONUT) (NUT = 81.4 % vs. NONUT = 49.6 %; $p < 0.05$). The NKQA had good internal consistency reliability with all nutrition subsections exhibiting an Chronbach's α greater than 0.7 ($\alpha > 0.7$). The NKQA also displayed a strong external reliability (r = 0.98; $p < 0.05$). However, the NKQA may have limited cultural applicability due to it only sampling British athletes participating in track and field.

3.2.1.2 The Nutrition for Sport Knowledge Questionnaire (NSKQ)

The Nutrition for Sport Knowledge Questionnaire (NSKQ) (Trakman et al., 2017) is an 87-question questionnaire with six subsections; (1) weight management; (2) macronutrients; (3) micronutrients; (4) sports nutrition; (5) supplements; (6) and alcohol. The NSKQ used all seven of the recommended validation methods, while also utilising classical test theory (Petrillo et al., 2015) and Rasch analysis (Lambert et al., 2013) to develop the questionnaire. Classical test theory is utilised to quantify measurement error and correct observed dependencies between variables such as correlations (Wright, 2015). It assumes that all questions are equal indicators of the intended measure (e.g. sports nutrition knowledge) (Petrillo et al., 2015). Rasch analysis is used to guide the development of surveys and questionnaires (Boone, 2016). It is an analytical model which evaluates questions using probability estimates (Boone, 2016). It aims to provide a more precise calculation of the questions and individuals answering them, increasing the validity of a questionnaire (Boone, 2016). The NSKQ displays good face and content validity as confirmed from sport nutrition experts (Trakman et al., 2017). The NSKQ is shown to have good construct validity and item discrimination as there is a significant difference between individuals who have had nutrition education and individuals who haven't ($p < 0.001$). The NSKQ was shown to have high internal consistency (Kruskal-Walis = 0.88) and strong external reliability ($r = 0.92$; $p < 0.001$). The NSKQ has also undergone item analysis based on classical test theory and the Rasch analysis model. The NSKQ is based on contemporary nutrition guidelines and is applicable to a variety of different sports and cultures due to being validated among a variety of different sports and standards.

3.2.1.3 Chosen Tool to Quantify Nutrition Knowledge

The study utilised the NSKQ to quantify players nutrition knowledge (Trakman et al., 2017; Trakman et al., 2019) due to its rigorous validation process and greater applicability to a variety of different sports (i.e. more relevant to squash players) and cultures. Previous studies had also utilised the NSKQ (Jenner et al., 2018; Trakman et al., 2018; McCrink et al., 2020) and therefore this allowed for a richer discussion and comparison of players nutrition knowledge.

3.3 Hypothesis

Previous research has demonstrated that athletes have 'poor' nutrition knowledge (Jenner et al., 2018= 46%; Trakman et al., 2018 = 46%; McCrink et al., 2020 = 40%). However, these were among cohorts of athletes which are of a lower standard to the ones utilised in the present study, with some research displaying a greater standard of athlete to possess greater nutrition knowledge (Harrison et al., 1991; Spendlove et al., 2012; Heikkilä et al., 2018). Therefore, it is hypothesised that elite squash players will have a greater nutrition knowledge than previous studies and may be 'average' rather than 'poor'.

3.4 Elite Squash Players Nutrition Knowledge and Influencing Factors

3.4.1 Abstract

Background: There is a reported mismatch between macronutrient consumption and contemporary macronutrient guidelines in elite standard squash players. Suboptimal dietary practices could be due to a lack of nutrition knowledge among players. Subsequently, the purpose of this study was to assess the sports nutrition knowledge of elite squash players through the Nutrition for Sport Knowledge Questionnaire (NSKQ) and provide an indication of whether players require nutrition support to increase their nutrition knowledge.

Methods: This cross-sectional study assessed the nutrition knowledge of 77 elite squash players via the NSKQ over the period of June 2020 to August 2020.

Results: Players conveyed average nutrition knowledge with a mean NSKQ score of 48.78 ± 10.06 (56.07% ± 11.56%). There were no significant differences in NSKQ score between male and female players ($p = .532$). There was found to be a weak positive association between world ranking and NSKQ score ($r = .208$) and age and NSKQ score ($r = .281$). Players who had a relevant undergraduate degree (e.g. BSc Sport & Exercise Science) had significantly greater NSKQ score than players with no relevant qualifications ($p = .022$). Players who consulted a sports nutritionist to obtain their main source of nutrition information were shown to have significantly greater knowledge than those who acquired knowledge from a sports scientist ($p = .01$) or the internet / social media ($p = .007$).

Conclusions: Players should consult with a sports nutritionist to increase their sport nutrition knowledge. Future research should quantify the effectiveness of a nutritional education intervention at increasing nutrition knowledge in players.

3.4.2 Background

Squash is a high intensity intermittent sport Jones et al., (2018) which is classified as one of the four major racket sports (Lees, 2003). Elite male squash players are reported to exhibit a mean energy expenditure of 4933 ± 620 kJ·h^{-1}, mean heart rate of 92 ± 3% heart rate maximum and mean respiratory exchange ratio of 0.94 ± 0.06 throughout simulated match play (Girard et al., 2007), conveying the high intensity nature of the sport (Jones et al., 2018). At elite standard, players are reported to train for more than 12 h per week, with squash-specific sessions such as pressure sessions and continuous rallies, eliciting heart rates above 90% heart rate maximum (Gibson et al., 2018; James et al., 2021). Due to the high energetic demands of elite squash, adequate energy intake is required to optimise health and physical performance (Kerksick et al., 2018; Mountjoy et al., 2018). Subsequently, sports nutritionists have become an integral part of high-performance teams to help promote optimal nutrition practices. Despite this, there is a paucity of information regarding specific nutritional recommendations for squash, unlike in other racket (Ranchordas et al., 2013) and high intensity intermittent sports (Collins et al., 2020). This makes it difficult for practitioners working with elite squash players, as they have to make recommendations based on non-specific guidelines (Burke et al., 2011).

Ventura-Comes et al., (2019) analysed the food habits of elite Spanish squash players using a food consumption frequency questionnaire and found that players under consumed carbohydrate-rich foods such as bread, potatoes, pasta and rice when compared to contemporary guidelines (Burke et al., 2011). Low frequency of carbohydrate rich foods are likely to result in low carbohydrate intakes in relation to guidelines, reducing high intensity intermittent performance (Burke et al., 2011). Mismatches between contemporary nutritional recommendations and players habitual nutritional practices suggest that elite squash players might lack the nutrition knowledge to have optimal dietary practices. An athlete's nutrition knowledge is one modifiable determinants of dietary behaviour (Trakman et al., 2016), with a weak positive correlation being reported between an athlete's nutrition knowledge and their diet quality (Heaney et al., 2011; Spronk et al., 2015). The association between nutrition knowledge and dietary behaviour is multifaceted and influenced by many other individual and environmental factors such as hunger and appetite, taste and food preferences, beliefs, culture, experiences, self- efficacy, financial status, peers, sporting culture, access to food and cooking skills (Basiotis et al., 1987; Heaney et al., 2011; Birkenhead & Slater, 2015; Spronk et al., 2015; Trakman et al., 2016). The evaluation of association between nutrition knowledge and diet quality is also complex due to a plethora of inadequately or partially validated instruments to assess nutrition knowledge (Heaney et al., 2011; Trakman et al., 2016) and inappropriate tools to quantify dietary intake (Heaney et al., 2011), such as 24-h dietary recalls and three-day self-reported food diaries, which have both been shown to poorly estimate micronutrient intake (Basiotis et al., 1987; Bingham et al., 1994).

Athletes energy requirements are also highly variable throughout macro-, meso- and microcycles, as many adopt a periodised training approach (Jeukendrup, 2017; Stellingwerff et al., 2019) complicating the assessment process (Heaney et al., 2010). Despite only a weak association between an athlete's nutrition knowledge and their diet quality, nutrition education interventions have been shown to increase athlete's nutrition knowledge and lead to greater dietary behaviours (Valliant et al., 2012), optimising physical performance (Rossi et al., 2017). Subsequently, increasing an athlete's nutrition knowledge is of interest to sport nutrition practitioners as it might enhance athlete's dietary practices (Valliant et al., 2012) and athletic ability (Rossi et al., 2017).

To date, no study has quantified the nutritional knowledge of elite squash players. Assessing the nutrition knowledge of elite squash players would help provide an indication of whether players require nutrition support and education to increase their nutrition knowledge and improve food choices to support high training and match demands, as well as a general healthy lifestyle. The main aim of the study was to assess the nutrition knowledge of elite squash players using the validated NSKQ (Trakman et al., 2017; Trakman et al, 2019). The Secondary aim of the study was to investigate the factors which may influence an elite squash players nutrition knowledge. Greater standards of education have been shown to positively influence athlete's nutrition knowledge (Zawila et al. 2003; Azizi et al., 2010; Jessri et al., 2010; Andrews et al., 2016; Abbey et al., 2017; Trakman et al., 2018), while sex (Douglas et al., 1984; Worme et al., 1990; Hamilton et al., 1994; Rosenbloom et al., 2002; Nichols et al., 2005; Condon et al., 2007; Dunn et al., 2007; Rash et al., 2008; Azizi et al., 2010; Jessri et al., 2010; Spendlove et al., 2012; Sedek & Yih, 2014; Webb & Beckford, 2014; Walker et al., 2014; Weeden et al., 2014; Hardy et al., 2016; Manore et al., 2017; Heikkilä et al., 2018; Patton-Lopez et al., 2018; Blennerhassett et al., 2018; Citarella et al., 2019), playing ability (Harrison et al., 1991; Hoogenbloom et al., 2009; Spendlove et al.,2012; Andrews et al., 2016; Hardy et al., 2016; Devlin et al., 2017; Heikkilä et al., 2018; Trakman et al., 2018; Lohman et al., 2019; Trakman et al., 2019), age (Reading et al., 1999; Jessri et al., 2010; Webb et al., 2014; Devlin et al., 2015; Hardy et al., 2016; Argôlo et al., 2018; Heikkilä et al., 2018), and main source of nutrition knowledge (Jessri et al., 2010; Trakman et al,. 2019) have all been reported to have equivocal influences on athlete's nutrition knowledge. Consequently, the study aimed to assess the association between age and world ranking on nutrition knowledge and quantify whether players standard of relevant education and main source of nutrition knowledge influence nutrition knowledge.

The final aim of the study was to survey what contemporary sports nutrition research elite squash players would like to see being conducted in the future. There are currently no specific nutritional guidelines for elite squash players. By surveying players, the aim was to ensure that all relevant nutrition research in elite squash is undertaken, specific to player's needs. This data can then be used to create a nutritional education intervention which is bespoke to elite squash players.

3.4.3 Methods

3.4.3.1 Participants

The research was approved by an institutional ethics committee (ER23597808). All participants who volunteered provided informed consent with the study being conducted according to the principles of the 7th revision of the Declaration of Helsinki (World Medical Association, 2001). A convenience sample of prospective participants were contacted through the Professional Squash Association (PSA) on two separate occasions (June 2020 and August 2020) and were provided with information about the study. Players were required to be a member of the PSA to take part in the study, with this forming the inclusion criteria for the study. Seventy-seven elite squash players took part in the study, 37 were male, and 40 were female. Responses were received from a global sample of the population (North America = 5; South America = 2; Europe = 55; Africa = 5; Asia = 6; and Oceania = 4). The mean average (± standard deviation) age and world ranking of the participants was 24 ± 5 and 190 ± 167 respectively. World rankings were taken from the PSA September rankings upon termination of the data collection period. Figure 4 details the distribution of the players world ranking.

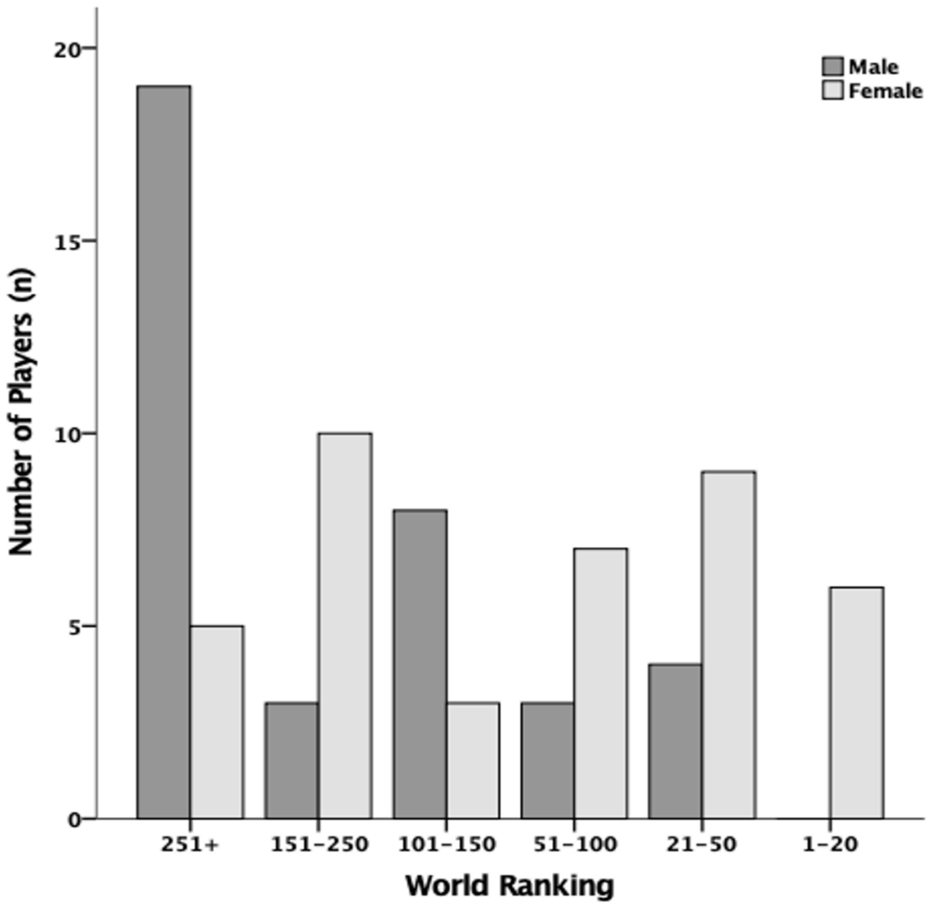

Figure 4. Distribution of players world ranking

3.4.3.2 Nutrition knowledge

Players' nutrition knowledge was measured via the validated NSKQ (Trakman et al., 2017), using the revised version (Trakman et al., 2019). The NSKQ was chosen over other validated nutrition knowledge questionnaires as it is has ample applicability across a variety of cultures (Trakman et al., 2017), is designed to be administered online (Trakman et al., 2017), has a high construct validity (Trakman et al., 2017) and underwent a comprehensive validation process utilising classical test theory (Wu et al., 2019) and Rasch analysis (Boone & Bolan, 2016). The questionnaire includes 87 questions with six subsections; weight management (n = 12), macronutrients (n = 30), micronutrients (n = 13), sports nutrition (n = 12), supplements (n = 12) and alcohol (n = 8). Nutrition knowledge was quantified using a scoring system set by Trakman et al. (2017) of: poor (0–49%), average (50–65%), good (66–75%) and excellent (76–100%).

The NSKQ was written in English and was distributed online via Qualtrics (Washington, USA). Players were informed that the questionnaire would take approximately 25 min to complete (Trakman et al., 2017) and instructed to complete the questionnaire in their own time without the use of resources (peers, books, internet etc.).

Two additional questions were asked upon completion of the NSKQ to quantify some of the factors influencing nutrition knowledge. Players were asked to 'detail any relevant qualifications which are specific to nutrition' (e.g. A-Level biology, BSc sport and exercise science etc.), as standard of education has been shown to positively influence nutrition knowledge (Zawila et al. 2003; Azizi et al., 2010; Jessri et al., 2010; Andrews et al., 2016; Abbey et al., 2017; Trakman et al., 2018). These were subsequently ordered into four groups, taking the participants highest standard of relevant education (no qualification, A-Level [physical education / sport, biology, chemistry etc.] undergraduate degree [sport and exercise science, nutrition or equivalent] and postgraduate degree [sport and exercise science, nutrition or equivalent]). Players were also asked 'where they obtained their main source of nutritional information from' to gain an understanding of how many players currently consult with a sport nutritionist. Athletes have been shown to gain their nutrition information from a variety of sources including nutritionists, strength and conditioning coaches, sport specific coaches, peers, the internet etc. (Jacobson et al., 2001; Abbey et al., 2017; Sedek & Yi, 2014; Folasire et al., 2015; Doering et al., 2016; Eskici & Ersoy, 2016; Judge et al., 2016; Kelly et al., 2016; Blennerhassett et al., 2018 Jenner et al., 2018 McCybbin et al., 2016). Players were provided six options, with them selecting the most relevant (sports nutritionist; conditioning coach or sport scientist; squash coach; peer review journal articles; internet or social media; and other).

Finally, players were asked to share what squash nutrition research they would like to see in the near future. This was split into six options with players able to select their top three (quantification of energy expenditure throughout training periods in elite squash players to create specific nutritional training guidelines; quantification of energy expenditure throughout competition periods in elite squash players to create specific nutritional competition guidelines; quantification of sweat sodium losses in elite squash players to create specific hydration guidelines; nutrition to support immune function in elite squash players; efficacy of ergogenic aids in elite squash; other). These options were devised as they underpin the relevant knowledge to create specific nutritional recommendations for elite squash players (e.g. how much energy do elite squash players expend during training and competition, what are players sweat sodium losses etc.) and this data can be used to develop a nutritional education intervention specific to elite squash players.

3.4.3.3 Statistical analysis

SPSS V 24.0 software (SPSS Inc., Chicago, IL) was used to perform the data analysis. All data was displayed as mean ± standard deviation for all participants with $p < 0.05$ being the criterion for significance among all statistical tests. The Kolmogrov-Smirnov test was used to check for normality. Levene's Test for Equality of Variances was used to assess homogeneity of variance. Independent Samples T-Test or Mann-Whitney U Test (for non-parametric analysis) was used to analyse the differences in overall NSKQ scores and sub-section scores between male and female players. Effect sizes were interpreted according to accepted thresholds (small: d = 0.2; moderate: d = 0.5; large = 0.8) (Cohen, 1988). Pearson's Correlation Coefficient or Spearman's Rank-Order Correlation was used to quantify the relationship between NSKQ score or section scores against age and world ranking. Pearson's Correlation Coefficient and Spearman's Rank-Order Correlation were interpreted according to accepted thresholds (very weak: r = 0–0.19; weak: r = 0.2–0.39; moderate: r = 0.4–0.59; strong: r = 0.6–0.79; very strong: r = 0.8–1) (Schober et al., 2018). A power calculation was undertaken to quantify the minimum sample size required for the study. A sample size of 42 was required (21 in each group) to achieve a statistical significance of $p < 0.05$. Unfortunately, there were no suitable relevant studies (e.g. study which quantified differences in nutrition knowledge between male and female individuals) which calculated the effect size, so a large effect size (d = 0.8) was chosen.

A One-Way Analysis of Variance (One-Way ANOVA) or Kruskal-Wallis K Test (for non-parametric analysis) was performed to calculate any significant differences between NSKQ score or section scores against standard of relevant education and main source of nutrition information. Where a significant main effect was observed, the Hochberg Post-Hoc pairwise comparison was used to determine which groups were statistically significant.

3.4.4 Results

3.4.4.1 NSKQ Score, Subsection Scores and Individual Question Responses

The mean NSKQ score was 48.78 ± 10.06 (56.07 % ± 11.56 %), defined as "average" nutrition knowledge. Figure 5 details players grand mean subsection scores. The highest scoring section was alcohol, with players demonstrating "good" knowledge. Players had "average" macronutrient, weight management and sports nutrition knowledge. Supplements was the lowest scoring section with players exhibiting "poor" nutrition knowledge. Players also had "poor" knowledge of micronutrients. An additional file details individual question scores (see Supplementary Tables 1–87 for Individual Question Scores).

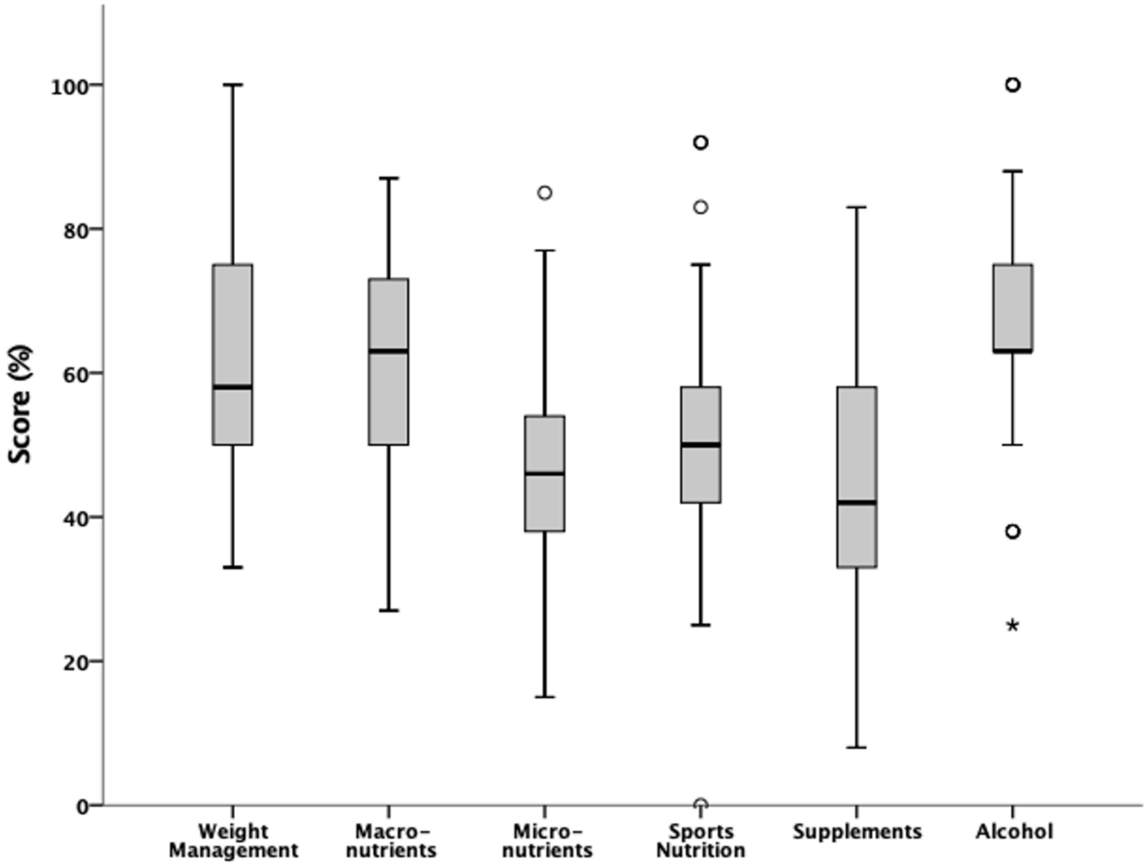

Figure 5. Players mean NSKQ subsection score

3.4.4.2 Differences Between Male and Female Players in NSKQ Score and Subsection Scores

Figure 6 details differences between male and female players NSKQ score, with Figure 7 detailing differences between male and female players subsection scores. There were no statistically significant differences between male and female players in NSKQ score or subsection scores ($p > 0.05$).

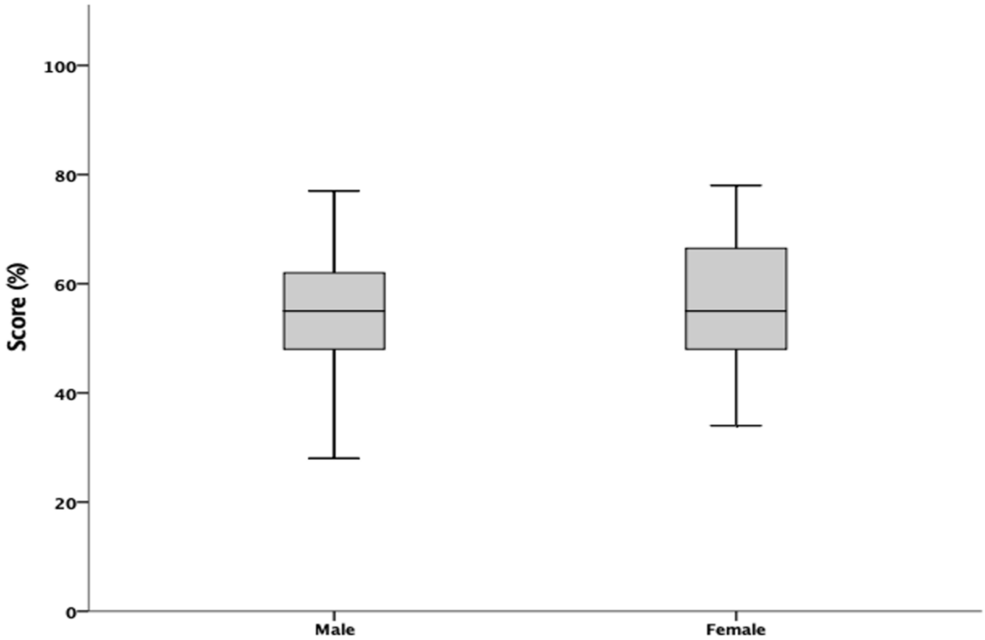

Figure 6. Differences between male and female players mean NSKQ scores

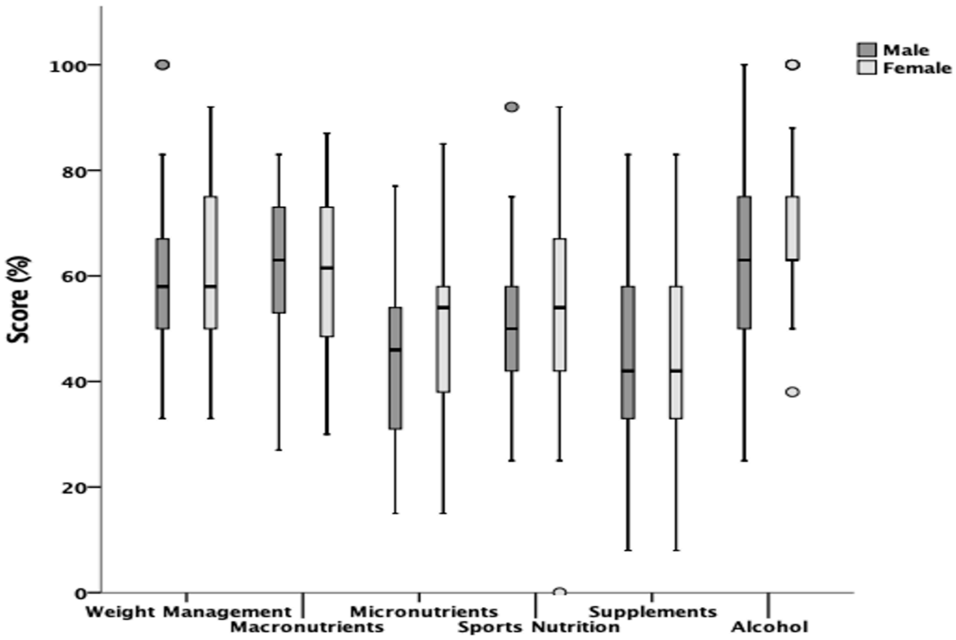

Figure 7. Differences between male and female mean NSKQ subsection scores

3.4.4.3 Association Between World Ranking and NSKQ Score and Subsection Score

World ranking had a weak positive association with NSKQ score (r = .208; p = .069) and weight management (r = .211; p = .066) subsection score. World ranking had a very weak positive association with macronutrient (r = .135; p = .241), micronutrient (r = .059; p = .610), sports nutrition (r = .137; p = .234), supplements (r = .154; p = .182) and alcohol (r = .170; p = .139) subsection scores.

3.4.4.3 Association Between Age and NSKQ Score and Subsection Score

Age had a weak positive association with NSKQ score (r = .281; p = .013), weight management (r = .288; p = .011), supplements (r = .255; p =) and alcohol (r = .215; p = .060) subsection scores. Age had a very weak positive association with macronutrient (r = .189; p = .099), micronutrient (r = .189; p = .100), and sports nutrition (r = .027; p = .813) subsection scores.

3.4.4.4 Effects of Standard of Relevant Education on NSKQ Score

Figure 8 details the effects of standard of relevant education on NSKQ score. Standard of education had a statistically significant effect on NSKQ score (p = .024). Hochberg post-hoc pairwise comparison revealed that players with a relevant undergraduate degree scored significantly better than players with no relevant qualification (p = .022; d = 1.3; CI = 1.15–22.09). No other statistically significant differences were observed across any of the groups when compared against each other.

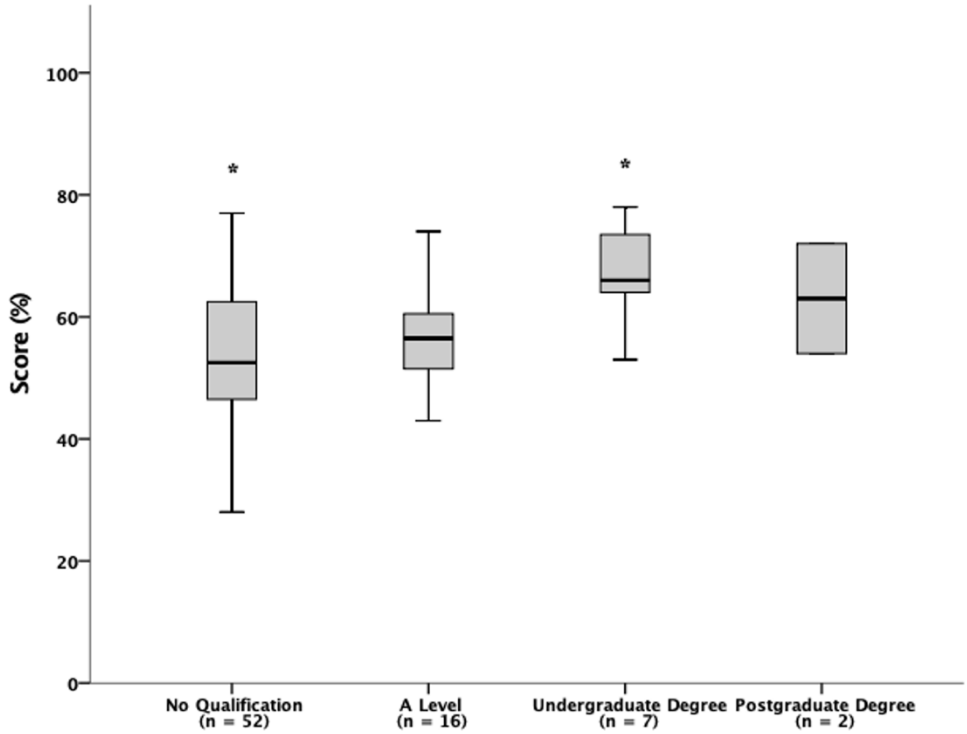

Figure 8. Effects of level of relevant education on NSKQ Score

3.4.4.5 Effects of Main Source of Nutrition Information on NSKQ Score

Figure 9 details the effects of main source of nutrition information on NSKQ and subsection scores. Players main source of nutrition information had a significant positive effect on NSKQ score (p = .000). Hochberg post-hoc pairwise comparison showed that players who received their main source of nutrition information from a sport nutritionist, nutritionist, registered dietitian or equivalent scored significantly higher than players who received their main source of nutrition information from a sport scientist (p = .010; d = 1.2; CI = 1.61–18.62) or the internet / social media (p = .007; d = 0.96; CI = 1.57– 15.62). No other significant differences were observed across any of the groups when compared against each other.

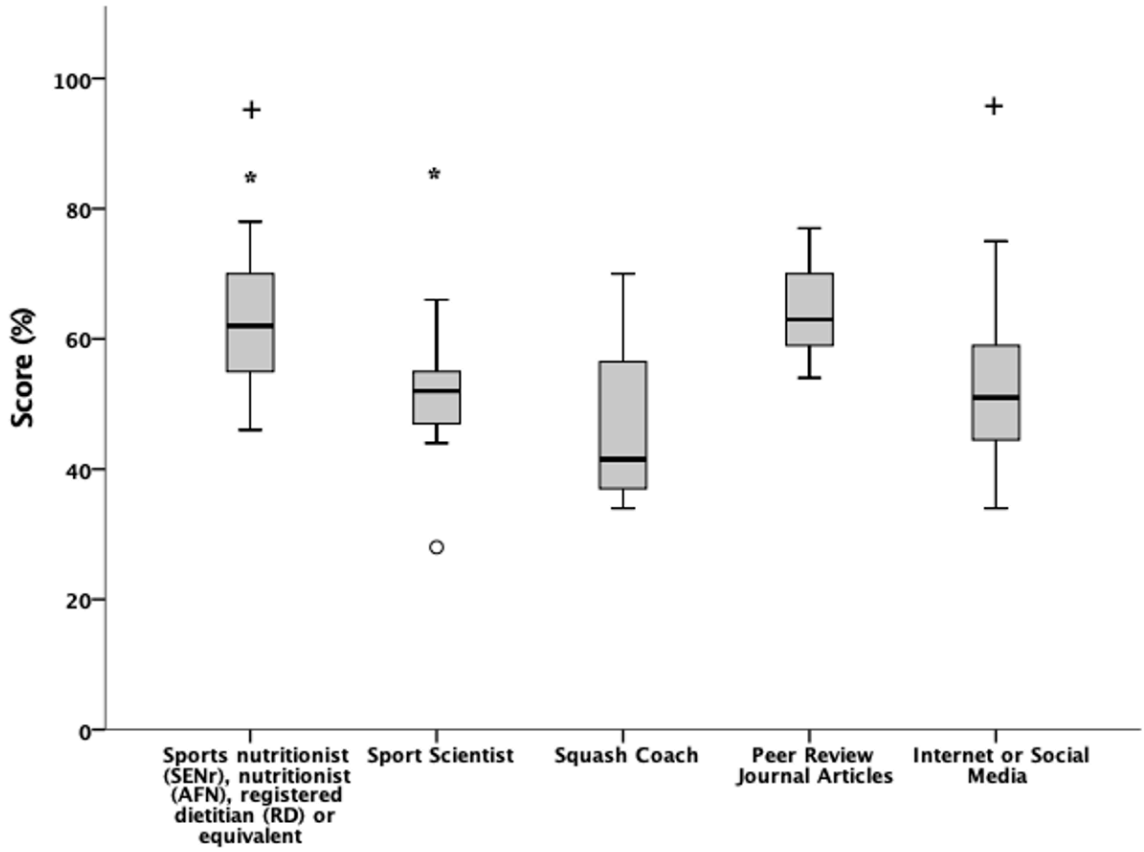

Figure 9. Effect of main source of nutrition information on NSKQ score

3.4.4.6 Future Sports Nutrition Research in Elite Squash

Figure 10 details players votes for future sports nutrition research in elite squash. The quantification of energy expenditure throughout training periods to create specific nutritional guidelines (n = 55; 71.43%) was the most popular area for future sports nutrition research in elite squash. The quantification of energy expenditure throughout competition periods to create specific nutritional competition guidelines was the second most popular (n = 34; 44.16%). Seventeen players stated they would like to see research regarding nutrition to support immune function (22.08%), with 16 players specifying they would like to see a quantification of ergogenic aids in squash (20.78%). The lowest scoring area of interest was the quantification of sweat sodium losses in squash to create specific nutritional guidelines (n = 10; 12.99%). Two players selected the 'other' suggesting "how to get everything into your diet while choosing plant based" and "the sustainability of a ketogenic diet for high performance in squash".

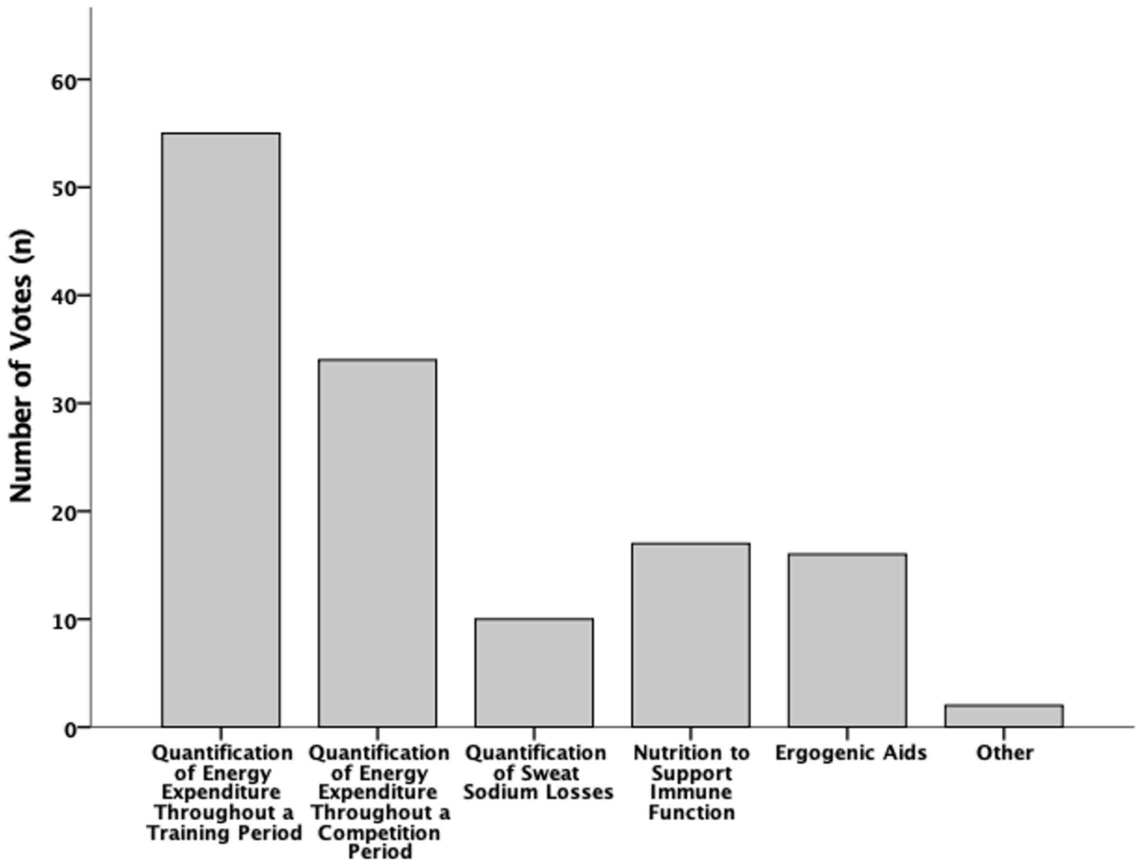

Figure 10. What sports nutrition research would elite squash players like to see conducted in the future

3.4.5 Discussion

The main aim of this study was to assess the nutrition knowledge of elite squash players. This study also aimed to quantify the factors which may influence an elite squash players nutrition knowledge. The final aim of the study was to survey what contemporary sports nutrition research elite squash players would like to see being conducted in the future. The main findings of this study were (1) elite squash players had average nutrition knowledge, (2) there were no differences in nutrition knowledge between male and female players, (3) age and world ranking had a weak positive association with nutrition knowledge, (4) players who had a relevant undergraduate degree were found to have better nutrition knowledge than those who had no relevant qualification, (5) players who obtained their main source of nutrition knowledge from a sports nutritionist were shown to have better nutrition knowledge than players who obtained from a sports scientist or the internet, and (6) players valued quantifying the energetic demands throughout a training period as the research they would like to see undertaken in the future.

3.4.5.1 Overall Nutrition Knowledge

Player's nutrition knowledge was average (56%). Consequently, elite squash players should aim to increase their nutrition knowledge, as this may lead to greater dietary behaviours (Valliant et al., 2012) and athletic ability (Rossi et al., 2017). Sport nutrition practitioners implement a variety of techniques to promote positive dietary behaviours, increasing nutrition knowledge in adolescent (Doyle-Lucas & Davy, 2011; Chapman. et al., 1997; Reading et al., 1999; Daniel et al., 2016; Nascimento et al., 2016; Philippou et al., 2017; Patton-Lopez et al., 2018; Heikkilä et al., 2019), collegiate (Kunkel et al., 2001; Abood et al., 2004; Valliant et al., 2012; Rossi et al., 2017) and elite athletes (Simpson et al., 2017). Future research should aim to quantify the effectiveness of a nutritional education intervention at increasing elite squash players nutrition knowledge.

Evaluations of players nutrition knowledge in comparison to other athletes is difficult, due to the heterogeneity of tools used to assess nutrition knowledge (Trakman et al., 2016; Tam et al., 2019). The NSKQ was devised as a universal tool to quantify athlete's nutrition knowledge and make comparisons among different sports (Trakman et al., 2017). However, there are many other factors such as sex, playing ability, age, standard of education and main source of nutrition knowledge which influence an athlete's nutrition knowledge (Trakman et al., 2016) making comparisons challenging. To date, three previous studies (Jenner et al., 2018; Trakman et al., 2018; McCrink et al., 2020) have used the NSKQ to assess sports nutrition knowledge. All three studies found athletes' sports nutrition knowledge to be poor (Jenner et al., 2018= 46%; Trakman et al., 2018 = 46%; McCrink et al., 2020 = 40%) in contrast to the present findings. A plausible explanation for this is that the standard of athlete was higher in the present study in relation to the aforementioned studies (Jenner et al., 2018; Trakman et al., 2018; McCrink et al., 2020). This study featured six of the world's top twenty squash players, and as a result these athletes may have greater access to resources (nutritionist, funding etc.) which may increase levels of nutrition knowledge (Trakman et al., 2016). Individual athletes such as elite squash players may also obtain personalised nutrition support which isn't available to team sport athletes due to time and cost limitations. This personalised support can focus on the key concepts which need to be addressed specific to the athlete's needs.

3.4.5.2 Key Concepts from Individual Questions

Players in the present study had poor knowledge of the contemporary carbohydrate and protein guidelines (see supplementary Tables 13 and 33) (Phillips, 2012; Burke et al., 2011). This is consistent with findings from Ventura-Comes et al., (2019) that elite Spanish squash players under consume carbohydrate in comparison to contemporary guidelines (Burke et al., 2011), with players rarely consuming foods which have a high carbohydrate content such as bread, potatoes, pasta and rice. Despite having poor knowledge of contemporary guidelines, players were able to identify the carbohydrate (see supplementary Tables 14–18) and protein (see supplementary Tables 32 and 42) content of foods, as well as appropriate protein sources to promote muscle growth post resistance training (see supplementary Tables 34–37). Players were also aware of what macro- nutrients to consume pre (see supplementary Table 59), during (see supplementary Table 64) and post exercise (see supplementary Table 66), as well as a suitable fuelling strategy (see supplementary Table 61) and snack during a 60–90-min session (see supplementary Table 65). This suggests that players may have greater procedural knowledge than declarative knowledge (Spronk et al., 2014) and indicates that while players are unaware of contemporary nutrition guidelines, they understand the nutritional composition of foods along with the appropriate time to consume them, enabling them to follow optimal fuelling and recovery strategies. Many of the carbohydrate sources Ventura- Comes et al., (2019) were reporting players to under consume were low glycemic index carbohydrates. It could be possible that squash players have a higher intake of high glycemic index carbohydrates. These are recommended around training sessions (Burke et al., 2011). Future research should aim to quantify the training loads and energy expenditures of elite squash players to determine the nutritional requirements of the sport, as reported in other racket (Ranchordas et al., 2013) and high intensity intermittent sports (Collins et al., 2020). This would convey whether contemporary non-specific nutrition guidelines (Burke et al., 2011) are relevant to elite squash players, with this data informing any nutrition education intervention undertaken with elite squash players. Fifty-five players (71%) surveyed in the present study conveyed that they would like to see this research undertaken. Players' dietary intakes should also be quantified alongside training loads, as reported in other high intensity intermittent sports (Morehen et al., 2016; Anderson et al., 2017). This would give an insight into whether players' dietary intake is optimal in relation to their training load (Jeukendrup, 2017;

Stellingwerff et al., 2019). Food consumption frequency questionnaires, as reported by Venutra-Comes et al., (2019) have been shown to display poor validity and reliability (Thompson & Subar, 2017) in comparison to other methods such as weighed food diaries, snap 'N' send and 24-h dietary recall (Bingham et al., 1994; Costello et al., 2017). Subsequently, more valid and reliable methods need to be employed to assess the energy intake and nutritional habits of elite squash players to obtain a better understanding of their dietary practices.

Players had poor micronutrient knowledge (45%). Quantifying players dietary intakes in future research would also provide an understanding of whether this lack of knowledge translates to poor diet quality. Tam et al., (2019) reported that only 38% of nutritional education interventions include information regarding micronutrients. It is feasible that sport nutritionists focus on educating athletes to achieve an optimal diet specific to their needs, rather than educating athletes about micronutrient roles and requirements.

Players also had poor supplementation knowledge (45%). This is consistent with findings from Ventura- Comes et al., (2018) who reported that elite Spanish squash players consumed ergogenic aids which had a lower efficacy such as glutamine, branch chain amino acids and flaxseed oil, rather than ones which had higher efficacy such as beta-alanine, creatine and sodium bicarbonate (Maughan et al., 2018). Players in the present study were unable to identify the rationale for use of beta-alanine supplementation (see supplementary Table 77). Beta-Alanine could enhance squash performance by increasing muscle carnosine stores and subsequent buffering capacity of the muscle (Saunders et al., 2017). Tam et al., (2019) reported that supplementation was the least frequent topic of nutrition education interventions (34%). It is plausible that athletes may only take supplements recommended by their sports nutritionist, with nutritionists prioritising achieving an optimal energy intake and greater diet quality, rather than a supplementation strategy. There is also a paucity of research on the efficacy of supplements on squash-specific performance. Therefore, sports nutritionists may not recommend supplements to elite squash players due to a lack of sport-specific evidence. Future research should aim to quantify the efficacy of ergogenic aids which have been shown to augment high intensity intermittent exercise (e.g. beta-alanine, sodium bicarbonate, creatine, caffeine and nitrates) (Forbes et al., 2020) in elite squash to establish a supplementation strategy specific to the sport.

3.4.5.3 Influencing Factors of Nutrition Knowledge

Sex was shown to have no significant differences on overall nutrition knowledge or any subsections (Figs. 3 and 4). Sex is reported to have an equivocal influence on nutrition knowledge with some studies reporting female athletes to have greater nutrition knowledge than male counterparts (Douglas

& Douglas, 1984; Worme et al., 1990; Dunn et al., 2007; Azizi et al., 2010; Jessri et al., 2010; Spendlove et al., 2012; Heikkilä et al., 2018; Citarella et al., 2019), whereas other studies convey no differences between sexes (Sedek & Yi, 2014; Hamilton et al., 1994; Rosenbloom et al., 2002; Nichols et al., 2005; Condon et al., 2007; Rash et al., 2008; Webb et al., 2014; Walker et al., 2014; Weeden et al., 2014; Hardy et al., 2016; Manore et al., 2017; Blennerhassett et al., 2018; Patton-Lopez et al., 2018). Assuming appropriate energy availability (Mountjoy et al., 2018), aside from iron intake in regularly menstruating females (Sim et al., 2019), the main determinants of a player's nutritional requirements are based on their training load, regardless of sex (Desbrow et al., 2019). Therefore, nutritional education requirements or nutrition knowledge shouldn't differ between sexes in elite squash players.

World ranking was shown to have a weak positive association with nutrition knowledge (r = .208). The influence of athlete ability on nutrition knowledge is equivocal with some studies showing a greater standard of athlete to possess greater nutrition knowledge (Harrison et al., 1991; Spendlove et al., 2012; Heikkilä et al., 2018), some studies conveying no differences (Hoogenbloom et al., 2009; Andrews et al., 2016; Hardy et al., 2016; Devlin et al., 2017; Lohman et al., 2019; Trakman et al., 2019) and others reporting non-elite Australian Football athletes to have greater nutrition knowledge than elite counterparts (Trakman et al., 2018). Differences in athlete ability and nutrition knowledge may be confounded by influencing factors. Many studies quantifying the nutrition knowledge of athletes are undertaken in tertiary educated individuals (e.g. collegiate athletes), with this level of education being shown to positively influence nutrition knowledge (Trakman et al., 2016). Sub-elite and recreational individuals are also anticipated to spend less time training than elite counterparts, potentially having more time for educational purposes.

Age was also shown to have a weak positive association with nutrition knowledge (r = .281) The influence of age on nutrition knowledge is equivocal with some studies reporting older athletes to display greater nutrition knowledge (Reading et al., 1999; Argôlo et al., 2018; Heikkilä et al., 2018) and others reporting no differences (Webb & Beckford, 2014; Jessri et al., 2010; Devlin et al., 2015; Hardy et al., 2016). Older athletes may have greater nutrition knowledge as time is required to be able to progress to higher levels of education (e.g. tertiary). Players may also not have access to a sports nutritionist in the early years of their career, as national governing bodies prioritise senior players who have a greater likelihood of achieving success, reducing the opportunity to increase their nutrition knowledge.

Players that had a relevant undergraduate degree re- ported higher nutrition knowledge than those that had no relevant qualifications (Fig. 5). This is to be expected given that undergraduate degrees (e.g. BSc Sport & Exercise Science) are designed to increase knowledge in a subject specific area, and many players cited that they had completed a nutrition module as part of their course. This is consistent with previous research which reports athletes who study or have studied at tertiary level have greater nutrition knowledge than those who have not (Zawila et al. 2003; Azizi et al., 2010; Jessri et al., 2010; Andrews et al., 2016; Abbey et al., 2017; Trakman et al., 2018).

Players who received their main source of nutrition information from a sport nutritionist were shown to score significantly higher than players who received their main source of nutrition information from a sport scientist, or the internet / social media (Fig. 5). This is in contrast to findings from Trakman et al., (2019) who found no differences in athlete's nutrition knowledge and main source of nutrition information. It should be noted that athletes in the aforementioned study were non-elite (Trakman et al., 2019). The level of nutrition support may vary between elite and non-elite athletes and may influence nutrition knowledge scores. Consequently, players should look to consult with a sports nutritionist to obtain nutrition information and be discouraged from using the internet / social media to increase their nutrition knowledge. Surprisingly, players who obtained their main source of nutrition information from a sports scientist were shown to have poor nutrition knowledge (44%). Sport scientists might be able to understand and communicate mechanistic underpinning. However, they may lack the ability to translate this into practical nutrition recommendations and coherent strategies for athletes.

3.4.5.4 Limitations

A limitation of the study is that it is impossible to know whether players cheated throughout completion of the NSKQ. Players were asked to complete the NSKQ without the use of resources (peers, books, internet etc.). No member of the research team was supervising players when they completed the questionnaire due to the universal nature of the study. Therefore, it is impossible to know whether players completed NSKQ with or without the use of resources. If players were to complete the NSKQ with resources this could influence their score and provide a false result. However, the lead author would expect scored to be greater than 'average' if players cheated. Another limitation of the study is that the NSKQ is not specific to an individual or sport. Therefore, while players may have poor nutrition knowledge, they may have a good understanding of nutrition in relation to their sport and this is not reflected in their score. A final limitation of the study is that despite responses from a global sample of the population, the questionnaire was only distributed in English. Consequently, some players may not have been able to understand questions or may have been deterred from completing the NSKQ.

3.4.6 Conclusions and Future Directions

This was the first study to quantify the nutrition knowledge of elite squash players. Players were found to have average nutrition knowledge (56%). Sex was shown to have no effect on players nutrition knowledge. Age and world ranking were shown to have a weak positive effect on nutrition knowledge. Players who had a relevant undergraduate degree had better nutrition knowledge than those who had no relevant education. Players who consulted with a sports nutritionist were shown to have better nutrition knowledge than those who obtained nutrition information from the internet or a sport scientist. Consequently, based on data from this study, elite squash players should aim to increase their nutrition knowledge by consulting with a sports nutritionist. Future research should aim to quantify the effectiveness of a nutrition education intervention at increasing the nutrition knowledge of elite squash players.

Players had poor knowledge of contemporary carbohydrate and protein guidelines with previous research reporting mismatches between guidelines and dietary in- takes (Burke et al., 2011). However, it is plausible that these guidelines are not specific to elite squash players and do not translate into poor dietary practices. Future research should quantify the training load and dietary practices of elite squash players to create specific nutritional recommendations for the sport. This will provide information on whether players dietary practices are optimal in relation to their training load and will create specific nutrition recommendations for elite squash players as exhibited in other racket (Ranchordas et al., 2013) and high intensity intermittent sports (Collins et al., 2020). This data can also be used to inform nutritional education interventions in elite squash players.

3.5 Supplementary Tables

Supplementary Table 1. Players Answers to Q1.1 Which nutrient do you think has the most energy (kilojoules/calories) per 100 grams (3.5 ounces)?

Carbohydrate		**Protein**		**Fat***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
45	58.44	5	6.49	26	33.77	1	1.30

*Denotes correct answer

Supplementary Table 2. Players Answers to Q1.2 Do you agree or disagree with the following statements about weight loss? Having the lowest weight possible benefits endurance performance in the long term

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
13	16.88	59	76.62	5	6.49

*Denotes correct answer

Supplementary Table 3. Players Answers to Q1.3 Do you agree or disagree with the following statements about weight loss? Eating more protein is the most important dietary change if you want to have more muscle

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
60	77.92	15	19.48	2	2.60

*Denotes correct answer

Supplementary Table 4. Players Answers to Q1.4 Do you agree or disagree with the following statements about weight loss? Eating more energy from protein than you need can make you put on fat

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
39	50.65	24	31.17	14	18.18

*Denotes correct answer

Supplementary Table 5. Players Answers to Q1.5 Do you think the diet changes below are good ways to lose weight? Swapping carbohydrates/energy dense foods for low-energy foods like vegetables

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
48	62.34	27	35.06	2	2.60

*Denotes correct answer

Supplementary Table 6. Players Answers to Q1.6 Do you think the diet changes below are good ways to lose weight? Eating margarine instead of butter

Yes		**No***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
23	29.87	36	46.75	23	29.87

*Denotes correct answer

Supplementary Table 7. Players Answers to Q1.7 Do you think the diet changes below are good ways to lose weight? Eating protein bars and shakes instead of yogurts, muesli/granola bars and fruits

Yes		**No***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
7	9.09	69	89.61	1	1.30

*Denotes correct answer

Supplementary Table 8. Players Answers to Q1.8 Do you think the diet changes below are good ways to lose weight? Choosing lower glycemic index (GI) carbohydrates to help regulate appetite

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
47	61.04	8	10.39	22	28.57

*Denotes correct answer

Supplementary Table 9. Players Answers to Q1.9 If they want to lose weight, athletes should:

Eat less than 50 grams (1.7 ounces) of carbohydrate per day		**Eat less than 20 g (0.7 ounces) of fat per day**		**Eat less calories / kilojoules than your body needs***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
6	7.79	12	15.58	45	58.44	14	18.18

*Denotes correct answer

Supplementary Table 10. Players Answers to Q1.10 To ensure they meet their energy (kilojoule/calorie) requirements, all athletes should:

Plan their diet based on their age, gender, body size, sport and training program*		**Eat based on their hunger and fulness signals**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
75	97.40	2	2.60	0	0

*Denotes correct answer

Supplementary Table 11. Players Answers to Q1.11 Which is a better recovery meal option for an athlete who wants to put on muscle?

A 'mass gainer' shake and 3-4 scrambled eggs		**Pasta with lean beef and vegetable sauce, plus a dessert of fruit, yogurt and nuts***		**A large piece of grilled chicken with side salad (lettuce, cucumber, tomato)**		**A large steak and fried eggs**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
17	22.08	34	44.16	16	20.78	6	7.79	4	5.19

*Denotes correct answer

Supplementary Table 12. Players Answers to Q1.12 Which is a better recovery meal option for an athlete who wants to lose weight?

A side salad with no dressing (lettuce, cucumber, tomato)		**A pure whey protein isolate (WPI) shake made with water**		**A mixed meal that includes a small-moderate serving of meat and carbohydrate plus a large side salad***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
3	3.90	10	12.99	62	80.50	2	2.60

*Denotes correct answer

Supplementary Table 13. Players Answers to Q2.1 An athlete doing a moderate to high-intensity endurance training program for about two hours should eat…

1-3 g carbohydrate per kg (0.016-0.048 ounces per lb) bodyweight per day		**5-7 g/kg, increasing up to 10 g/kg with intense training competition loads of carbohydrate per day***		**75-85 % of total daily kilojoule / calorie intake as carbohydrate**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
17	22.08	34	44.16	4	5.19	22	28.57

*Denotes correct answer

Supplementary Table 14. Players Answers to Q2.2 Which options have enough carbohydrate for recovery from about 1 hour of high intensity aerobic exercise? Assume the athlete weighs about 70kg and has an important training session again tomorrow; 1 medium banana?

Enough		**Not enough***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
13	16.88	60	77.92	4	5.19

*Denotes correct answer

Supplementary Table 15. Players Answers to Q2.3 Which options have enough carbohydrate for recovery from about 1 hour of high intensity aerobic exercise? Assume the athlete weighs about 70kg and has an important training session again tomorrow; 1 cup of quinoa and 1 tin of tuna?

Enough		Not enough*		Not sure	
n	**%**	**n**	**%**	**n**	**%**
60	77.92	12	15.58	5	6.49

*Denotes correct answer

Supplementary Table 16. Players Answers to Q2.4 Which options have enough carbohydrate for recovery from about 1 hour of high intensity aerobic exercise? Assume the athlete weighs about 70kg and has an important training session again tomorrow; 1 cup of plain yogurt?

Enough		Not enough*		Not sure	
n	**%**	**n**	**%**	**n**	**%**
3	3.90	71	92.21	3	3.90

*Denotes correct answer

Supplementary Table 17. Players Answers to Q2.5 Which options have enough carbohydrate for recovery from about 1 hour of high intensity aerobic exercise? Assume the athlete weighs about 70kg and has an important training session again tomorrow; 1 cup of baked beans on two slices of bread?

Enough*		Not enough		Not sure	
n	**%**	**n**	**%**	**n**	**%**
57	74.03	13	16.88	7	9.09

*Denotes correct answer

Supplementary Table 18. Players Answers to Q2.6 Which food has the most carbohydrate?

One cup (168 g / 5.6 ounces) boiled rice*		Two slices of white sandwich loaf bread		One medium (150 g / 5 ounces) boiled potato		1 medium (150 g / 5 ounces) ripe banana		Not sure	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**

33	42.86	15	19.48	16	20.78	6	7.79	7	9.09

*Denotes correct answer

Supplementary Table 19. Players Answers to Q2.7 Do you agree or disagree with these statements about fat; The body needs fat to fight off sickness?

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
36	46.75	18	23.38	23	29.87

*Denotes correct answer

Supplementary Table 20. Players Answers to Q2.8 Do you agree or disagree with these statements about fat; Athletes should not eat more than 20g of fat per day

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
15	19.48	41	53.25	21	27.27

*Denotes correct answer

Supplementary Table 21. Players Answers to Q2.9 Do you agree or disagree with these statements about fat; When we increase the intensity of exercise, the % of fat we use as a fuel also increases

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
40	51.95	34	44.16	3	3.90

*Denotes correct answer

Supplementary Table 22. Players Answers to Q2.10 Do you agree or disagree with these statements about fat; When we exercise at a low intensity, our body mostly uses fat as a fuel

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
42	54.55	26	33.77	9	11.69

*Denotes correct answer

Supplementary Table 23. Players Answers to Q2.11 Do you think these foods are high in fat; Cheddar cheese?

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
72	93.51	3	3.90	2	2.60

*Denotes correct answer

Supplementary Table 24. Players Answers to Q2.12 Do you think these foods are high in fat; Margarine?

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
53	68.83	17	22.08	7	9.09

*Denotes correct answer

Supplementary Table 25. Players Answers to Q2.13 Do you think these foods are high in fat; Mixed nuts?

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
63	81.82	12	15.58	2	2.60

*Denotes correct answer

Supplementary Table 26. Players Answers to Q2.14 Do you think these foods are high in fat; Honey?

Yes		**No***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
9	11.69	59	76.62	9	11.69

*Denotes correct answer

Supplementary Table 27. Players Answers to Q2.15 Do you agree or disagree with the statements about protein? Protein is the main fuel that muscles use during exercise

Agree	**Disagree***	**Not sure**

n	%	n	%	n	%
20	25.97	53	68.83	4	5.19

*Denotes correct answer

Supplementary Table 28. Players Answers to Q2.16 Do you agree or disagree with the statements about protein? Vegetarian athletes can meet their protein requirements without the use of protein supplements

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
64	83.12	10	12.99	3	3.90

*Denotes correct answer

Supplementary Table 29. Players Answers to Q2.17 Do you agree or disagree with the statements about protein? An experienced athlete needs more protein than a young athlete who is just starting training

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
23	29.87	43	55.84	11	14.29

*Denotes correct answer

Supplementary Table 30. Players Answers to Q2.18 Do you agree or disagree with the statements about protein? The body has a limited ability to use protein for muscle protein synthesis

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
48	62.34	8	10.39	21	27.27

*Denotes correct answer

Supplementary Table 31. Players Answers to Q2.19 Do you agree or disagree with the statements about protein? A balanced diet with enough kilojoules/calories (energy) has enough protein for most athletes

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
43	62.34	24	31.17	10	12.99

*Denotes correct answer

Supplementary Table 32. Players Answers to Q2.20 Which food has the most protein?

Two eggs		100 g (3 ounces) of raw skinless chicken breast*		30 g (1 ounce) of almonds		Not sure	
n	%	n	%	n	%	n	%
14	18.18	51	66.23	5	6.49	7	9.09

*Denotes correct answer

Supplementary Table 33. Players Answers to Q2.21 The protein needs of a 100 kg (220 lb) well trained resistance athlete are closest to:

100 g (1 g/kg)		150 g (1.5 g/kg)*		500 g (5 g/kg)		They should eat as much protein as possible		Not sure	
n	%	n	%	n	%	n	%	n	%
8	10.39	38	49.35	11	14.29	4	5.19	16	20.78

*Denotes correct answer

Supplementary Table 34. Players Answers to Q2.22 Which of these foods do you think have enough protein to promote muscle growth after a bout of resistance exercise? 100g (3 ounces) chicken breast

Enough*		Not enough		Not sure	
n	%	n	%	n	%
72	93.51	5	6.49	0	0

*Denotes correct answer

Supplementary Table 35. Players Answers to Q2.23 Which of these foods do you think have enough protein to promote muscle growth after a bout of resistance exercise? 30g (1 ounce) Yellow cheese

Enough		Not enough*		Not sure	
n	%	n	%	n	%

11	14.29	56	72.73	10	12.99

*Denotes correct answer

Supplementary Table 36. Players Answers to Q2.24 Which of these foods do you think have enough protein to promote muscle growth after a bout of resistance exercise? 1 cup baked beans

Enough		**Not enough***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
38	49.35	32	41.56	7	9.09

*Denotes correct answer

Supplementary Table 37. Players Answers to Q2.25 Which of these foods do you think have enough protein to promote muscle growth after a bout of resistance exercise? 1/2 cup cooked quinoa

Enough		**Not enough***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
19	24.68	53	68.83	5	6.49

*Denotes correct answer

Supplementary Table 38. Players Answers to Q2.26 Do you think these foods have all the essential amino acids needed by the body? Beef steak

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
40	51.95	25	32.47	12	15.58

*Denotes correct answer

Supplementary Table 39. Players Answers to Q2.27 Do you think these foods have all the essential amino acids needed by the body? Eggs

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
44	57.14	20	25.97	13	16.88

*Denotes correct answer

Supplementary Table 40. Players Answers to Q2.28 Do you think these foods have all the essential amino acids needed by the body? Lentils

Yes		**No***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
33	42.86	32	41.56	12	15.58

*Denotes correct answer

Supplementary Table 41. Players Answers to Q2.29 Do you think these foods have all the essential amino acids needed by the body? Cow's milk

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
37	48.05	27	35.06	13	16.88

*Denotes correct answer

Supplementary Table 42. Players Answers to Q2.30 The amount of protein in skim milk compared to full cream milk is:

Much less		**About the same***		**Much more**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
12	15.58	39	50.65	9	11.69	17	22.08

*Denotes correct answer

Supplementary Table 43. Players Answers to Q3.1 Do you agree or disagree with these statements on vitamins and minerals? Calcium is the main component of bone

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
64	83.12	6	7.79	7	9.09

*Denotes correct answer

Supplementary Table 44. Players Answers to Q3.2 Do you agree or disagree with these statements on vitamins and minerals? Vitamin C is an antioxidant

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
47	61.04	11	14.29	19	24.68

*Denotes correct answer

Supplementary Table 45. Players Answers to Q3.3 Do you agree or disagree with these statements on vitamins and minerals? Thiamine (Vitamin B1) is needed to take oxygen to muscles

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
22	28.57	14	18.18	41	53.25

*Denotes correct answer

Supplementary Table 46. Players Answers to Q3.4 Do you agree or disagree with these statements on vitamins and minerals? Iron is needed to turn food into usable energy

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
27	35.06	24	31.17	26	33.77

*Denotes correct answer

Supplementary Table 47. Players Answers to Q3.5 Do you agree or disagree with these statements on vitamins and minerals? Vitamin D enhances calcium absorption

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
43	55.84	7	9.09	27	35.06

*Denotes correct answer

Supplementary Table 48. Players Answers to Q3.6 Do you agree or disagree with these statements on vitamins and minerals? Meat, chicken and fish are good sources of zinc

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
49	63.64	7	9.09	21	27.27

*Denotes correct answer

Supplementary Table 49. Players Answers to Q3.7 Do you agree or disagree with these statements on vitamins and minerals? Wholegrain foods are good sources of vitamin C

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
18	23.38	36	46.75	23	29.87

*Denotes correct answer

Supplementary Table 50. Players Answers to Q3.8 Do you agree or disagree with these statements on vitamins and minerals? Fruit and vegetables are good sources of calcium

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
16	20.78	49	63.64	12	15.58

*Denotes correct answer

Supplementary Table 51. Players Answers to Q3.9 Do you agree or disagree with these statements on vitamins and minerals? Fatty fish is a good source of vitamin D

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
40	51.95	21	27.27	16	20.78

*Denotes correct answer

Supplementary Table 52. Players Answers to Q3.10 Do you agree or disagree with these statements on vitamins and minerals? Women who have a monthly period need more iron than men

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
56	72.73	4	5.19	17	22.08

*Denotes correct answer

Supplementary Table 53. Players Answers to Q3.11 Do you agree or disagree with these statements on vitamins and minerals? Athletes aged 15 to 24 years need 500 mg of calcium each day

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
24	31.17	8	10.39	45	58.44

*Denotes correct answer

Supplementary Table 54. Players Answers to Q3.12 Do you agree or disagree with these statements on vitamins and minerals? A fit person eating a balanced diet can improve their athletic performance by eating more vitamins and minerals from food

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
56	72.73	9	11.69	12	15.58

*Denotes correct answer

Supplementary Table 55. Players Answers to Q3.13 Do you agree or disagree with these statements on vitamins and minerals? Vitamins contain energy (kilojoules/calories)

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
23	29.87	41	53.25	13	16.88

*Denotes correct answer

Supplementary Table 56. Players Answers to Q4.1 Athletes should drink water to:

Keep plasma (blood) volume stable*		**Allow proper sweating**		**All of the above**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
9	11.69	4	5.19	61	79.22	3	3.90

*Denotes correct answer

Supplementary Table 57. Players Answers to Q4.2 Experts think that athletes should:

Drink 50-100 ml (1.7-3.3 fluid ounces) every 15-20 minutes		**Drink sports drinks (e.g. Powerade) rather than water when exercising**		**Drink to a plan, based on bodyweight changes during training sessions performed in a similar climate***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
22	28.57	3	3.90	47	61.04	5	6.49

*Denotes correct answer

Supplementary Table 58. Players Answers to Q4.3 How much sodium (salt) should fluid consumed for hydration purposes (during exercise) contain?

Al least 11-25 mmol/L (approx. 250-575 mg/L)*		**At least 4-8 mmol/L (approx. 90-185 mg/L)**		**None**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
6	7.79	19	24.68	6	7.79	46	59.74

*Denotes correct answer

Supplementary Table 59. Players Answers to Q4.4 Before competition, athletes should eat foods that are high in:

Fluids, fats and carbohydrate	**Fluids, fibre and carbohydrate**	**Fluids and carbohydrate***	**Not sure**

n	%	n	%	n	%	n	%
20	25.97	15	22.08	42	54.55	0	0

*Denotes correct answer

Supplementary Table 60. Players Answers to Q4.5 Do you agree or disagree with the statements on carbohydrate? Eating carbohydrates when you exercise makes it harder to build strength and muscles

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
6	7.79	63	81.82	8	10.39

*Denotes correct answer

Supplementary Table 61. Players Answers to Q4.6 Do you agree or disagree with the statements on carbohydrate? In events lasting 60 - 90 minutes, 30- 60 g (1.0 - 2.0 ounces) of carbohydrates should be eaten per hour

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
41	53.25	11	14.29	25	32.47

*Denotes correct answer

Supplementary Table 62. Players Answers to Q4.7 Do you agree or disagree with the statements on carbohydrate? Eating carbohydrates when you exercise will help keep blood sugar levels stable

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
48	62.34	14	18.18	15	19.48

*Denotes correct answer

Supplementary Table 63. Players Answers to Q4.8 Some athletes get a sore stomach if they eat during exercise. What might make stomach pain worse?

Having gels rather than water or sports drinks*	**Having small amounts of water at a time**	**Having sports drinks with different types of carbohydrates (e.g.**	**Not sure**

				fructose and sucrose)			
n	%	n	%	n	%	n	%
27	35.06	5	6.49	34	44.16	11	14.29

*Denotes correct answer

Supplementary Table 64. Players Answers to Q4.9 During a competition, athletes should eat foods that are high in:

Fluids, fibre and fat		Fluids and protein		Fluids and carbohydrate*		Not sure	
n	%	n	%	n	%	n	%
2	2.60	7	9.09	67	87.01	1	1.30

*Denotes correct answer

Supplementary Table 65. Players Answers to Q4.10 Which is the best snack to have during an intense 90-minute training session?

A protein shake		A ripe banana*		A handful of nuts		Not sure	
n	%	n	%	n	%	n	%
2	2.60	70	90.91	5	6.49	0	0

*Denotes correct answer

Supplementary Table 66. Players Answers to Q4.11 After a competition, athletes should eat foods that are high in?

Protein, carbohydrate and fat		Only protein		Only carbohydrate		Carbohydrate and protein*		Not sure	
n	%	n	%	n	%	n	%	n	%
30	38.96	5	6.49	1	1.30	41	53.25	0	0

*Denotes correct answer

Supplementary Table 67. Players Answers to Q4.12 How much protein do you think experts say athletes should eat after resistance exercise?

0.3 g/kg bodyweight (approx. 15-25 g [0.53-0.88 ounces) for most athletes*		**1.0 g/kg bodyweight (approx. 50-100 [1.9-2.3 ounces) for most athletes**		**1.5 g/kg bodyweight (approx. 150-230 g [5.3-10.6 ounces) for most athletes**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
19	24.68	23	29.87	22	28.57	17	22.08

*Denotes correct answer

Supplementary Table 68. Players Answers to Q5.1 Do you agree or disagree with the statements about vitamin and mineral supplements? Vitamin C should always be taken by athletes

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
31	40.26	37	48.05	9	11.69

*Denotes correct answer

Supplementary Table 69. Players Answers to Q5.2 Do you agree or disagree with the statements about vitamin and mineral supplements? B vitamins should be taken if energy levels are low

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
32	41.56	14	18.18	31	40.26

*Denotes correct answer

Supplementary Table 70. Players Answers to Q5.3 Do you agree or disagree with the statements about vitamin and mineral supplements? Salt tablets should be taken by athletes that get cramps when they exercise

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
41	53.25	18	23.38	18	23.38

*Denotes correct answer

Supplementary Table 71. Players Answers to Q5.4 Do you agree or disagree with the statements about vitamin and mineral supplements? Iron tablets should be taken by all athletes who feel tired and are pale

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
40	51.95	24	31.17	13	16.88

*Denotes correct answer

Supplementary Table 72. Players Answers to Q5.5 All supplements are tested to make sure they are safe, don't have any contamination.

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
18	23.38	55	71.43	4	5.19

*Denotes correct answer

Supplementary Table 73. Players Answers to Q5.6 Supplement labels may sometimes say things that are not true.

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
65	84.42	8	10.39	4	5.19

*Denotes correct answer

Supplementary Table 74. Players Answers to Q5.7 Do you agree or disagree with the statements about supplements? Creatine makes the brain think that exercise feels easier

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
9	11.69	44	57.14	24	31.17

*Denotes correct answer

Supplementary Table 75. Players Answers to Q5.8 Do you agree or disagree with the statements about supplements? Caffeine makes muscles able to work harder even without more oxygen

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
13	16.88	45	58.44	19	24.68

*Denotes correct answer

Supplementary Table 76. Players Answers to Q5.9 Do you agree or disagree with the statements about supplements? Beetroot juice (nitrates) makes muscles feel less sore after exercise

Agree		**Disagree***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
39	50.65	12	15.58	26	33.77

*Denotes correct answer

Supplementary Table 77. Players Answers to Q5.10 Do you agree or disagree with the statements about supplements? Beta-Alanine can decrease how much acid muscles make during intense exercise

Agree*		**Disagree**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
21	27.27	8	10.39	48	62.34

*Denotes correct answer

Supplementary Table 78. Players Answers to Q5.11 Which supplement does not have enough evidence in relation to improving body composition or sporting performance?

Caffeine		**Ferulic acid***		**Bicarbonate**		**Leucine**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
12	15.58	8	10.39	11	14.29	2	2.60	44	57.14

*Denotes correct answer

Supplementary Table 79. Players Answers to Q5.12 WORLD ANTI-DOPING AGENCY (WADA) bans the use of….

Caffeine		**Bicarbonate**		**Carnitine**		**Testosterone***		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
0	0	0	0	3	3.90	69	76.62	5	6.49

*Denotes correct answer

Supplementary Table 80. Players Answers to Q6.1 How much ethanol (pure alcohol) is there in a standard drink?

1-2 g / 0.03-0.06 fluid ounces		**8-14 g / 0.3-0.6 fluid ounces***		**30-50 g / 1.2-2.0fluid ounces**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
12	15.58	34	44.16	2	2.60	29	37.66

*Denotes correct answer

Supplementary Table 81. Players Answers to Q6.2 Which is an example of a "Standard Drink"?

30-45 ml / 1-1.5 fluid ounces of pure spirits*		**One quarter of a bottle (175 ml / 6 fluid ounces) of red wine**		**A pint (425 ml / 14 fluid ounces) of full-strength beer**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
21	27.27	14	18.18	29	37.66	13	16.88

*Denotes correct answer

Supplementary Table 82. Players Answers to Q6.3 Do you think alcohol can make you put on weight?

Yes*		**No**		**Not sure**	
n	**%**	**n**	**%**	**n**	**%**
75	97.40	2	2.60	0	0

*Denotes correct answer

Supplementary Table 83. Players Answers to Q6.4 How many drinks do you think experts say are the most we should have in one day?

Two*		Three		Four		Not sure	
n	%	n	%	n	%	n	%
53	68.83	7	9.09	5	6.49	12	15.58

*Denotes correct answer

Supplementary Table 84. Players Answers to Q6.5 Do you agree or disagree with the statements on alcohol? If someone does not drink at all during the week, it is okay for them to have five or more drinks on a Friday or Saturday night

Agree		Disagree*		Not sure	
n	%	n	%	n	%
7	9.09	68	88.31	2	2.60

*Denotes correct answer

Supplementary Table 85. Players Answers to Q6.6 Do you agree or disagree with the statements on alcohol? Drinking lots of alcohol can make it harder to recover from injury

Agree*		Disagree		Not sure	
n	%	n	%	n	%
67	87.01	3	3.90	7	9.09

*Denotes correct answer

Supplementary Table 86. Players Answers to Q6.7 Do you agree or disagree with the statements on alcohol? Alcohol makes you urinate more

Agree*		Disagree		Not sure	
n	%	n	%	n	%
57	74.03	11	14.29	9	11.69

*Denotes correct answer

Supplementary Table 87. Players Answers to Q6.8 "Binge drinking" (also referred to as heavy episodic drinking) is defined as:

Having two or more standard alcoholic drinks on the same occasion		Having four to five standard alcoholic drinks on the same occasion*		Having seven to eight standard alcoholic drinks on the same occasion		Not sure	
n	**%**	**n**	**%**	**n**	**%**	**n**	**%**
6	7.79	39	50.65	25	32.47	7	9.09

*Denotes correct answer

4.0: Study Three – Doubly Labelled Water Assessment of Elite Male-Squash Player's Energy Balance During a Seven Day Training Microcycle

4.1 Study Summary and the Golden Thread

After conducting a systematic review (see section 2) on the available physiological and nutritional literature within squash, it was highlighted that there were many gaps in the literature such as: (1) no one had previously quantified the energy expenditure of elite players throughout a training microcycle; (2) while players dietary habits had previously been quantified (Ventura-Comes et al., 2019), this had been via a food frequency questionnaire, with food frequency questionnaires being shown to display poor validity and reliability (Thompson & Subar, 2017). Therefore, more valid and reliable methods were required to quantify players energy intakes and dietary habits. As no one had previously quantified players energy expenditure or intake during a training microcycle, there were no nutritional guidelines specific to elite squash players and their training load. Consequently, it was difficult to appropriately advise players on how much energy to consume in relation to their training load to optimise health and physical performance.

Study two highlighted that players had 'average' nutrition knowledge (see section 3). They were shown to have poor knowledge of contemporary macronutrient guidelines, although were still able to identify appropriate pre, during and post exercise nutrition strategies. The NKSQ was based on non-specific nutrition guidelines and therefore it is important to consider whether these are appropriate for elite squash players. Many of the players questioned this.

Anecdotally players were shown to experience high training loads, with some players displaying sub optimal nutrition strategies. An example of this was an elite player who was diagnosed with chronic fatigue syndrome, thought to be due to training consistently with low energy availability (Logue et al., 2018) because of their high training loads and suboptimal energy intake.

The study aimed to quantify the energy balance of elite male squash players. The study had also planned to quantify the energy balance of elite female squash players as well, however, the 'performance problems' such as high training loads were predominantly experienced in male players. Therefore, due to this and the cost implications of the doubly labelled water technique to assess energy expenditure, a cohort of three male players were chosen. The study also aimed to estimate energy intake through self-reported 7-day food diary to provide an indication of players energy balance and whether they were fuelling appropriately to optimise their health and physical performance. This data could then be fed back to players to optimise their dietary habits, while providing knowledge of the energy expenditure of elite male squash players to guide over players competing in the sport.

4.2 Justification of Methodology

4.2.1 Energy Expenditure

The energy expenditure of an individual can be measured through many techniques such as direct calorimetry, indirect calorimetry, the doubly labelled water technique, metabolic equivalent, and heart rate monitoring (Ainslie et al., 2003; Hills et al., 2014; Lam & Ravussin, 2016).

4.2.1.1 Direct Calorimetry

Direct calorimetry is concerned with the first law of thermodynamics, that energy cannot be created or destroyed but that every living organism is in a state of constant energy exchange with its environment (Duroudier, 2016). All metabolic processes within the body such as muscular contractions, the synthesis of macronutrients, and the maintenance of bodily functions such as breathing produce heat, with this heat production being continually exchanged with an individual's surrounding environment (Kenny et al., 2017). Calorimeters can be used to measure energy expenditure by quantifying the heat produced from metabolic processes by an individual, and exchange with its environment (Kenny et al., 2017). Direct calorimetry measures all aspects of heat transfer such as conduction, convection, evaporation and radiation (Webb, 1980). Energy expenditure via direct calorimetry is quantified in either an isothermic or gradient layered chamber (Kenny et al., 2017). Typically, a chamber is layered by a space which is maintained at the same temperature as the inside layer. Heat production, and therefore energy expenditure is then calculated by the change in air temperature and humidity between the two chamber layers (Kenny et al., 2017). Direct calorimetry is seen as the reference standard for quantifying human metabolism (Kenny et al., 2017). A key limitation of direct calorimetry is that it cannot be used to quantify energy expenditure in many activities, such as squash, due to the technique requiring analysis to take place in a chamber. Therefore, assessments of energy expenditure in free living individuals are impossible.

4.2.1.2 Indirect Calorimetry

Indirect calorimetry is concerned with quantifying energy expenditure through the amount of energy released when energy substrates are oxidised, rather than heat production. Weir (1949) proposed the calculation:

$$Total\ Heat\ Output\ [Kcal] = 3.9\ x\ oxygen\ used\ [L] + 1.11\ x\ carbon\ dioxide\ produced\ [L]$$

Consequently, energy expenditure can be calculated through oxygen consumption and carbon dioxide production. Indirect calorimetry is measured predominantly through open circuit spirometry (Mataweh et al., 2018). Indirect calorimetry can be measured using a whole-room respiratory chamber, similar to direct calorimetry, or using a metabolic cart (Lam & Ravussin, 2016). Whole-room respiratory chamber analysis involves inputting air at a known gas composition into an airtight chamber, while constantly sampling outflowing air, measuring oxygen and carbon dioxide concentrations (Chen et al., 2020). Like direct calorimetry, a key limitation of this technique is that individuals are confined to a chamber and therefore quantifying free living energy expenditure outside of the chamber is impossible. Metabolic carts combine automatic and continual metabolic gas analysis systems. Indirect calorimetry measures the difference in oxygen and carbon dioxide contents between inspired and expired air, as well as per minute ventilation, enabling the calculation of oxygen consumption and carbon dioxide production (Anslie et al., 2003). Indirect calorimetry calculates the respiratory exchange ratio, informing the ratio of carbohydrate and fat being oxidised (McClave et al., 2003). Caloric equivalents for carbohydrate and fat can then be used to calculate the energy expenditure of an individual (McClave et al., 2003). Metabolic cart systems are attached to an individual by either a face mask, mouthpiece, metabolic hood, or canopy hood (Anslie et al., 2003). Some of these systems are fixed and require the individual to be in a static location, such as lying down (such as the metabolic hood), or on a treadmill or ergometer (such as the Cosmed Quark CPET; Cosmed, 2024). Portable metabolic carts are also available, such as the Cosmed K5 (Cosmed, 2024), whereby the system and power supply are attached to a backpack, allowing for analysis in free living conditions. The Cosmed K4 (previous version prior to the Cosmed K5), has previously been used to quantify the energy expenditure of elite male squash players during simulated match play (Girard et al., 2007).

4.2.1.3 Doubly Labelled Water

The doubly labelled water technique is seen as the reference standard of measuring energy expenditure in free living individuals and is a variation of indirect calorimetry, whereby energy expenditure is calculated via the quantification of carbon dioxide production (Westerterp, 2017*a*). The doubly labelled water technique involves enriching the body water of an individual with heavy oxygen (^{18}O) and heavy hydrogen (^{2}H) and calculating the differences in washout kinetics between the isotopes. The oxygen isotope mixes with body water as well as carbon dioxide in bicarbonate pools and is therefore lost as water and carbon dioxide (Westerterp, 2017*a*). This contrasts with the hydrogen isotope which only mixes with body water, and as a result is only lost as water (Westerterp, 2017*a*). Consequently, the rate of carbon dioxide production, and as a result energy expenditure, can be calculated through quantifying the washout of the oxygen and hydrogen isotopes through the following formula:

$$rCO_2(mol) = \left(\frac{N}{2}\right)(K_{18} - K_2)$$

rCO_2 = Rate of carbon dioxide production
mol = Molecule
N = Body water volume (mol)
2 = Constant reflecting that 1 mol CO_2 removes 2 oxygen atoms
K_{18} = Elimination rate of heavy oxygen (^{18}O)
K_2 = Elimination rate of heavy hydrogen (^2H)

Individuals are typically dosed with at least 1.8 g water per kilogram of body water with 10% heavy oxygen (^{18}O) and 0.12 g water per kilogram of body water with 99% heavy hydrogen (^2H) (International Atomic Energy Agency, 2009). Initial background enrichment of body water for heavy oxygen is increased by 180 ppm from 2000 ppm to 2180 ppm, whereas initial background enrichment of body water for heavy hydrogen is increased by 120 ppm from 150 ppm to 270 ppm (Westerterp, 2017*a*). This level of isotope enrichment is considered safe and there are not foreseen to be any health-related issues (Jones & Leathdale, 1991). Samples to quantify oxygen and hydrogen isotope washouts are typically collected via urine but can be collected through blood or saliva (Westerterp, 2017*a*). A baseline urine sample is firstly collected to measure the initial background enrichment level of body water for heavy oxygen and heavy hydrogen, before consuming the bolus dose of heavy oxygen and heavy hydrogen. Although there are varying protocols for equilibration (^{18}O and ^2H to mix with body water and bicarbonate pools) depending on the body water component of an individual, this is typically done overnight (Westerterp et al., 1995). Further samples are then collected to quantify the washout of heavy oxygen (^{18}O) and heavy hydrogen (^2H). In its simplest form, this could be one sample at the termination of the observation period, typically 7 to 21 days after initial enrichment. However, samples are usually taken on a daily or bi-daily basis. Samples are typically stored in cryogenic vials to prevent isotope fractionation through evaporation (Schoeller et al., 1986) and isotope exchange through perfusion (Westerterp et al., 1995). The samples are then analysed via isotope ratio mass spectrometry by either converting or equilibrating the urine samples into simple gases with heavy oxygen (^{18}O) being converted into CO_2 and heavy hydrogen (^2H) being converted into H_2 (Westerterp, 2017*a*). The difference between the two isotopes quantifies the carbon dioxide production, with this being converted into an estimate of energy expenditure (Brouwer, 1957). This estimate is shown to be negligible not exceeding ± 2% (Black et al., 1986). Overall, the doubly labelled water technique is shown to have an accuracy of 2 to 8% in adult individuals when compared against direct calorimetry, with variations in accuracy depending on the loading dose of the isotopes, length of the analysis and number of samples collected (Schoeller, 1988). The sample analysis has an accuracy of <0.5 ppm, displaying high levels of accuracy (Wong & Clarke, 2012; Wong & Clarke, 2015).

4.2.1.4 Metabolic Equivalents

Metabolic equivalents (METs) can be used to estimate energy expenditure (Jetté & Sidney, 1990). One MET is defined as equates the amount of oxygen consumed at rest while sitting in a chair and can be calculated through the following formula:

$$One\ MET = 3.5mL/O_2/\min x\ kg\ body\ mass$$

Indexes have been developed to quantify the MET of a variety of activities (Ainsworth et al., 2000*a*; Ainsworth et al., 2000*b*; Herrmann et al., 2024), enabling the estimation of energy expenditure by converting the time spent performing a particular activity by its MET. METs are typically used in epidemiological studies whereby there are many participants, enabling them to self-report their physical activities (Bryne et al., 2005). Body mass will affect the energy expenditure of an individual so METs are calculated in terms of O_2 per unit of body mass (Jetté & Sidney, 1990). The accuracy of METs are influenced by an individual's ability to report their physical activity level and consequently it may have low levels of inter-rater reliability (Blair et al., 1985; Jetté & Sidney, 1990). The energy expenditure of an individual is also influenced by the accuracy of the MET level of an activity and therefore if this is incorrect, there will be inaccuracies in energy expenditure. Metabolic equivalents were created to quantify energy expenditures in large populations of health research, and not specifically to quantify energy expenditure with precision (Ainsworth et al., 2000*a*; Ainsworth et al., 2000*b*; Herrmann et al., 2024). Metabolic equivalents have been shown to overestimate resting energy expenditure in health individuals by 20-35%, developing concerns about its validity (Bryne et al., 2005).

4.2.1.5 Heart Rate Monitoring

Heart rate monitoring can be utilised to estimate energy expenditure as there is a linear relationship between heart rate and oxygen consumption (Achten & Jeukendrup, 2003), as well as useful assessment of physical activity intensity (Ainslie et al., 2003). It is understood that there are many inter-individual differences such as age, sex, fitness level, and movement efficiency which can affect heart rate (Achten & Jeukendrup, 2003). Therefore, while heart rate may be appropriate to quantify energy expenditure in a large cohort of individuals, it lacks validity when analysing individual participants in studies (Spurr et al., 1988; Ceesay et al., 1989; McCrory et al., 1997). Spurr et al., (1998) reported that there were -15% to + 20% in energy expenditure among individuals when compared against indirect calorimetry. To counteract this, an individualised calibration of heart rate can be quantified to calculate energy expenditure (Christensen et al., 1983). This can be achieved by putting an individual through a variety of progressive intensity workloads ranging from light to strenuous, while measuring heart rate, oxygen consumption (VO_2), and carbon dioxide production

(VCO_2) (Spurr et al., 1988). Despite this, other factors such as emotional stress, dehydration, environmental conditions such as ambient temperature and humidity, and illness may all influence heart rate while not influencing VO_2 and consequently energy expenditure (Christensen et al., 1983; Spurr et al., 1988). Another limitation of utilising heart rate monitoring to calculate daily energy expenditure is that while there is a close relationship between heart rate and energy expenditure at moderate to severe intensities, there isn't a relationship at rest or low intensity activity (Ceesay et al., 1989). Energy expenditure estimates over a 24-hour period have been shown to have up to a 30% error in individuals (Davidson et al., 1997).

4.2.1.6 Chosen Tools to Quantify Energy Expenditure

The study utilised the doubly labelled water technique to quantify energy expenditure over the 7-day microcycle. Despite direct calorimetry being proposed as the reference standard for human metabolism, this was not possible in the present study, due to measuring energy expenditure in free living individuals while undergoing their training programme (i.e. can't live in the calorimeter). Indirect calorimetry has been utilised in squash before (Girard et al., 2007), using the Cosmed K4. While this may be appropriate to measure metabolism during matchplay, although it may alter players movement characteristics on court, it is unrealistic to wear during a 7-day microcycle. For example, the battery life of the system is four hours (Cosmed, 2024*c*) and is also likely to disrupt sleeping habits, both from a practicality perspective, and also to change the battery every four hours during periods of sleep. Metabolic equivalents are typically used during epidemiological studies and rely on and would rely on an accurate MET index for squash. This is likely to have not been quantified using elite squash players (due to being predominantly used in a health setting) and therefore may lack validity. Heart rate may be accurate during periods of activity but shown to have high variability and lack validity in comparison to direct calorimetry during periods of rest. Therefore, the doubly labelled water technique was seen as the reference standard measure of energy expenditure in free living individuals and utilised in the study.

To quantify energy availability, active energy expenditure needs to be quantified. Indirect calorimetry such as the Cosmed K4 may be the most reliable and valid tool, however, this system may alter players movement characteristics on court or in resistance-based sessions (e.g. trying to squat with the system attached). Players also trained during periods when the principal researcher was not present, due to players being based in a variety of locations. Therefore, each player would have to set the system up each time for each session and this was seen as an unrealistic burden on the players. Consequently, as heart rate has been shown to be accurate during periods of moderate to strenuous activity, this was utilised to quantify active energy expenditure during exercise and subsequently this data was used to calculate the energy availability of each player. This method is not without limitations as discussed in the 'discussion section' (see section 4.3.5).

4.2.2 Energy Intake

The energy intake of an individual can be quantified through 24 hours dietary recall, self-reported food diaries, food frequency questionnaires, and image assisted dietary assessment such as snap-N-send (Lam & Ravussin, 2016; Costello et al., 2017).

4.2.2.1 Twenty-Four-Hour Dietary Recall

Twenty-four-hour dietary recalls involve interviewing an individual to ascertain their dietary intake over the previous 24 hours (Lam & Ravussin, 2016). The quality of data collected depends on the skill of the practitioner interviewing the individual and the individuals buy in to accurately report back their intake (Lam & Ravussin, 2016). Checklists and structure questions may optimise the consistency of the recall process and probe for forgotten foods and meals. A disadvantage of the 24-hour dietary recall is that if completed on a single basis, it may lack representability and therefore multiple recalls over a period may be more appropriate to obtain a greater insight into an individual's dietary habits.

4.2.2.2 Self-Reported Food Diaries

Self-reported food diaries require individuals to write down everything they consume over a specific period (e.g. 3-7 days). Individuals may alter their dietary habits as they are aware that they are being recorded (Ravelli & Schoeller, 2020). To increase the accuracy of reporting, individuals may be asked to weigh their food intake (Burrows et al., 2019) and is seen as the gold standard of energy intake reporting (Lam & Ravussin, 2016). However, this can be impractical for individuals. More recently, electronic applications such as My Fitness Pal (MyFitnessPal Inc, San Francisco, USA) and Nutritics (Nutritics Ltd, Ireland) have been developed whereby individuals can input their own dietary intake. This makes it more plausible to record the dietary intakes of large populations of individuals such as in epidemiological studies. Energy intake quantified by electronic applications have been shown to be comparable to food diaries collected by dietitians (Raatz et al., 2015) and have been validated against nutritional biomarkers (Lassale et al., 2015; Lassale et al., 2016).

4.2.2.3 Food Frequency Questionnaire

A food frequency questionnaire is routinely used in epidemiological studies and requires individuals to report how frequently they consume certain foods throughout a specific period (Lam & Ravussin, 2016). Food frequency questionnaires are typically utilised to rank individuals and their dietary habits rather than quantify energy expenditure (Lam & Ravussin, 2016). They are reported to have low accuracy when measuring energy intake, underestimating energy intake by up to 36% (Molag et al., 2007). Food frequency questionnaires have weak to moderate correlation (Oxford food frequency questionnaire = 0.4-0.6; Cambridge food frequency questionnaire = 0.3-0.4; Bingham et al., 1994).

4.2.2.4 Image Assisted Dietary Assessments

Image assisted dietary assessments involve using an image as a reference of food intake. This can also be combined with text to provide a description of the food such as what the meal contains or the weight of ingredients (Gemming et al., 2015). This method has been validated among elite adolescent athletes, displaying a small mean bias for underreporting energy intake over a 96-hour period (-0.75 $MJ \cdot day^{-1}$; 95% confidence interval [CI] for bias = -5.7% to -2.2%, $p < 0.001$; Costello et al., 2017). A limitation of image assisted dietary assessments is that the dietary analysis relies upon picture-based portion size estimation by the analyser. Inter-practitioner reliability has been shown to be poor with sports nutrition practitioners underreporting energy intake in simple day meals and complex day meals (Simple day meals: mean difference = −1.5 $MJ \cdot day^{-1}$, typical error of estimates = 10.1%; complex day meals: mean difference = -1.2 $MJ \cdot day^{-1}$; typical error of estimates = 17.8%; Stables et al., 2021).

4.2.2.5 Chosen Tools to Quantify Energy Intake

The present study utilised a combination of weighed food method, Snap'N'Send and 24-hour dietary recall (Bingham et al. 1994; Costello et al., 2017). These three methods combined have been shown to enhance the reliability of the assessment of energy intake (Thompson and Subar, 2017) and is consistent with other studies which have quantified the dietary intake of elite athletes (Anderson et al., 2017; Anderson et al., 2019; Hannon et al., 2021; Stables et al., 2023). Despite being previously utilised with elite squash players, food frequency questionnaires were not utilised due to their low accuracy when measuring energy intake.

4.3 Hypothesis

Elite male squash players are shown to have high energy expenditures during simulated match play (Girard et al., 2007) and are reported to engage in 11 training session per week, conveying the high training demands of players during a microcycle (James et al., 2021). Previous research looking at the energy balance of elite athletes has reported mismatches between energy intake and energy expenditure, with athletes often under fuelling. Based on anecdotal data collected by the researcher, they had also experienced high energy expenditures (>5,000 Kcals), with mismatches in energy intake (Anderson et al., 2017). Therefore, it was hypothesised that elite male squash players would have high energy expenditures during a microcycle (4000-5000 Kcals·day), with a mismatch in energy intake.

4.4 Doubly Labelled Water Assessment of Elite Male Squash Player's Energy Balance During a Seven Day Training Microcycle

4.4.1 Abstract

No previous research has quantified the energy balance of elite male squash players during a training microcycle. Consequently, the aim of this study was to concurrently quantify energy expenditure (EE), energy intake (EI) and energy availability (EA) among a cohort of elite male squash players to understand the energy balance of elite male squash players. Three elite male squash players were assessed during a 7-day training microcycle for TL (via heart rate monitoring, and sRPE), EE (via doubly labelled water technique), and EI (via weighed food method, Snap'N'Send photographic method, and 24-hour dietary recall). Mean daily EE was 4,210 ± 1,017 Kcals, with mean daily EI being 3,389 ± 981 Kcals, conveying a mean daily negative energy balance of 821 Kcals. Mean EA over the microcycle was 31.68 ± 17.91 $Kcal \cdot kg^{-1}$ $FFM \cdot d^{-1}$ indicating reduced EA. The study highlights that elite male squash players exhibit a high energy expenditure throughout a training microcycle and may follow poor nutrition strategies such as severe energy restriction, leading to low energy availability and sub optimal carbohydrate intake. These sub optimal nutritional practices may lead to reduced training performance and symptoms of relative energy deficiency in sport.

4.4.2 Introduction

Squash is a high intensity intermittent racket sport (Lees, 2003). At elite standard, squash requires a blend of technical, tactical, physical, and psychological capabilities (Jones et al., 2018). During simulated match play, elite male players are reported to elicit a mean energy expenditure of 1179 ± 148 $Kcal \cdot h^{-1}$, mean heart rate of 92 ± 3 % heart rate maximum, mean blood lactate concentrations of 8.3 ± 3.4 $mmol \cdot L^{-1}$, and mean respiratory exchange ratio of 0.94 ± 0.04 (Girard et al., 2007). This highlights the high intensity nature of the sport and high energetic demands placed on players to maintain performance during match play.

To sustain the high intensity demands of squash and simultaneously enhance technical capabilities, elite squash players engage in a variety of on and off-court training sessions (Gibson et al., 2019; James et al., 2021). These include group (i.e. conditioned games and routines), technical (i.e. 1-1 session with a coach), match play, ghosting (i.e. simulated squash-specific movements such as lunges into areas of the court), conditioning, and resistance sessions (Gibson et al., 2019; James et al., 2021). James et al., (2021) quantified the training load of elite Malaysian squash players across a variety of internal (i.e. psychophysiological) and external demands (i.e. musculoskeletal) (Neilsen et al., 2018; Impellizzeri et al., 2019). Players engaged in a mean total of 11 training sessions per week, equating to a mean training time of 258 minutes per week. James et al., (2021) reported that group sessions were the longest in duration (79 ± 12 min), eliciting the greatest session rating of perceived exertion (sRPE) (5793 ± 1477 a.u.) and high intensity movements (189 ± 88 >3.5 $m \cdot s^{-1}$) due to their longer duration in comparison to other sessions. Match play sessions were shown to have the greatest mean heart rate (81 ± 6 % HR_{max}) and greatest time > 90% heart rate maximum (10 ± 10 min), while conditioning sessions were shown to have the greatest RPE (77 ± 16 a.u.) and player load (519 ± 153 a.u.).

Given the apparent fluctuations of training load on a session-by-session basis, it is likely that energy expenditure is highly variable on a session-by-session basis. Consequently, the concept of 'periodised' nutrition has been developed (Jeukendrup, 2017) to ensure athletes are fuelling appropriately throughout variable training loads to optimise health (Mountjoy et al., 2023), achieve body composition goals (Stellingwerf et al., 2019), and augment training adaptations (Impey et al., 2018). It is also likely that elite male squash players have a high energy expenditure due to the high intensity demands of the sport (Girard et al., 2007). This may put players at risk of low energy availability (Mountjoy et al., 2023). Energy availability is a concept which is defined as the left-over dietary energy which can be utilised for optimal function of bodily systems after accounting for exercise energy expenditure, expressed relative to an individual's fat free mass (Areta et al., 2021; Mountjoy et al., 2023). Chronic low energy availability, historically defined at a threshold of <30 $Kcal \cdot kg^{-1}$ $FFM \cdot d^{-}$

[1] has been shown exhibit a variety of negative health outcomes in male athletes such as impaired reproductive function (Hooper et al., 2017), impaired bone health (Heikura et al., 2018;), impaired gastrointestinal function (Kuikman et al., 2021), impaired energy metabolism and regulation (Stenqvist et al., 2021), impaired haemological status (Hennigar et al., 2021), impaired glucose metabolism (Kojima et al., 2022), mental health issues (Torstveit et al., 2019), self-reported sleep disturbances (Pardue et al., 2017), impaired cardiovascular function (Langan-Evans et al., 2021), reduced skeletal muscle function (Pasiakos et al., 2010), impaired growth and development (Nindl et al., 2007) and reduced immunity (McGuire et al., 2023). These also have negative consequence on performance outcomes in male athletes such as decreased athlete availability (Drew et al., 2018), decreased training response (Woods et al., 2018), decreased recovery (Gillbanks et al., 2022), decreased motivation (Gillbanks et al., 2022), decreased muscle strength (Jurov et al., 2022), decreased endurance performance (Keay et al., 2018), and decreased power performance (Woods et al., 2018). Despite these potential negative consequences, there is currently no research quantifying either the energy expenditure, energy intake, or overall energy balance of elite male squash players. Therefore, it is difficult for sports nutrition practitioners to provide evidence-based recommendations to elite male squash players, due to a paucity of information regarding specific nutrition recommendations in the sport. This is unlike in other racket sports such as tennis (Ranchordas et al., 2013) and high intensity intermittent sports such as soccer (Collins et al., 2020).

The doubly labelled water technique is the reference standard method of assessing energy expenditure in free-living individuals (Westerterp, 2017). The doubly labelled water technique has been used to provide estimates of energy expenditure in other sports such as tennis (Ellis et al., 2021; Ellis et al., 2023*a*; Ellis et al., 2023*b*), table tennis (Sagayama et al., 2017) and badminton (Watanabe et al., 2008), as well as other high intensity intermittent sports such as basketball (Silva et al., 2013), rugby league (Costello et al., 2018; Smith et al., 2018; Costello et al., 2019), rugby union (Morehen et al., 2016; Smith et al., 2018), and soccer (Ebine et al., 2002; Anderson et al., 2017; Anderson et al., 2019; Brinkmans et al., 2019; Hannon et al., 2021; Morehen et al., 2022; Dasa et al., 2023; Stables et al., 2023). Much of the literature has also quantified dietary intake alongside energy expenditure (Ebine et al., 2002; Silva et al., 2013; Morehen et al., 2016; Anderson et al., 2017; Sagayama et al., 2017; Anderson et al., 2019; Brinkmans et al., 2019; Hannon et al., 2021; Morehen et al., 2021; Dasa et al., 2023; Stables et al., 2023) to report any mismatches in recommendations and practice (Heikura et al., 2017). This data has enabled the creation of sport-specific nutritional guidelines to guide practitioners to appropriately advise athletes in other sports such as tennis (Ranchordas et al., 2013) and soccer (Collins et al., 2020).

To estimate athletes' total energy expenditure, a physical activity level (PAL) score can also be calculated (Westerterp, 2013). The PAL score is defined as any energy expended through bodily movements from skeletal muscle and is calculated as a magnitude of an individual's resting metabolic rate (RMR) and their energy expenditure (Westerterp, 2013). The PAL score is a useful tool to quantify the physical demands of an individual or sport (i.e. no physical activity; sedentary and light activity; moderately active; vigorously active) and can be used to compare individual's activity levels or between sports (Westerterp, 2013). No previous research has quantified the PAL score of elite male squash players and doing so would enable for comparison of physical activity levels in comparison to different sports, relative to an individual's resting metabolic rate and energy expenditure.
Research into the dietary habits of elite Spanish squash players via a food consumption frequency questionnaire (Ventura-Comes et al., 2019) conveyed that players practices are sub-optimal, under consuming carbohydrate rich foods such as bread, potatoes, pasta, and rice in comparison to non-specific carbohydrate guidelines (Burke et al., 2011). This may indicate that players do not consume enough carbohydrate to sustain their training load and may be at risk of low carbohydrate availability (Kojima et al., 2020; Mountjoy et al., 2023), which often occurs simultaneously with low energy availability (Logue et al., 2018). Turner et al., (2021) reported that although players had poor knowledge of contemporary macronutrient guidelines, they were still able to identify optimal pre, during and post exercise nutrition strategies. Consequently, it is relevant to consider whether non-specific carbohydrate and energy expenditure guidelines are suitable for elite squash players. Food frequency questionnaires have also been shown to display poor validity and reliability (Thompson & Subar, 2017) and therefore more valid and reliable methods to quantify dietary intake such as weighed food diaries, Snap 'N' Send and 24-h dietary recall (Bingham et al., 1994; Costello et al., 2017) need to be employed.

Therefore, the aim of this study was to 1) quantify energy expenditure using the doubly labelled water technique, and 2) estimate energy intake through self-reported 7-day food dairy. This work is original because it is the first to report the energy balance of elite squash players throughout a microcycle, using the most rigorous methodological tool, doubly labelled water, and have a significant practical impact for the field by providing a basis from which to provide specific nutritional recommendations for elite squash players in context to their training load.

4.4.3 Methods

4.4.3.1 Participants

Three elite or world class (McKay et al., 2022) male squash players took part in the study. Table 5 outlines the characteristics of each player. All players remained injury free throughout the course of the study and followed a decentralised training programme. Training was undertaken in a variety of facilities across the country. The research was approved by an institutional ethics committee (ER33101394). All participants provided informed consent before taking part and data were collected according to the principles of the 7th revision of the Declaration of Helsinki (World Medical Association, 2001).

Table 5. Player's characteristics

Player (n)	**Player level (McKay et al., 2022)**	**Age (y)**	**Stature (m)**	**Body Mass (kg)**	**Sum of 8 skinfolds (mm)**	**Resting Metabolic Rate (Kcals)**	**Player goals**
1	5	25	1.85	90.2	75.6	2141	Optimise body composition
2	5	22	1.85	81.8	51.4	1814	Fuel appropriately for training
3	4	23	1.80	75.6	51.7	-	Fuel appropriately for training
Mean ± SD		23 ± 2	183 ± 2.9	84.5 ± 7.2	59.6 ± 13.9	1978 ± 231	-

4.4.3.2 Study Design

Figure 11 displays a schematic overview of the study. The study was cross sectional in design. Data was collected during a 7-day microcycle within a pre-season training period. The week before the 7-day microcycle, each player's RMR and body composition were calculated (see below). Player three's RMR data was rendered void due to faulty equipment. Total energy expenditure was quantified using doubly labelled water technique (Westerterp, 2017). Total energy intake was measured via Snap'N'Send (Costello et al., 2017), weighed food method (Bingham et al., 1994), and 24-hour dietary recall (Bingham et al. 1994). Training load was quantified using heart rate monitoring and rating of perceived exertion during each training session. Players undertook their regular training regime as prescribed by their squash team.

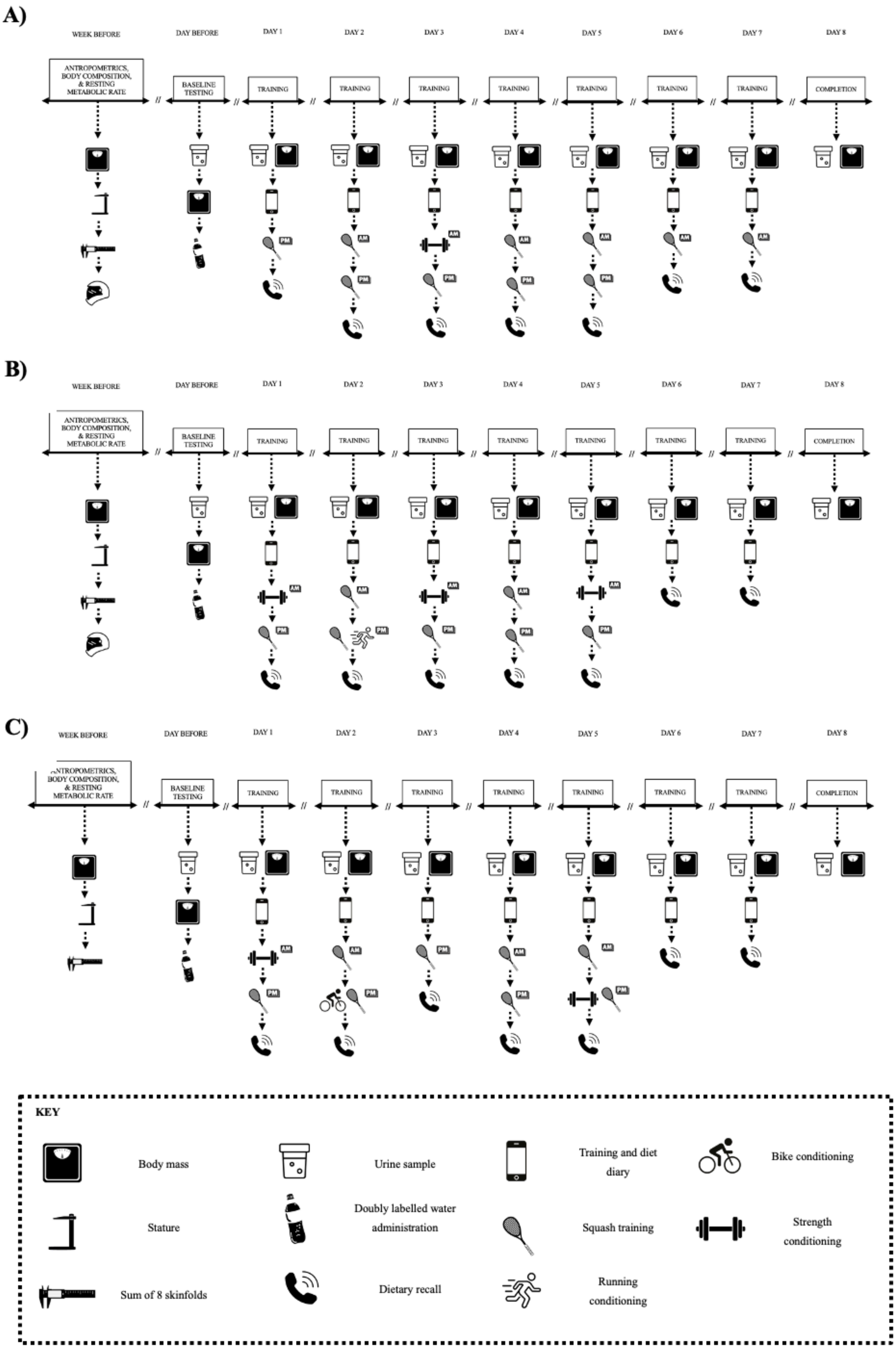

Figure 11. Schematic overview of (a) player one's study overview (b) player two's study overview (c) player three's study overview

4.4.3.3 Anthropometrics, Body Composition & Resting Metabolic Rate

Participants wore lightweight clothing for measurements of stature, body mass and sum of eight skinfold assessment, ensuring all jewellery was removed. Participant's stature and body mass were quantified using a stadiometer and scales (SECA, Alpha 220, Hamburg, Germany), with this being measured to the nearest 0.1 cm and 0.1 kg respectively. Measurements were undertaken by an International Society for the Advancement of Kinanthropometry (ISAK) level one practitioner according to ISAK guidelines (Marfell-Jones et al., 2006). Two measurements were taken for each anthropometric measurement, with a third being taken if the first two measured had a variability greater than 2%. The mean value was recorded where two measures were taken, with the median being recorded where three measures were taken.

Upon completion of all anthropometric measures, RMR was measured via open circuit indirect calorimetry (GEM Nutrition Ltd, UK), using the protocol outlined by Bone and Burke (Bone & Burke, 2018). The calorimeter was calibrated against known gas concentrations "zero" (0.0% O_2 and 0.0% CO_2) and "span" (20.0% O_2 and 1.0% CO_2) gases (BOC, Guildford, UK), prior to each assessment. After calibration and before data collection, participants relaxed for 10 minutes under a transparent ventilated hood in a supine position, in a dark, quiet, thermoneutral room. Subsequently, data was collected over a 20-minutes (2 x 10-minute duplicates), in which data from the second 10-minutes was used to quantify RMR. VO_2 and VCO_2 were quantified using the Haldane transformation (Haldane, 1918) and energy expenditure (Kcals·day^{-1}) using the Weir equation (Weir, 1949).

4.4.3.4 Training Load

Due to players undergoing training in different locations, each player reported their training via the mobile application WhatsApp (Facebook, California, USA) to quantify training load throughout the 7-day microcycle. Heart rate monitoring was used to quantify the cardiovascular demand of each session, with each player wearing a Polar H10 Heart Rate Sensor Band (Polar, Kempele, Finland) from the start of the warm-up to the completion of the warm-down of each session. The Heart rate sensor band transmitted data via bluetooth to the Polar Beat application (Polar, Kempele, Finland), storing the heart rate data, which was subsequently exported into a comma-separated value (CSV) file. Rating of perceived exertion (RPE) was quantified using the Foster modified CR10 scale (Foster et al., 2001) after each completed session. This was multiplied by the duration of each session to quantify session rating of perceived exertion (sRPE; Foster et al., 2001). The session duration was classified as the start of the warm-up to the completion of the warm-down. Players reported their RPE through the mobile application WhatsApp (Facebook, California, USA) when the principal investigator was not present. Players were educated on how to interpret the Foster modified CR10 scale prior to the 7-day microcycle so they could correctly interpret the scale, increasing the validity of the data collected.

4.4.3.5 Energy Expenditure

On the day before the 7-day microcycle, players were weighed to the nearest 0.1 kg (SECA, 875, Hamburg, Germany). Players then provided a baseline urine sample which was collected into a 35 ml cryogenic vial. Players then drank a single bolus dose of hydrogen (deuterium ^2H) and oxygen (^{18}O) stable isotopes in the form of water ($^2H_2{}^{18}O$) through glass vials. The desired dose was 5 % deuterium ^2H and 10 % ^{18}O. This was calculated according to each player's body mass, measured to the nearest decimal place, using the calculation:

$$^{18}O \text{ Dose} = [0.65 \text{ (body mass, g) x DIE}] / \text{IE}$$
$$\text{DIE} = \text{Desired initial enrichment} = 618.923 \text{ x body mass (kg)}^{-0305}$$
$$\text{IE} = \text{Initial enrichment} = 10\ \% = 100{,}000 \text{ ppm}$$

To ensure that all the bolus dose of doubly labelled water was consumed, each glass vial was refilled with additional water, with each player consuming.

During the 7-day microcycle, each player deposited their second urine pass of the day into a 35 ml cryogenic vial, with this being stored and frozen at -80ºC for subsequent analysis. The time of players' second urine pass of the day was recorded, as well as their body mass to the nearest 0.1 kg (SECA, 875, Hamburg, Germany). The first urine pass of the day was not used due to this being stored in the bladder overnight and therefore an inaccurate measure of energy expenditure (Westerterp, 2017). Urine samples were analysed to quantify total energy expenditure. Samples were compressed into capillary tubes before being vacuum distilled (Westerterp, 2017). The water from the subsequent distillate was used, being analysed in a liquid water analyser (Los Gatos Research; Berman et al., 2012). Samples were corrected to correct delta values to parts per million by analysing alongside three laboratory standards for each isotope and three international standards (Standard Light Arctic Precipitate, Standard Mean Ocean Water and Green Ice Sheet Precipitation). A two-pool model equation (Schoeller, 1988) was used to convert isotope enrichment to energy expenditure, assuming a food quotient of 0.85.

Fat free mass (FFM) was quantified from total body water analysis (^{18}O dilution space), with this technique being shown to have a 6.03 ± 0.93 % analytic error, within the acceptable range (Speakman et al., 2021)

4.4.3.6 Energy Intake

Energy intake was quantified through a self-reported 7-day food dairy via weighed food method, Snap'N'Send and 24-hour dietary recall (Bingham et al. 1994; Costello et al., 2017). These three methods combined have been shown to enhance the reliability of the assessment of energy intake (Thompson and Subar, 2017). Food diaries were completed via the mobile application WhatsApp (Facebook, California, USA), with players sending across details of any food or drink they consumed (i.e. name, mass and cooking methods), as well as an accompanying photo which was timestamped. Food diaries were cross-referenced with 24-hour dietary recall by the principal researcher after each day of completion. Each player attended an introductory workshop on how to complete the self-reported food diary as well as undergoing a three-day practice food diary prior to the two-week in season training period to highlight any issues or questions involving the self-reported food diary process.

Upon completion of the 7-day microcycle, food diaries were analysed by a Sport and Exercise Nutrition Register (SENr) accredited nutritionist using the nutrition analysis software Nutritics (Nutritics Ltd, Ireland). To ensure consistency of analysis, the principal researcher analysed all 7 days of each players' food diary. Energy intake was reported in kilocalories (Kcals) and kilocalories per kilogram of fat free mass ($Kcal \cdot kg \cdot FFM^{-1}$). Macronutrient intakes were analysed and reported in grams (g) and grams per kilogram of body mass ($g \cdot kg \cdot bm^{-1}$).

4.4.3.7 Statistical Analysis

All data are presented as mean ± standard deviation (*SD*). Training load data is reported for descriptive purposes. Physical activity level (PAL) was quantified through the following formula (FAO, et al., 2004; Westerterp, 2017):

$$Physical\ Activity\ Level = \frac{Mean\ energy\ expenditure}{Resting\ metabolic\ rate}$$

Total energy expenditure in relation to fat free mass was calculated through the following formula:

$$Kcalkg - 1\ FFM = \frac{Total\ energy\ expenditure\ (Kcals)}{Fat\ free\ mass\ (kg)}$$

Energy availability was calculated through the following formula:

$$Energy\ availability = \frac{Exercise\ energy\ expenditure - energy\ intake}{Kcalkg - 1\ FFM}$$

4.4.4 Results

4.4.4.1 Training Load

Table 6 displays the mean training load data for feeding, ghosting, group, match play, conditioning, and strength sessions among the three players.

Table 6. Mean training load data

Type of Session	Number of sessions (*n*)	Duration (min)	Mean Heart Rate (beats·min^{-1})	Maximum Heart Rate During the Session (beats·min^{-1})	Energy Expenditure (Kcals)	RPE	sRPE (a.u.)
Feeding	2	65 ± 28	128 ± 17	158 ± 10	641 ± 74	4 ± 0	260 ± 113
Ghosting	2	100 ± 0	137 ± 10	192 ± 3	1137 ± 209	8 ± 1	800 ± 141
Group	11	99 ± 25	133 ± 9	178 ± 9	1036 ± 225	7 ± 2	672 ± 283
Match play	5	91 ± 30	140 ± 10	182 ± 10	1102 ± 249	7 ± 2	696 ± 293
Conditioning	2	89 ± 10	135 ± 2	184 ± 9	874 ± 21	6 ± 0	534 ± 59
Strength	6	88 ± 30	114 ± 19	172 ± 13	665 ± 272	7 ± 2	573 ± 210

4.4.4.2 Energy Balance

Table 7 displays mean and individual energy expenditure and energy intake data.

Table 7. Mean and individual energy expenditure and energy intake data

		Mean	Player 1	Player 2	Player 3
Daily Energy Expenditure	Kcals·d^{-1}	4210 ± 1017	4746	4847	3037
	Kcal·kg·d^{-1}	49.82 ± 12.04	52.62	59.25	40.17
	Kcal.kg^{-1}.FFM	62.96 ± 10.72	68.34	69.92	50.61
	MJ·d^{-1}	17.61 ± 4.26	19.86	20.28	12.71
	kJ·kg·d^{-1}	208.45 ± 50.38	220.16	247.9	168.07
	kJ·FFM·d^{-1}	263.42 ± 44.85	285.93	292.55	211.75
Physical Activity Level (PAL)		2.5 ± 0.4	2.2	2.7	-
Daily Energy Intake	Kcals·d^{-1}	3389 ± 981	2354 ± 588	4305 ± 1120	3507 ± 658
	MJ·d^{-1}	14.18 ± 4.1	9.85 ± 2.46	18.01 ± 4.69	14.67 ± 2.75
Energy Availability	Kcal·kg^{-1} FFM·d^{-1}	32 ± 18	11	42	42
Carbohydrate	g	318 ± 149	282 ± 61	557 ± 120	318 ± 118
	g·kg·bm^{-1}	4.7 ± 2.1	2.9 ± 0.7	7 ± 1.5	4.2 ± 1.6

Protein	g	177 ± 37	145 ± 56	168 ± 39	218 ± 52
	g·kg·bm^{-1}	2.3 ± 0.6	1.7 ± 0.7	2.1 ± 0.5	2.9 ± 0.7
Fat	g	128 ± 44	78 ± 29	156 ± 73	151 ± 27
	g·kg·bm^{-1}	1.7 ± 0.6	0.9 ± 0.3	2.0 ± 0.9	2 ± 0.4
Fibre	g	31 ± 6	26 ± 12	29 ± 8	37 ± 8

MJ = Megajoules; kJ = Kilojoules

4.4.4.3 Player One

Player one's characteristics are reported in Table 5, with the players training schedule and load being reported in Table 8.

Table 8. Training schedule and load for player one

Microcycle Day	**Training Session (*n*)**	**Type of Session**	**Duration (min)**	**Mean Heart Rate (beats·min^{-1})**	**Max Heart Rate (beats·min^{-1})**	**Energy Expenditure (Kcals)**	**RPE**	**sRPE (a.u.)**
1	1	Match play	108	139	178	1403	7	756
Daily Total			**108**			**1403**		**756**
2	2	Group	115	125	176	1200	5	575
	3	Group	83	141	173	1109	6	498
Daily Total			**198**			**2309**		**1073**
3	4	Strength	73	149	173	1053	9	657
	5	Match play	82	151	178	1238	9	738
Daily Total			**155**			**2291**		**1395**
4	6	Group	94	138	182	1206	7	658
	7	Match play	50	145	169	659	5	250
Daily Total			**144**			**1865**		**908**
5	8	Group	81	134	168	1001	6	486
	9	Match play	60	144	173	800	6	360
Daily Total			**141**			**1801**		**846**
6	10	Group	64	143	173	884	6	384
Daily Total			**64**			**884**		**384**
7	11	Group	45	140	165	589	4	180
Daily Total			**45**			**589**		**180**
Mean ± STDEV	-	-	78 ± 22	141 + 7	174 ± 5	1013 ± 256	6 ± 2	504 ± 194

Mean daily energy expenditure for player one over the 7-day microcycle was 4746 Kcals, equating to a PAL of 2.2. When expressed in relation to FFM, energy expenditure was 68.34 Kcal·kg^{-1} FFM. Mean daily energy intake over the 7-day microcycle being reported as 2354 ± 588 Kcals·d^{-1}, resulting in a mean energy balance of -2,392 Kcals·d^{-1}. Consequently, energy availability was 11 Kcal·kg^{-1} FFM·d^{-1}. Figures 12A-C display the mean and daily macronutrient intake in grams (g), mean and daily macronutrient intake in g.kg.bm (g.kg.bm), and mean and daily energy intake (Kcals). Supplementary Table 88 reports player one's daily energy, macronutrient, and fibre intake.

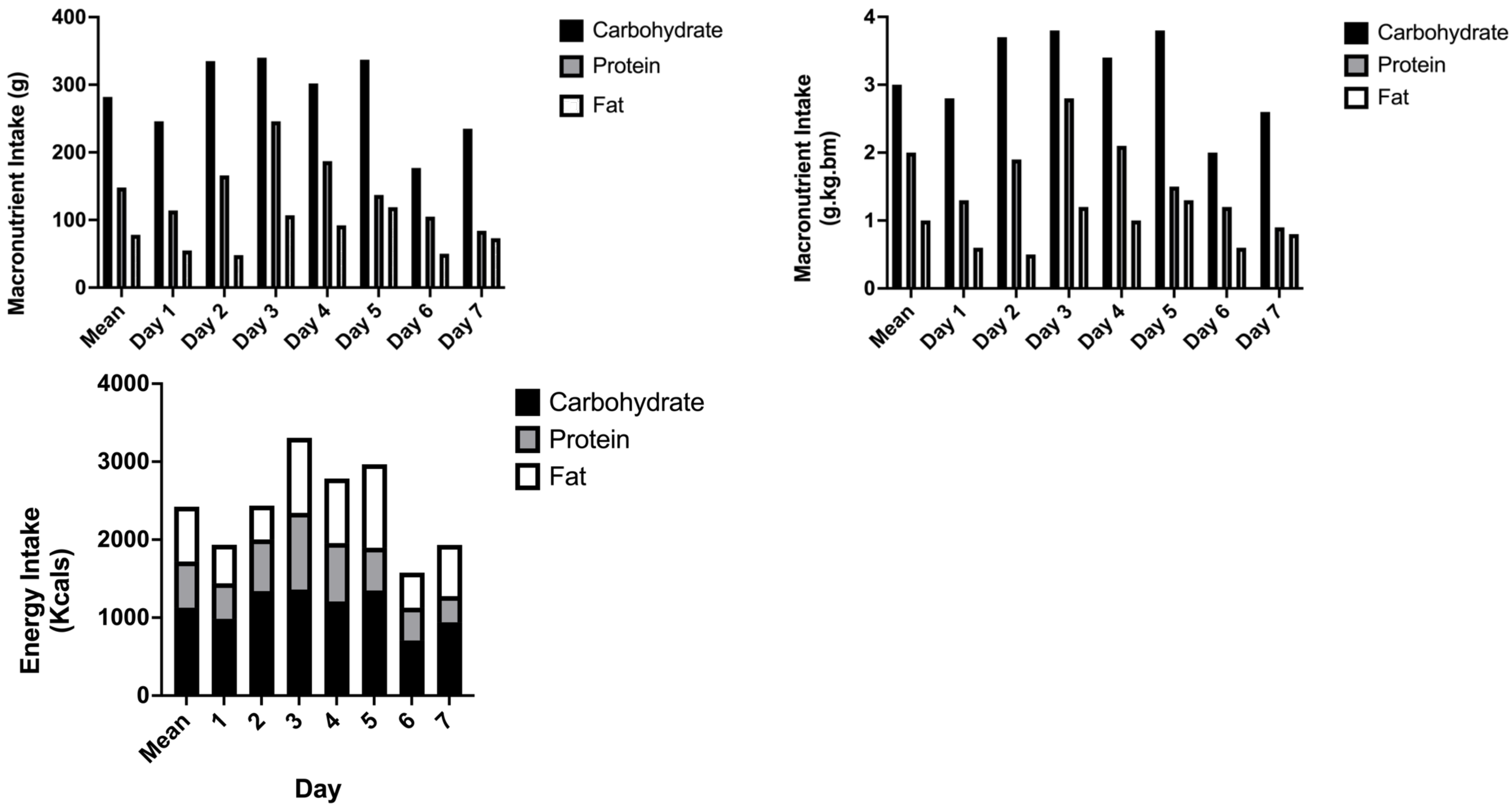

Figure 12. Player one's daily macronutrient intake reported in (A) grams and (B) grams per kilogram of body mass and (C) daily energy intake reported in Kcal

4.4.4.4 Player Two

Player two's characteristics are reported in Table 5, with the players training schedule and load being reported in Table 9.

Table 9. Training schedule and load for player two

Microcycle Day	Training Session (*n*)	Type of Session	Duration (min)	Mean Heart Rate (beats·min^{-1})	Max Heart Rate (beats·min^{-1})	Energy Expenditure (Kcals)	RPE	sRPE (a.u.)
1	1	Strength	133	105	186	832	6	798
	2	Group	125	146	192	1251	8	1000
Daily Total			**258**			**2083**		**1798**
2	3	Ghosting	100	144	194	1285	7	700
	4	Conditioning	96	136	190	889	6	576
Daily Total			**196**			**2174**		**1276**
3	5	Strength	90	118	181	745	8	720
	6	Group	80	125	176	772	4	320
Daily Total			**170**			**1517**		**1040**
4	7	Feeding	85	116	151	693	4	340
	8	Group	122	138	194	1454	8	976
Daily Total			**207**			**2147**		**1316**
5	9	Strength	95	97	176	483	6	570
	10	Match play	96	143	195	1231	8	768
Daily Total			**191**			**1714**		**1338**
Mean	-	-	102 ± 18	127 + 17	184 ± 14	964 ± 318	7 ± 2	677 ± 231

Mean daily energy expenditure for player two over the 7-day microcycle was 4,847 Kcals, equating to a PAL of 2.7. When expressed in relation to FFM, energy expenditure was 69.92 Kcal·kg^{-1} FFM. Mean daily energy intake over the 7-day microcycle was reported as 4305 ± 1120 Kcals·d. This conveys a mean energy balance of -542 Kcals per day. Consequently, energy availability was 42 Kcal·kg^{-1}FFM·d^{-1}. Figures 13A-C display the mean and daily macronutrient intake in grams (g), mean and daily macronutrient intake in g.kg.bm (g.kg.bm), and mean and daily energy intake (Kcals). Supplementary Table 89 reports player two's daily energy, macronutrient, and fibre intake.

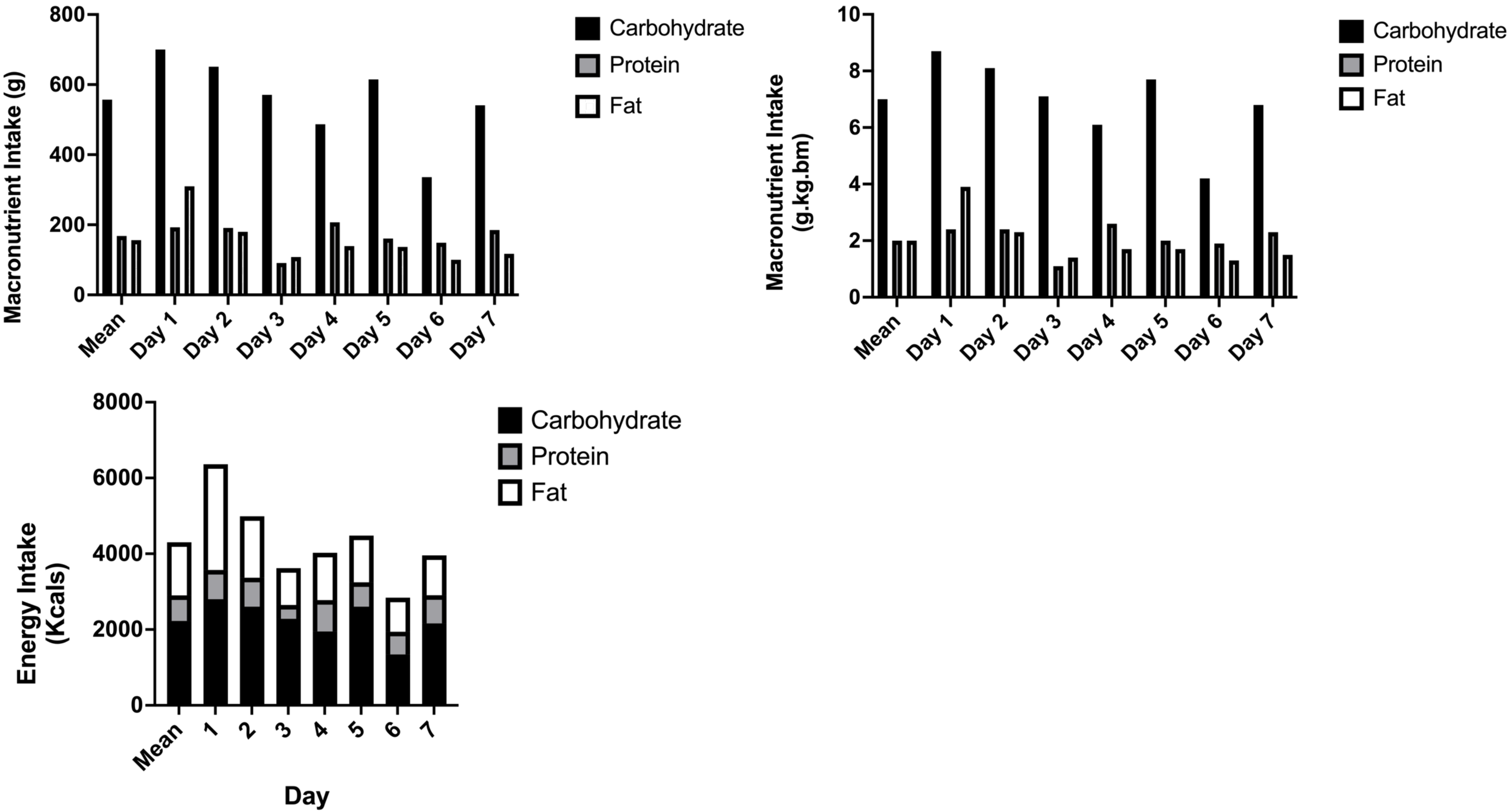

Figure 13. Player two's daily macronutrient intake reported in (A) grams and (B) grams per kilogram of body mass and (C) daily energy intake reported in Kcals

4.4.4.5 Player Three

Player three's characteristics are reported in Table 5, with the players training schedule and load being reported in Table 10.

Table 10. Training schedule and load for player three

Microcycle Day	Training Session (*n*)	Type of Session	Duration (min)	Mean Heart Rate (beats·min^{-1})	Max Heart Rate (beats·min^{-1})	Energy Expenditure (Kcals)	RPE	sRPE (a.u.)
1	1	Strength	42	106	154	283	5	210
	2	Group	121	124	182	1072	8	968
Daily Total			**163**			**1355**		**1178**
2	3	Ghosting	100	130	190	989	9	900
	4	Conditioning	82	133	177	859	6	492
Daily Total			**182**			**1848**		**1392**
3	5	Match play	133	124	186	1176	8	1064
Daily Total			**133**			**1176**		**1064**
4	6	Group	134	122	177	968	8	1072
	7	Group	81	126	165	783	5	405
Daily Total			**215**			**1751**		**1477**
5	8	Group	79	134	183	833	9	711
	9	Strength	96	106	159	595	5	480
Daily Total			**175**			**1428**		**1191**
Mean ± STDEV	-	-	96 ± 30	123 + 10	175 ± 13	835 ± 267	7 ± 2	630 ± 372

Mean daily energy expenditure for player three over the 7-day microcycle was 3037 Kcals. When expressed in relation to FFM, energy expenditure was 50.61 Kcal·kg^{-1} FFM. Mean daily energy intake over the 7-day microcycle was reported as 3507 ± 658 Kcals·day. This conveys a mean energy balance of +470 Kcals per day. Consequently, energy availability was 42 Kcal·kg^{-1} FFM·d^{-1}. Unfortunately, the PAL could not be calculated due to faulty equipment when measuring resting metabolic rate. Over the 7-day microcycle, the player engaged in 11 training sessions, with Table 3 conveying the training load of these sessions. Figures 14A-C display the mean and daily macronutrient intake in grams (g), mean and daily macronutrient intake in g.kg.bm (g.kg.bm), and mean and daily energy intake (Kcals). Supplementary Table 90 reports player three's daily energy, macronutrient, and fibre intake.

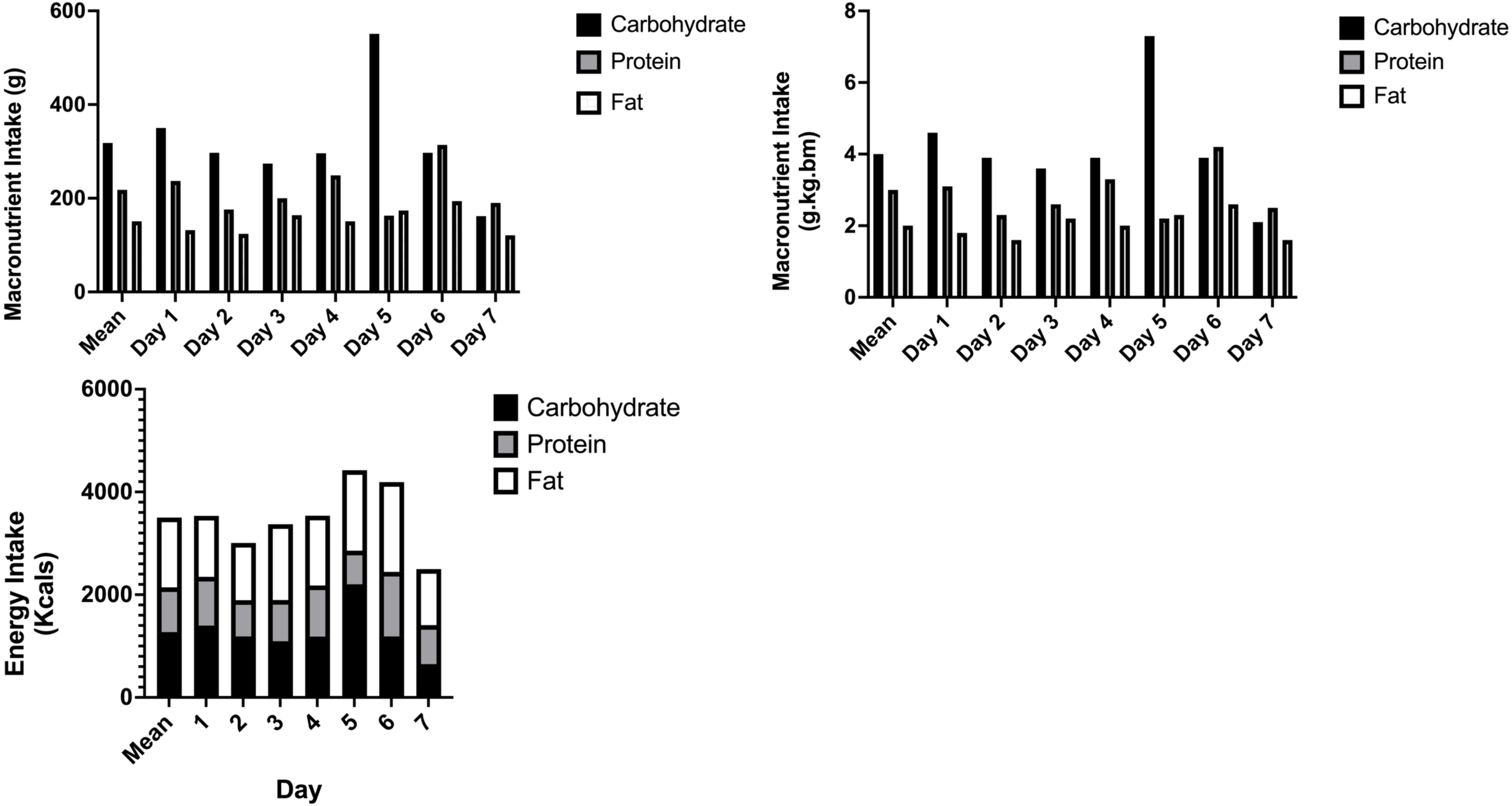

Figure 14. Player three's daily macronutrient intake reported in (A) grams and (B) grams per kilogram of body mass and (C) daily energy intake reported in Kcals

4.4.5 Discussion

The main aims of this study were to 1) quantify energy expenditure using the doubly labelled water technique, and 2) estimate energy intake through a self-reported 7-day food dairy. The main findings of the study were (1) elite male squash players expended a mean daily energy expenditure of 4,210 ± 1,017 Kcals (2) players ingested a mean daily energy intake of 3,389 ± 981 Kcals (3) players exhibited a mean daily energy balance of -821 Kcals; (4) players had a mean energy availability of 32 ± 18 Kcal·kg^{-1} FFM·d^{-1} throughout the microcycle (5) the mean PAL score of elite squash players was 2.5 ± 0.4. This work is original in that it is the first study to quantify the energy balance of elite male squash players, using the reference standard and highly rigorous doubly labelled water technique. This work will make a significant impact in the field by providing a basis for specific nutritional practices. Quantifying the energy balance of elite male squash players highlights players current practices and whether they are optimal in relation to their training load, while providing data to create specific nutritional guidelines for squash players to inform future practice. This study implemented rigorous methodological procedures such as the doubly labelled water method which is the reference standard to assess energy expenditure (Westerterp, 2017). The study also utilised a combination of three methods to assess energy intake, a self-reported 7-day food dairy via weighed food method, Snap'N'Send and 24-hour dietary recall (Bingham et al. 1994; Costello et al., 2017), with these three methods combined have been shown to enhance the reliability of the assessment of energy intake (Thompson and Subar, 2017).

In the first investigation of its kind, using the doubly labelled water method, we identified the mean energy expenditure among the three players over the 7-day microcycle was 4,210 ± 1,017 Kcals. The doubly labelled water method provides a robust assessment of energy expenditure through enriching an individual with heavy oxygen (^{18}O) and hydrogen (^{2}H) and measuring the difference in the washout kinetics of the isotopes (Westerterp, 2017). It is the only method of measuring energy expenditure without interference to the behaviour of individuals, and therefore seen as the reference standard for measuring energy expenditure in free living individuals (Westerterp, 2017). To contextualise the energy expenditure data reported in elite male squash players, it is relevant to compare to other racket sports and high intensity intermittent sports which have utilised the doubly labelled water method. Ellis et al., (2021) reported the energy expenditure of an elite male tennis player. Data collection was split into two separate periods, with period one being a training microcycle with one professional ATP international match, and period two being a competition microcycle consisting of five ATP international matches and a reduced training load. During period one, the tennis player expended less energy than reported in the present study, expending 3712 Kcals·d^{-1} or 56.3 Kcal·kg^{-1} FFM when expressed relative to FFM, less than elite male squash players (62.96 ± 10.72 Kcal·kg^{-1} FFM). Consequently, elite male squash players are reported to expend 13.4% more than elite male tennis players during a training microcycle. During the competition period, the tennis player expended more than the present study, expending 5520 Kcals·d^{-1} or 83.7 Kcal·kg^{-1} FFM when expressed relative to FFM. This highlights the variance in energy expenditure on a microcycle basis and the influence of match play on the energy expenditures of tennis players. The present study quantified the training load and energy expenditure of elite male squash players during a training microcycle, and future research should aim to quantify the player load and energy expenditure of elite male squash players during a competition. This would ascertain whether the player load and energy expenditure are greater during competition periods, as experienced in elite male tennis and devise specific nutritional guidelines for elite male squash players during competition.

The present study reports that energy expenditure in elite male squash players was greater than reported in elite male soccer players during an in-season microcycle (3566 ± 585 Kcals·d^{-1}; Anderson et al., 2017). Elite soccer players during an in-season microcycle are reported to have rest days and reduced training load to facilitate preparation and recovery for competitive matches (Malone et al., 2015), unlike elite squash players who will sustain consistent training loads until they reach a competition phase. Elite male squash players were shown to expend less energy than elite rugby league players during an in-season training and competition microcycle (5374 ± 645 Kcals·d^{-1}; Morehen et al., 2016). Elite rugby league players body masses are reported to be greater than elite squash players (rugby league = 94.7 ± 6.7 kg [Morehen et al., 2016]; squash = 84.5 ± 7.2 kg), with body mass being shown to be a determinant of energy expenditure (Westerterp, 2017*b*). This is also supported in our results given the energy expenditure of player 1 at 90 kg was greater than player 3 at 75 kg. Collision based activity has also been shown to increase total daily energy expenditure through an increase in collision induced muscle damage (Costello et al., 2018), and this may increase the energy expenditure of rugby league players in comparison to squash players.

The PAL of elite squash players was 2.5 ± 0.4. PAL. Values of 2.5 are reported as the 'upper limit' for 'sustained lifestyle' and in an unclassified range above the range (2.0-2.4) associated with 'vigorous lifestyle' (Westerterp, 2013). The PAL value observed is greater than elite male tennis players during a training microcycle (2.2; Ellis et al., 2021), elite soccer players during an in-season training and competition microcycle (1.75 ± 0.13; Brinkmans et al., 2019), but less than elite rugby league plays during an in-season training and competition microcycle (2.9; Morehen et al., 2016). Consequently, this study reports a valid and accurate assessment of energy expenditure among elite male squash players during a training microcycle, in combination with a PAL value which can be utilised to devise squash specific nutritional recommendations.

Energy availability is a well-established concept to support individuals' health and performance (Areta et al., 2021; Mountjoy et al., 2023). Due to the high energy expenditure and PAL value experienced by players in the present study, players need to ensure that they are consuming enough energy to fuel their training. Mean energy intake among the three players over the 7-day microcycle was 3,389 ± 981 Kcals, resulting in a mean daily energy balance of -821 Kcals. On an individual level, player one reported a mean daily energy balance of -2,392 Kcals·d^{-1} and body mass reduction of 2.1 kg over the seven day microcycle; player two reported a mean daily energy balance of -542 Kcals·d^{-1} and body mass increase of 0.8 kg over the seven day microcycle; and player three reported a mean daily energy balance of +470 Kcals·d^{-1} and body mass reduction of 0.5 kg over the seven day microcycle. Increases in body mass while in a negative energy balance such as in player two suggest there is likely to be an underreporting of energy intake, rather than undereating, a common phenomenon within nutritional science (Black et al., 1993). Indeed, research in elite male soccer (Anderson et al., 2017; Brinkmans et al., 2019) and rugby league players (Morehen et al., 2016) all reported lower energy intakes than energy expenditures despite body mass remaining stable throughout the duration of the microcycles. Mean energy availability among the three players over the microcycle was 31.68 ± 17.91 Kcal·kg^{-1} FFM·d^{-1}. When reported individually, players two and three had an energy availability of 42.35 Kcal·kg^{-1} FFM·d^{-1} and 41.69 Kcal·kg^{-1} FFM·d^{-1} respectively, indicating reduced energy availability according to the International Olympic Committee's Consensus Statement of Relative Energy Deficiency in Sport (Mountjoy et al., 2023). Player one exhibited an energy balance of –2,392 Kcals·d^{-1} and energy availability of 11 Kcal·kg^{-1} FFM·d^{-1}, indicating low energy availability according to the International Olympic Committee's Consensus Statement of Relative Energy Deficiency in Sport (Mountjoy et al., 2023). Low energy availability has many negative consequences on health and performance-based outcomes (Mountjoy et al., 2023). Therefore, it is crucial appropriate nutrition strategies are devised to support optimal, health, wellbeing and performance. This study reports valid and accurate data to help support elite male squash players to adopt appropriate nutrition strategies and mitigate against low energy availability (see practical application section). A potential limitation of the study was that exercise energy expenditure, and subsequently energy availability was calculated through heart rate monitoring rather than the gold standard indirect calorimetry. Heart rate monitoring was shown to yield a non-significant (1.2 ± 6.2 %; p = >0.05) mean underestimate of total energy expenditure in comparison to indirect calorimetry (Ceesay et al., 1989). Consequently, due to the nature of the study and inability to measure exercise energy expenditure through indirect calorimetry, heart rate monitoring was used to quantify expenditure. The Polar H10 band was selected, as this has been shown to have the greatest RR signal strength during high intensity activities and high correlation to an electrocardiography Holter monitor (Gilgen-Ammann et al., 2019).

Squash is a high intensity intermittent sport (Girard et al., 2007), and, therefore, carbohydrates play a key role in energy metabolism (Van Loon et al., 2001). Previous research into the dietary habits of elite Spanish squash players has suggested that players under-consume carbohydrate rich foods such as bread, potatoes, pasta, and rice (Ventura-Comes et al., 2019). Mean carbohydrate intake was 4.7 ± 2.1 $g{\cdot}kg{\cdot}bm^{-1}$ among players, which highlights under-fuelling in comparison to non-specific sports nutrition carbohydrate guidelines (Burke et al., 2011). Burke et al., (2011) proposed a carbohydrate target intake of 6-10 $g{\cdot}kg{\cdot}bm^{-1}$ for individuals engaging in 1-3 hours of high intensity activity per day. Low carbohydrate availability often occurs simultaneously with low energy availability (Logue et al., 2018). Indeed, player one's carbohydrate intake was a mean of 2.9 ± 0.7 $g{\cdot}kg{\cdot}bm^{-1}$ over the microcycle which is lower than non-specific guidelines (Burke et al., 2011). Carbohydrate intake appears to be individualised with player two consuming 7 ± 1.5 $g{\cdot}kg{\cdot}bm^{-1}$ and player three consuming 4.2 ± 1.6 $g{\cdot}kg{\cdot}bm^{-1}$. Players' nutritional choices are highly individualised and based on a variety of different physiological, cultural, psychological, social, and economic factors (Birkenhead & Slater, 2015). Nutrition knowledge is one of those factors which can influence the food choice of players (Birkenhead & Slater, 2015). To this extent, the data presented in this study aims to increase knowledge through increasing understanding of the energy expenditure of elite squash players throughout a microcycle, and as a result, the energy and carbohydrate requirements of elite squash players.

Periodised nutrition is a well-established concept to ensure athletes fuel appropriately throughout variable training loads (Jeukendrup, 2017). Elite squash players appear to have variable training loads with player one's daily training duration, daily exercise energy expenditure, and daily sRPE ranging from 45 to 198 minutes, 589 to 2,309 Kcals and 180 to 1,395 respectively; players two's ranging from 170 to 258 (daily training duration), 1,517 to 2,174 (daily exercise energy expenditure), and 1,040 to 1,798 (daily sRPE); and players three's ranging from 133 to 215 (daily training duration), 1,176 to 1,848 (daily exercise energy expenditure), and 1,064 to 1,477 (daily sRPE). A limitation of the doubly labelled water technique is its inability to provide day to day energy expenditure assessments, hence energy expenditure being expressed over a 7-day microcycle in this study. It is likely that energy expenditure varied on a day-to-day basis and while nutritional recommendations can be devised to account for the energy expenditure over a microcycle, day to day recommendations may be appropriate to optimise training adaptation (Impey et al., 2017), body composition (Stellingwerf, 2019) and physical performance (Jeukendrup, 2017). There was some evidence of energy periodisation within the present study with player one's energy intake varying from 1932 Kcals (daily sRPE = 180) to 3306 Kcals (daily sRPE = 1,395); player two's energy intake varying from 2834 Kcals (daily sRPE = 0) to 6,361 Kcals (daily sRPE = 1,798); and player three's energy intake varying from 2,499 Kcals (daily sRPE = 0) to 4,421 Kcals (daily sRPE = 1,191).

4.4.6 Practical Applications

The present study demonstrates that elite male squash players exhibit a high energy expenditure throughout a training microcycle and follow inappropriate nutrition strategies such as sub optimal carbohydrate intake or in one case, severe energy restriction, leading to low energy availability. This may lead to a wide range of health and performance-based consequences (Mounjoy et al., 2023). One of the aims of the paper was to increase the understanding of the energy expenditure of elite male squash players throughout a microcycle, so that energy and carbohydrate guidelines can be devised. Consequently, for an 85 kg player (the mean of the three players body mass in this study) wanting to achieve energy balance, if protein intake was fixed at the suggested guidelines of 1.4 to 2 $g \cdot kg \cdot bm^{-1}$ (119g to 170g; 476 Kcals to 680 Kcals; Jäger et al., 2018) and fat intake was fixed at 30% of total energy intake (1.6 $g \cdot kg \cdot bm^{-1}$; 140g; 1263 Kcals; Kerksick et al., 2018), carbohydrate intake should be between 2,267 and 2,471 Kcals (depending on the individuals protein intake), equating to 567 to 618 g or 6.6 to 7.2 $g \cdot kg \cdot bm^{-1}$ of carbohydrate per day. The training load data suggests that elite male squash players have a varied training load, and therefore players should work with a registered sport dietitian or sports nutritionist to optimally periodise their energy and carbohydrate intake alongside their training load to maximise training adaptations and performance (Jeukendrup, 2017).

4.5 Supplementary Tables

Supplementary Table 88. Player one's daily energy, macronutrient and fibre intake

Day	Energy (Kcals)	CHO (g)	CHO (g.kg.bm)	PRO (g)	PRO (g.kg.bm)	FAT (g)	FAT (g.kg.bm)	Fibre (g)
1	1934	246	2.8	114	1.3	55	0.6	23
2	2443	335	3.7	148	1.9	48	0.5	37
3	3306	340	3.8	246	2.8	107	1.2	47
4	2779	302	3.4	187	2.1	92	1	24
5	2507	231	2.6	129	1.4	119	1.3	21
6	2578	177	2	105	1.2	50	0.6	19
7	1932	235	2.6	84	0.9	73	0.8	14
Mean ± STDEV	2354 ± 588	282 ± 61	2.9 ± 0.7	145 ± 56	1.7 ± 0.7	78 ± 29	0.9 ± 0.3	26 ± 12

Supplementary Table 89. Player two's daily energy, macronutrient and fibre intake

Day	Energy (Kcals)	CHO (g)	CHO (g.kg.bm)	PRO (g)	PRO (g.kg.bm)	FAT (g)	FAT (g.kg.bm)	Fibre (g)
1	6361	700	8.7	193	2.4	310	3.9	36
2	4992	651	8.1	191	2.4	180	2.3	43
3	3624	571	7.1	91	1.1	108	1.4	29
4	4029	487	6.1	207	2.6	139	1.7	30
5	4337	615	7.7	161	2	137	1.7	26
6	2834	336	4.2	149	1.9	100	1.3	19
7	3955	541	6.8	185	2.3	117	1.5	22
Mean ± STDEV	4305 ± 1120	557 ± 120	7 ± 1.5	168 ± 39	2.1 ± 0.5	156 ± 73	2.0 ± 0.9	29 ± 8

Supplementary Table 90. Player two's daily energy, macronutrient and fibre intake

Day	Energy (Kcals)	CHO (g)	CHO (g.kg.bm)	PRO (g)	PRO (g.kg.bm)	FAT (g)	FAT (g.kg.bm)	Fibre (g)
1	3519	350	4.6	237	3.1	132	1.8	45
2	3005	297	3.9	176	2.3	124	1.6	44
3	3371	274	3.6	200	2.6	164	2.2	35
4	3539	296	3.9	249	3.3	151	2	43
5	4421	551	7.3	163	2.2	174	2.3	37
6	4194	297	3.9	314	4.2	194	2.6	31
7	2499	162	2.1	190	2.5	121	1.6	24
Mean ± STDEV	3507 ± 658	318 ± 118	4.2 ± 1.6	218 ± 52	2.9 ± 0.7	151 ± 27	2 ± 0.4	37 ± 8

5.0: Study Four – Fluid Balance, Sodium Losses, and Hydration Practices of Elite Squash Players During Training

5.1 Study Summary and the Golden Thread

After conducting a systematic review (see section 2) on the available physiological and nutritional literature within squash, it was highlighted that elite squash players sweat rates and sweat [Na^+] of throughout a training session hadn't been quantified. Sweat rates and sweat [Na^+] are highly individualised (Baker, 2017), and anecdotally it was highlighted that many of the players had high sweat rates. As previously discussed in 'Defining the Performance Problem' (see section 1.3), one player had to change their t-shirt, socks and shoes after each break in training due to their high sweat rates, to prevent excess sweat on the court floor. This player's sweat rate was later quantified to have a sweat rate of 2.12 $L \cdot h^{-1}$ (player one data; see section 5.3). England Squash players traditionally train twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. Therefore, another performance problem was whether this short recovery period in-between sessions gives players the opportunity to optimally rehydrate from one session to the next. Therefore, the aim of this study was to quantify each players sweat rate and sweat [Na^+] to develop an individualised hydration strategy for them. The study also aimed to quantify whether it was feasible to optimally rehydrate from when training session to the next when there was a limited time period in between sessions.

5.2 Justification of Methodology

5.2.1 Pre-Exercise Hydration Status

The hydration status of individuals can be measured through many techniques including: blood variables such as haematocrit (Oppliger & Bartok, 2002), plasma osmolarity (Sollanek et al., 2011), serum sodium (Chacko et al., 2011), hormonal variables (Schrier et al., 1979; Stachenfeld et al., 1996); urine variables such as urine specific gravity, urine osmolarity (Shirreffs & Maughan, 1998; Fernández-Elías et al., 2014), saliva variables such as saliva osmolarity and flow rate (Walsh et al., 2004; Oliver et al., 2008); stable isotope dilution (Al-Ati et al., 2015); dual-energy X-ray absorptiometry (Pietrobelli et al., 1996); bioelectrical impedance (De Lorenzo et al., 1997), and neutron activation analysis (Yasumura et al., 1983).

5.2.1.1 Plasma Osmolarity

Plasma osmolarity is seen as the reference standard measure of hydration (Barley et al., 2020), with dehydration being measured through quantifying the concentration of solutes in the blood (Popowski et al., 2001), using freezing point osmometry (Oppliger & Bartok, 2002; Cheuvront et al., 2010). Despite being seen as the reference standard measure of hydration, plasma osmolarity is shown to lack sensitivity when detecting mild hypohydration (<3%) (Hamouti et al., 2013). Plasma osmolarity is also influenced by food, as water shifts from the vasculature and into the gut during digestion (Gill et al., 1985). Plasma osmolarity is highly individualised and therefore data should be compared to previous measures rather than thresholds (Cheuvront & Kenefick, 2010), making it a more useful method to quantify changes in hydration status over time. Plasma osmolarity was dismissed as the study was only utilising a stand-alone pre-exercise hydration test, results would be difficult to interpret.

5.2.1.2 Serum Sodium

Serum sodium is a similar technique to plasma osmolarity whereby the concentration of sodium is measured in the blood, with dehydration altering electrolyte concentrations within the blood (Cheuvront & Kenefick, 2014). Consequently, much of the limitations of plasma osmolarity are also applicable to serum sodium (Edelman et al., 1958; Cheuvront & Kenefick, 2014).

5.2.1.3 Saliva Variables (Osmolarity & Flow Rate)

Saliva variables such as saliva osmolarity and flow rate can be used to quantify hydration status (Barley et al., 2020), however, these are typically utilised during heat stress related exercise or conditions of fluid restriction (Walsh et al., 2004; Oliver et al., 2008). Saliva osmolarity is reported to have approximately 10 times greater variability than plasma osmolarity or urine specific gravity (Cheuvront et al., 2010) due to it being influenced by food and fluid ingestion (Ely et al., 2011). Exercise has also been shown to alter levels of salivary sodium and potassium which could influence salivary osmolarity measures (Ben-Aryeh et al., 1989; Ljungberg et al., 1997).

5.2.1.4 Hormonal Variables

Hormonal variables such as arginine-vasopressin, renin, aldosterone and atriopeptin have been suggested as markers which can quantify hydration status due to the relationship between fluid balance and these hormones (Schrier et al., 1979; Stachenfeld et al., 1996). However, the method is expensive and has shown poor reliability with Brandenberger et al., (1989) demonstrating changes in endocrine responses to quantify hydration status, while other studies has displayed no change (Zerbe et al., 1991; Ahokoski et al., 1999).

5.2.1.5 Stable Isotope Dilution

Stable isotope dilution can be utilised to measure total body water and provide an indication of hydration status (Schoeller et al., 1980). This method involves consuming trace amounts of deuterium oxide (^2H_2O). It is expensive and requires high levels of technical expertise (Armstrong, 2007). It also requires multiple samples taken over the hours post consumption of the deuterium oxide. Stable isotope dilution was not feasible in the present study due to players being required to measure pre-exercise hydration status and players being required to train while samples may need to be collected.

5.2.1.6 Neutron Activation Analysis

Neutron activation analysis determines hydration status by using radiation detectors to measure electrolytes to quantify extracellular and intracellular fluid volume (Armstrong, 2007). It is reported to be an accurate measure of total body water, although only estimates it through quantifying electrolyte levels, rather than directly calculating it (Armstrong, 2007). The measure takes roughly one hour to complete and may be impractical in the field due to requiring expensive equipment and a high level of technical expertise (Duren et al., 2008).

5.2.1.7 Dual-Energy X-Ray Absorptiometry

Dual-energy X-ray absorptiometry can be utilised to calculate hydration status through quantifying total body water (Going et al., 1993). This may lack reliability due to much of total body water being stored in lean body mass, with this depending on the concentration of muscle glycogen and not exclusively hydration status (Pietrobelli et al., 1996). In terms of the present study, logistically it was improbable to assess pre-exercise hydration status via dual-energy X-ray absorptiometry as there wasn't a scanner located at the training facility.

5.2.1.8 Bioelectrical Impedance

Bioelectrical impedance can measure hydration status through quantifying total body water (De Lorenzo et al., 1997). This has similar reliability issues to dual-energy X-ray absorptiometry as it measures total body water stored in lean mass which is dependent on the concentration of muscle glycogen. Typical error measurements for total body water when quantified through bioelectrical impedance range between 1.5-2.5 kg (Oppliger & Bartok, 2002). The data can also be influenced by a variety of factors such as the individuals position of the scanner, physical activity states and food consumption (Thomas et al., 1992)

5.2.1.9 Urine Variables (Specific gravity and Osmolarity)

Urinary variables such as urine specific gravity and urine osmolarity can be used to quantify an individual's hydration status (Cheuvront & Kenefick, 2014). Urine specific gravity measures hydration status by quantifying the urine density of a urine sample in relation to double distilled water (Cheuvront & Kenefick, 2014). Urine osmolarity assesses the hydration status of an individual through the solute content of urine, quantifying its freezing point depression (Cheuvront & Kenefick, 2014), or through a refractometer. Urine assessments are seen as less expensive and invasive than blood variables (Cheuvront & Kenefick, 2014) and therefore are regularly utilised in the laboratory and field (Barley et al., 2020).

5.2.1.10 Chosen Tool to Quantify Pre-Exercise Hydration Status

Urine osmolarity has been utilised in the field previously and is seen as a quick and easy way to quantify an individual's hydration status prior to exercise. Consequently, this tool was utilised to measure pre-exercise hydration status.

5.2.2 Sweat Sodium Losses

Sodium is an electrolyte lost in sweat (Sato, 1977). Sodium plays a role in a variety of physiological functions such as maintaining fluid balance (Shirreffs & Maughan, 1998), stimulating nerve impulse transmissions (Matthews, 2003) and muscular contractions (Kuo & Ehrlich, 2015). Sweat [Na^+] are individualised due to a variety of factors such as sex, maturation phase, medical conditions, and genetic differences (Baker, 2017). Sweat [Na^+] can be measured using a variety of tools and divided into whole body methods and local body methods to quantify sweat sodium losses.

5.2.2.1 Whole Body Methods to Quantify Sweat Sodium Losses

Whole body washdown is a whole-body method used to quantify sweat sodium losses

5.2.2.1.1 Whole Body Washdown

The reference method for quantifying sweat Na^+ loss is whole-body washdown (Shirreffs & Maughan, 1997; Armstrong & Casa, 2009). Sweat Na^+ losses are calculated by an individual exercising in a plastic frame which supports a large polythene bag (Shirreffs & Maughan, 1997). The individuals sweat runs off during the exercise bout and is collected in the polythene bag (Shirreffs & Maughan, 1997). Upon the completion of exercise, the fluid left in the bag is the individuals sweat (Shirreffs & Maughan, 1997). This is subsequently analysed by ion chromatography (Doorn et al., 2015). Unfortunately, the whole-body washdown method is limited to a controlled laboratory setting and whereby the exercise modality is limited to stationary exercise such as a cycle ergometer (Armstrong & Casa, 2009) and therefore not appropriate for the present study due to sweat [Na^+] being collected during a training session (see section 5.3.3).

5.2.2.2 Local Body Methods to Quantify Sweat Sodium Losses

Methods to quantify local sweat [Na^+] are typically utilised within studies, as these are easier to administer in a practical setting (Baker, 2017). Local sweat [Na^+] measurements appear to overestimate sweat [Na^+] losses in comparison to whole body sweat [Na^+] measurements (Baker et al., 2009). The differences between local and whole body sweat [Na^+] measurements depend on the anatomical site measured and methodology utilised (Patterson et al., 2000). Sweat [Na^+] collected from the forearm, scapula and chest is shown greater be 25-100% greater than whole body whole body sweat [Na^+] measurements (Patterson et al., 2000). Despite this, studies have shown local sweat [Na^+] measurements to be highly correlated with whole body sweat [Na^+] measurements (Baker, 2017).

5.2.2.2.3 Sweat Stimulation Techniques

There are three types of sweat stimulation techniques: (1) pharmacological; (2) passive thermal heat stress; and (3) exercise. Pharmacological techniques are concerned with methods which stimulate sweating in a local anatomical position through the utilisation of a small electrical current to drive charged cholinergic agonists, such as pilocarpine iontophoresis (Gibson & Cooke, 1959). This induces sweating through stimulating muscarinic receptors on sweat glands (Gibson & Cooke, 1959). Passive thermal heat stress refers to sweating being induced through an increase in core temperature (Baker, 2017). Exercise refers to sweating being induced through the commencement of exercise as the body has heat loss mechanisms, such as sweating, to enable evaporative heat loss, maintain heat balance and attenuate further increases in body temperature (Sawka et al., 2015). Local sweat rate is reported to be higher when stimulated through passive thermal heat stress or exercise in comparison to pharmacologically induced sweating. This is due to pharmacologically induced sweating being stimulated by local cholinergic sweat glands, rather than other mediators such as temperature, blood flow, exercise pressor reflex, and adrenergic stimulation which are experienced through passive thermal heat stress or exercise (Shibasaki & Crandall, 2010; Shibasaki et al., 2003). Methods to quantify sweat [Na^+] are equivocal with some studies reporting a higher [Na^+] (Schwachman & Mahmoodian, 1966; Sato et al., 1970), some reporting a lower [Na^+] (Schwachman & Mahmoodian, 1966) and some reporting a similar [Na^+] (Sant'Agnese & Powell, 1962).

5.3 Hypothesis

Sweat rates and sweat [Na^+] are highly individualised depending on internal and external factors Baker, 2017). Therefore, it was hypothesised that due to the training session being conducted in controlled moderate environmental conditions, sweat rates and sweat [Na^+] concentrations would be similar to mean values of other high intensity intermittent sports (~ 1 $L \cdot h^{-1}$; 40 $mmol \cdot L^{-1}$; Baker, 2017). It was also hypothesised that players who had 21 h and 30 min to rehydrate would be able to do so, whereas players who were training the same day and had 2 h and 30 min to rehydrate wouldn't be able to.

5.4 Fluid Balance, Sodium Losses and Hydration Practices of Elite Squash Players During Training

5.4.1 Abstract

Elite squash players are reported to train indoors at high volumes and intensities throughout a microcycle. This may increase hydration demands, with hypohydration potentially impairing many key performance indicators which characterise elite squash performance. Consequently, the main aim of this study was to quantify the sweat rates and sweat [Na^+] of elite squash players throughout a training session, alongside their hydration practices. Fourteen (males = seven; females = seven) elite or world class squash player's fluid balance, sweat [Na^+] and hydration practices were calculated throughout a training session in moderate environmental conditions (20 ± 0.4 °C; 40.6 ± 1% RH). Rehydration practices were also quantified post-session until the players' next training session, with some training the same day and some training the following day. Players had a mean fluid balance of −1.22 ± 1.22% throughout the session. Players had a mean sweat rate of 1.11 ± 0.56 $L\cdot h^{-1}$, with there being a significant difference between male and female players ($p < 0.05$), and a mean sweat [Na^+] of 46 ± 12 $mmol\cdot L^{-1}$. Players training the following day were able to replace fluid and sodium losses, whereas players training again on the same day were not. These data suggest the variability in players hydration demands and highlight the need to individualise hydration strategies, as well as training prescription, to ensure players with high hydration demands have ample time to optimally rehydrate.

5.4.2 Introduction

Squash is a high intensity intermittent sport (Jones et al., 2018), with elite male squash match play shown to exhibit a mean energy expenditure of 4933 ± 620 kJ· h^{-1}, a mean heart rate of 92 ± 3% heart rate maximum, and a respiratory exchange ratio of 0.94 ± 0.06 among players (Girard et al., 2007). Elite squash players' training sessions aim to replicate the high intensity demands of the sport to prepare players appropriately for the rigours of match play (James et al., 2021). Elite squash players are purported to have high training loads, often engaging in more than one training session per day, spending a total training time greater than 12 h per week, with much training eliciting heart rates greater than 90% heart rate maximum (Gibson et al., 2019; James et al., 2021). Consequently, these high training loads may increase the hydration demands of players, as there is less time to rehydrate from one session to the next. Moreover, most of these training sessions take place indoors. High exercise intensities, as experienced during elite squash players' training sessions (Gibson et al., 2019; James et al., 2021), elevate the body's core temperature (Gleeson, 1998). Indeed, 39 min of competitive match play among national standard squash players has been shown to increase core temperature by approximately 1–2 °C (~37 °C to ~39 °C) (Blanksby et al., 1980). As a result, the body has heat loss mechanisms, such as increased skin blood flow and the onset of sweating, to enable evaporative heat loss, maintain heat balance and attenuate further increases in body temperature (Sawka et al., 2015).

Hypohydration is defined as a body water deficit greater than an individual's daily fluctuation (Sawka et al., 2015). Hypohydration decreases the plasma volume of blood (Dill & Costil, 1974), reducing cerebral (Trangmar et al., 2014) and muscle blood flow (Gonzalez-Alonso et al., 1998), increasing heart rate and cardiovascular strain at any given intensity (Montain et al., 1998). Consequently, hypohydration may impair many key performance indicators which characterise elite squash performance (James et al., 2018), such as aerobic capacity (Armstrong et al., 1985; Walsh et al., 1994; McConell et al., 1997; Cheuvront et al., 2005; Ebert et al., 2007; Stearns et al., 2009; Casa et al., 2010; Castellani et al., 2010; Kenefick et al., 2010; Merry et al., 2010; Lopez et al., 2011; Bardis et al., 2013; Davis et al., 2014; Fleming & James, 2014; Logan-Sprenger et al., 2015; James et al., 2017; Adams et al., 2018; Adams et al., 2019; Deshayes et al., 2019; Funnell et al., 2019), anaerobic power (Jones et al., 2008; Savoie et al., 2015; Nuccio et al., 2017), muscular endurance (Montain et al., 1998; Savoie et al., 2015; Caterisano et al., 1988; Bigard et al., 2001), lower-body muscular strength (Ftaiti et al., 2001; Judelson et al., 2007; Hayes et al., 2010; Kraft et al., 2010; Botwell et al., 2013; Minshull et al., 2013; Wilson et al., 2014; Savoie et al., 2015), cognitive function (Baker et al., 2007; D'Anci et al., 2009; MacLeod & Sunderland, 2012; Smith et al., 2012; Wittbrodt & Millard-Stafford, 2012), and sport specific technical skills (McGregor et al., 1999; Devlin et al., 2001; Dougherty et al., 2006; Baker et al., 2007; Gamage et al., 2016; Nuccio et al., 2017).

Accordingly, it is important that squash players have an appropriate hydration strategy to maintain their physical and cognitive performance on court. Developing an optimal hydration strategy is not a one-size-fits-all approach. An athlete's sweat rate is the main determinant of their hydration strategy (Sawka et al., 2007), with sweat rates being highly individualised due to genetic phenotypes, such as sweat secretion rate per gland (Baker et al., 2016). Barnes et al., (2019) found a high variability in athletes' sweat rates across a variety of sports, such as running, cycling, American football, tennis, and soccer, reporting absolute whole body sweat rates ranging from 0.16 to 5.73 $L \cdot h^{-1}$. As well as fluids, Na^+ is also an important factor in a player's hydration strategy. Na^+ is an electrolyte lost in sweat, which has been shown to maintain plasma levels of vasopressin and aldosterone, promoting whole-body and extracellular fluid retention (Shirreffs & Maughan, 1998). Na^+ containing fluids have been shown to optimise re-hydration post-exercise (Evans et al., 2017). Like sweat rates, sweat [Na^+] is also highly individualised, with Ranchordas et al., (2017) reporting sweat [Na^+] ranging from 11.2 $mmol \cdot L^{-1}$ to 86.5 $mmol \cdot L^{-1}$ among professional male team sport athletes (soccer, rugby, American football, baseball and basketball). Consequently, an individual's hydration strategy is personalised, depending on the individual, their sweat rate, and their sweat [Na^+].

Previous research has quantified the fluid balance, sweat [Na^+] losses and hydration practices of athletes in a variety of racket sports, such as tennis (Bergeron, 2003; Bergeron et al., 1995; Lott & Galloway, 2011; Tippet et al., 2011) and badminton (Abian-Vicen et al., 2012), as well as high intensity intermittent sports, such as soccer (Maughan et al., 2004; Maughan et al., 2005; Shirreffs et al., 2005; Maughan et al., 2007; Shirreffs & Maughan, 2008; Aragon-Vargas et al., 2009; Horswill et al., 2009; Kilding et al., 2009; Kurdak et al., 2010; Da Silva et al., 2012; Duffield et al., 2012; Gibson et al., 2012; Phillips et al., 2014; Rollo et al., 2021; Tarnowski et al., 2022), American football [Godek et al., 2005*a*; Godek et al., 2005*b*; Stover et al., 2006; Godek et al., 2006; Yeargin et al., 2006; Stofan et al., 2007; Godek et al., 2010*a*; Godek et al., 2010*b*; Yeargin et al., 2010), basketball [Osterberg et al., 2009; Brandenburg et al., 2012; Thigpen et al., 2014; Vukasinovic-Vesic et al., 2015), field hockey (MacLeod & Sunderland, 2009); ice hockey (Palmer & Spriet, 2008; Palmer et al., 2010; Logan-Sprenger et al., 2011; Gamble et al., 2019), Gaelic football (Newell et al., 2008), rugby league (Meir et al., 2003; O'Hara et al., 2010), and rugby union (Cosgrove et al., 2014; Jones et al., 2015). Despite this, no study has quantified the fluid balance, sweat [Na^+] or hydration practices of elite squash players during a training session. Calculating the fluid balance, sweat [Na^+] and hydration practices of elite squash players during a training session would provide players, coaches, and practitioners with information to optimise players' hydration practices throughout training.

Therefore, the primary aim of this study was to quantify the sweat rates and sweat [Na^+] of elite squash players throughout a training session. A secondary aim was to investigate players' hydration practices during the training session (i.e., hydration status pre-session, fluid and Na^+ intake during and post-session) to determine whether these were optimal in relation to a players individualised sweat rate and sweat Na^+ losses. A final aim of the study was to determine players' pre-conceived sweat rate, sweat [Na^+], and cramping frequency, and to quantify the relationship between these, players' sweat rates, and players' sweat [Na^+].

5.4.3 Materials and Methods

5.4.3.1 Experimental Design

Data was collected during a training session with an England Squash senior squad in March 2021. This training session was the first of a training microcycle. The training session was consistent with training that would normally be undertaken at an England Squash senior squad and consisted of players' habitual warm up, squash-specific routines and conditioned games. The training session lasted 90 min (from 10:00 to 11:30). Player's pre-exercise hydration status was assessed before the session through urine osmolarity; players' sweat rate, fluid and food intake measured during the session; and players' sweat [Na^+] quantified post-session. Players completed a food and drink diary immediately after the session until the time of their next training session, in order to quantify their rehydration practices.

5.4.3.2 Participants

Fourteen (males = 7, females = 7) elite (tier 4) and world class (tier 5) (McKay et al., 2022) squash players (male (age = 25 ± 5 years; stature = 184 ± 2 cm; body mass = 78.9 ± 7.3 kg); female (age = 25 ± 4 years; stature = 169 ± 7 cm; body mass = 63.7 ± 8.6 kg) volunteered to take part in the study. All experimental procedures and risks were explained to the players, with written informed consent being collected before data collection. The research was approved by an institutional ethics committee (ER28778154) and conducted in accordance with the principles of the 7th revision of the Declaration of Helsinki (World Medical Association, 2001).

5.4.3.3 Fluid Balance

Upon arrival, a pre-exercise urine sample was assessed for urine osmolarity (Vitech Scientific LTD, UK) to quantify the pre-exercise hydration status of players. Values of <700 $mOsmol \cdot kg^{-1}$ were used as a guide for euhydration (Sawka et al., 2007). Urine osmolarity has been reported to be a valid and reliable instrument to assess athlete's hydration status (Shirreffs & Maughan, 1998). Players' stature was measured prior to the training session using a stadiometer (SECA, Alpha 213, Hamburg, Germany). Pre- and post-exercise nude body mass was assessed in conjunction with food and fluid balance to quantify whole body sweat loss through the following equation:

$$\text{Total sweat mass loss} = \text{Post exercise body mass (Nude body mass post exercise} - \text{Food and fluid intake during exercise} + \text{urine and stool output during exercise)} - \text{Nude body mass pre-exercise}$$

Players were instructed to collect all urine and stools passed during the training session in pre-weighted containers. There were frequent breaks in the training session whereby players had the opportunity to consume fluid and/or food, as is common practice in squash training sessions. Players were instructed not to squirt or spit fluid from their drink bottles. A Wahoo TickrX (Atlanta, GA, USA) was used alongside the Wahoo mobile application to assess heart rate during the training session. Post-session, players rating of perceived exertion (RPE) was recorded using the CR10 Scale (Borg, 1998) and multiplied by the duration of the session (min) to calculate sRPE (Haddad et al., 2017).

5.4.3.4 Sweat Sodium Collection and Analysis

Sweat samples were collected according to the methods of Ranchordas et al., (2017). Players were rested for 5 minutes prior to the sweat sample being collected. Post the 5-min rest period, the left mid-forearm was cleaned with an alcohol wipe as well as purified water to remove any dirt and sweat from the skin. It was also checked for breaks, fissures, or any inflammation (Cram & Rommen, 1989). Two stainless-steel electrodes and iontophoretic discs were then applied to the cleaned area. The iontophoretic discs consisted of a solid agar gel which consisted of 96% water, 0.5% pilocarpine nitrate and trace antifungal compounds. Consequently, sweat was induced to the left mid-forearm where the electrodes and iontophoretic discs were placed, through a 1.5-mA iontophoretic current, lasting for 5 min (Webster Sweat Inducer, Wescor Inc., Logan, UT, USA). The iontophoretic discs were subsequently removed, and the stimulated area cleaned with purified water and blot dried. A tailored plastic disk was applied to the induced area (Macroduct Sweat Collector, Wescor Inc.). An 85 µL sweat sample was then collected via hydraulic pressure. This typically took 10 to 30 min, with samples less than 85 µL discarded. A blunt-fill needle and syringe was used to eject the sweat sample from the collection disk. This passed through a conductivity cell (Sweat CheckTM, Wescor Inc.), which quantified NaCl molarity from the sweat sample conductivity. The conductivity cell was cleaned and calibrated before each test using deionised water and a dummy sample of a known sodium concentration, respectively.

Pilocarpine iontophoresis has been validated against the Gibson and Cooke Gauze technique (Mastella et al., 2000), as well as displaying strong correlations with flame photometry (Riedi et al., 2000) and qualitative pilocarpine iontophoresis (Hammond et al., 1994). Pilocarpine iontophoresis has conveyed excellent absolute ($CV < 2.6\%$) and relative reliability ($ICC > 0.99$) (Goulet et al., 2017).

5.4.3.5 Post Session Fluid and Sodium Consumption

Players' post-session fluid (L) and Na^+ (mg) consumption were calculated through a self-reported food and drink diary. Food and drink diaries were completed via the mobile application WhatsApp (Facebook, Menlo Park, CA, USA), with players sending across details of any food or drink they consumed (i.e., name, mass and cooking methods), as well as an accompanying photo, which was timestamped. The calculation of fluid intake also included any fluids consumed through food consumed. Players were instructed to complete the food and drink diary immediately after training until the time of their next training session. For seven players, this was 14:00 the same day (amount of time in between sessions = 2 h 30 min between session) (same day training session group), whereas, for the other seven players, this was 09:00 the next day (amount of time in between sessions = 21 h and 30 min) (following day training session group). Food and drink diaries were analysed by the principal researcher, who is a Sport and Exercise Nutrition Register (SENr) accredited nutritionist, using the nutrition analysis software Nutritics (Nutritics Ltd, Swords, Ireland).

5.4.3.6 Perceived Sweat Rate and Sweat Sodium Concentration Measures

During the sweat [Na^+] collection, participants were asked three questions regarding their perceived sweat rate, frequency of cramps and perceived sweat [Na^+]. The questions (and answers) were as follows: (1) "How would you classify your sweat rate?" (low, moderate, high, very-high); (2) "How often do you suffer from muscle cramps?" (never, rarely, sometimes, often); (3) "Do you think you lose a lot of Na^+ in your sweat?" (no, yes). Before answering question three, participants were asked to consider whether they felt sweat irritating their eyes. These questions were asked to quantify whether players' preconceptions regarding their sweat rate and sweat Na^+ losses were correct, and whether players altered their hydration strategy accordingly (e.g., if a player preconceives a high sweat rate, are they more likely to consume more fluid during the session). These questions have been shown to provide sufficient reproducibility in identifying relationships between participants sweat rate (ICC = 1.0), frequency of cramps (ICC = 0.9), sweat [Na^+] perceptions (ICC = 0.7), and quantifiable variables (Ranchordas et al., 2017).

5.4.3.7 Statistical Analysis

SPSS V 24.0 software (SPSS Inc., Chicago, IL, USA) was used to perform the data analysis. All data was displayed as mean ± standard deviation for all participants, with $p < 0.05$ being the criterion for significance among all statistical tests. The Shapiro-Wilk test was used to assess normal distribution. Levene's Test for Equality of Variances was used to assess homogeneity of variance. Independent Samples T-Test or Mann-Whitney *U* Test (for non-parametric analysis) was used to analyse the differences in (1) sweat rates between males and females, (2) the differences in sweat Na^+ losses between males and females, and (3) post-session hydration strategies between the two subsequent training groups (same day training session group vs. following day training session group). Comparison between the same day training session group and the following day training session group were analysed through comparing (1) post-session fluid consumption, and (2) post-session Na^+ consumption between the two groups. Effect sizes were interpreted according to accepted thresholds (small: $d = 0.2$; moderate: $d = 0.5$; large = 0.8) (Cohen, 1988). Pearson's Correlation Coefficient or Spearman's Rank-Order Correlation (for non-parametric analysis) was used to quantify the relationship between (1) players perceived sweat rate and their sweat rate, (2) players' sweat $[Na^+]$ and their self-reported cramping frequency, (3) players' sweat $[Na^+]$ and their self-reported sweat $[Na^+]$. Pearson's Correlation Coefficient and Spearman's Rank-Order Correlation were interpreted according to accepted thresholds (very weak: r = 0-0.19; weak: r = 0.2-0.39; moderate: r = 0.4-0.59; strong: r = 0.6-0.79; very strong: r = 0.8-1). A power calculation was undertaken to quantify the minimum sample size required for the study. A sample size of 42 was required (21 in each group) to achieve a statistical significance of $p < 0.05$. Unfortunately, there were no suitable relevant studies (e.g. study which quantified differences in sweat losses between male and female individuals) which calculated the effect size, so a large effect size (d = 0.8) was chosen.

5.4.4 Results

5.4.4.1 Environmental Conditions

Mean temperature throughout the training session was 20 ± 0.4 °C, with mean humidity $40.6 \pm 1\%$.

5.4.4.2 Pre-Session Urine Osmolarity

Figure 15 conveys players' pre-session urine osmolarity. Mean pre-session urine osmolarity among players was 453 ± 283 $mOsmol \cdot kg^{-1}$, with individual values ranging from 130 $mOsmol \cdot kg^{-1}$ to 1000 $mOsmol \cdot kg^{-1}$. Eleven players (79%) reported a value < 700 $mOsmol \cdot kg^{-1}$, indicating euhydration (Sawka et al., 2007), with the remaining three players reporting values >with the remaining three players report- 700 $mOsmol \cdot kg^{-1}$, denoting hypohydration (Sawka et al., 2007).

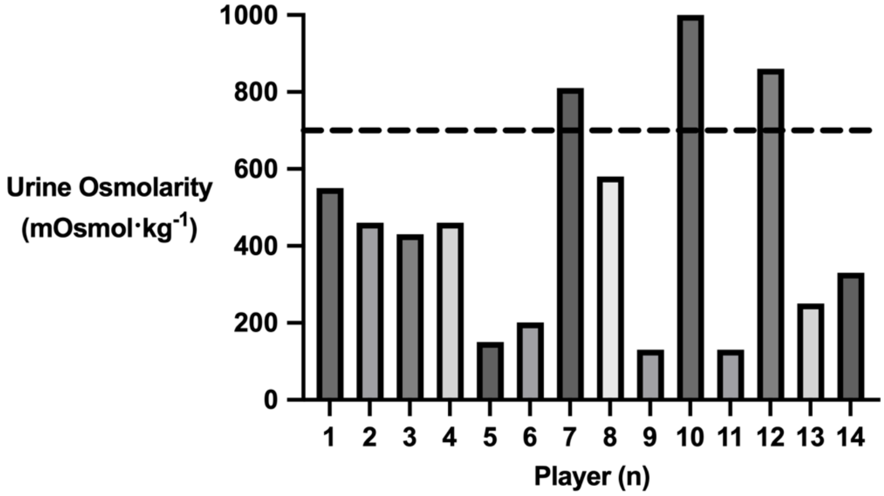

Figure 15. Player's pre-session urine osmolarity. Dotted line denotes 700 mOsmol·kg^{-1}

5.4.4.3 Training Load

Table 11 conveys the training load of each player throughout the training session

Table 11. Players training load throughout the training session

Participant (n)	Sex (M/F)	Duration (min)	Mean Heart Rate (beats.min^{-1})	Mean % of Age Predicted Heart Rate Maximum (%)	Maximum Heart Rate (beats.min^{-1})	Maximum % of Age Predicted Heart Rate Maximum (%)	RPE (*n*/10)	sRPE (AU)
1	M	90	153	78	190	97	7	630
2	M	90	151	77	185	94	7	630
3	M	90	149	75	189	95	6	540
4	F	90	144	76	188	99	5	450
5	F	90	132	69	173	91	5	450
6	F	90	162	81	189	95	7	630
7	F	90	131	68	175	91	6	540
8	M	90	157	82	191	100	6	540
9	M	90	145	78	178	96	4	360
10	M	90	124	63	161	81	7	630
11	M	90	157	79	184	92	6	540
12	F	90	158	79	185	93	7	630
13	F	90	121	61	161	82	3	270
14	F	90	162	82	191	96	4	360
Mean ± SD	-	90	146 ± 14	75 ± 7	181 ± 10	93 ± 6	6 ± 1	514 ± 119

5.4.4.4 Fluid Balance, Sweat Rate and Sweat Sodium Composition

Figure 16 conveys the body mass loss/gain of players throughout the training session. Eleven players lost body mass throughout the session, while three players gained mass. The mean body mass loss/gain was −0.91 ± 0.95 kg. This equated to a mean body mass loss/gain percentage of −1.22 ± 1.22%.

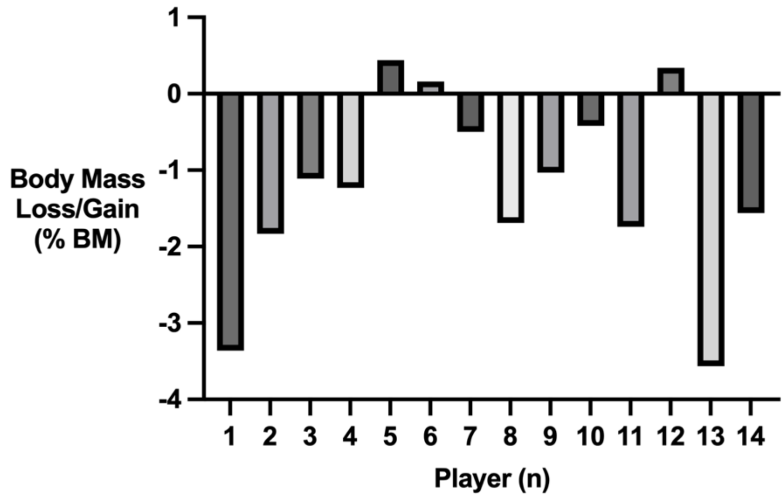

Figure 16. Players body mass loss/gain during the training session (% body mass)

Players had a mean sweat mass loss of 1.66 ± 0.92 kg and mean fluid intake of 0.79 ± 0.31 L throughout the training session. This equated to a mean sweat rate and fluid intake of 1.11 ± 0.56 $L \cdot h^{-1}$ and 0.53 ± 0.21 $L \cdot h^{-1}$, respectively. Figure 17 displays the % of fluid replaced during the training session. Players replaced a mean amount of 62 ± 38% of fluids which were lost during the session. Three players replaced more than 100% of their sweat losses during the session.

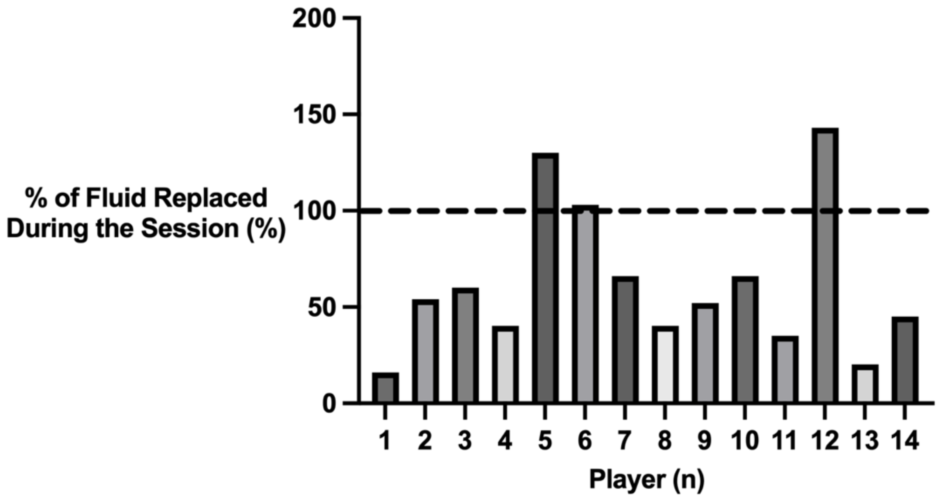

Figure 17. % of fluid replaced by each player during the training session. Dotted line denotes 100% of fluid replaced during the session

Figure 18 conveys players' sweat $[Na^+]$. Players mean sweat $[Na^+]$ was 46 ± 12 $mmol \cdot L^{-1}$. Players had a mean sweat Na^+ rate of 934 ± 248 $mg \cdot L \cdot h^{-1}$, equating to a mean total Na^+ loss of 1598 ± 1023 mg throughout the training session.

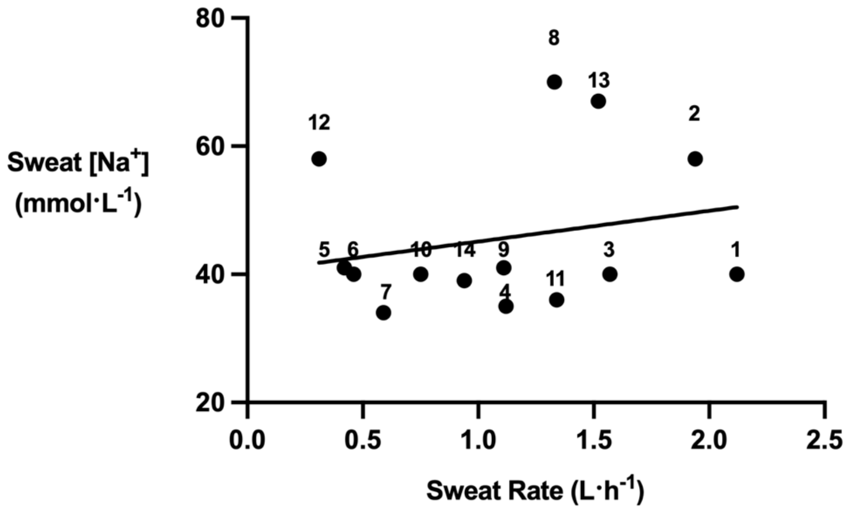

Figure 18. Players' sweat [Na^+] losses. Number (n) above the symbol denotes the player number

5.4.4.5 Differences in Sweat Rates and Sweat Sodium Rates between Males and Females

Male players had a significantly greater sweat rate in comparison to female players (males = 1.47 ± 0.45 $L{\cdot}h^{-1}$; females = 0.78 ± 0.45 $L{\cdot}h^{-1}$; $p = 0.01$; $d = 1.53$; CI = 0.16–1.22). There were no significant differences in sweat [Na^+] (males = 46 ± 12 $mmol{\cdot}L^{-1}$; females = 44 ± 12 $mmol{\cdot}L^{-1}$; $p = 0.53$; $d = 0.16$; CI = −13.09–16.23

5.4.5.6 Post Session Fluid and Sodium Intake

Figure 19 conveys the post-session fluid intake in relation to suggested post-session fluid intake (Sawka et al., 2007), while Figure 20 displays the post-session Na^+ intake in relation to suggested post-session Na^+ intake (Sawka et al., 2007). There was a significant difference between post-session fluid ($p = 0.002$; $d = 2.2$; CI = 0.859–2.848) and post-session Na^+ intake ($p = 0.011$; $d = 1.46$; CI = 242.6–2174.8) in the following day training session group and the same day training session group. All seven players in the following day training session group replaced 1.5 L of fluid for every kilogram of body mass lost throughout training, with five replacing the amount of Na^+ lost during the session. Only two out of the seven players in the same day training session group managed to replace 1.5 L of fluid for every kilogram of body mass lost throughout the training session, with only one player managing to replace the amount of Na^+ lost.

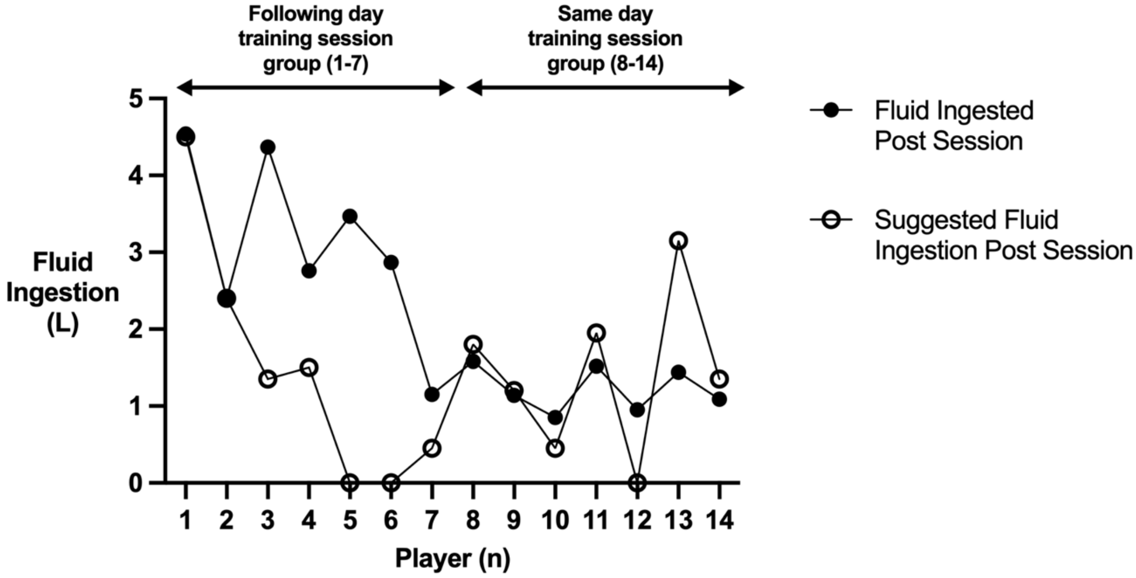

Figure 19. Players post session fluid ingestion in relation to their suggested post session fluid ingestion

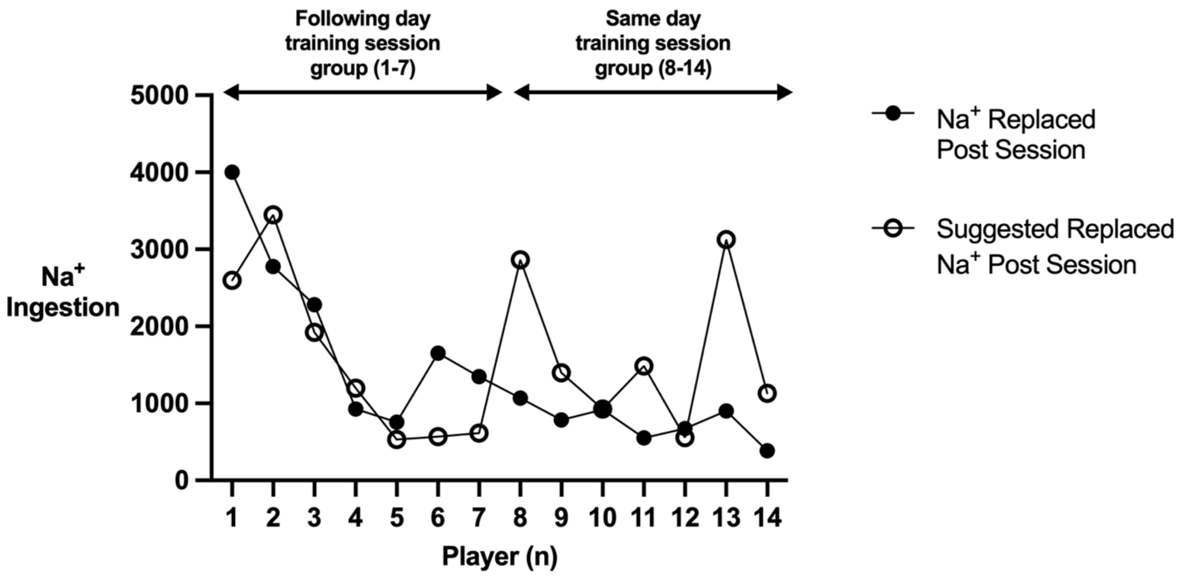

Figure 20. Players post session Na^+ ingestion in relation to their suggested post session Na^+ ingestion

5.4.5.7 Relationship Between Players Perceived Sweat Rate and Sweat Sodium Losses

There was a moderate positive association between players perceived sweat rate (Q1) and sweat rate (r = 0.51; p = 0.62), a very weak positive association between perceived incidence of cramps (Q2) and sweat [Na^+] (r = 0.01; p = 0.97), and a very weak negative association between perceived sweat [Na^+] (Q3) and sweat [Na^+] (r = −0.02; p = 0.95).

5.4.6 Discussion

The primary aim of this study was to quantify the fluid balance, sweat rates and sweat [Na^+] of elite squash players during a training session. The secondary aims were to (1) quantify the differences in sweat rates and sweat [Na^+] between male and female elite squash players; (2) calculate players hydration practices during the training session to determine whether these were optimal in relation to players' sweat rate and sweat Na^+ losses; (3) to establish whether players who have two training sessions on the same day, have sufficient time to appropriately rehydrate in comparison to players who are next training the following day; (4) to determine players perceived sweat rate, sweat [Na^+] and cramping frequency and to quantify the relationship between these and players' sweat rates and sweat [Na^+].

The main findings were (1) elite squash players had a mean fluid balance of −1.22 ± 1.22% throughout the session; (2) elite squash players had a mean sweat rate of 1.11 ± 0.56 $L \cdot h^{-1}$; (3) elite squash players had a mean sweat [Na^+] of 46 ± 12 $mmol \cdot L^{-1}$; (4) males had a significantly greater sweat rate than females; (5) players in the same day training session group were not able to replace fluid and sweat Na^+ losses, whereas players in the following day training session group were able to do so; (6) there was a moderate positive, but non-significant association between players perceived sweat rate and their sweat rate.

5.4.6.1 Pre-Session Hydration Status

Pre-session urine osmolarity conveyed that 11/14 players (79%) commenced the training session euhydrated (<700 $mOsmol \cdot kg^{-1}$; Sawka et al., 2007), with a mean pre-session urine osmolarity of 453 ± 283 $mOsmol \cdot kg^{-1}$. Previous research investigating the pre-exercise hydration status of athletes in a variety of sports is equivocal, with some athletes displaying euhydration pre-exercise (Maughan et al., 2004; Godek et al., 2005; Maughan et al., 2007; Newell et al., 2008; Horswill et al., 2009; Kilding et al., 2009; MacLeod et al., 2009; Kurdak et al., 2010; Duffield et al., 2010; O'Hara et al., 2010; Logan-Sprenger et al., 2011; Brandenburg et al., 2012; Gibson et al., 2012; Jones et al., 2015; McLean et al., 2016; Gamble et al., 2019; Tarnowski et al., 2022) and others displaying hypohydration pre-exercise (Godek et al., 2005; Maughan et al., 2005; Stover et al., 2006; Yeargin et al., 2006; Palmer et al., 2008; Shirreffs & Maughan, 2008; Osterberg et al., 2009; Palmer et al., 2010; Yeargin et al., 2010; Lott & Galloway, 2011; Tippet et al., 2011; Da Silva et al., 2012; Duffield et al., 2012; Cosgrove et al., 2014; Phillips et al., 2014; Thigpen et al., 2014; Arnaoutis et al., 2015; Vukasinovic-Vesic et al., 2015; Rollo et al., 2021; Tarnowski et al., 2022). Athletes' hydration status appears to be individualised, as exhibited by the range in values recorded in the present study (150 $mOsmol \cdot kg^{-1}$ to 1000 $mOsmol \cdot kg^{-1}$). Indeed, previous research displays high variability among cohorts of athletes (Maughan et al., 2004; Godek et al., 2005; Maughan et al., 2005; Stover et al., 2006; Yeargin et al., 2006; Maughan et al., 2007; Newell et al., 2008; Palmer et al., 2008; Shirreffs and Maughan, 2008; Horswill et al., 2009; Kilding et al., 2009; MacLeod et al., 2009; Osterberg et al., 2009; Kurdak et al., 2010; O'Hara et al., 2010; Palmer et al., 2010; Yeargin et al., 2010; Logan-Sprenger et al., 2011; Lott & Galloway, 2011; Tippet et al., 2011; Brandenburg et al., 2012; Da Silva et al., 2012; Duffield et al., 2012; Gibson et al., 2012; Cosgrove et al., 2014; Thigpen et al., 2014; Phillips et al., 2014; Arnaoutis et al., 2015; Vukasinovic-Vesic et al., 2015;McLean et al., 2016; Gamble et al., 2019; Rollo et al., 2021; Tarnowski et al., 2022).

The present data was collected at the start of a training micro-cycle, whereby players may have had ample opportunity to ensure euhydration prior to the session. Godek et al., (2005) reported American Collegiate Football players to be in a euhydrated state at the start of a training week (urine specific gravity = 1.017 ± 0.06), but experienced hypohydration from training days two to eight (urine specific gravity => 1.020). Future research should aim to quantify the hydration status of elite squash players throughout a micro-cycle, and whether there is a compounding effect of a player's training demands on hydration status.

5.4.6.2 Fluid Balance

Elite squash players had a mean sweat rate of 1.11 ± 0.56 $L \cdot h^{-1}$ during the training session. To our knowledge, no other racket sport has quantified the sweat rates of players throughout a training session, making it difficult to compare. Abián-Vicén et al., (2012) and Lott and Galloway (2011) quantified the sweat rates of elite badminton players and university tennis players through match play, when performed indoors at moderate environmental conditions (temperature = 17–24 °C; humidity 40–60%), respectively. They reported similar sweat rates to the present data, with elite badminton players shown to have a sweat rate of 1.08 ± 0.53 $L \cdot h^{-1}$ and tennis players a sweat rate of 1.10 ± 0.4 $L \cdot h^{-1}$. Environmental conditions of sports performed indoors can be regulated, and therefore players intraindividual sweat rates are primarily influenced by the intensity of effort, the clothing they wear, and their hydration status (Baker, 2017). Research has shown that elite squash match play may be performed at a higher intensity in comparison to training sessions (Girard et al., 2007; Gibson et al., 2019; James et al., 2021). Consequently, future research should aim to quantify the sweat rates of elite squash players during match play to quantify differences, in comparison to training. This would also allow for greater comparison against other racket sports as this data has previously only been collected during match play (Lott & Galloway, 2011; Abián-Vicén et al., 2012).

It is difficult to compare elite squash players' sweat rates to high intensity intermittent sports performed outdoors, due to differences in environmental conditions. Maughan et al., (2004) reported elite soccer players' sweat rates to be 1.4 ± 0.3 $L \cdot h^{-1}$ during a training session, although this was performed at a wet globe temperature of 26.6 °C and relative humidity of 54.8%. Environmental conditions have been shown to influence sweat rates (Baker, 2017). Rollo et al., (2021) reported that elite male soccer players had a higher sweat rate when performing high intensity training in hot environmental conditions (WGBT = 29 ± 1 °C; RH = 52 ± 7%; sweat rate = 1.43 ± 0.23) in comparison to cool environmental conditions (WGBT = 15 ± 7 °C; RH = 66.6%; sweat rate = 0.98 ± 0.21), due to an increase in the contribution of evaporative requirement for heat balance (Gangon et al., 2013; Baker, 2017). Elite squash tournaments are played all around the world in a variety of environmental conditions (Professional Squash Association 2023*a*). This includes hot conditions, such as when the 2022 Professional Squash Association World Championships were staged outdoors in Cairo, Egypt (Professional Squash Association 2023*b*). Consequently, future research should quantify the sweat rates of elite squash players during hot conditions to compare differences to moderate environmental conditions (temperature = 17–24 °C; humidity 40–60%). This would help players ascertain whether different hydration strategies are required when competing in hot and humid environmental conditions.

The present study highlights the interindividual variation in sweat rates among players. Sweat rates ranged from 0.31 to 2.12 $L \cdot h^{-1}$, conveying that a player's hydration strategy is not a one size fits all approach. This is consistent with data collected by Barnes et al., (2019), who, despite reporting a mean whole body sweat rate of 1.13 ± 0.58 $L \cdot h^{-1}$ among a variety of different team & skill sport athletes, conveyed a sweat rate range of 0.16 to 5.73 $L \cdot h^{-1}$. Interindividual variations in sweat rates may be due to genetic phenotypes of an individual's sweat glands, such as the size of the gland and its methacholine sensitivity (Sato & Dobson, 1970; Sato & Sato, 1983).

Players consumed a mean fluid intake of 0.53 ± 0.21 $L \cdot h^{-1}$ during the training session. This is reported to be less than elite soccer players through training (0.97 ± 0.3 $L \cdot h^{-1}$; Maughan et al., 2004), elite badminton players during match play (1.08 ± 0.5 $L \cdot h^{-1}$; Abián-Vicén et al., 2012), and university tennis players throughout match play (1.09 ± 0.63 $L \cdot h^{-1}$; Lott & Galloway, 2011). The lower fluid intakes of elite squash players could be due to individuals not wanting to consume high volumes of fluid while performing squash specific movements such as lunges and changes of direction (Vučković et al., 2003), or alternatively, there may not be the opportunity to consume fluids as in other high intensity intermittent sports. The opportunities for fluid consumption of elite squash players during training are normally unscheduled and intermittent breaks in play at the coaches' discretion. This contrasts with competitive match play, whereby players are allowed 120s at each game interval before the next game starts. Thus, future research should also aim to quantify whether this alters the fluid consumption dynamics in comparison to training.

Players replaced 62 ± 38% of fluid lost during the training session, with three players consuming more than 100% of their sweat losses during the session. Consequently, players had a mean body mass loss/gain of −0.91 ± 0.95 kg, equating to a mean body mass loss/gain percentage of −1.22 ± 1.22%. This is a greater body mass loss in comparison to elite badminton players (−0.35 ± 0.67%; Abián-Vicén et al., 2012) and university tennis players (−0.15 ± 0.79%; Lott & Galloway, 2011). This appears to be due to the lower volumes of fluid consumed during squash. The present study conveys the variability in fluid balance among elite squash players, highlighting the need for an individualised approach to hydration. Three players increased body mass during the session, while two players reported a body mass loss greater than 2%, the associated threshold for a decline in physical and cognitive performance (Sawka et al., 2007). Previous research has quantified the effects of hypohydration on sport-specific performance in basketball (Dougherty et al., 2006; Baker et al., 2007*a*; Baker et al., 2007*b*), cricket (Devlin et al., 2001; Gamage et al., 2016), field hockey (MacLeod & Sunderland, 2012), golf (Smith et al., 2012), horse racing (Wilson et al., 2014), and soccer (McGregor et al., 1999). Future research should aim to quantify if, and at what level, hypohydration decreases squash-specific performance (Jones et al., 2018).

5.4.6.3 Sweat Sodium Losses

Elite squash players had a mean sweat [Na^+] of 46 ± 12 $mmol{\cdot}L^{-1}$. This is comparable to data collected by Ranchordas et al., (2017), who conveyed a mean sweat [Na^+] of 44 ± 13 $mmol{\cdot}L^{-1}$ across a variety of different sports (soccer, rugby, American football, baseball and basketball), utilising the same technique (pilocarpine iontophoresis). The present data equated to a mean sweat Na^+ rate of 934 ± 248 $mg{\cdot}L{\cdot}h^{-1}$, and a mean total Na^+ loss of 1598 ± 1023 mg throughout the training session. Na^+ can be easily consumed in the diet through adding NaCl (i.e., table salt) to meals or sport hydration/electrolyte tablets to water (most commercially available ones contain ~400–1000 mg Na^+). Consequently, players should aim to consume approximately 1000 mg of Na^+ per hour of squash training to replace Na^+ losses.

The present study exhibited high variability in sweat [Na^+], ranging from 34 $mmol{\cdot}L^{-1}$ to 70 $mmol{\cdot}L^{-1}$. Therefore, while this recommendation of 1000 mg of Na^+ per hour of squash training may be advisable for players with moderate sweat [Na^+], players with a high sweat [Na^+] may require a more aggressive strategy to replace sweat Na^+ losses. Variability in sweat [Na^+] may be due to heat acclimation, through an increased Na^+ ion reabsorption capacity of the eccrine sweat gland (Buono et al., 2007; Chinevere et al., 2008), as well as the sweat glands increased sensitivity to aldosterone (Kirby, 1986) or differences in dietary Na^+ intake (Sigal & Dobson, 1968; Allsopp et al., 1998).

5.4.6.4 Differences Between Males and Females

Male players had a significantly greater sweat rate in comparison to female players ($p = 0.015$). This is consistent with findings from Barnes et al., (2019), who found that males had a significantly greater sweat rate than females during a variety of different sports and intensities. Differences in sweat rate between males and females could be due to fluctuations in the female sex hormones, estrogen and progesterone (Giersch et al., 2020; Rodriguez-Giustiniani et al., 2022). Transcapillary fluid dynamics have been reported to be altered as a result of differing levels of estrogen and progesterone, influencing intracellular and extracellular fluid balance (Stachenfeld et al., 2001). Female sex hormones may also influence thresholds for synthesis and release of arginine vasopressin, a volume regulatory hormone (Stachenfeld et al., 2002), as well as influencing fluid regulatory dynamics by increasing interstitial fluid during the luteal phase (Stachenfeld et al., 2001). These physiological changes at various time points throughout a female player's menstrual cycle may influence sweat rate, increasing water retention (Stachenfeld, 2008).

There were no significant differences between males and females in sweat [Na^+] ($p = 0.53$). This is consistent with Barnes et al., (2019), who found no significant differences between male and female athletes across a variety of different sports. Female sex hormones influence on net Na^+ balance is equivocal (Rodriguez-Giustiniani et al., 2022), and variations in sweat [Na^+] are likely to be due to interindividual and intraindividual differences (Baker, 2017), as previously discussed (see Section 5.3.6.3).

5.4.6.5 Post-Session Fluid and Sodium Consumption

Current ACSM guidelines recommend consumption of 1.5 L of fluid for every kilogram of body mass lost during exercise as well as replacing any Na^+ lost (Sawka et al., 2007). All seven players in the following day training session group replaced 1.5 L of fluid for every kilogram of body mass lost throughout the training, with five replacing the amount of Na^+ lost during the session. Only two of the seven players in the same day training group managed to replace 1.5 L of fluid for every kilogram of body mass lost throughout the training session, with only one player managing to replace the amount of Na^+ lost. Players in the following day training session group had 21 h and 30 min to rehydrate, whereas players in the same day training session group had 2 h and 30 min to complete the same rehydration. Consequently, differences in fluid and Na^+ consumption post-session could be due to a lack of time in-between training sessions, poor time management, and/or logistical issues (e.g., fluids are not available for players to consume). As a result, players should work with sports science practitioners and coaches to devise their training schedule and training load with consideration to their hydration demands. Players should also ensure that they are adequately prepared according to their hydration demands (e.g., have enough fluids and appropriate Na^+ containing foods) to ensure they optimally rehydrate in between sessions. Squash players often engage in more than one training session per day (Gibson et al., 2019; James et al., 2021). Future research should aim to track the hydration status alongside body mass and hydration practices throughout squash players' microcycle, in order to determine whether there is a compounding effect of training on players' hydration status.

5.4.6.6 Players' Perceived Sweat Rate, Sweat Sodium Losses and Perceived Incidence of Cramps

There was a moderate positive association between perceived sweat rate and sweat rate. This is consistent with findings in male and female division II basketball players during practice, who were able to estimate sweat losses in relation to actual sweat losses during sport-specific practice ($r = 0.87$; $p < 0.001$; Thigpen et al., 2014). Sweat rates may be easy for squash players to determine due to visual cues, such as the amount of sweat on apparel or on the court while playing.

Players were shown to perceive a very weak negative association between their perceived sweat [Na^+] and their sweat [Na^+]. This suggests that players could not predict how much Na^+ they lost in their sweat, and contrasts with findings from Ranchordas et al., (2017) of a strong positive correlation between athletes' sweat [Na^+] and self-reported [Na^+] ($r = 0.82$; $p < 0.001$). [Na^+] in sweat may be more difficult to predict, as there is no visual stimulus, unlike sweat rates, aside from Na^+ residue on apparel, which is only visible in darker coloured clothing.

Players also conveyed a very weak positive association between perceived incidence of cramps and sweat [Na^+]. This is consistent with findings from Ranchordas et al., (2017) who found the same weak positive correlation ($r = 0.18$; $p = 0.015$). The causes of cramp are ambiguous and therefore a causative relationship between cramps and electrolyte depletion is equivocal (Maughan & Shirreffs, 2019).

5.4.6.7 Limitations

There are a few limitations to the present study. Firstly, players may have been aware that their hydration status was being assessed prior to the training session. Players were partially blinded, as they were asked to provide a urine sample prior to the training session without clarification as to why. However, some players may have guessed that this was to quantify hydration status and altered hydration practices pre-session accordingly (i.e., consumed more fluids to ensure they were euhydrated). Urine osmolarity is also reported to lack clinical sensitivity in comparison to blood tonicity when measuring hydration status (Hew-Butler et al., 2018). Despite this, urine osmolarity has been reported to be a reliable and practical instrument in assessing athlete's hydration status in the field (Shirreffs & Maughan, 1998).

Another limitation is that the study may not have been suitably powered to detect significant differences between means. Retrospectively, a power calculation was performed which reported a sample size of 42 was required (21 in each group) to achieve a statistical significance of $p < 0.05$. Despite this, the statistical analysis was able to detect statistically significant differences in sweat rates between males and females, which is consistent with the literature in this area (Barnes, 2019), as well as differences in post session fluid and post-session Na^+ intake among the two training groups.

Another potential limitation is the technique used to measure sweat [Na^+]. Pilocarpine iontophoresis is a regional sweat collection technique, with the present study utilising a player's forearm to quantify sweat [Na^+]. Taylor & Machado-Moreira (2013) reported variations in regional sweat [Na^+], with regional sweat [Na^+] techniques also shown to overvalue sweat [Na^+] in comparison to whole body sweat [Na^+] (Shirreffs & Maughan, 1997) (whole body Na^+ loss = 51.6 ± 18.3 mM; regional Na^+ loss = 75.3 ± 21.9 mM). However, due to the nature of the squash, the whole body sweat [Na^+] technique proposed by Shirreffs & Maughan (1997) is not plausible. Other research (Patterson et al., 2000; Baker et al., 2009) has collected samples from various sites of the body (e.g., forearm, quadricep etc.), and ran either a regression equation or combined measures into an arithmetic mean to develop a measure of whole body sweat [Na^+]. However, these regression equations are derived from sweat-patch tests, which may compromise the validity of their results (Ranchordas et al., 2017). The local sweat response to pilocarpine iontophoresis is proposed to differ in comparison to exercise induced sweating, due to differences in the sudomotor response (Vimieiro-Gomes et al., 2005; Baker, 2017). Exercise-induced sweating is modulated through a variety of local and central mediators, such as skin blood flow and exercise pressor reflex (Shibasaki et al., 2003; Shibasaki & Crandall, 2010). Despite this, differences in sweat [Na^+] composition between pharmacologically induced sweat (i.e., pilocarpine iontophoresis) and thermally induced sweat (i.e., during exercise) are equivocal, with some studies reporting pharmacologically induced to have greater sweat [Na^+] and some reporting similar sweat [Na^+] (Shwachman & Mahmoodian, 1966; Sato et al., 1970). Consequently, as the techniques employed in the present study are valid and reliable (see Section 5.3.3.4), we opted for pilocarpine iontophoresis.

Finally, another limitation of this study is that we did not quantify female players' hormonal status to better understand how this may influence their sweat rate. Female sex hormones may influence female players' sweat rates (see Section 5.3.6.4).

5.4.7 Practical Applications

This study highlights that it is possible to collect hydration-related data in elite squash players and conveys a framework to determine them. It also displays the variability in hydration demands across players and emphasises the importance of individualised hydration strategies, rather than a one-size-fits-all approach. For example, player 1 had a sweat rate of 2.12 $L \cdot h^{-1}$ and sweat [Na^+] of 40 $mmol \cdot L^{-1}$, losing 3.17 L of fluid and 2589 mg of Na^+ throughout the session. This contrasts with player 5, who had a sweat rate of 0.42 $L \cdot h^{-1}$ and sweat [Na^+] of 41 $mmol \cdot L^{-1}$, losing a total fluid and Na^+ loss of 0.63 L and 530 mg respectively. Consequently, the hydration strategies employed with each player may be different, even though the training loads may be the same. Player 5 had a low hydration demand, and fluid and Na^+ losses can be accounted for throughout or immediately post-session. This is unlike player 1, who had a high hydration demand, with it being unlikely to replace sweat and Na^+ losses during the session, requiring an aggressive rehydration strategy post-session, as well as consideration of the proximity of the next training session undertaken.

6.0: Synthesis

6.1 Achievement of Thesis Aims

This chapter provides a synthesis of the main aims of the PhD programme, as discussed in 'Aims of the PhD (See section 1.5). To ensure these were achieved, each study had a specific aim:

Aim 1)

To systematically review the current physiological and nutritional literature within squash to determine the quality of literature and identify gaps where knowledge was required.

Evidence of Achievement:

This aim was addressed via study one, which systematically reviewed all the physiological and nutritional literature conducted within squash (see section 2).

Aim 2)

To quantify the nutrition knowledge of elite squash players to help provide an indication of whether players require nutrition support and education to increase their nutrition knowledge, and improve food choices to support high training and match demands, as well as a general healthy lifestyle

Evidence of Achievement:

The nutrition knowledge of elite squash players was quantified in study two (see section 3.0). This acted as a screening process for England Squash funded players and as a result, 1-1 bespoke nutrition support was provided to many players.

Aim 3)

To concurrently quantify energy expenditure and energy intake among a cohort of elite male squash players throughout a 7-day training microcycle. This data can be used to create specific nutritional recommendations for the sport so that sports nutritionists can better advise players to optimise their health and performance

Evidence of Achievement:

The energy expenditure and energy intake of elite male squash players during a 7-day training microcycle was quantified in study three (see section 4.0). Practical recommendations were provided in 'practical applications' (see section 4.3.6) which propose nutritional recommendations for elite male squash players.

Aim 4)

To quantify the sweat rates and sweat [Na^+] of elite squash players throughout a training session to provide players, coaches, and practitioners with information to optimise players' hydration practices throughout training.

Evidence of Achievement:

The sweat rates and sweat [Na^+] of elite squash players throughout a training session was quantified in study four (see section 5.0). Players were provided with individualised hydration strategies specific to their sweat [Na^+] as discussed in 'Practical Implications' (see section 5.3.7)

6.2 General Discussion

As discussed in 'defining the performance problem' (see section 1.3). The aim of this PhD was to answer specific 'performance problems' which were identified by the researcher, players, and coaches. These were:

1) England Squash have never had a full-time nutritionist working in the sport, and there seems to be some ambiguity regarding the impact nutrition can have on performance. Therefore, what are players understanding of nutrition?

2) Anecdotally, players were seen to have high training loads with much of this training performed at a high intensity. As a result, do players know their energy expenditure and how to fuel and recover effectively from session to session to optimise their health, physical performance and training adaptations?

3) Due to high training loads anecdotally experienced and cultural preferences of the sport, squash players generally train twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. Does this give players enough opportunity to optimally recover and rehydrate from one session to the next or should coaches and players reconsider their training schedules and periodisation to facilitate greater recovery to maximise the training response?

4) Anecdotally, some players were shown to have high sweat rates. This was so apparent that one player had to change their t-shirt, socks and shoes after each break in training due to their high sweat rates, to prevent excess sweat on the court floor. This player's sweat rate was later quantified to have a sweat rate of 2.12 $L{\cdot}h^{-1}$ (player one data; see section 5.3). A 'performance problem' was how do we ensure squash players which have high sweat rates are optimally hydrated when they have high training loads and limited time in-between training sessions?

Consequently, the PhD programme aimed to answer these performance problems to optimise the health and physical performance of players.

6.2.1 Physiological and Nutritional Considerations for Elite Squash: A Systematic Review

Study one aimed to (1) ascertain whether the 'performance problems' identified in the 'Defining the Performance Problems' (see section 1.3) could be solved from the available literature; (2) collate all the previous research conducted and provide a critique of the literature to guide practitioners, coaches, and players on how best to interpret the contemporary data; (3) identify gaps in the literature to guide researchers on the future directions within squash.

The study highlighted that none of the 'performance problems' identified in the 'Defining the Performance Problems' (see section 1.3) could be solved from the available literature. Therefore, this directed the aims of the rest of the PhD programme as it set out to solve the remaining 'performance problems' highlighted. The systematic review also outlined that much of the research conducted in squash (1) has low validity as it is conducted on recreational and not elite players; (2) is of poor or moderate methodological quality which are predominantly observational studies rather than intervention based control trials; (3) is outdated as much of it was conducted prior to the 2009 rule change and therefore may not be valid due to changes in playing dynamics (Murray et al., 2016). Lastly, the systematic review provides a consensus for players, coaches, and practitioners to interpret the data, while proposing many future directions to advance research and evidence-based practice within squash.

6.2.2 Elite Squash Players Nutrition Knowledge and Influencing Factors

Study two aimed to (1) assess the nutrition knowledge of elite squash players; (2) quantify the factors which may influence an elite squash players nutrition knowledge; (3) survey what contemporary sports nutrition research elite squash players would like to see being conducted in the future.

The study found that players had 'average' nutrition knowledge. This is greater than athletes in other sports who reported 'poor' nutrition knowledge (Jenner et al., 2018= 46%; Trakman et al., 2018 = 46%; McCrink et al., 2020 = 40%). Team England and Academy players from England Squash were fed back their NSKQ score and this acted as a screening process to many players who had 'poor' or 'average' nutrition knowledge. Previous research has quantified the effectiveness of nutrition education interventions on athletes' nutrition knowledge (Tam et al., 2019). It was proposed that a nutrition education framework was to be developed over the coming years to increase players nutrition knowledge, however this did not materialise, as discussed in the synthesis section (see section 6.0). Instead, players who required nutrition support were provided 1-1 nutrition support to optimise their health and physical performance. Questions were raised about the appropriateness of the non-specific nutritional guidelines used in the NSKQ, as many of the players who scored poorly felt that the questions were incorrect. Therefore, there was an increased ambition to quantify the energy expenditures of elite squash players to create specific nutritional guidelines for squash. This data could also be included in any nutrition education framework which was previously proposed.

6.2.3 Doubly Labelled Water Assessment of Elite Male Player's Energy Balance During a Seven Day Training Microcycle

Study three was the first study to quantify the energy expenditure over a 7-day microcycle in elite male squash players. It generates the knowledge to create specific nutritional guidelines for elite male squash players (see practical applications; section 4.3.6), which could be utilised by other players who didn't take part in the study but have comparable training loads. The study also quantifies players energy intake over the 7-day microcycle, and subsequently overall energy balance, to determine whether these habits were optimal in relation to players energy expenditure. The study found that elite male squash players expended a mean daily energy expenditure of 4,210 ± 1,017 Kcals (2) players ingested a mean daily energy intake of 3,389 ± 981 Kcals (3) players exhibited a mean daily energy balance of -821 Kcals; (4) players had a mean energy availability of 32 ± 18 $Kcal \cdot kg^{-1}$ $FFM \cdot d^{-1}$ throughout the microcycle (5) the mean PAL score of elite squash players was 2.5 ± 0.4. For context, elite squash players are reported to expend 13.4% more energy than elite male tennis players during a training microcycle than an elite tennis player during a microcycle (Squash = 4,210 $Kcals \cdot d^{-1}$ vs. Tennis = 3712 $Kcals \cdot d^{-1}$)

The study displays that two players energy balances are appropriate, but player one exhibited low energy availability. Elite male squash players who didn't partake in this study may also have mismatches in their energy balance and this study highlights the need to ensure appropriate energy intake in relation to training load to optimise health and physical performance. It may be appropriate to quantify the energy balance in other cohorts of elite squash players to determine whether low energy availability is systemic within the sport.

6.2.4 Fluid Balance, Sodium Losses and Hydration Practices of Elite Squash Players During Training

Study four was the first to quantify the sweat rates and sweat Na^+ losses of elite squash players during a training session. The study found that (1) elite squash players had a mean fluid balance of −1.22 ± 1.22% throughout the session; (2) elite squash players had a mean sweat rate of 1.11 ± 0.56 $L \cdot h^{-1}$; (3) elite squash players had a mean sweat $[Na^+]$ of 46 ± 12 $mmol \cdot L^{-1}$; (4) males had a significantly

greater sweat rate than females; (5) players in the same day training session group were not able to replace fluid and sweat Na^+ losses, whereas players in the following day training session group were able to do so; (6) there was a moderate positive, but non-significant association between players perceived sweat rate and their sweat rate. For context, the sweat rates reported are similar to other racket sports such as elite badminton players (Abián-Vicén et al., (2012) =1.08 ± 0.53 L·h^{-1}) and university tennis players (Lott and Galloway, (2011) = 1.10 ± 0.4 L·h^{-1}).
This generates the knowledge to create specific hydration for players specific to their sweat [Na^+] as discussed in 'Practical Implications' (see section 5.3.7). The study also displays that 2 hours and 30 minutes is not enough time to optimally rehydrate and if a player is to engage in another high intensity training session, whereby sweat rate would be high, physical performance may be compromised. Consequently, this study may inform training design and prescription of elite squash players to appropriately periodise players load or alter training times to facilitate optimal recovery protocols.

6.3 Limitations

The limitations of each study are presented below. Some limitations were already discussed in each study, so these are referenced rather than repeated in detail.

6.3.1 Physiological and Nutritional Considerations for Elite Squash: A Systematic Review

The PEDro scale is primarily intended for evaluating the methodological quality and reporting of randomized controlled trials and certain types of clinical controlled trials (Cashin & McAuley, 2019). Therefore, it poses the question of whether the widespread low-quality ratings of the studies conducted in squash are truly accurate being reported in this way. The studies methods were determined 'a piori' and therefore the researcher wasn't sure whether the available scientific literature conducted in squash would contain observational studies or randomised controlled trials. While many studies were observational, there were some randomised controlled trials in the scientific literature (Romer et al., 2001; Bottoms et al., 2006; Raman et al., 2014), with the researcher wanting to maintain consistency among the tools utilised. It may have been more appropriate to utilised different tools depending on the type of study (e.g. case study, observational, randomised controlled trial) such as the National Heart, Lung and Blood Institute Study Quality Assessment Tools which provides a different tool for each type of study (National Heart, Lung and Blood Institute, 2021).

Another limitation is that there may be inherent bias from the researcher when interpreting the data. As previously discussed in this thesis, the researcher has previously competed at squash on the Professional Squash Association Tour as well as spending time in the performance environment to develop a needs analysis of the ‘performance problems’ experienced within squash. Therefore, the researcher may have had their own perceptions of the sport (e.g. the sport is becoming more intense), which is communicated in the systematic review.

6.3.2 Elite Squash Players Nutrition Knowledge and Influencing Factors

The studies limitations are discussed in section 3.3.5.4

6.3.3 Doubly Labelled Water Assessment of Elite Male Player’s Energy Balance During a Seven Day Training Microcycle

A limitation of the doubly labelled water technique is its inability to provide day to day energy expenditure assessments, hence energy expenditure being expressed over a 7-day microcycle in this study. This is due to energy expenditure being quantified through the elimination rate of each isotope. The elimination rate is roughly 7-14 days, depending on the dose of heavy oxygen (^{18}O) and heavy hydrogen (^{2}H). Daily energy expenditure can only be calculated by dividing the total energy expenditure by the assessment period and this method makes it difficult to quantify the energetic demands of different training sessions or days. It is likely that energy expenditure varied on a day-to-day basis and while nutritional recommendations can be devised to account for the energy expenditure over a microcycle, day to day recommendations may be appropriate to optimise training adaptation (Impey et al., 2017), body composition (Stellingwerff, 2019) and physical performance (Jeukendrup, 2017).

A potential limitation of the study was that exercise energy expenditure, and subsequently energy availability was calculated through heart rate monitoring rather than the gold standard indirect calorimetry. Heart rate monitoring was shown to yield a non-significant (1.2 ± 6.2 %; p = >0.05) mean underestimate of total energy expenditure in comparison to indirect calorimetry (Ceesay et al., 1989). Consequently, due to the nature of the study and inability to measure exercise energy expenditure through indirect calorimetry, heart rate monitoring was used to quantify expenditure. The Polar H10 band was selected, as this has been shown to have the greatest RR signal strength during high intensity activities and high correlation to an electrocardiography Holter monitor (Gilgen-Ammann et al., 2019).

Another potential limitation is the small sample size included in the study. While there was no statistical analysis performed in the study, one of the aims of the study was to increase the understanding of the energy expenditure of elite male squash players throughout a microcycle, so that energy and carbohydrate guidelines can be devised. However, it may be difficult to devise energy and carbohydrate guidelines which are generalised to all elite male squash players due to variations in training among different cohorts of players. It also states that players follow inappropriate nutrition strategies such as sub optimal carbohydrate intake or in one case, severe energy restriction, leading to low energy availability. Consequently, due to player one following sub-optimal practices, the mean data suggests that players under fuel, however, this isn't representative of the other two players or potentially the wider squash community. To minimise this, we presented the data as mean and individual data to provide a richer narrative.

6.3.4 Fluid Balance, Sodium Losses and Hydration Practices of Elite Squash Players During Training

The studies limitations are discussed in section 5.3.6.7

6.4 Future Research and Practice

While this PhD programme has increased knowledge by: (1) systematically reviewing all of the available physiological and nutritional research conducted within squash; (2) quantifying the nutrition knowledge of elite squash players; (3) measuring the energy expenditure and energy intake of elite male squash players during a 7-day training microcycle; (4) calculating the sweat rates and sweat [Na^+] of elite squash players during a training session, the systematic review (see section 2.0) highlighted that there is still much research to be conducted within squash to advance research and evidence-based practice within squash. Table 12 outlines some of the key areas for future research and practice in an easy-to-read format, rather than repeating text from the systematic review.

Table 12. Future directions for elite squash research

Research Section	Research Question	What studies as the research question been formulated from?	Rationale
During Match Play	Quantify the energy requirements and physiological responses during match play in elite male players	Study one and study three	Determine whether rule changes have affected the energy requirements and physiological responses during elite male match play
	Quantify the energy requirements and physiological responses during match play in elite female players	Study one and study three	The energy requirements and physiological responses during elite female match play have never been quantified and current practitioners working with female squash players must interpret through data collected in male players
	Quantify muscle and blood metabolites in elite squash match play among male and female players	Study one and study three	Squash matches can last >90 minutes, with high intensity intermittent exercise lasting around this duration being shown to completely deplete muscle glycogen stores in individual muscle fibers, reducing high intensity performance. Quantifying the muscle and blood metabolites in an elite squash match play among male and female players would enable the ability to make specific

			nutritional recommendations based on the substrate utilisation during match play and determine the factors which contribute to fatigue during match play
	Quantify the player load and energy expenditure of elite male and female squash players using the doubly labelled water technique during a competition period alongside current competition dietary practices	Study one and study three	This would create specific nutritional guidelines during competition for elite male and female players. By tracking current competition dietary practices, this quantifies whether they are optimal and appropriate
	Quantify whether there are any alterations in neuromuscular function after elite squash match play in male and female players	Study one	This has previously been researched in recreational players, with peripheral fatigue potentially reducing physical performance in subsequent matches. However, peripheral fatigue may not be prevalent post-match play in elite players due to the conditioning sessions players undertake
	Quantify the muscle damage, inflammatory, immune and performance responses following matchplay in elite male and female players	Study one	Specific physiological and nutritional recovery strategies can be devised and determine whether logistical changes, such as the duration of time inbetween matches needs to be altered by the World Squash Federation and Professional Squash Association to ensure high quality matches and product.
During Training	Quantify the energy expenditures of elite female squash players throughout a training microcycle alongside current dietary practices using the doubly labelled water technique	Study one and study three	This would create specific nutritional guidelines during training, as had been done in other racket and high intensity intermittent sports. Players dietary intakes should also be reported alongside energy expenditure to quantify whether players current dietary habits are optimal
Doubles Squash	Quantify the energy requirements and physiological responses during match play in male, female, and mixed doubles	Study one and study three	Ascertain the characteristics of the game, and whether there are any differences in comparison to singles squash

Anthropometrical Characteristics	Quantify the anthropometrical characteristics of elite male and female squash players	Study one	This would quantify the body composition of elite squash players and whether there are any differences between sexes, ethnicities and playing styles
Physiological Characteristics	Quantify the physiological characteristics of elite male and female squash players.	Study one	It is currently difficult to compare between studies as they have been performed on players of differing standard and a variety of tests (e.g. incremental treadmill test or incremental squash test) to quantify variables. Murray et al., (2016) reported that the intensity of match play is increasing, however, much of the data collected is prior to the 2009 rule change (e.g. lactate threshold) and key data is missing such as the lactate threshold of elite female players. Therefore, collecting this data would define the physiology of an elite squash players
Nutrition Knowledge	Quantify the effectiveness of a nutrition education intervention at increasing the nutrition knowledge of elite squash players	Study one and study two	Elite squash players were shown to have ‘average’ nutrition knowledge with nutritional education interventions shown to increase nutrition knowledge and practices. Consequently, this should be quantified in elite squash players
Macronutrient and Micronutrient Intake of Elite Players	Quantify the sustainability of elite players diets	Study one and study three	Consuming a sustainable diet is a developing area of sports nutrition and determining the sustainability of elite players diets helps quantify whether any changes are required to make them more sustainable
Hydration	Quantify the sweat rates of elite squash players during hot conditions to compare differences to moderate environmental conditions (temperature = 17–24 ◦C; humidity 40–60%).	Study one and study four	Elite players compete in hot environments such as the 2022 Professional Squash Association World Championships, which was held outdoors in Cairo, Egypt. This would help players determine whether differing hydration strategies are appropriate when

			competing in hot and humid environmental conditions.
	Quantify the sweat rates and sweat $[Na^+]$ of players during match play	Study one and study four	Research has shown that elite squash match play may be performed at a higher intensity to training sessions, with exercise intensity being an intraindividual factor in individuals sweat rates
Supplements	Quantify the effects of beta-alanine supplementation on squash-specific repeated sprint ability	Study one	Beta-alanine supplementation may be beneficial for squash players to buffer any accumulation of H^+ during match play, and augment multiple sprint ability, a key performance indicator of elite squash
	Quantify the effects of sodium bicarbonate supplementation on squash-specific repeated sprint ability	Study one	Sodium bicarbonate supplementation has been shown to increase high intensity exercise and high intensity intermittent exercise across a variety of sports and activities such as running, cycling, rowing, and swimming. Consequently, it may be beneficial to buffer any accumulation of H^+ during match play, and augment multiple sprint ability, a key performance indicator of elite squash.
	Quantify the effects of caffeine ingestion on the key performance indicators of elite squash performance such as speed, multiple sprint ability and aerobic endurance, alongside cognitive and technical tasks (e.g. shot accuracy) to ascertain whether caffeine ingestion is beneficial in a squash-specific context.	Study one	Caffeine ingestion has been shown to optimise many of the key performance indicators associated with elite squash performance such as muscular strength, anaerobic power, muscular endurance, aerobic endurance, and increase specific aspects of cognitive function such as reaction time, attention, and vigilance
	Quantify the effects of inorganic nitrate supplementation on the key performance indicators of elite squash performance such as speed, multiple sprint ability, and aerobic endurance	Study one	Inorganic nitrate consumption may increase endurance performance through reducing the oxygen cost of exercise, as well as increasing repeated sprint ability through augmenting the contractile function of type II muscle fibres. This may optimise squash-specific performance

Figure 21. Future directions Infographic

6.5 Reflections from a Researcher and Practitioner

As stated in my acknowledgments and throughout section one of this thesis, there have been many high and lows throughout this PhD process. I would classify myself as a practitioner first and foremost. From day one of starting my PhD, I was embedded within the Squash sports science sport medicine and coaching teams providing nutrition support to their Team England, Academy, Development, and Potential pathway squads throughout the duration of the PhD programme.

Practitioners' development can be split into three areas:

- **Technical knowledge –** Do they understand the basic biochemistry and nutritional science which underpins the sport
- **Skills –** Do they have the appropriate skills in their armoury to work in elite sport such as time management, communication, presenting etc.
- **Application –** Can they apply their technical knowledge and skills to a specific scenario or sport

Throughout the PhD process, I have developed these in my practitioner and researcher roles within Squash, as well as roles at Chelsea FC and latterly at Aquatics GB providing nutrition support to Olympic and Paralympic swimmers in the build-up to the Paris 2024 Olympic and Paralympic Games.

It was initially difficult to get traction with the PhD as England Squash's main motivation was to have me embedded as a performance nutrition practitioner rather than a researcher. On my first day of the PhD, I was handed a case load of athletes to provide nutrition support to. Much was a continuation of the work from my internship I had completed the previous year while completing my masters. Alongside this, I began work on my literature review, scoping out all the published literature within Squash. The common theme from my practitioner work was that the energy expenditures of Squash players were high, and the intensity of the game was increasing. There was also ambiguity of whether players had appropriate nutritional strategies to fuel appropriately for the work required. This led to the creation of the initial golden thread of the PhD:

1) Systematic review – Systematically reviewing all the physiological and nutritional literature within Squash

2) Anthropometrical and Physiological Characteristics of Elite Squash Players – Quantify the anthropometrical (stature, mass, body fat %) and physiological characteristics (lactate thresholds, VO_{2max}) of elite squash players

3) Game Analysis of Elite Male and Female Squash Players – Similar to Girard et al., (2007) but hypothesised that the intensity of match play had increased

4) Energy Expenditures of Elite Squash Players Throughout a Microcycle – Similar to Study Four in the thesis but would also include elite female squash players

As I continued practitioner work, other 'performance problems' started to develop:

1) Many players didn't feel they required nutrition support despite me observing their nutrition practices to be sub optimal

2) Due to high training loads anecdotally experienced and cultural preferences of the sport, squash players generally trained twice per day from the hours of 09:30 to 11:30 and 14:00 to 16:00. This impinged on their time to recover from one session to the next

3) Anecdotally, some players were shown to have high sweat rates. Combined with limited recovery time in between sessions

I started data collection for my first study in January 2020, quantifying the anthropometrical and physiological characteristics of elite squash players. However, in March 2020, COVID-19 happened and the whole of the country was in lockdown. There was ambiguity on how this would affect my PhD. I was initially told it would be two weeks, however, the dates to restart data collection kept on being pushed back causing anxiety and frustration. In June / July 2020, it was decided that I would need to rethink my PhD as there was ambiguity on whether I would be able to get back into the lab and collect any physical data.

Therefore, alongside completing my systematic review, I began to quantify players nutrition knowledge. This data could be collected online and would be utilised to demonstrate to the players that their knowledge and subsequent practices may be suboptimal, meaning that they would be more likely to engage in nutrition support and my research.

At this stage, elite athletes were able to start training again, but Covid-19 was still rife. Unfortunately, I was unable to work with any of the players or collect any physical data due to restrictions put in place by England Squash. I felt that this was blunting my progress in the PhD as well as a practitioner as I was not able to develop many of the skills I required. I therefore started looking at other roles within sports nutrition and in July 2021 started working as a performance nutrition consultant for Chelsea FC two days a week. This settled me as I was able to develop my practitioner skills on a weekly basis and be embedded within an elite sporting environment, something I was not able to do with England Squash, partly due to COVID-19 and partly due to Squash following a decentralised programme.

Alongside this, I pleaded with Squash to enable me to collect physical data on the players so that I could complete my PhD. I presented to them a 'performance problem' on sweat rates, identifying that some players have high sweat rates and limited time to recover in-between sessions. This was presented on a Friday and by Tuesday I was collecting the data. This demonstrates the chaos of elite sport and while many studies have meticulous planning to execute the data collection period, I was thrust into it.

I subsequently presented my energy expenditures study to England Squash as the final 'performance problem' and was enabled to contact players to collect the data. This is different to how many PhD's may operate as they would be driven by the Director of Studies or external partner such as England Squash to provide the participants. For myself, this mean scrambling around, messaging players and trying to give a sales pitch as to why this data would be important and how we could align with their busy training schedules. I was lucky enough to recruit three participants and this data was collected in the summer of 2022.

The finishing of my data collection coincided with me taking on a new role as Performance Nutritionist at Aquatics GB. I had had issues in my other role at Chelsea FC due to the football club owner being sanctioned by the Government for their involvement in the Russian invasion of Ukraine. There were a lot of ambiguities around contracts etc. I was then thrust into the world of Olympic and Paralympic sport, working at three Aquatics GB Performance Centres in Loughborough, Bath and Manchester. This put significant strain on my ability to write up my PhD thesis and took two years to get across the line.

6.6 Summary and Conclusions

In conclusion, the data generated from the PhD programme has contributed new knowledge and understanding to the squash literature, having a significant practical impact for the field. Study one identified that much of the research conducted in squash (1) has low validity as it is conducted on recreational and not elite players; (2) is of poor or moderate methodological quality which are predominantly observational studies rather than intervention based randomised controlled trials; (3) is outdated as much of it was conducted prior to the 2009 rule change and therefore may not be valid due to changes in playing dynamics (Murray et al., 2016); (4) there are many future directions to advance research and evidence-based practice within squash which are presented in Table 12. Study one also highlighted that none of the ‘performance problems’ identified from the needs analysis had been previously answered from the scientific literature.

Study two quantified that elite squash players had ‘average’ nutrition knowledge. Therefore, this provided the rationale to provide nutrition support to many of England Squash’s elite players who felt that their nutrition habits were optimal. It stimulated conversations around what ‘optimal’ nutrition was for elite squash players and shaped the following studies to try and define this by quantifying the energy expenditures of players during a training microcycle, alongside their current energy intake (study three), as well as their sweat sodium loses during a training sessions, alongside their hydration habits.

Study three quantified the energy balance of elite male squash players over a 7-day microcycle It generated the knowledge to create specific nutritional guidelines for elite male squash players (see practical applications; section 4.3.6), which could be utilised by other players who didn’t take part in the study but have comparable training loads. The study also quantified players energy intake over the 7-day microcycle, and subsequently overall energy balance, to determine whether these habits were optimal in relation to players energy expenditure. The study displayed that two players energy balances are appropriate, but player one exhibited low energy availability. These players were provided with feedback to optimise their nutrition habits, while it also highlights that other players may be at risk of low energy availability, if they have comparable training loads to the ones experienced in the study and inadequate nutritional strategies.

Study four quantified the sweat rates and sweat Na^+ losses of elite squash players during a training session. This generates the knowledge to create specific hydration for players specific to their sweat [Na^+] as discussed in ‘Practical Implications’ (see section 5.3.7). For example, the player detailed in ‘performance problem four’ was provided with a bespoke hydration strategy to optimise their hydration habits based on their sweat rate and sodium losses which they could implement throughout training. The study also highlighted that 2 hours and 30 minutes is not enough time to optimally rehydrate and if a player is to engage in another high intensity training session, whereby sweat rate would be high, physical performance may be compromised. Consequently, this study informed the training design and prescription of England Squash’s elite players to appropriately periodise players load, or alter training times to facilitate optimal recovery protocols.

7.0: References

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