An Evaluation of the Nutritional Practices and Energy Requirements of Elite Female Soccer Players: A Mixed Methods Investigation

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Abstract

In recognition of the increasing growth and professionalism of the women's game (Fédération Internationale de Football Association, 2017, 2019; Petty and Pope 2019), there have been multiple calls for a strategic and multidisciplinary research agenda that seeks to improve the health and performance of the female soccer player (Datson et al. 2017; Nassis et al. 2021). Indeed, in a recent audit of research, it was demonstrated that the existing research base is not comparable to the men's game (Okholm Kryger et al. 2021). In terms of potential research priorities, this audit identified that nutrition-related research is less studied when compared with other sub-disciplines of sport and exercise science (Okholm Kryger et al. 2021). Furthermore, the nutritional guidelines that are currently directed to female athletes are based on research primarily conducted on males (Moore et al. 2021). This lack of female specific research is of concern given that female athletes are susceptible to chronic low energy availability (Heikura et al. 2021), the result of which can manifest as symptoms associated with the female athlete triad or relative energy deficiency in sport models (Nattiv and Lynch 1994; Mountjoy et al. 2023). Therefore, the aim of this thesis was to determine energy requirements and current nutritional practices of elite female soccer players, using a mixed methods approach.

Based on previous observations suggesting the existence of under-fuelling within this population, the aim of Study One was to qualitatively explore player and stakeholder perceptions of nutrition practices in support of female soccer players' development and performance. Semi-structured interviews (36 ± 18 mins in length) were conducted with 47 participants, including players (n = 12), parents (n = 9), coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5) and medical staff (n = 5). Via thematic analysis, data provided an insight into the nutrition culture within elite women's soccer. Data demonstrate that considerable confusion and misconceptions exist amongst players and stakeholders regarding the theoretical underpinning and practical application of meeting energy requirements. As such, it is perceived that players 'under-fuel', which is likely caused by misunderstandings about the impact of carbohydrate intake on body composition, a fear of weight gain and the associated impact upon body image. The 'carbohydrate fear' that is experienced by players is exacerbated by external pressures arising from social media, key stakeholders (e.g., coaches) and the skinfold culture surrounding measurement of body composition. Such cultural issues are amplified by the lack of full-time professionally accredited nutritionists overseeing the provision of nutrition support. Indeed, the infrastructure supporting the women's game (e.g. staffing resource, on-site food provision, player education programmes, etc.) was considered incomparable to the men's game. When taken together, our data provide a platform for which to develop organisational, stakeholder and player centred education and behaviour change interventions that strive to promote a positive performance nutrition culture within the women's game.

Given the perceived practice of under-fuelling and the associated implication for menstrual cycle irregularities, the aim of Study Two was to qualitatively explore player and stakeholder perceptions of menstrual health support within elite female soccer. Using the same methodology and participant group as Study One, data demonstrate that elite female soccer players experience a range of physical and psychological symptoms primarily at the onset of and during menses (as also perceived by stakeholders), with most participants perceiving these symptoms to impact performance. Nonetheless, menstrual health support is perceived as minimal and although players have their menstrual status tracked, they report little understanding as to why or how this information is used. This confusion was also present among stakeholders, often as a result of uncertainty about the evidence supporting the need for menstrual health support. The perceived lack of support may also be reflective of a culture where conversations about the menstrual cycle are not normalised. Overall, this may result in failure to identify and treat menstrual irregularities despite non-coaching staff members perceiving them to be common amongst players. These data support the need for individualised support based on the lived experiences of individual players and support staff. Furthermore, our research identifies the need for organisational, stakeholder and player centred education programmes (led by experts in female athlete health) that create an environment where players receive personalised menstrual health support.

Study One qualitatively explored a culture of under-fuelling within the women's game (as comprising both adult and adolescent players), the consequence of which may have acute performance and chronic health implications. However, the dietary practices of "adolescent" players, a population who may be particularly at risk of negative implications of under-fuelling, are yet to be explored. Accordingly, within Study Three we aimed to quantify energy and carbohydrate intake, physical loading and estimate energy availability in international adolescent female soccer players (n = 23; age, 17.9 ± 0.5 years) during a 10-day training and game schedule comprising two match days on days six (MDa) and nine (MDb). The players self-reported their energy intake via the remote food photography method, whilst the physical loading and associated exercise energy expenditure were assessed via global positioning system technology. The relative carbohydrate intake was significantly greater (all $p < 0.05$) on the day before the first match (MD-1a) (4.1 ± 0.8 $g \cdot kg^{-1}$), on the day before the second match (MD-1b) (4.3 ± 1.1 $g \cdot kg^{-1}$), MDa (4.8 ± 1.2 $g \cdot kg^{-1}$) and MDb (4.8 ± 1.4 $g \cdot kg^{-1}$) in comparison to most other days to most other days (<4 $g \cdot kg^{-1}$). The mean daily measured energy availability over the 10-day period was 34 ± 12 $kcal \cdot kg\ FFM^{-1} \cdot day^{-1}$ (with six players, i.e., 34%, presenting low energy availability), though, when adjusting the energy intake for potential under-reporting, these values changed substantially (44 ± 14 $kcal \cdot kg\ FFM^{-1} \cdot day^{-1}$, only one player was classed as presenting low energy availability). Such data suggest that the prevalence of low energy availability amongst female team sport athletes may be over-estimated. Nonetheless, players may still be under-fuelling for the work required in relation to daily CHO recommendations (i.e., >6 $g \cdot kg^{-1}$) for intensive training and game schedules. These data provide further evidence for the requirement to create and deliver targeted player and stakeholder education and behaviour change interventions (especially for younger athletes) that aim to promote increased daily carbohydrate intake in female soccer players.

It is acknowledged within Study Three that low energy availability may be overestimated in previous research, given the inaccuracies of directly measuring energy intake. Therefore, a gold standard approach to exploring the prevalence of low energy availability and accuracy of energy availability assessment within this population is required. Accordingly, Study Four aimed to quantify total daily energy expenditure (via the doubly-labelled water method), energy intake and energy availability. Adolescent female soccer players (n = 45; 16 ± 1 years) completed a 9–10 day 'training camp' representing their national team. Absolute and relative total daily energy expenditure was 2683 ± 324 and 60 ± 7 $kcal \cdot kg^{-1}$ FFM, respectively. Mean daily energy intake was lower ($P < 0.01$) when players self-reported using the remote food photography method (2047 ± 383 $kcal \cdot day^{-1}$) over a 3-day period versus doubly labelled water derived energy intake, accounting for body mass changes (2545 ± 518 $kcal \cdot day^{-1}$) over 7–8 days, representing a mean daily Δ of 499 ± 526 $kcalday^{-1}$ and 22% error when using the remote food photography method. Estimated energy availability was different ($P < 0.01$) between methods (doubly labelled water: 48 ± 14 $kcal \cdot kg^{-1}$ FFM, range: 22–82; remote food photography method: 37 ± 8 $kcal \cdot kg^{-1}$ FFM, range: 22–54), such that prevalence of low energy availability (<30 $kcal \cdot kg^{-1}$ FFM) was lower in doubly labelled water compared with remote food photography method (5% vs. 15%, respectively). Data demonstrate the potential to significantly underestimate energy intake when using self-report methods. This approach can therefore cause a misrepresentation and an over-prevalence of LEA, which is the underlying aetiology of 'relative energy deficiency in sport'.

In summary, this thesis used a mixed methods approach to assess nutritional practices and energy requirements of elite female soccer players. To meet daily energy requirements, data demonstrate that total daily carbohydrate intake should at least be equivalent to 5 $g \cdot kg$ $BM \cdot day^{-1}$. However, the nutrition culture within the women's game may not always be conducive to optimal fuelling practices, owing to challenges associated with social opportunity (e.g. social media, comments, etc.) and reflective motivation, all of which are aligned around player and stakeholder perceptions of optimal body composition. Despite previously observation of low energy availability within this population, the data also demonstrate that prevalence of low energy availability is likely over-estimated primarily because of inaccuracies associated with dietary assessment methods. When taken together, this thesis provides a platform for which to formulate targeted education and behaviour change strategies for players, stakeholders and practitioners alike.

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Declaration

I declare that the work in this thesis, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own. All attempts have been made to ensure that the work is original and does not, to the best of my knowledge, breach any copyright laws and has not been taken from the work of others, apart from the works that have been fully acknowledged within the text. No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning. Elements of the work presented herein have been published in peer-reviewed journals. Where this is the case, acknowledgements have been provided.

Publications & Presentations

Publications of the work listed within this thesis are as follows:

Study One

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Study Two

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Study Three

McHaffie, S. J., Langan-Evans, C., Strauss, J. A., Areta, J. L., Rosimus, C., Evans, M. & Morton, J. P. (2023). Under-Fuelling for the work required? Assessment of dietary practices and physical loading of adolescent female soccer players during an intensive international training and game schedule. *Nutrients*, 15(21), 4508.

Study Four

McHaffie, S. J., Langan-Evans, C., Strauss, J. A., Areta, J. L., Rosimus, C., Evans, M. & Morton, J. P. (2024). Energy expenditure, intake and availability in female soccer players via doubly labelled water: Are we misrepresenting low energy availability? *Experimental physiology.*

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Abbreviations

ACL: Anterior cruciate ligament

AU: Arbitrary units

BIA: Bioelectrical impedance analysis

BMD: Bone mineral density

BM: Body mass

CHO: Carbohydrate

CO_2: Carbon dioxide

COM-B Model: Capability Opportunity and Motivation Behaviour Model

DEXA: Dual-Energy X-ray Absorptiometry

DLW: Doubly labelled water

EB: Energy balance

EE: Energy expenditure

EEE: Exercise energy expenditure

EI: Energy intake

FA: Football Association

FIFA: Fédération Internationale de Football Association

FFM: Fat-free mass

FM: Fat mass

GPS: Global positioning system

H_2O: Water

HR: Heart rate

HSR: High-speed running

Kcal: Kilocalories

$Km.h^{-1}$: Kilometres per hour

LEA: Low energy availability

LSR: Low-speed running

MC: Menstrual cycle

MD: Match day

MET: Metabolic equivalent of task

NEAT: Non-exercise activity thermogenesis

O_2: Oxygen

PAL: Physical activity level

PAEE: Physical activity energy expenditure

RMR: Resting metabolic rate

RPE: Rate of perceived exertion

REDs: Relative energy deficiency in sport

RFPM: Remote food photography method

SD: Standard deviation

SENr: Sport and Exercise Nutrition register

SPR: Sprint running

TDEE: Total daily energy expenditure

TD: Total distance

TEF: Thermic effect of food

UEFA: Union of European Football Associations

VHSR: Very high-speed running

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Chapter One

General Introduction

The aim of this General Introduction is to provide a brief overview and introduction to the area of research to provide the rationale for the aims and objectives of this thesis.

1.1. Background

Soccer (more commonly referred to as football in the UK) is the most popular sport in the world (Luxbacher, 2013), with women's soccer growing rapidly world-wide within recent years, including an increase in professionalism at the elite level (UEFA, 2023). Despite this rapid growth, women's soccer is significantly less popular in terms of participation and viewership globally than men's soccer (Tang et al., 2022). This is in part a knock-on-effect of the English Football Association (FA) issuing a ban in 1921, prohibiting women's football matches from taking place, which was only uplifted in 1971. Consequently, both the quantity and quality of research published on women's soccer are significantly lower and not comparable to that within men's soccer (Okholm Kryger et al., 2022). This may also be a result of women being significantly underrepresented within sport and exercise science research in general (Cowley et al., 2021). Therefore, due to the previously mentioned increased professionalism of the sport and current gender disparity in research, it is unsurprising that there has been a call in recent years for a strategic and multidisciplinary research agenda that seeks to improve the health and performance of female soccer players (Nassis et al., 2022).

The increase in professionalism within the sport has led to heightened demands in several areas. Specifically, there has been an increase in training volume as more nations adopt a full-time model. Additionally, the intensity of match play has escalated at both the club and international level (Datson et al., 2017), with more high-speed running (HSR) completed during matches (Andersson et al., 2010). It may be assumed that the energetic demands of the sport have also increased, based on amplified training volume and match play demands. However, research into the energy requirements of elite female soccer has only been conducted in recent years and remains minimal, with only three studies completed to date (Brinkmans et al., 2024; Dasa et al., 2023; Morehen et al., 2021), using the gold-standard doubly-labelled water (DLW) technique (Nagy, 1983). However, all three studies were completed solely within senior players, which is a concern given that adolescence is a pivotal period of significant physical development, including altered body composition, metabolic and hormonal fluctuations, maturation of organ systems and establishment of nutrient deposits, which may all affect future health (Sawyer et al., 2012). Therefore, establishing the demands below senior level is particularly important, as adequate energy is not only required to meet the substrate demands of training and match play but also for physical development (Petrie et al., 2004; Unnithan & Goulopoulou, 2004). Without an understanding of the specific energetic demands within the adolescent population, practitioners risk applying adult-based recommendations that may not meet developmental needs, potentially compromising both health and long-term performance trajectories (Patton & Viner, 2007; Sawyer et al., 2012). Moreover, as adolescence is a key phase for building lifelong nutrition habits, identifying and addressing the barriers to adequate energy and carbohydrate intake within this group is essential to establishing effective, age-appropriate nutrition strategies supported by empirical data

(Bassett et al., 2015; Desbrow et al., 2019). The absence of such research highlights a substantial knowledge gap within both sport science and applied practice concerning the optimization of health and performance in developing female soccer players.

Total daily energy expenditure (TDEE) is made up of four components, including basal metabolism, thermic effect of food (TEF) and physical activity energy expenditure (PAEE), comprised of both non-exercise activity thermogenesis (NEAT) and exercise energy expenditure (EEE) (Manore & Thompson, 2015). NEAT and EEE are the most variable components of TDEE and the PAEE of elite female soccer players is substantial, contributing to moderate to high energy requirements (Brinkmans et al., 2024), therefore it is important that sport, age and gender specific values of TDEE are established, providing the platform for establishing population specific nutrition guidelines and strategies. However, although a Nutrition Consensus Statement exists for elite soccer (Collins et al., 2021), this is not specific to female soccer players, with the majority of guidelines based primarily on research within male players. Although this statement acknowledges this and makes distinctions between male and female players, no female-specific nutritional guidelines for soccer exist, let alone guidelines specific to adolescent players. Within the limited research, a common theme when measuring energy intake (EI) is the reporting of under-fuelling, particularly with regards to carbohydrate (CHO) intake, with many studies at the elite level reporting that female soccer players struggle to meet current guidelines for CHO intake (Brinkmans et al., 2024; Dasa et al., 2023; Morehen et al., 2021; Moss et al., 2021). This a concern given that CHO is the primary fuel for muscle during high intensity exercise, such as soccer (Bangsbo et al., 1994). However, it must be acknowledged that each of these studies uses self-reported methods of measuring EI in addition to all reporting no significant changes in body mass throughout the data collection period, which brings into question the accuracy of reported under-fuelling. Therefore, there remains a need to measure the dietary practices of elite adolescent players, in addition to calculating overall EI using more rigorous methodology that EI values based on direct measurement can be compared to. Furthermore, given that under-fuelling has been previously reported, there is a need to explore potential barriers to adequate nutritional intake within elite female soccer. Although some quantitative research has emerged within nutrition for elite female soccer, as mentioned, there is a lack of qualitative research and a need to better understand the culture surrounding nutrition support. Determining this will help to inform nutrition strategies based on behaviour change models, such as the 'Capability, Opportunity and Motivation Behaviour (COM-B) model (Atkins & Michie, 2015; Michie et al., 2011), as gaining a greater understanding of the "capability, opportunity and motivation" of players, is fundamental to changing behaviour.

Furthermore, under-fuelling with regards to overall EI is a concern within sport due to the potential for players to be in a state of low energy availability (LEA). Energy availability (EA) is defined as the amount of dietary energy available to sustain physiological function after subtracting the energetic cost of exercise (Loucks et al., 2011), with LEA traditionally categorised using laboratory derived classifications of < 30 kcal·kg $FFM^{-1} \cdot day^{-1}$ (Loucks et al., 1998; Loucks & Thuma, 2003). LEA may manifest in symptoms relating to the 'Relative Energy deficiency In Sport' (REDs) model, defined as a syndrome of impaired physiological and psychological function caused by exposure to problematic (prolonged and/or severe) LEA (Mountjoy et al., 2023), however empirical evidence supporting the REDs model is limited (Jeukendrup et al. 2024). Whether categorised as REDs or otherwise, some of the symptoms related to LEA are female specific, such as an impact on menstrual status and function (Nattiv & Lynch, 1994). Therefore, understanding player-experiences surrounding menstrual health support is also critical. Elite female soccer is of no exception to documented prevalence, with LEA reported to be prevalent at the senior level (Brinkmans et al., 2024; Dasa et al., 2023; Morehen et al., 2021), yet it is currently unassessed within elite adolescent players. Therefore, due to the potential performance and health implications of inadequate energy intake and heightened energetic demands of growth and maturation, it is of high priority to better understand the nutritional practices and energy demands of elite female soccer, particularly within adolescent players.

1.2. Aims and Objectives of This Thesis

The primary aim of this thesis is to determine energy requirements and nutritional practices of elite female soccer players, using a mixed methods approach.

This will be achieved through the following objectives:

1. The aim of Study One was to qualitatively explore player and stakeholder perceptions of nutrition practices in support of female soccer players' development and performance (Chapter Three).
2. The aim of Study Two was to qualitatively explore player and stakeholder perceptions of menstrual health support within elite female soccer (Chapter Four).
3. The aim of Study Three was to quantify energy intake, carbohydrate intake, physical loading and estimated energy availability in elite international female soccer players during a 10-day training and game schedule comprising two match days. (Chapter Five).
4. The aim of Study Four was to quantify total daily energy expenditure (via the doubly-labelled water method), energy intake and energy availability in elite international female soccer players during a training and game schedule (Chapter Six).

The outcomes of this thesis will be to:

1. Inform sport nutrition guidelines for women's soccer.
2. Inform education and behaviour change strategies that aim to improve nutrition culture and dietary practices within women's soccer.

Chapter Two

Literature Review

The aim of this Literature Review is to introduce key theoretical concepts and provide a summary and critical appraisal of the relevant current literature.

2.1. Introduction to Women's Soccer

2.1.1. The Foundation of the Sport

The foundations of soccer were laid with the establishment of The English Football Association (The FA) in 1864. While the men's game has seen continuous growth since then, women's soccer has faced a far more complex and challenging journey. Despite initial growth, with women's soccer attracting crowds in the tens of thousands (Martensson, 2010), progress was abruptly halted on December 5th, 1921. On this date, The FA imposed a ban preventing women's teams from playing football on League and Association-affiliated grounds, arguing that soccer was "quite unsuitable for women and ought to be discouraged" due to its supposedly strenuous nature. Prior to the ban, women's matches were well-attended, with approximately 150 women's teams regularly playing to large crowds by 1921 (Williams, 2003). For instance, the 'Dick Kerr Ladies' team often drew crowds in the tens of thousands, with attendance reaching as high as 53,000 the year before the ban was enforced (Skillen et al., 2022).

The decision to ban women's soccer effectively shaped the sport into a predominantly male-dominated sport in one of the world's most significant football-playing nations (Williams & Hess, 2015). Although the justification for the ban was partially rooted in medical claims that playing football was "damaging" to women and could lead to infertility (Williams, 2003), it is widely accepted that the ban stemmed from the perception that women's soccer posed a threat to the men's game (Harris, 2007).

2.1.2. The Professionalisation of Women's Soccer

The 1921 ban had a significant impact on the growth of women's soccer, causing the sport to fall further behind men's soccer in both participation and viewership. Women not being allowed to play in FA-accredited facilities (Skillen et al., 2022) marginalized women's football socially, culturally, and economically (Williams, 2006). This ultimately rendered the game financially unviable, however, the ban was lifted in 1971. Nevertheless, while men's soccer had been professional since 1888, opportunities for women to play soccer semi-professionally did not arise until 2000, with Fulham FC emerging as the first semi-professional women's club in England. On a broader scale, semi-professionalism in England did not take hold until 2011, and the sport eventually achieved full professional status in 2018 with the founding of the Women's Super League (WSL) (Culvin, 2019). Williams (2013) notes that the establishment of the WSL contributed to increased media coverage of women's football, a rise in sponsorship revenue, and the professional remuneration of female players. As a result, earning a livelihood as a soccer player was no longer an opportunity reserved exclusively for men. Since its inception, the FA WSL has undergone several reconfigurations, with the a major restructuring occurring in the 2018/19 season requiring all clubs in the FA WSL to transition to full-time status. In 2024, the governance of the league was transferred from The FA to NewCo (a club-operated body established to run the women's professional game), marking a significant shift towards greater commercial independence and alignment with models seen in elite men's football.

This restructuring was made possible by the rapid growth of the sport, which has been mirrored on the international stage, with women's soccer tournaments attracting increased viewership worldwide. International women's soccer has continued to break viewership records at the 2015, 2019, and 2023 World Cups (FIFA, 2023). Training for elite competitions like the World Cup, the European Championship, and the WSL requires a challenging balance between rigorous training and adequate recovery, as noted by Hughes & Leavey (2012). Therefore, research specifically focused on women's soccer is essential for providing the necessary support to players across multiple disciplines, including nutrition, in order to enhance health and performance.

2.1.3. Research within Women's Soccer

Although women's soccer has garnered increased attention from sports academics worldwide (Pfitser et al., 2015), it still falls significantly short of the men's game in terms of research volume and depth. Research in men's soccer is well-established, whereas the study of women's soccer is still in its developmental stage. Indeed, a recent audit of research conducted to date has demonstrated that the existing research base is not comparable to that of the men's game (Okholm Kryger et al., 2022). It remains uncertain and frequently debated whether insights derived from men's football can be effectively applied to the women's game to achieve an accurate and comprehensive understanding of it. Consequently, many unanswered questions persist regarding the demands of women's soccer, which results in uncertainty regarding nutritional strategies and there have been multiple calls for a strategic and multidisciplinary research agenda aimed at improving the health and performance of female soccer players (Datson et al., 2017; Nassis et al., 2021).

2.2. Physical Demands of Elite Female Soccer

2.2.1. Rationale to Monitor Training and Match Demands

To establish a comprehensive definition of workload in a sporting context, Quarrie et al. (2017) described "load" in team sports as encompassing "the total stressors and demands applied to the players," including both sport-related and non-sport-related stressors. They emphasized that the impact of load on athlete performance, well-being, and injury risk should be considered from both acute and cumulative perspectives. Therefore, workload should be understood as the sum of all stressors (both physical and non-physical) in terms of their immediate and long-term effects. Therefore, quantifying and utilizing training and match workload is a valuable objective for sport science staff, as it informs strategies aimed at maximising performance and reducing the risk of injury (Xiao et al., 2021; Gabbett et al., 2010; Watson et al., 2017) and should guide nutrition strategies.

In the early years of workload monitoring in sports, the "rating of perceived exertion" (RPE) was established (Borg, 1970) and used by teams and within individual sports (Haddad et al., 2014;

McGuigan et al., 2004; Scott et al., 2013; Sweet et al., 2004). Whereas RPE provides a subjective measure of exercise demands based on the individual's experience and perception, the advent of global positioning system (GPS) technology has offered an objective means to measure physical load. Therefore, there has been a significant increase in the use of GPS systems within soccer in recent years (Hennessy et al., 2018)

2.2.2. Training Demands of Elite Female Soccer

Athletic or sport-specific training involves systematically executing exercises to enhance physical capabilities and develop skills tailored to a sport (Viru & Viru, 2000). When performed correctly, an exercise bout induces a physiological response that serves as a stimulus for adaptation, which the nature, intensity, and duration of this stimulus determines (Booth & Thomason, 1991). Training load can be classified as either internal or external, with external load encompassing the organisation, duration, and quantity of training and match play, often tracked using GPS technology. While it is well established in men's soccer that individuals within the same team are exposed to and respond to different training stimuli, due to factors such as their position, tactical role, and coaching methodology (Bangsbo et al., 2006), there is limited data outlining the current training demands in elite women's soccer. This is particularly true at the youth level, where only a small number of studies have addressed this area, including recent investigations by Costa et al. (2022), Lechner et al. (2023), and Reynolds et al. (2021) that provide insights into the physical and physiological demands experienced by youth soccer players.

2.2.2.1. Total Distance

The earliest study to measure the external demands of training in women's soccer using GPS technology was conducted by Mara et al. (2015a), during a preseason week. They reported a mean total distance (TD) of 6581 ± 847 meters per training session. This value is notably higher than data published in more recent years, likely due to the higher intensity typical of preseason training. Mara et al. also observed significant differences in TD and HSR across training days, providing evidence of short-term training periodisation (a framework for systematically varying an athlete's training to optimize performance and recovery (Brown et al., 2018)) at the elite level.

Subsequently, the same authors measured training load across an entire season with a larger sample size (n = 17). They found similar values for mean daily TD during preseason (6646 ± 111 meters), with a slight reduction in-season (5347 ± 106 meters). Initially, these findings suggested that the training demands of elite female soccer players were higher than those of their male counterparts. However, more recent studies have reported values more aligned with those found in men's soccer, such as Clemente et al. (2019), who reports mean total daily distances ranging from ~3000 to ~5000 meters within male soccer. This mirrors findings from Douchet et al. (2021), who measured TD values during preseason in the Women's French First Division, reporting 3870 ± 870 meters during a low-intensity week and 5090 ± 620 meters during a high-intensity week. Additionally, two recent studies by Dasa et al. (2023) and Brinkman et al. (2024), which focused on measuring EE, also reported training load over a 14-day period, with TD values on training days reported as 5063 ± 982 meters and ~2000–6000 meters, respectively. However, these studies only provide a "snapshot" of training load over short periods, limiting their ability to offer a comprehensive view of a full season. In contrast, Romero-Moraleda et al. (2021) conducted a longer-term study on players in the Spanish First Division. They reported mean TD values ranging from 2496 ± 1639 meters on a recovery day (MD+1) to 4975 ± 1319 meters three days before a match (MD-3). This study identified a pyramid-shaped weekly micro-cycle, with the highest loads occurring in the middle of the week and lower loads closer to match day, a strategy consistent with strategies sported in men's soccer, with the aim of promoting readiness and reducing fatigue.

Recent research in international soccer has also highlighted internal and external training load variations. Doyle et al. (2021) reported TD values ranging from 3339 meters (MD-7) to 5934 meters (MD-5) during a seven-day training camp. Similar findings were reported by Morehen et al. (2021), who measured EE and found comparable training load values, ranging from 2927 ± 862 meters (MD-1) to 6340 ± 537 meters (MD-3).

Table 2.2. Total distance, population characteristics and duration of study of research within elite female soccer that measured training load using GPS technology.

Reference	Sample Size	Population Characteristics	Duration of Study	TD (m)
Douchet et al., 2021	19	French First Division team Age: 24.2 ± 2.3	Pre-season/2 weeks	3870 ± 870; 5090 ± 620 (mean daily during a light and heavy training week)
Doyle et al., 2022	18	International Team, placed 33rd in FIFA rankings Age: 24.2 ± 4.4	Competitive International Training Camp/1 week	3339 to 5935 (range of mean daily values)
Mara et al., 2015a	8	Elite Club Team Aged 23-30	Pre-season/1 week	6581 ± 847 (mean daily)
Mara et al., 2015b	17	Elite Club Team Age not reported	Pre-season and competitive/18 weeks	6646 ± 111; 5347 ± 106 (mean daily during pre-season; in-season)
Romero-Moraleda et al., 2021	18	Spanish First Division Age: 26.5 ± 5.7	Competitive/5 months	2496 ± 1639 to 4975 ± 1319 (Range of mean daily values)
Xiao et al., 2021	74	NCAA Age not reported	Competitive/3 seasons	110.12 km (average distance over a 4-week span, including matches)
Morehen et al. 2021	13	English National Team Age not reported	Competitive International Training Camp/12 days	2927 ± 862 to 6340 ± 537 3339 to 5935 (Range of mean daily values)
Dasa et al. 2023	51	Norwegian Premier and First Division Age: 22 ± 4	In-season/14 days	5063 ± 982 (mean daily)
Brinkman et al. 2023	15	Dutch First Division Age not reported	In-season/14 days	~2000 to ~6000m (range of mean daily values)

2.2.2.2. Thresholds and High-Speed Running

Although training demands can be compared between studies using TD values, this is not a true measure of intensity as it does not account for the speed of any given distance. GPS technology does allow for the measurement of speed, with speed zones typically established, to determine time spent in varying intensities, such as HSR or 'sprint' distance (SPR) (Mara et al., 2017). However, to date, a number of studies have measured speed at varying speed zones during training (Table 2.2.), therefore, comparison between studies is in essence futile, due to the variety of speed zones used within these studies, therefore there is a need to standardise thresholds that are specific to female players (Vescovi et al., 2011). Some solutions that would result in the standardisation of thresholds have been proposed, such as adapting the common threshold use for HSR distance within men's soccer (14.4 $km{\cdot}h^{-1}$) by -10% to 12.6 $km{\cdot}h^{-1}$ (Scott & Lovell., 2018), with the rationale being that the physical capacity of elite female players is 10% lower than their male counterparts (Mujika et al., 2009). In addition, speed zones have been suggested within research, such as <3.33, ≥3.34 – 4.44, ≥4.45 – 5.55 and ≥5.56 $m{\cdot}s^{-1}$ for low-speed running (LSR), HSR, very high-speed running (VHSR) and SPR, respectively, by Bradley and Vescovi (2015). More recently, new thresholds were suggested by Park et al. (2019), for HSR (3.46 $m{\cdot}s^{-1}$), VHSR (5.29 $m{\cdot}s^{-1}$) and SPR (6.26 $m{\cdot}s^{-1}$) using linear-mixed modelling, based on data collected within international players over 4 years. To add to this, Harkness-Armstrong et al. (2021) has suggested thresholds for youth players using spectral clustering, based on data collected within 50 matches at under 14s and under 16 level. However overall, although an aligned approach with regards to consistent speed thresholds may now be in place at senior (Park et al. 2019) and youth level (Harkness-Armstrong 2022), adequate literature does not currently exist to confidently outline the demands of training, including no data at youth international level. This is essential for informing training prescription and maximise athletic development of players, encompassing the development of appropriate nutrition guidelines and strategies tailored to female players, accounting for differing age groups.

2.2.3.3. Factors Modulation Training Load

Regarding factors modulating training load, two studies observed that players covered more total and HSR distance (>12.2 $km{\cdot}h^{-1}$) during pre-season compared to the early competitive season, with a subsequent decrease towards the end of the season (Mara et al., 2015a; Clemente et al., 2019). In contrast, three other studies found that total and HSR distances (>12.6 km/h and maximal aerobic speed) remained consistent during training sessions throughout international tournaments, independent of the data from official matches (Scott and Lovell, 2018; Costa et al., 2022; Doyle et al., 2022).

The link between training load and fatigue has been explored in several studies (Mara et al., 2015b; Costa et al., 2018, 2019, 2021; Scott and Lovell, 2018; Douchet et al., 2021; Fernandes et al., 2021). Self-reported fatigue measures are also significantly associated with training (e.g., HSR distance) on the preceding day during a tournament (Scott and Lovell, 2018). Additionally, Scott and Lovell (2018) noted a small negative association (r = −0.20) between self-reported fatigue, muscle soreness and HSR distance covered, whether using fixed (>12.6 $km \cdot h^{-1}$) or individual thresholds, during a 21-day training camp. Conversely, Mara et al. (2015b) found no correlation between self-reported fatigue and sleep times with HSR covered (>12.6 $km \cdot h^{-1}$), though muscle soreness was moderately negatively correlated with training load parameters during the pre-season.

During a 9-day international tournament, Costa et al. (2019) found no significant within-subject correlations between post-training night sleep parameters (e.g., total sleep time and sleep efficiency) and external training load metrics (e.g., distance and HSR distance). However, Costa et al. (2021) identified small to moderate within-subject correlations (r = −0.43 to −0.17) between internal training load (session RPEs and training impulse) and sleep parameters (sleep duration and efficiency) during a 14-day competitive period.

2.2.3. Match demands of Elite Female Soccer

Gaining a greater understanding of match demands helps to determine the appropriate training stimulus, helping to reduce injury risk and enhance training adaptation, whilst mitigating the risk of over-training (Scott et al., 2013). Specifically, in the context of adolescent soccer, this should prepare players for the demands of match play at a specific playing standard or within a specific age group, preparing players to transition between levels of the game and informing talent identification. (Harkness-Armstrong et al. 2022). There remains limited research regarding match demands of the sport. Although research is limited, various narrative reviews have been conducted, which summarise the demands of match play (Datson et al., 2014; Davis & Brewer, 1993; Griffin et al., 2021; Martinez-Lagunas et al., 2014; Randell et al. 2021 and Vescovi et al. 2021). Despite this, it remains challenging to compare between studies given the complexity of the sport (Bradley et al. 2018; Paul et al. 2015) and the broad range of thresholds applied to measure match demands, as mentioned previously.

2.2.3.1. Total Distance

Studies that have measured match demands are summarised in Table 2.2. The earliest studies (Davis & Brewer, 199; Krustrup et al. 2005; Mohr et al. 2008) used video tape to track TD, with the earliest (Davis & Brewer, 1993) reporting that female soccer player covered a TD of 8.5 ± 2.2 km, which is an outlier amongst the other findings, with the two more recent studies that used video tape analysis (Krustrup et al. 2005; Mohr et al. 2008), both reporting mean TDs of 10.3 km. Following this, optical tracking (a computerized semiautomated multicamera image recognition system) was used by two studies in 2017, reporting TDs during match play at international (Datson et al. 2017) and domestic (Mara et al. 2017b) level of 10.3 ± 0.9 km and 10.0 ± 0.8 km, respectively. These findings somewhat mirror more recent studies that use GPS technology (Andersson et al. 2010; Hewitt et al. 2014; Ramos et al. 2017; Trewin et al. 2018; Ramos et al. 2019; Sausama et al. 2019; Jagim et al. 2020; Scott et al.

2020a), since GPS units have become commonly used by elite teams with similar values reported. Therefore, although methodological variation must be acknowledged, studies that have measured TD report similar values of ~10km during a 90-minute match, across a range of standards at both domestic and international level. Mean TD values range from 9.5 km to 10.4 km across 13 studies, excluding the earliest study (Davis & Brewer, 1993), which was based on the analysis of video-taped data. In recent years, although there has been a rise in studies quantifying women's soccer match-play characteristics, these studies have primarily focused on senior international (39%) and domestic (43%) players, with only seven studies addressing the match-play characteristics of adolescent soccer players, including; U20 (Ramos et al. 2017, Ramos et al. 2019), U17 (Vescovi et al. 2014, Peek et al. 2021, Ramos et al. 2019), U16 (Harkness-Armstrong et al. 2021, Harkness-Armstron et al. 2020, Vescovi et al. 2014, Peek et al. 2021), U15 (Vescovi et al. 2014, Harris et al. 2019, Peek et al. 2021), U14 (Harkness-Armstrong et al. 2021, Harkness-Armstrong et al. 2020, Harris et al. 2019, Peek et al. 2021) and U13 age-groups (Harris et al. 2019, Peek et al. 2021), which are all included in table 2.2.

2.2.3.2. Thresholds and High-Speed Running

Given that similar values have been reported of TD, it could be assumed that no differences in intensity exist across playing standard, however this does not account for running speed. As mentioned previously, it is difficult to draw comparisons between HSR or SPR data between studies due to thresholds only being standardised recently, posing significant challenges in achieving a consensus on the data (Bradley & Vescovi, 2015). This lack of a standardised approach is problematic, as limited comparisons can be made within the scientific literature and may consequently result in misinterpretation of training and match-play physical characteristics, although, all data is included within Table 2.2, including thresholds applied within each study.

Table 2.2. Total distance, population characteristics and duration of study that measured match load within elite female soccer.

Reference	Sample Size	Population Characteristics	Measurement Technology	TD	Speed Thresholds	HSR Distance	SPR Distance
Scott et al. (2020a)	220	Senior Domestic League - USA	GPS	Not measured	HSR >19.0 $km{\cdot}h^{-1}$ SPR >22.5 $km{\cdot}h^{-1}$	350-666 m	98-248 m
Mara et al. (2017a)	12	Senior Domestic League - Australia	Optical tracking	Not Measured	HSR 12.2 – 19.1 $km{\cdot}h^{-1}$ SPR >19.4 $km{\cdot}h^{-1}$	1772-2917 m	417-850 m
Ramos et al. (2019)	45	International U17, U20 and Senior - Brazil	GPS	7.9 - 10.4 km	HSR 15.6 – 20.0 $km{\cdot}h^{-1}$ SPR >20 $km{\cdot}h^{-1}$	348-840 m	139-379 m
Datson et al. (2017)	107	Senior International - Netherlands	Optical tracking	10.3 ± 859 km	HSR 19.8 – 25.1 $km{\cdot}h^{-1}$ SPR >25.1 $km{\cdot}h^{-1}$	608 ± 181 m	168 ± 82 m
Sausaman et al. (2019)	23	Senior Domestic League – USA College	GPS	9.5 ± 300 km	HSR 15.1 – 18.0 $km{\cdot}h^{-1}$ SPR >18.1 – 25.0 $km{\cdot}h^{-1}$	1014 ± 118 m	428 ± 70 m
Ramos et al. (2017)	12	International U20 - Brazil	GPS	Not Measured	HSR 15.6 – 20.0 $km{\cdot}h^{-1}$ SPR >20 $km{\cdot}h^{-1}$	508-859 m	113-331 m
Jagim et al. (2020)	25	Domestic League – USA College	GPS	9.8 ± 2715 km	HSR 15.0 – 18.99 $km{\cdot}h^{-1}$ SPR >19.0 $km{\cdot}h^{-1}$	658-916 m	140-403 m
Andersson et al. (2010)	17	Senior International and Domestic League - Sweden and Denmark	GPS	International: 9.9 ± 1.8 km Domestic: 9.7 ± 1.4 km	HSR 18 – 24.9 $km{\cdot}h^{-1}$ SPR >25 $km{\cdot}h^{-1}$	International: 1530 ± 100 m Domestic: 1330 ± 900 m	International: 256 ± 57 m Domestic: 221 ± 45 m
Hewitt et al. (2014)	58	Senior International - Australia	GPS	9.6 ± 0.2 km	HSR 12.0 – 18.99 $km{\cdot}h^{-1}$ SPR >19.0 $km{\cdot}h^{-1}$	2407 ± 125 m	338 ± 30 m
Krustrup et al. (2005)	14	Senior Domestic League - Denmark	Video tape	10.3 km	HSR 18.0 – 25 $km{\cdot}h^{-1}$ SPR >25 $km{\cdot}h^{-1}$	1310 m	160 m
Mara et al. (2017b)	12	Senior Domestic League - Australia	Optical tracking	10.0 ± 0.8 km	HSR 12.24 – 19.44 $km{\cdot}h^{-1}$ SPR >19.44 $km{\cdot}h^{-1}$	2452 ± 636 m	615 ± 258 m
Mohr et al. (2008)	19 / 15	Senior International and Domestic League – Sweden and Denmark	Video tape	10.3 ± 0.2 km	N/A	1680 ± 90 m / 1300 ± 100 m	N/A
Trewin, et al. (2018)	45	Senior International	GPS	10.4 ± 1.0 km	SPR >19.98 $km{\cdot}h^{-1}$	930 ± 348 m	Not measured

2.2.3.3. Factors Modulating Match Play

Based on the papers reviewed, physical characteristics tend to improve with advancing age-groups and higher playing standards and vary according to playing positions. Additionally, physical performance declines between halves, with the first 15 minutes of match-play being the most physically demanding (Harkness-Armstrong et al. 2022). Although comparisons are challenging to draw, considering the most common velocity thresholds across respective velocity zones reveals that HSR distance and the percentage of TD covered increase with higher playing standards and as age groups progress. Specifically, HSR (defined as running >15 km/h) accounts for 13.8-17.9% of running at international level (Andersson et al. 2010), 5.9-17% of running at domestic level (Bradley et al. 2014, Bendiksen et al. 2013, Andersson et al. 2010, Krustrup et al. 2005, Panduro et al. 2022, Romero-Moraleda et al. 2021) and 10.1-13.5% at college level (Ishida et al. 2021, Jagim et al. 2020, Sausaman et al. 2019). The TD and percentage of TD covered at VHSR, defined as running >19 km.h, also increases in line with playing standards. There is a vast disparity between youth (Harkness-Armstrong et al. 2021) and senior (Scott et al. 2020b) playing standards, with player covering 3.5-6.4% and 1.5-4.2% of running as VHSR and at senior and youth level, respectively. Senior international and domestic players cover similar SPR distances when using the common SPR threshold of >20 km/h (Andersen et al. 2016, Vescovi et al. 2014, Griffin et al. 2021, Nakamura et al. 2017, Ramos et al. 2017, Ramos et al. 2019). In contrast, studies by Ramos et al. (2017) and Vescovi (2014) observed a progressive increase in SPR distances covered by youth players as they move from U17 to U20 and senior international age-groups, and from U15 to U17 domestic age-groups, respectively. This progressive increase in absolute distances and distances covered at high speeds across playing standards and age-groups may result from increasing physical capacities, greater match-specific fitness, increased technical-tactical demands and/or differing contextual factors within playing standards (Harkness-Armstrong et al. 2022). Furthermore, the increase in absolute distances between age-groups may also be due to differing match durations between youth and senior match play (Harkness-Armstrong et al. 2021, Harkness-Armstrong et al. 2020, Vescovi et al. 2014), making comparisons difficult to draw.

2.3. Energy Expenditure

All metabolic processes in the body ultimately lead to heat production, which defines the rate of energy metabolism. EE involves generating energy through the combustion of energy-containing substrates such as CHOs, fats, proteins, and alcohol. This metabolic process requires oxygen and produces carbon dioxide and heat, a concept first discovered by Antoine-Laurent de Lavoisier (Lavoisier, 1801) in the late 18th century:

$$(\text{substrate} + O_2 \rightarrow CO_2 + H_2O + \text{heat})$$

EE (together with EI) is generally measured in kilojoules (KJ) or megajoules (MJ). The most widely recognized unit of energy, however, is the kilocalorie (kcal), equivalent to 1000 calories. One kilocalorie equals 4.184 KJ. To put it in perspective, one calorie represents the energy required to raise the temperature of one gram of water by one degree Celsius. Human total EE consists of three main components: Basal metabolic rate (BMR), the TEF, and the EE of activity (activity thermogenesis). However, when assessing the EE of athletes, given the physical demands of exercise, activity thermogenesis is broken down into two components, NEAT and EEE (Manore & Thompson, 2006). This allows for a distinction between exercise (e.g. training sessions) and non-exercise activities such as fidgeting, spontaneous muscle contractions, and maintaining posture when not lying down, making up the remaining portion of the daily EE for most individuals (Levine et al. 2005). It is important to acknowledge that some uncertainty and subjectivity exists, regarding whether some activities should be categories as NEAT or EEE. The variability in these components leads to differences in daily EE between individuals. Additionally, EE measurements can be utilized to assess the thermic effects of various foods, nutrient compositions, beverages, medications, and psychological factors. Total EE is therefore an accumulation of the previously mentioned values, RMR, TEF and AEE categorised into NEAT and EEE and ultimately determines energetic demands, with regards to overall EI to maintain physical function and BM (Manore & Thompson, 2015). Total daily EE (TDEE) is therefore total EE for one day.

2.3.1. Exercise Energy Expenditure

Recent studies have begun to collect values of EEE within elite female soccer. For instance, Dasa et al. (2023) conducted research within the highest tier of Norwegian female soccer, however, although they utilised GPS derived EEE to calculate EA raw EEE values were not reported. Historically, EEE during matches has been reported as 1,100 kcal (Brewer et al., 1994) and 644 kcal (Mara et al, 2015a). However, these studies present methodological issues, such as the unclear subtraction of Resting Metabolic Rate (RMR) from EEE calculations, potentially leading to overreported values. Additionally, these studies simulated match-play using three 20-minute periods, which do not accurately represent true competitive matches. A modern solution to these limitations is the use of GPS technology, the most frequently used microtechnology in elite sports for measuring physical activity (Hennessy et al., 2018). While GPS-derived EEE may be valid for steady-state sports like cycling (Burke et al., 2018), its accuracy for measuring EEE within intermittent sports such as soccer is questionable (Oxendale et al., 2017). The nature of soccer involves significant accelerations, decelerations, and directional changes, which GPS devices may not accurately capture due to factors like anaerobic energy production and lactate accumulation that are not accounted for in aerobic measurement. Furthermore, EEE outputs can vary between manufacturers based on their data processing algorithms (Thornton et al., 2019; Terziotti et al., 2018), typically resulting in an underestimation of EEE (Oxendale et al., 2017; Buccheit et al., 2015; Stevens et al., 2015; Brown et al., 2016). Even devices designed for soccer, which incorporate metabolic power concepts (Osgnach et al., 2010; Di Prampero et al., 2015), struggle with accuracy. Therefore, the validity of EEE measurements in intermittent sports using tracking devices remains ambiguous. This is compounded by the fact that existing metabolic power models are based on data from male athletes, ignoring significant physiological differences between sexes, such as economy, efficiency, and body composition, which influence EEE (Sandbakk et al., 2018). Accurate EEE measurement is crucial, as inaccurate EEE measurements may lead to incorrect EI prescriptions, affecting fuelling, recovery, and nutritional periodisation.

Recent research has further highlighted these challenges. Dasa et al. (2021) assessed the accuracy of various GPS trackers in elite female soccer players, finding that all devices were biased—underestimating EEE during high-intensity intermittent exercise and overestimating during lower intensity. Similarly, Guebels et al. (2014) examined EEE measurement methods in female college athletes, revealing significant variability in EEE values depending on the method used, emphasizing the difficulty in defining and accurately measuring EEE beyond "planned EEE." Activities such as walking, social games, and hobbies introduce additional uncertainties, further complicating the accurate quantification of EA. However, GPS remains one of the most accurate an often the most convenient means by which to measure EEE within the context of elite sport, despite its limitations.

2.3.2. The Energetic Costs of Puberty

During puberty, females experience a substantial increase in energetic demands driven by rapid growth, changes in body composition, and reproductive development (Glass et al. 2022; Brabin & Brabin 1992; Jasienska 2020; Cheng et al. 2016; Spadano et al. 2005). This period requires significantly increased nutritional intake to support height and muscle mass expansion, increased fat stores, and the onset of hormone-driven processes and menstrual function (Brabin & Brabin 1992; Jasienska 2020; Roa et al. 2018). Large-scale reviews and longitudinal data consistently demonstrate higher resting and total energy expenditure in pubertal compared to prepubertal females, even after adjusting for body size or fat-free mass (Cheng et al. 2016; Spadano et al. 2005).

Meeting these enhanced energy requirements is essential for healthy skeletal maturation, reproductive system development, and long-term health, a demand not adequately addressed by generic "adult" sport nutrition recommendations (Glass et al. 2022; Jasienska 2020). Failure to meet these unique energetic costs can compromise bone accrual, growth, and reproductive function, reinforcing the need for population-specific nutrition guidelines for female athletes who are entering or progressing through puberty (Roa et al. 2018; Jasienska 2020; Glass et al. 2022).

2.3.3. Energy Expenditure of Elite Female Soccer Players

Initial investigations into the EE of elite soccer players date back to the late 1970s (Reilly & Thomas, 1979). Since then, numerous studies have quantified TDEE in both elite male (Anderson et al., 2017; Briggs et al., 2015) and female soccer players. Among elite female soccer players, 12 studies have investigated EE, with all findings summarized in Table 2.3. Of these studies, nine focus on senior players, with eight of these measuring EE in the context of club-level soccer (Dasa et al., 2023; Brinkmans et al., 2024; Dobrowolski et al., 2020; Yli-Piipari et al., 2019; Mara et al., 2015b; Fogelhom et al., 1995; Behrens et al., 2020; Martin et al., 2006), and one at the international level (Morehen et al., 2021). The studies conducted at the youth level cover a range of ages, with mean ages of 12.2 ± 1.8 (Cherian et al., 2018), 14.8 (Braun et al., 2018), and 15.7 ± 0.7 years (Gibson et al., 2011). The range in sample sizes across these studies varies significantly, reflecting the challenges and logistical constraints often encountered in sports science research, particularly in the context of elite real-world environments. For example, the study by Braun et al. (2018) included 56 youth players from a domestic league in Germany, representing one of the larger sample sizes among the reviewed studies. In contrast, Mara et al. (2015b) analysed data from just 8 adult domestic league players in Australia, highlighting the difficulty in recruiting large cohorts of elite athletes for detailed metabolic studies in the field. This variation in sample size may influence the generalizability of the findings, as smaller studies might not capture the full diversity of EE patterns across different playing styles, positions, or levels of competition. Another notable aspect of these studies is their relatively short duration, often limited to a few days or weeks. For instance, Morehen et al. (2021) conducted their research over a 12-day period during an international training camp, while Dasa et al. (2023) and Brinkmans et al. (2024) measured EE over 14 days in domestic league players. The brevity of these studies is a common limitation in sports science, where extended monitoring is logistically challenging. However, short study durations may not fully capture the seasonal variations in EE that could occur over the course of an entire competitive season, potentially leading to an incomplete understanding of the long-term energy demands faced by elite female soccer players.

A clear pattern emerges when examining the methodologies used in these studies. Notably, the three highest values of TDEE reported for elite female players (Dasa et al., 2023; Brinkmans et al., 2024; Morehen et al., 2021) were all obtained using the DLW method, widely regarded as the gold standard for measuring EE. The accuracy of this method suggests that when alternative methods, such as accelerometery or METs derived from physical activity diaries, are used, underreporting of EE is likely. This underreporting appears to be most pronounced with activity diaries, where values of 2240 $kcal \cdot day^{-1}$ (Behrens et al., 2020) and 2154 $kcal \cdot day^{-1}$ (Martin et al., 2006) were observed. Even within studies that used accelerometry, the reported values remain lower than those from DLW, with 2703 $kcal \cdot day^{-1}$ (Dobrowolski et al., 2020), 2485 $kcal \cdot day^{-1}$ (Yli-Piipari et al., 2019), and 2274–2926 $kcal \cdot day^{-1}$ (Mara et al., 2015b) reported in the Polish, USA, and Australian domestic leagues, respectively. The DLW technique is widely recognized as the gold standard for assessing TDEE in free-living conditions. First employed nearly 40 years ago to evaluate TDEE in humans (Schoeller, 1988), DLW has since been utilized across various athletic populations, including elite male soccer teams (Anderson et al., 2017; Brinkmans et al., 2019). This method involves tracking the elimination of isotopes of hydrogen and oxygen in body water, which enables precise measurement of carbon dioxide production and, consequently, EE. The DLW technique allows for the measurement of TDEE over periods ranging from 4 to 20 days (Ainslie et al., 2003), and it exhibits a precision of 2-8% when compared to direct calorimetry (Schoeller, 1988). Given its high level of precision and reliability, the DLW method is particularly valuable in studies where accurate measurement of EE is critical, such as in elite athletes who experience significant variations in energy output due to their training and competition schedules. Its accuracy and the ability to assess TDEE in real-world conditions make DLW indispensable for obtaining valid and reliable data in the context of sports nutrition and energy balance (EB) research.

In contrast, other methods like accelerometery and activity diaries, while more accessible and less costly, have significant limitations. Accelerometers may not capture all forms of physical activity, particularly those involving upper body movements or resistance training (Ho et al. 2020). Moreover, physical activity diaries rely on self-reporting, which is subject to recall bias and inaccuracies (Welk et al. 2014). These factors likely contribute to the lower TDEE values observed in studies using these methods. The underreporting of EE by these alternative methods can lead to an underestimation of an athlete's true energy needs, potentially impacting nutritional strategies and therefore overall performance. Additionally, the differences in reported TDEE values could also be attributed to the higher playing standards in more recent studies, given that the three DLW studies were all carried out since 2022 (Dasa et al., 2023; Brinkmans et al., 2023; Morehen et al., 2022).

The three DLW studies highlight EE measurements in senior female soccer players from domestic leagues in Norway and the Netherlands, as well as within the England national team. Notably, the TDEE reported for international players from the England team (2693–2753 kcal·day; Morehen et al., 2022) appears slightly lower than that of players in the domestic leagues of Norway (2918 kcal·day; Dasa et al., 2023) and the Netherlands (2882 kcal·day; Brinkmans et al., 2023). This difference may be attributed to several key factors. In the studies that used DLW, Morehen et al. (2021) focused on international players during a 12-day training camp that included only two competitive matches. The study's design, which involved periods of rest, travel, and recovery, potentially contributed to the relatively lower TDEE observed compared to both DLW studies completed at the club level (Dasa et al., 2023; Brinkmans et al., 2023). The inclusion of travel days and structured rest days following matches might have reduced overall EE, as international camps often prioritize recovery to ensure peak performance during games. In contrast, Dasa et al. (2023) assessed Norwegian domestic league players over a continuous 14-day period during the regular season. This study also used the DLW method but captured a period of consistent training and competitive match play without the interruptions typical of international camps. Therefore, given the same methodology was used, scheduling differences likely explain the higher TDEE observed in these players. Similarly, Brinkmans et al. (2023) studied players from a top-tier Dutch domestic league, with TDEE measured over 14 days during the in-season period. Like the Norwegian study, the uninterrupted sequence of training and matches may have contributed to the higher TDEE observed compared to the international level (Morehen et al., 2022). Overall, the differences in TDEE between international and domestic players may be attributed to the nature of the competitive environments, but further research is needed to establish this. These findings underscore the importance of context when assessing EE in elite female soccer players, as variations in training, competition, and recovery periods can significantly influence the results.

The three studies focusing on EE in youth female soccer players report values that are remarkably consistent despite differences in age. TDEE values range from 2403 $kcal \cdot day^{-1}$ in German players aged 14.8 years (Braun et al., 2018) to 2442 $kcal \cdot day^{-1}$ in Indian players aged 12.2 ± 1.8 years (Cherian et al., 2018) and 2546 $kcal \cdot day^{-1}$ in American players aged 15.7 ± 0.7 years (Gibson et al., 2011). The similarity in these values suggests that energy demands are relatively stable across this adolescent age range, despite physiological changes occurring during this period. However, the lack of data using the DLW method in adolescent players indicates a critical gap in the literature. To better understand EE in this group, future research should prioritize collecting DLW data, which would provide more accurate and reliable insights into the energy needs of adolescent female soccer players. One possible reason for the absence of DLW studies in youth populations is the significant cost and logistical challenges associated with this method. Funding for research on younger athletes is often limited, and as a result, these studies may not be prioritized. However, this lack of research is concerning, given that adolescence is a critical period of growth and development (Desbrow et al. 2014). Understanding the energy demands of the sport at this stage is essential for developing effective nutritional strategies that support growth and maturation of elite athletes.

Table 2.3. A summary of studies that have measured EE within elite female soccer.

Reference	Sample Size	Population Characteristics	Methodology	Total Daily EE (kcal·day^{-1})
Dasa et al. 2023	51	Adult Domestic League, Norway Age: 22.0 ± 4.0	DLW	2918
Brinkmans et al. 2023	15	Adult Domestic League, Netherlands Age: 22.9 ± 4.5	DLW	2882
Morehen et al. 2022	24	Adult International Team, England Age: 25.6 ± 3.5	DLW	2693 - 2753
Dobrowolski et al. 2020	31	Adult Domestic League, Poland Age: 22.7 ± 4.2	Accelerometery	2703
Yli-Piipari et al. 2019	13	Adult Domestic League, USA Age range: 16–41 years	Accelerometery	2485
Mara et al. 2015	8	Adult Domestic League, Australia Age: Not reported	Accelerometery	2274 - 2926
Fogelholm et al. 1995	12	Adult Domestic League, Finland Age: Not reported	Activity Diary	2251
Behrens et al. 2020	20	Adult Domestic League, USA Age: Not reported	Activity Diary	2240
Martin et al. 2006	16	Adult Domestic League Age: Not reported	Activity Diary	2154
Gibson et al. 2011	33	Youth Domestic League Age: 15.7 ± 0.7	Activity Diary	2546
Cherian et al. 2018	19	Youth Domestic League, India Age: 12.2 ± 1.8	Portable Metabolic Analyser	2442
Braun et al. 2018	56	Youth Domestic League, Germany Age:14.8 ± 0.7	Activity Diary	2403

2.4. Nutritional Requirements of Female Soccer Players

2.4.1 Nutrition Guidelines for Elite Female Soccer Players

Current nutritional guidelines in soccer fail to distinguish between male and female athletes, despite the significant physiological differences between the sexes, which are likely to influence dietary needs (Ansdell et al. 2020). Therefore, it is probable that much of what is currently applied in female soccer nutrition is extrapolated from strategies that have proven effective in male soccer players. This lack of differentiation could have detrimental implications for female athletes. For example, CHO intake ranges have been suggested based on training period and external load, such as 4-8 $g{\cdot}kg^{-1}$ for pre-season, 3-8 $g{\cdot}kg^{-1}$ for in-season with one match per week, 6-8 $g{\cdot}kg^{-1}$ for in-season with congested fixture periods, and less than 4 $g{\cdot}kg^{-1}$ for off-season training. However, these guidelines are not specifically designed based on research in females, highlighting a significant gap in the literature and the need for female-specific nutritional recommendations, failing to account for physiological differences. For instance, female soccer players generally have lower lean body mass and higher body fat percentages (16–23%) compared to males, as well as 12–26% lower maximal oxygen uptake (VO2max) and reduced leg strength, which influence endurance and power outputs (Milanović et al., 2017; Pedersen et al., 2019). Such sex-based physiological distinctions necessitate tailored nutritional strategies that reflect the unique metabolic and functional demands of female soccer players. However, nutritional practices of female players have been researched and can be compared to generic guidelines.

2.4.2. Habitual EI of Elite Female Soccer Players

Understanding the habitual EI of elite female soccer players is critical for optimising performance, supporting recovery, and maintaining long-term health. Adequate EI fuels the physical demands of training and competition, supports immune function, and reduces the risk of injuries. However, the methodologies used to assess EI vary widely, with weighed food diaries, non-weighed food diaries and 24-hour recall used to gather data over varying periods of time. Across the literature, 29 studies have investigated EI in elite female soccer players. Among these, 14 studies used food diaries, with a mix of weighed and non-weighed methods, while 11 studies employed 24-hour recalls, and 4 utilized other dietary assessment techniques. Early studies on EI in elite female soccer players often relied on short-term, non-weighed food diaries or 24-hour recalls, which may have contributed to underreporting. For example, Fogelhom et al. (1995) used a 3-day food diary to assess EI in Finnish domestic league players, reporting a mean intake of 2143 ± 401 $kcal{\cdot}day^{-1}$. Similarly, Clark et al. (2003) employed a 3-day food diary in American domestic league players, finding EIs ranging from 1865 to 2251 $kcal{\cdot}day^{-1}$. These early studies provided foundational insights into the dietary habits of female soccer players but may lacked the methodological rigor seen in more recent research, potentially affecting the accuracy of the reported EIs. Furthermore, they may not be representative of current nutritional habits, given how drastically the game has changed in recent years, in terms of professionalism.

The potential for underreporting in dietary assessment studies, particularly those relying on methods such as the RFPM is significant. The large variance between methods observed in various studies (Table 2.4.) highlights these inaccuracies, which have been well-documented across both retrospective and prospective assessment techniques (Capling et al., 2017; Gemming et al., 2014; Livingstone & Black, 2003; Martin et al., 2012; Poslusna et al., 2009; Rollo et al., 2016; Thompson et al., 2010). Despite this, RFPM has become increasingly popular in the field of sport nutrition research and applied practice. However, athletes may forget to report all food intake or underreport certain foods, particularly those perceived as unhealthy, leading to an underestimation of actual EI. This bias, compounded by errors associated with participant behaviour, such as inaccurate reporting of food leftovers, failure to document snacks and drinks or the burden on researchers to provide frequent prompts, further complicates the accuracy of the data. Moreover, the ability of the coder to accurately estimate portion sizes and account for hidden ingredients, such as cooking oils, adds another layer of potential error. Previous studies have shown that applied sport nutrition practitioners can under-estimate meal energy content by approximately 10%, with individual variation between coders ranging from −47% to +18% (Stables et al., 2021). These findings underscore the need for cautious interpretation of dietary intake data collected through RFPM and similar methods.

Recent studies have adopted more rigorous methodologies, with a shift towards weighed food diaries and longer assessment periods. For instance, Morehen et al. (2021) used a 4-day weighed food diary to report a mean daily EI of 1923 ± 357 $kcal \cdot day^{-1}$ in the England national team. While weighed food diaries are considered more accurate, non-weighed food diaries might still provide valuable insights into habitual dietary patterns. These methods, although less precise, might capture more natural eating behaviours since they do not require the same level of diligence and intervention as weighed diaries. Athletes may be more likely to record what they eat without altering their behaviour to meet perceived expectations, potentially offering a more authentic reflection of their usual dietary intake. Interestingly, of the studies that reported BM (Morehen et al. 2021; Dasa et al. 2023; Brinkmans et al. 2023), no significant changes in BM among the players were found, despite the apparent under-fuelling suggested within these papers. This raises the question of whether these athletes are indeed under-fuelling or if the reported low intakes are a result of underreporting, with Brinkmans and colleagues stating "As players' BM did not change (median change 0.0% −0.7 to 1.0) during the study period, the lower EI suggests underreporting rather than undereating". This indicates that the players' actual EIs are sufficient to maintain BM, but inaccuracies in reporting EI due to methodological challenges obscure this reality. This potential discrepancy underscores the importance of considering underreporting when interpreting dietary data and emphasizes the need for continued refinement of dietary assessment methods in athletic populations.

EI studies on youth female soccer players also show variability. For example, Braun et al. (2018) reported a mean daily EI of 2403 ± 195 kcal·day in German players aged 14.8 years using a 7-day food diary. In contrast, McKinlay et al. (2021) found a lower intake of 1622 ± 139 kcal·day in Canadian players aged 14.3 years using a 1-day food diary. Although McKinlay et al. report the lowest levels of EI, they utilised a 1-day food diary. This is likely insufficient to capture the true EI of adolescent athletes. A single day's intake may not represent typical eating patterns, especially given variability in daily activities, appetite, and access to food. This short assessment period increases the risk of both over- and underestimations, making it difficult to draw reliable conclusions from the data. Therefore, given the challenges mentioned previously regarding recall bias, there is a fine balance to be had between having sufficient data to draw a conclusion and data collection over a period that is too long, resulting in high levels of participant burden. It is important to note that the energy demands of youth players at this developmental stage are not yet fully understood. The nutritional needs of adolescents are influenced by numerous factors, including growth spurts, hormonal changes, and varying levels of physical activity, all of which complicate the assessment of adequate EI, with a lack of EE data to compare intake to. As such, it is challenging to make definitive conclusions about whether these reported intakes are sufficient to meet the players' needs.

2.4.3. Habitual Macronutrient Intake of Elite Female Soccer Players

2.4.3.1 Carbohydrate Intake

CHO intake is essential for sustaining the high energy demands of soccer, yet the studies reviewed demonstrate considerable variation in reported intake, reflecting differences in player populations, methodologies, and the understanding of CHO's role in performance. For instance, Santos et al. (2016) reported a mean intake of 5.5 ± 0.9 $g \cdot kg \cdot day^{-1}$ in Brazilian domestic league players using a 3-day 24-hour recall, while Morehen et al. (2022) found a significantly lower intake of 3.5 ± 0.9 $g \cdot kg \cdot day^{-1}$ in the England national team using a 4-day weighed food diary. Furthermore, studies like Brinkmans et al. (2023) highlighted how CHO intake can vary depending on the type of day assessed, such as training versus match days, further complicating direct comparisons between studies.

Despite these variations, the majority of studies found that mean CHO intake values were closer to the lower end of recommended ranges. Consequently, there is a critical need for nutritionists to educate athletes on the importance of CHO intake and to develop strategies that align consumption with the specific demands of training and competition, as previously suggest within men's soccer (Anderson et al. 2017). Recommendations for CHO intake also emphasise the timing of consumption, particularly in the hours leading up to a match, during the match, and in the recovery period afterward (Colins et al. 2021). However, studies examining the effects of CHO ingestion before and during matches have found negligible differences in performance, perceptual changes, and physiological responses between high CHO and mixed macronutrient meals consumed four hours before competition (Wynne et al. 2021).

2.4.3.2 Protein and Fat Intake

Compared to CHO, there is less data on protein and fat intake in female soccer players; however, available evidence suggests that players generally meet current guidelines more comfortably. According to the UEFA consensus statement by Collins et al. (2021), recommended protein intake ranges from 1.2 to 1.7 $g \cdot kg^{-1} \cdot day^{-1}$, while fat should contribute approximately 20–30% of total energy intake to support essential fatty acid needs and overall health. Studies consistently report female players consume protein within or slightly below this range and adequate dietary fat, with less variability than carbohydrate intake. This suggests better alignment with nutritional recommendations for protein and fat, though ongoing monitoring and tailored nutrition strategies remain important to optimise health and performance.

Table 2.4. A summary of studies that have measured EI within elite female soccer.

Reference	Sample Size	Population Characteristics	Methodology	Mean Daily EI (kcal·day^{-1})	Mean Daily CHO Intake (g·kg·day^{-1})	Mean Daily Protein Intake (g·kg·day^{-1})	Mean Daily Fat Intake (g·kg·day^{-1})
Guzmán et al. 2011	24	Adult domestic league, Spain	7-day 24-hour Recall	3050 ± 140	N/A	N/A	N/A
Reed et al. 2013	19	Adult Domestic League, USA	3-day Food Diary	2161 - 2794	5.0 - 7.0	1.0 - 2.0	1.0 - 2.0
Dasa et al. 2023	51	Adult Domestic League, Norway	3-day 24-hour Recall	2274 ± 450	4.0 - 4.5	1.5 - 1.7	1.3 - 1.4
Brinkmans et al. 2023	15	Adult Domestic League, Netherlands	4-day 24-hour Recall	2344	3.2 – 5.3	N/A	N/A
Santos et al. 2016	21	Adult Domestic League, Brazil	3-day 24-hour Recall	2306 ± 405	5.5 ± 0.9	2.0 ± 0.5	N/A
Gravina et al. 2012	28	Adult Domestic League, Spain	8-day Food Diary	2271 ± 578	N/A	N/A	N/A
Fogelhom et al. 1995	12	Adult Domestic League, Finland	3-day Food Diary	2143 ± 401	N/A	N/A	N/A
Moss et al. 2021	30	Adult Domestic League, England	5-day Food Diary	2124 ± 444	3.3 ± 0.6	1.8 ± 0.4	1.3 ± 0.4
Behrens et al. 2020	20	Adult Domestic League, USA	3-day Food Diary	2112 ± 505	N/A	N/A	N/A
Mullinix et al. 2003	18	Adult Domestic League, USA	7-day Food Diary	2015 ± 19	N/A	N/A	N/A
Abood et al. 2004	15	Adult Domestic League, USA	3-day Food Diary	1969 ± 414	N/A	N/A	N/A
Magee et al. 2020	18	Adult Domestic League, USA	4-day Food Diary	1931 ± 371	3.7 ± 1.0	1.2 ± 0.4	1.1 ± 0.4
Morehen et al. 2021	24	Adult International Team, England	4-day Weighed Food Diary	1923 ± 357	3.5 ± 0.9	1.9 ± 0.2	1.4 ± 0.3
Martin et al. 2006	16	Adult Domestic League, England	7-day Food Diary	1904 ± 366	4.1 ± 1.0	1.2 ± 0.3	0.9 ± 0.2
Yli-Piipari et al. 2019	13	Adult Domestic League, USA	4-day Food Diary	1894 ± 428	4.2 ± 2.3	1.6 ± 1.1	1.3 ± 0.9

Clark et al. 2003	13	Adult Domestic League, USA	3-day Food Diary	1865 - 2251	4.3 - 5.2	1.0 - 1.4	N/A
Leão et al. 2022	14	Adult Domestic League, Portugal	7-day Food Diary	1764 ± 495	N/A	N/A	N/A
Pilis et al. 2019	15	Adult Domestic League, Poland	3-day Food Diary	1714 ± 335	3.6 ± 1.1	1.4 ± 0.4	N/A
Dobrowolski et al. 2020	31	Adult Domestic League, Poland	4-day Food Diary	1548 ± 452	N/A	N/A	N/A
Drobowolski et al. 2019	41	Adult Domestic League, Poland	3-day Food Diary	1476 ± 434	3.3 ± 1.2	1.2 ± 0.4	N/A
Braun et al. 2018	56	Youth Domestic League, Germany Age: 14.8 ± 0.7	7-day Food Diary	2403 ± 195	5.4 ± 1.1	1.4 ± 0.3	1.4 ± 0.4
Cherian et al. 2018	19	Youth Domestic League, India Age: 12.2 ± 1.8	3-day Weighed Food Diary	2243 ± 320	4.8 – 10.9	1.0 – 2.0	0.8 ± 0.39
Gibson et al. 2011	33	Youth Domestic League Age: 15.7 ± 0.7	4-day Food Diary	2079 ± 460	5.0 ± 1.6	1.4 ± 0.3	1.2 ± 0.4
Łuszczki et al. 2021	34	Youth Domestic League, Poland Age: 15.4 ± 4.2	1-day Food Diary	1872 ± 255	N/A	N/A	N/A
McKinlay et al. 2022	13	Youth Domestic League, Canada Age: 14.3 ± 1.3	1-day Food Diary	1622 ± 139	N/A	N/A	N/A

2.5. Energy Availability and Relative Energy Deficiency in Sport

2.5.1. Energy Balance and Availability

EA and EB are similar but distinct concepts in sports nutrition and particularly important for athletes engaged in high-intensity sports like soccer. EA represents the energy available to sustain physiological functions after the energy cost of exercise has been met. It is calculated by subtracting EEE from total EI and then normalizing this value relative to FFM (Nattiv et al., 2007). On the other hand, EB refers to the broader equilibrium between total EI and total EE, including all daily activities, not just exercise. While EB gives a general overview of an athlete's energy status, EA provides a more specific insight into the energy available for essential bodily functions beyond exercise. For elite female soccer players, maintaining adequate EA is crucial for both optimal performance and overall health and therefore it is the concept of EA that is now more widely researched within female soccer (Martinho et al. 2024).

2.5.2. Energy Availability

A critical threshold for EA is identified at less than 30 kcal·kg $FFM^{-1} \cdot day^{-1}$, which often aligns with RMR (Ihle & Loucks, 2004; Loucks, 2003). When EA falls below this threshold, it can lead to unfavourable physiological changes, impacting metabolic function, reproductive health, and bone integrity (Loucks & Thuma, 2003; Loucks et al., 2011; Nattiv et al., 2007). LEA has also been found to arise from factors such as disordered eating, intentional weight loss, inadvertent undereating, or clinical eating disorders (De Souza et al., 2017a). these conditions can negatively affect both health and performance due to changes in endocrine function and metabolism. From a bioenergetic perspective, energy used for one bodily process cannot be repurposed for another, making it a finite resource that the body must prioritize (Bronson, 1985; Loucks, 2020). Maintaining homeostasis can be challenging in elite female soccer due to the high energy demands of training and competition, especially when dietary intake is insufficient. Research has shown that low EA is particularly relevant for female athletes, especially as more women participated in sports during the 1960s and '70s, leading to increased reports of menstrual disturbances (Slater et al., 2017). This spurred research into the causes of amenorrhea and other physiological issues in athletic females, ultimately identifying low EA as the primary factor (Loucks & Thuma, 2003; De Souza et al., 2014). This research contributed to the development of the Female Athlete Triad model, which links EA to reproductive and bone health (De Souza et al., 2014). The topic has expanded to include models like REDs, focusing on broader physiological disruptions caused by low EA (Mountjoy et al., 2023). Although interest in this area is growing, particularly in preventing its negative effects, there is still limited evidence (Areta et al., 2021; Jeukendrup et al., 2024).

2.5.3. Energy Availability Origins

As female sports participation increased, research began to explore the prevalence of amenorrhea and other physiological issues in athletic females (Loucks & Horvath, 1985; Slater et al., 2017). Early studies cited various factors, such as body composition, training, and diet, as potential causes. However, the belief that body composition was the primary driver of these issues was challenged when findings showed that menstrual irregularities occurred regardless of body fat levels or changes (Loucks & Horvath, 1985). Attention soon shifted to the "stress of exercise" and "energy drain" as key factors. In the context of sports where high training loads are common, Feicht et al. (1978) found a strong correlation between high training mileage and secondary amenorrhea in female athletes, independent of BM differences. Similarly, Warren (1980) observed that adolescent ballet dancers, despite lower BM, experienced delayed menarche and amenorrhea, which were closely linked to high activity levels rather than BM. These findings led to the development of the "caloric balance" theory by Winterer et al. (1984), suggesting that the brain prioritizes energy for vital functions, including reproductive health, based on available energy.

The first controlled study on EA in humans by Loucks & Callister (1993) further solidified the concept. They demonstrated that low EA rather than exercise stress itself, led to significant reductions in key hormones like triiodothyronine (T3). Follow-up studies by Loucks et al. (1998) confirmed that LEA, whether induced by exercise or dietary restriction, impacted reproductive hormones, emphasizing that the energy cost of exercise alone was not the culprit. This body of work established LEA as a critical factor in physiological disturbances, forming the basis of the Female Athlete Triad model (Nattiv et al., 2007). Subsequent models like the Male Athlete Triad and REDs extended these findings to males and linked LEA to broader health and performance issues (Mountjoy et al., 2023). However, some of the additional effects proposed by the REDs model remain debated within the scientific community due to limited empirical support (De Souza et al., 2014). Furthermore, evidence of LEA within elite female soccer players is still relatively limited and contested due to methodological challenges of measuring EA.

2.5.4. Calculating Energy Availability

As mentioned, EA is defined as the difference between EI and net EEE, relative to an individual's FFM. Therefore, this equation (EA = (EI - EEE)/FFM)) provides a measure of the energy available for physiological processes after accounting for the energy expended during exercise (Loucks, 2020). Initially, EA was calculated by subtracting gross exercise EE from EI and normalizing this value to total BM (Loucks & Callister, 1993). However, recognizing that FFM, rather than FM, is the metabolically active component of the body, the formula was refined to subtract total exercise EE from EI, then divide by FFM (Loucks & Heath, 1994b).

Research has shown that when EA falls below 30 kcal·kg $FFM^{-1}\cdot day^{-1}$, athletes are at significant risk of developing LEA and its associated complications, such as hormonal disruptions, decreased bone mineral density (BMD), and impaired metabolic functioning (Loucks et al., 2003). These thresholds are largely derived from two foundational studies that adjusted EA levels in sedentary women, having them engage in exercise at intensities of 10, 20, 30, and 45 kcal·kg $FFM^{-1}\cdot day^{-1}$ over a period of five days. The findings demonstrated that when EA levels were at or below 30 kcal·kg $FFM^{-1}\cdot day^{-1}$, significant changes in hormonal and metabolic markers were observed (Loucks et al. 1994a; Loucks et al. 1994b; Loucks et al. 2003). These alterations in EA were consistent with changes in the hypothalamic-pituitary-gonadal (HPG) axis hormones, which are mechanistically linked to the onset of amenorrhea (Loucks et al. 1994a; Loucks et al. 1994b; Loucks et al. 2003). Additionally, shifts in markers of bone resorption and formation were observed, with a reduction in bone formation evident in each LEA condition and an increase in bone resorption under more severe LEA (Ihle et al. 2004). Although the mathematical equation for determining EA appears straightforward, its accuracy is limited for several reasons (Burke et al. 2018). First, there is no uniform consensus on what constitutes "exercise" versus "non-exercise activity thermogenesis," leading to varied interpretations of net energy expenditure. Second, energy intake is typically assessed using food diaries, which are prone to significant underreporting, with errors averaging 19% and potentially reaching up to 60% (Capling et al. 2017). Lastly, the accuracy of estimating EEE varies widely by sport and depends on factors such as the device used (e.g., accelerometers or heart rate monitors), whether activity is self-reported, and mechanical efficiency, among others (Hills et al. 2014). Despite these thresholds being debated and challenges of calculating EA, it remains a fundamental tool for monitoring athlete health.

Firstly, with regards to measuring EI, traditional methods like food diaries, dietary recalls, and questionnaires, which are often inaccurate due to underreporting and participant burden (Burke et al., 2018; Tarnowski et al., 2023). One method that has been proposed to enhance the accuracy of calculating EI and EA is the EB method. This method uses changes in body energy stores (ΔES), measured through changes in FM and FFM, multiplied by their known metabolizable energy densities (9.5 kcal/g for FM and 1.0 kcal/g for FFM). By combining these measurements with TDEE, the EB method provides an objective measure of EI, which can then be used to calculate EA more precisely (Tarnowski et al. 2023). This method is particularly valuable for long-term assessments, where traditional self-reporting methods for EI are prone to underreporting and inaccuracies (Capling et al., 2017). The EB method, by focusing on objective measurements of EI and expenditure, offers a more reliable approach for these calculations, especially when combined with tools like DEXA for body composition and DLW for free-living EE (Burke et al., 2018). Despite the advantages of the EB method, it is still not widely recognized in sports medicine, where traditional methods are more commonly used, although it has recently been suggested for use within elite sport by Tarnowski et al. (2023), due to the advantage of overcoming challenges of other methods of measuring EI. Its potential to provide more accurate and representative assessments of prolonged EA highlights the need for greater adoption in both research and practical settings.

Exercise EE is similarly difficult to quantify, particularly in team sports or complex activities where standard devices like heart rate monitors or accelerometers may not fully capture the energy cost (Burke et al., 2018). Moreover, the measurement of FFM, which is critical in calculating EA, can vary depending on the methodology used (Dzator et al. 2022). Measurements of FFM are generally obtained using generic equations, which can vary widely and are often developed based on different population groups. As a result, these equations only offer an estimate of an individual's FFM. Even with gold standard methods and standardized measurement procedures, errors of 2–3% are common (Ackland et al. 2012). However, at the individual level, and when using techniques frequently employed in sports settings—such as bioelectrical impedance or skinfold measurements—these errors can be considerably larger due to the accumulation of measurement inaccuracies and daily fluctuations.

This variability combined with inconsistencies in measuring EI (previously discussed in this literature review) highlights the need to critically evaluate the methods used in these studies rather than accepting measurements of LEA at face value. The complexity of this field is further compounded by the fact that the categorization of LEA as <30 kcal/kg FFM/day is typically based on laboratory studies that assume homogeneous patterns of EI and exercise-related expenditure (Burke et al., 2018). In contrast, athletes in free-living conditions, such as those examined in these studies, often experience daily variations in training volume and intensity, which in turn affects EEE. This variability challenges the application of universal categories for defining LEA, as the threshold of <30 kcal/kg FFM/day may not be appropriate across different contexts (De Souza et al., 2022; Lieberman et al., 2018; Salamunes et al., 2024). Given these challenges, accurately quantifying EA in free-living athletes to diagnose LEA remains difficult. Consequently, conclusions drawn from field data should be made with caution, while tightly controlled laboratory studies offer more reliable insights by minimizing the limitations associated with free-living assessments (Burke, et al., 2018).

In summary, the methodology used to measure EI, EEE and FFM, along with the inherent challenges in defining what constitutes ‘exercise,’ can lead to variable outcomes in the assessment of EA (Ackerman et al., 2023; Areta et al., 2021). Therefore, it is essential to consider the methodologies employed in these studies carefully and to interpret the findings within the broader context of methodological limitations and the specific conditions under which the data were collected.

In addition, tools for symptom assessment specific to LEA exist, such as the LEAF-Q (Melin et al. 2014) and LEAM-Q (Lundy et al. 2022), although eleven exist (eight of which are validated) with the purpose of predicting LEA, according to a recent review (Sim et al. 2021). The lack of a standardized method for assessing symptoms presents a challenge, as many tools fail to recognize that these symptoms could stem from factors either linked to or independent of LEA. Although these tools are typically validated within specific populations, they are often applied broadly across different athlete groups. More recently, studies have sought to diagnose LEA (and REDs) via symptom presentation (Burke et al. 2018; Mountjoy et al. 2018). Although this has been proposed more recently, as part of the latest REDs consensus statement (although this does not mention LEA), via the REDs CAT2 (Mountjoy et al. 2023), as reviewed by Stellingworth et al. (2023). The main issue lies in the assumption that identifying common symptoms automatically reveals the underlying cause, without considering other key factors. Therefore, the diagnosis of LEA based solely on symptomology is flawed, as concluded by a recent review (Jeukendrup et al. 2024).

2.5.5. EA within Elite Female Soccer

The concept of EA has become increasingly relevant in the context of female soccer, with implications for both performance and overall health. Table 2.5. provides a summary of the key findings from several studies investigating EA in various populations of female soccer players. The studies reviewed demonstrate considerable variability in mean EA values across different cohorts. For instance, Moss et al. (2021) reported a mean EA of 35 ± 10 kcal·kg FFM·day^{-1} among adult domestic league players in England, with a prevalence of LEA (<30 kcal·kg FFM·day^{-1}) at 23%. In contrast, Morehen et al. (2022) observed significantly lower mean EA values in an adult international team from England, with an average EA of 18 ± 9 kcal·kg FFM·day^{-1} and a striking 88% prevalence of LEA. This prevalence of 88% is the highest within female soccer research and although it could be assumed that this group of players had particularly low EI or high EEE, no significant change in BM was observed within this study. Therefore, it seems more likely that this high prevalence is inaccurate, as it was not reflected in body composition changes, which would be expected over a 12-day period. The means by which EEE was calculated is particularly interesting within this study, as rather than measuring EEE directly (for example, via GPS), PAEE was used within the EA equation. PAEE was calculated by subtracting RMR and TEF from TDEE, therefore accounting for activity beyond training and EEE. Although lower values were reported of 36% and 23% on match days and training days, respectively, within club soccer (Dasa et al. 2023), the same methodology for calculating EEE (or perhaps more accurately, PAEE) was adopted and no significant changes in BM were observed.

Further, Reed et al. (2013) provided a longitudinal view of EA across different phases of the season in an adult domestic league in the USA. The study highlighted that EA varied significantly depending on the season phase, with pre-season LEA group values as low as 20 ± 4 kcal/kg FFM/day and mid-season LEA group values remaining at 20 ± 2 kcal/kg FFM/day. The prevalence of LEA was highest mid-season at 33%, decreasing to 12% post-season. This most likely demonstrates the contribution of exercise EE to low EA. In youth populations, Cherian et al. (2018) and Braun et al. (2018) have reported

EA. Cherian et al. found EA values of 32 ± 10 kcal/kg FFM/day in U12 players, and 24 ± 12 kcal/kg FFM/day in U16 players from India, with a 58% prevalence of LEA. Similarly, Braun et al. observed a mean EA of 30 kcal/kg FFM/day among German youth players, with 50% of the sample falling below the LEA threshold.

2.5.6. The Female Athlete Triad

The Female Athlete Triad is a syndrome commonly observed in physically active females, characterized by three interconnected components: LEA, menstrual dysfunction, and low BMD. First identified by the American College of Sports Medicine (ACSM) in 1992, the Triad was initially defined by the presence of eating disorders (ED), amenorrhea, and osteoporosis, particularly in athletes participating in appearance-based or endurance sports (Yeager et al., 1993). However, the role of inadequate nutrition and EA in driving these conditions was not fully integrated into the model at that time. In 1997, the ACSM released a position stand that began to recognize LEA as a key factor in the Triad, moving beyond the sole focus on disordered eating (Otis et al., 1997). By 2007, LEA was officially acknowledged as the primary driver of the physiological dysregulations observed in female athletes, leading to an understanding of the Triad as a spectrum (Nattiv et al., 2007). This spectrum ranges from optimal health, characterized by sufficient EA, normal menstrual function (eumenorrhea), and strong bone health, to severe clinical outcomes like functional hypothalamic amenorrhea and osteoporosis, resulting from prolonged LEA.

The Female Athlete Triad model explains that female athletes can exist anywhere along this spectrum, with their health outcomes influenced by dietary and training practices. LEA, which can occur with or without a clinically diagnosed eating disorder, disrupts hormonal balance and bone metabolism. This disruption can manifest as sub-clinical menstrual disturbances, such as oligomenorrhea, anovulation, or luteal phase deficiency, and may lead to reduced bone formation and increased resorption, resulting in low BMD (De Souza et al. 2014; Nattiv et al., 2007). At the severe end of the spectrum, prolonged LEA has been directly linked to the impairment of reproductive function by affecting the pulsatile release of gonadotropin-releasing hormone from the hypothalamus, which in turn disrupts the release of luteinizing hormone (Loucks & Heath, 1994b; Loucks et al., 1998). Similarly, LEA can lead to alterations in key bone-protective hormones, contributing to the uncoupling of bone resorption and formation, and potentially causing osteoporosis (Ihle & Loucks, 2004).

Prevalence studies show that athletes can present with one or more components of the Triad. While it is sufficient to exhibit only one component to be diagnosed with the Triad, the prevalence rates vary widely: 16% to 60% of athletes show one component, 2.7% to 27% show two components, and 0% to 16% present all three components (Gibbs et al., 2013). These rates are higher in athletes participating in lean or aesthetic sports, and adolescent athletes are particularly at risk due to a higher prevalence of menstrual disturbances. Despite its significance, research on the Female Athlete Triad among female soccer players is limited. A study by Sundgot-Borgen and Torstveit (2007) on 17 Norwegian national soccer players found that 24% had an eating disorder, 9.3% had menstrual dysfunction, and 13% had a history of stress fractures, underscoring the importance of further investigation within this population.

2.5.7. Relative Energy Deficiency in Sport

In 2014, the International Olympic Committee (IOC) introduced the REDs model, expanding on the Female Athlete Triad to include a broader spectrum of health and performance consequences resulting from LEA. Unlike the Triad, the REDs model recognizes that LEA impacts a wide range of physiological and psychological functions in both female and male athletes, beyond the three components recognised within the female athlete triad. The model emphasises that the effects of LEA are not confined to reproductive health and bone integrity but extend to other areas, including immune function, cardiovascular health, metabolic rate, muscle strength, and cognitive function (Mountjoy et al., 2014).

The REDs model was further refined in 2018 and again in 2023, reflecting the latest research and understanding in the field. The 2018 update provided a comprehensive review of the literature, while the 2023 revision introduced the concept of a continuum of low EA. This continuum differentiates between "adaptable" and "problematic" LEA. Adaptable LEA refers to short-term, manageable energy deficits that result in expected physiological adjustments with minimal long-term consequences. In contrast, problematic LEA is associated with prolonged or severe energy deficits that can lead to significant health and performance impairments (Mountjoy et al., 2023). The 2023 update to the REDs model defines it as a syndrome of impaired physiological and psychological functioning due to problematic LEA. This updated definition acknowledges that the detrimental outcomes of REDs can affect various systems in the body, including energy metabolism, reproductive function, musculoskeletal health, immunity, glycogen synthesis, and cardiovascular health. These impacts can individually or synergistically lead to decreased well-being, increased injury risk, and diminished sports performance (Mountjoy et al., 2023). However, the consensus statement does not reference any primary evidence or objective criteria to clearly differentiate between adaptable and problematic LEA, aside from relying on the appearance of symptoms. This is a notable limitation, as much of the research supporting the REDs model has focused on adaptable LEA rather than problematic LEA. While the new consensus acknowledges that other factors may contribute to the development of REDs, potentially independent of EA, these are classified as "moderating factors". A supporting paper provides an extensive list of such factors, including various differential diagnoses that could explain the signs and symptoms of REDs (Burke et al. 2023). However, this list is likely incomplete and may be impractical for clinicians and practitioners to use effectively. Although addressing these factors might be outside the consensus statement's scope, they are crucial for guiding athletes in maintaining both health and performance.

REDs research has predominantly focused on leanness and endurance sports, where the prevalence of LEA is believed to be higher due to the critical role of BM in performance (Logue et al., 2018; Mountjoy et al., 2014). However, the scope of REDs also encompasses other athletic populations, including female soccer players. While studies have explored individual symptoms of REDs, such as LEA and BMD, the occurrence of clustered REDs indicators in soccer players remains under-researched. Despite this, existing studies have highlighted the potential consequences of REDs in female soccer, including menstrual dysfunction, reduced BMD, hormonal imbalances, and increased injury risk (Reed et al., 2014; Prather et al., 2016; Dasa et al. 2024), although evidence for this is limited (Jeukendrup et al. 2024).

2.5.8. (Mis)diagnosis of REDs

It is important to note that while the REDs model provides a comprehensive framework for understanding the wide-ranging effects of LEA, many of the proposed consequences lack robust empirical evidence and are often based on anecdotal clinical observations (De Souza et al., 2014). As the field of REDs research continues to evolve, there is a clear need for further long-term, controlled studies to better understand the full impact of LEA on health and performance, particularly in diverse athletic populations such as female soccer players.

In summary, many researchers and practitioners operate under the assumption that REDs is a well-established phenomenon and that both LEA and REDs are highly prevalent among athletes (Sesbreno et al., 2023; Logue et al., 2018; Logue et al., 2021; Magee et al., 2020; Rogers et al., 2021). Some studies have even reported 100% prevalence of LEA in athletes (Schaal et al., 2021), with rates as high as 88% in female soccer players (Morehen et al., 2021). However, methodological limitations may lead to an overestimation of LEA prevalence, which could in turn inflate the perceived risk of REDs.

Table 2.5. A summary of studies that have measured EA within elite female soccer.

Reference	Sample Size	Population Characteristics	Methodology	Mean EA (kcal·kg FFM·day⁻¹)	Low EA (<30 kcal·kg FFM·day⁻¹) Prevalence
Moss et al. 2021	30	Adult Domestic League, England	EA Equation EI: 5-day Food diary FFM: DEXA EEE: METs	35 ± 10	23%
Reed et al. 2014	19	Adult Domestic League, USA	EA Equation EI: 3-day Food diary FFM: Dexa EEE: HR and Activity Diary	Pre-season LEA group: 20 ± 4 Pre-season Non-LEA group: 52 ± 5 Mid-season LEA group: 20 ± 2 Mid-season Non-LEA group: 43 ± 3	Pre-season: 26% Mid-season: 33% Post-season: 12%
Reed et al. 2013	17	Adult Domestic League, USA	EA Equation EI: 3-day Food Diary FFM: DEXA EEE: HR and Activity Diary	Mid-season: 35 ± 4 Post-season: 45 ± 4	Mid-season: 33% Post-season: 26%
Dasa et al. 2023	51	Adult Domestic League, Norway	EA Equation EI: 3-day 24-hour Recall FFM: DEXA EEE: DLW Derived	Match Day: 36.7 ± 17.7 Training Day: 37.9 ± 11.7	Match Day: 36% Training Day: 23%
Morehen et al. 2022	24	Adult International Team, England	EA Equation EI: 4-day Weighed Food Diary FFM: DEXA EEE: DLW Derived	18 ± 9	88%
Dobrowolski et al. 2020	31	Adult Domestic League, Poland	EA Equation EI: 3-day Food Diary FFM: BIA EEE: METs	25 ± 11	65%
Cherian et al. 2018	19	Youth Domestic League, India Age: 12.2 ± 1.8	EA Equation EI: 3-day Weighed Food Diary FFM: Skinfold Measurements EEE: Portable Metabolic analyser	U12s: 32 ± 10 U16s: 24 ± 12	58%
Braun et al. 2018	56	Youth Domestic League, Germany Age: 14.8 ± 0.7	EA Equation EI: 7-day Food Diary FFM: Predictive Equations EEE: Activity Diary	30	50%

2.5.9. Causes of LEA

The models of the Female Athlete Triad, Male Athlete Triad, and REDs acknowledge that factors such as disordered eating or eating disorders, along with other mental health conditions like compulsive exercise or exercise addiction, can lead to LEA. However, these models also recognize that a variety of other factors may contribute to LEA in athletes, whether or not disordered eating is present (De Souza et al., 2014; Mountjoy et al., 2023; Nattiv et al., 2021). In terms of EI, restrictive dietary practices beyond those linked to eating disorders—such as vegetarianism or other restrictive diets, fasting, or the intentional restriction of dietary intake to manage BM or avoid weight gain during injury recovery—can also lead to LEA (Burke et al., 2018; Nattiv et al., 2007). A lack of education or awareness of current nutritional guidelines, which has been demonstrated in endurance athletes (Sampson et al., 2023), could also result in reduced dietary intake and subsequently contribute to LEA.

On the other hand, female soccer players who have high exercise EE due to their demanding training and competition schedules may unintentionally experience LEA if they are unaware of the need to increase their EI accordingly. This issue is further exacerbated when athletes are unable or unaware of how to adequately adjust their nutrition to match their EE (Burke et al., 2018; Loucks et al., 2011). For example, Moss et al. (2020) have shown that elite female soccer players, similarly to cyclists (Heikura et al., 2019), tend to have reduced EA on competition days and during intense training periods compared to rest days. This suggests that these athletes may either inadvertently or intentionally under-fuel on days with higher energy demands. Additionally, on days of intense training, where multiple hours of exercise are required, players may face limited opportunities to consume sufficient energy outside of their training sessions, further compounding a potential reduction in EA.

However, there is limited data regarding the cumulative impact of these factors on the daily fluctuations in EA that female soccer players may experience under real-world conditions. Future research is needed to better understand the relationships between exercise EE, dietary intake, and EA in free-living female soccer players. Such insights could inform interventions aimed at optimising EA in this population and contribute to the design of future studies examining the physiological effects of LEA under controlled conditions.

2.7. Summary and Direction for Future Research

The evolution of women's soccer into a professional sport has highlighted an urgent need for sport science research (Datson et al. 2017; Nassis et al. 2021). Although some progress has been made, the research landscape remains predominantly focused on male athletes, and the growth of the sport has not been matched by a corresponding increase in research specific to women’s soccer (Okholm Kryger et al. 2021). Consequently, there have been numerous calls for research at the elite level of the women’s game (Datson et al. 2017; Nassis et al. 2021), which is essential for a deeper understanding of the physical and physiological demands of the sport. This understanding should inform the foundations for nutritional support and guidelines.

Current research on the physical demands of elite female soccer players, particularly at the adolescent level, remains insufficient. The studies reviewed reveal a lack of comprehensive data on training loads and match demands, with inconsistencies in the application of speed thresholds (Harkness-Armstrong et al. 2022). While GPS technology has been employed to assess physical loading, there is a notable absence of data capturing the demands of training and match activities in adolescent players at the international level. This gap is particularly concerning given the critical developmental stage of these athletes (Desbrow et al. 2014).

Understanding EE is vital for developing nutrition strategies that support the rigorous demands placed on elite female soccer players. However, only three studies to date have measured EE at the elite level using the gold-standard DLW method (Dasa et al., 2023; Brinkmans et al., 2023; Morehen et al., 2022). Therefore, further research is necessary, particularly focusing on adolescent athletes, as all three existing DLW studies were conducted in senior club or international environments. Additionally, there is a significant gap in understanding the EI of adolescent female soccer players, which is crucial for supporting their development and performance (Desbrow et al. 2014). Methodological challenges exist, and it is essential to consider appropriate methods for measuring EI to obtain an accurate representation of current habits. Future research should prioritize the use of more accurate and objective measures, such as the DLW method paired with measurements of changes in BM (Tarnowski et al. 2023), to assess EI and availability more reliably. Documenting nutritional habits will help shape educational interventions aimed at elite players. Furthermore, a deeper understanding of the culture surrounding nutrition, as well as the experiences of players and stakeholders regarding nutritional support, is required to implement effective behaviour change strategies.

Finally, LEA has been reported as prevalent within elite female soccer. However, questions remain regarding the reliability of measurement techniques used in previous research. Given the potential for self-reported EI to underestimate actual EI, it is hypothesized that levels of low EA may have been previously overestimated in female soccer players. Moreover, the lack of research on adolescent players is an area that warrants further exploration, with careful attention paid to methodology, particularly considering the challenges of collecting accurate data outside of a laboratory setting.

In conclusion, this literature review identifies critical gaps in the current research on nutrition in elite female soccer players, particularly at the adolescent level. The studies presented emphasise the need for more accurate, comprehensive, and context-specific research that accounts for the unique methodological challenges, especially in measuring EI and EA. Additionally, a better qualitative understanding of the environment is needed to address challenges identified by previous research.

Given the predominance of observational and experimental studies in sport nutrition, the rationale for starting this thesis with a qualitative approach is to capture the nuanced lived experiences of elite female players and the complex social and environmental factors influencing their nutrition. Qualitative methods provide a unique opportunity to explore the *how* and *why* behind dietary behaviours, beyond the *what* quantified in quantitative research (Bentley et al. 2025). This interpretivist paradigm acknowledges athletes as situated individuals within dynamic high-performance cultures, enabling a richer, more holistic understanding of nutrition practices and barriers that pure physiological measures alone cannot uncover (Jenner et al. 2021). The extended immersion and reflexive practice in qualitative inquiry further enhance the credibility and practical relevance of findings, ultimately guiding tailored interventions that are sensitive to the real-world context of female elite soccer (Bentley et al. 2025).

Chapter Three

Study One

A Qualitative Analysis of Player and Stakeholder Perceptions of the Nutrition Culture Within Elite Female Soccer

This paper was published in Science and Medicine in Football (2022):

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3.1. Abstract

Purpose: This qualitative study explores player and stakeholder perceptions of the role of nutrition in supporting player development and performance in elite female soccer.

Methods: Semi-structured interviews (36 ± 18 mins in length) were conducted with 47 participants, including players (n = 12), parents (n = 9), coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5) and medical staff (n = 5). Via thematic analysis, data provided an insight into the nutrition culture within elite women's soccer.

Results and conclusions: Data demonstrate that considerable confusion and misconceptions exist amongst players and stakeholders regarding the theoretical underpinning and practical application of meeting energy requirements. As such, it is perceived that players 'under-fuel', which is likely caused by misunderstandings about the impact of CHO intake on body composition, a fear of weight gain and the associated impacts upon body image. The 'CHO fear' that is experienced by players is exacerbated by external pressures arising from social media, key stakeholders (e.g., coaches) and the skinfold culture surrounding measurement of body composition. Such cultural issues are amplified by the lack of full-time professionally accredited nutritionists overseeing the provision of nutrition support. Indeed, the infrastructure supporting the women's game (e.g. staffing resource, on-site food provision, player education programmes, etc.) was considered incomparable to the men's game. When taken together, our data provide a platform for which to develop organisational, stakeholder and player centred education and behaviour change interventions that strive to promote a positive performance nutrition culture within the women's game.

3.2. Introduction

In recognition of the increasing growth and professionalism of the women's game (Fédération Internationale de Football Association 2017, 2019; Petty and Pope 2019), there have been multiple calls for a strategic and multidisciplinary research agenda that seeks to improve the health and performance of the female soccer player (Datson et al. 2017; Nassis et al. 2021). Indeed, in a recent audit of research conducted to date, it was demonstrated that the existing research base is not comparable to the men's game (Okholm Kryger et al. 2021). In terms of potential research priorities, this audit identified that nutrition-related research is less studied when compared with other sub-disciplines of sport and exercise science (Okholm Kryger et al. 2021). Furthermore, the nutritional guidelines that are currently directed to female athletes are based on research primarily conducted on males (Moore et al. 2021). This lack of female specific research is of particular concern given that female athletes are susceptible to chronic LEA (Heikura et al. 2021), the result of which can manifest as symptoms associated with the female athlete triad or REDs models (Nattiv and Lynch 1994; Mountjoy et al. 2018). In this way, female players may also be susceptible to negative health outcomes such as disordered eating, extreme weight loss, amenorrhea and low BMD (Brown and Knight 2021; Langbein et al. 2021).

In a step towards female-specific guidelines, we recently provided the first report to assess TDEE using the DLW technique) of international standard female soccer players (Morehen et al. 2021). Although we observed a relative TDEE (i.e., 50 kcal.kg^{-1} FFM, comparable to their male counterparts (Anderson et al. 2017), it is noteworthy that 88% of the players presented with LEA when EI was assessed during a 4-day training period, as defined as an EA <30 kcal.kg^{-1} FFM. Furthermore, only one of the 24 players consumed the recommended amount of CHO intake (e.g. 6–8 g.kg^{-1} BM) on the day prior to the game, thus it is likely that players commenced match play with sub-optimal muscle glycogen stores (Krustrup et al. 2022). Additionally, mean daily CHO intake during the assessment period was 3.3 g.kg^{-1} BM, and players did not adjust daily CHO intake in line with the daily physical training load and demands, as is suggested based on CHO guidelines for soccer (Collins et al. 2021). Our data were comparable to previous observations of female professional players from the English WSL (Moss et al. 2021), thereby suggesting that female players 'under-fuel' in relation to the energetic requirements of daily training and match play.

The precise reasons underpinning the prevalence of 'under-fuelling' are not yet understood. On the one hand, it could simply be that female players (and associated stakeholders, e.g., coaches, sport science staff, parents, etc.) are not yet aware of the recommended nutritional guidelines and hence, the requirement to fuel is not actively encouraged. Alternatively, there may be various organisational and financial (e.g., lack of qualified staff and practical on-site food provision) factors that present as a reduced opportunity to engage with sound nutritional practices. Moreover, there may be underlying belief systems and misconceptions amongst players and stakeholders that manifest as a reluctance to actually consume a sufficient energy (and CHO) intake, potentially occurring where players are exposed to an environment where 'body composition' is emphasised as a performance priority and high CHO diets are thought though to promote body fatness (Kerr et al. 2006; Jankauskiene and Pajaujiene 2012; Beckner and Record 2016; Hyatt and Kavazis 2019). In consideration of all the above, the first step in changing future behaviour is to therefore understand the reasons behind current activities that are limiting the desired approaches (Michie et al. 2011). Considering such factors through the lens of theoretical models such as the COM-B framework and behaviour change wheel (Michie et al. 2011, 2014) may help to provide a basis to formulate improved behaviour change interventions.

With the above in mind, the aim of the present study was to explore player and stakeholder perceptions of nutrition practices in support of female soccer players' development and performance. Using a qualitative analysis, we interviewed a cohort of players (n = 12), parents (n = 9), coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5) and medical staff (n = 5) from elite women's soccer at both club and international level. Our data provides a starting point to formulate organisational and individual educational and behaviour change strategies that aim to create a positive culture surrounding nutrition for the female soccer player.

3.3. Methods

To explore players' and key stakeholders' perceptions on the role of nutrition in influencing player development and performance, we took a qualitative approach. Qualitative research provides a route to understand the experiences and perceptions of individuals within complex social environments (Sparkes and Smith 2014). As such, it was deemed an appropriate methodology for the present study. This manifests in the methods described below that were employed to provide a credible and transparent account of nutritional practices in elite women's soccer.

Sample

To gain detailed and multiple insights into the perceptions of nutrition in elite female soccer, players, parents and staff in varying roles (all currently working in and residing in England) were purposefully invited to take part in the study. This approach is comparable to previous qualitative explorations of nutrition practices in professional sport (Martin et al. 2017; Logue et al. 2021), which values the perceptions of those who experience a phenomenon, and enables the development of a broad understanding of the soccer context in question. The inclusion criteria for the purposeful sample included those above 16 years old, who had experiences of elite female football in England, within one of the roles (e.g., player, parent, coach etc.). To recruit this sample, some participants were contacted through gatekeepers of their respective governing bodies via an email including details of the study and participant information details. Convenience sampling was also used to contact other participants who met the inclusion criteria. This convenience sample was appropriate to reflect a range of experiences. All players (n = 12) recruited were aged above 16 years old and competed in elite women's soccer, representing teams in the WSL (n = 9) or The FA Women's Championship (n = 3) in England. Some players also competed at senior (n = 4) and youth (n = 7) international level at the time of the study. Parents or guardians (n = 9) also took part, all of whom currently live with an elite female soccer player, aged 16–18 years. Staff members invited to the study all currently work full-time in elite women's soccer, at club level or international level, in varying roles. These roles included technical coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5), and medical staff (n = 5). Together, this sample enabled the generation of an in depth understanding of nutrition in elite women's soccer. Institutional ethical approval was granted by the ethics committee and, as condition of this, further details of the participants are not provided to avoid direct identification. All participants provided verbal and written informed consent before completing the interview, including child assent and carer consent forms for those under the age of 18 years. Consistent with qualitative research (Sparkes & Smith, 2014), the sample size was not decided a priori, but determined by the analysis, with recruitment stopping for each participant group once saturation was experienced. This involved the lead researcher ceasing to recruit participants when no new insights were derived from further interviews.

Data collection

Semi-structured interviews (36 ± 18 mins) with cameras on were conducted with all participants using online software (Zoom Video Communications, California, USA) and were audio-recorded. A parent was present in the room for all interviews with players under the age of 18 years (n = 5). These interviews provided accessible and safe spaces for participants to share their experiences and perceptions. An 'open ended' (Gall et al. 2003) format was adopted, presenting all questions in a conversational and informal manner, to allow maximum voluntary contribution and detail. For example, questions began with phrases such as, 'What are your thoughts on ..?' and 'In your opinion ..?'. Following this, naturally occurring probing questions (Gratton and Jones 2004) were asked to gain more detail. This format of enquiry allowed participants the liberty to express their experiences and opinions with minimal constraints and to self-navigate towards areas they felt significant (Braun and Clarke 2013). The interview was centred on determining the participants' perceptions of the nutritional priorities and challenges of elite female soccer players. The questions were created with the study aims in mind; however, it was difficult to base the questions on previous research due to a lack of qualitative studies conducted in elite female soccer players (Okholm Kryger et al. 2021). The interview was split into three domains: (1) 'Participant background and demographic', (2) 'Perceived impact of nutrition on performance with an emphasis on priorities and challenges', and (3) 'Female specific performance nutrition priorities and challenges, detailed in Table 3.1 (note, the full data set derived from domain 3 is not presented in the present paper due to scope). In order to determine the viability of the interview questions for use with athletes and stakeholders, pilot interviews were conducted with two female players and three staff members, which were not included as part of the final analysis. The wording of some questions was adjusted following these trial interviews based on feedback, to make the questions more accessible to all.

Analysis

All interviews were transcribed verbatim and Nvivo10 software (QSR International, London, England) was used as a data management tool to store data. Primarily an inductive approach was taken, in order to prioritise the voices of those with experience in elite female soccer. The lead author identified meaningful segments of text based on the question domains. As part of the analysis process, these meaningful segments were subject to initial (open) coding (Saldaña 2021). Once this initial coding was complete, codes were revisited as part of a focused process to identify potential themes across the data, and to consider the research aim. Themes were subsequently developed over several iterations by the lead researcher. Through discussion with the research team, these themes were refined in order to provide a credible and trustworthy 'common thread' (Sparkes and Smith 2014), which is presented in the findings to come.

Rigour

In order to ensure credible and transparent perceptions of nutritional practices in elite women's soccer, several procedures were undertaken. These procedures aspired to add rigor whilst maintaining a coherent qualitative focus on understanding the subjective and multiple perspectives of the participants (Sparkes and Smith 2009; Smith and McGannon 2017). For example, interviews were conducted by a researcher trained in qualitative methods and experienced as a nutritionist in women's soccer. Mindful of their own subjectivities, interview questions were examined by a critical friend to ensure they were not leading. Pilot interviews were conducted to ensure questioning and probing were accessible to participants. A range of views from players, parents and staff were gathered. A critical friend (Smith 2018) who is detached from nutrition practices in elite sport was also used to check and challenge data analysis, theme generation and the presentation of selected quotes that come. The role of the critical friends is 'not to "agree" or achieve consensus, rather to encourage reflexivity by challenging each other's' construction of knowledge (Cowan and Taylor 2016). Consistent with this, the critical friend challenged the coding process and themes were refined over time to provide a credible account of participants' experiences.

Table 3.1. Player interview guide and aims – Wording adjusted for stakeholders (note, the full data set derived from domain 3 is not presented in the present paper)

Questions	Prompts	Aim

Domain 1: Participant background and demographic		
Can you tell me about your journey as a footballer so far?	Clubs, age started, setbacks, injuries.	Understand their background and experience.
How are training and matches going at the moment?	Club schedule, international schedule, any challenges.	Understand their history in terms of standard and training schedule.
Can you tell me about what kind of support you currently get from staff?	Size of staff team, sport science, nutrition, part/full time, internal/external.	Understand the level of support they have had and responsibility for nutrition.
Domain 2: Perceived impact of nutrition on performance - priorities and challenges		
Have you received much nutrition advice throughout your career so far?	Who from? Was it useful? Method of support.	Understand their experience of nutrition support.
Has your attitude towards nutrition or nutrition knowledge changed over time?	What has impacted this?	Understand their perceptions of the importance of nutrition.
What are your thoughts on nutrition and whether it impacts performance?	What areas? To what extent? Matches, training?	Understand what areas they perceive nutrition to impact and why.
Can you tell me about your approach to these areas of performance?	Strategy in place? Optimal? Barriers?	Understand their level of knowledge and practice.
Have you experienced any nutrition challenges?	When? Why? Areas of performance?	Understand what nutritional challenges they face and why.
Is there any support you have received to overcome these challenges that has been helpful?	Why? What else would be helpful?	Understand what they perceive to be helpful.
Domain 3: Female specific performance nutrition priorities and challenges		
Do you think any of the priorities previously mentioned are more of a challenge because you are female?	If so, why? Physiological or cultural?	Understand if their previous perceptions are female specific.
Do you think contraceptive status or the menstrual cycle impacts performance?	Their status? Why? Tracking, area of performance.	Understand if they perceive/experience a performance impact of the menstrual cycle.
Do you think this impacts your nutrition at all?	Positively or negatively? Appetite? Intentional?	Understand if and how nutrition habits/needs are impacted.
In your opinion, is support in this area is necessary?	Any experience? What is helpful? Who should be responsible?	Understand what they think support should look like in reality.

3.4. Results and findings

Following data synthesis and analysis, four themes were established that present a narrative of the nutrition culture within elite women's soccer. These themes are presented below, with player and stakeholder quotes presented verbatim to support the narrative.

Theme one – fuelling is important but under-fuelling is common

When initially asked to identify performance nutrition priorities for elite female soccer players, participants across all groups identified a range of components such as fuelling, body composition, hydration, supplementation and recovery. Fuelling (the act of consuming enough energy to meet energy demands) emerged as the most consistent theme, where a specific focus was placed on adequate CHO intake for match day performance. Indeed, most players (n = 9/12) identified the importance of fuelling for match day performance. One player specifically discussed the positive impact she has felt on her performance since being made aware of the importance of CHO intake. This awareness came as a result of receiving more nutrition support at both club and international level.

> ***Player 1:*** One of the best examples from last season I can give is the FA Cup Final when we went to extra time. I think a lot of things were quite fresh, ideas and strategies, so I think that we did really well in that game. We covered a lot of ground and I don't think you can do that unless you are doing things correctly prior to the game and then during the game.

Whilst 'fuelling well' was identified as facilitative to performance, 'under-fuelling' (i.e., the act of consuming insufficient energy and CHO to meet energy demands) was also identified by some players as having a negative impact on match day performance, as well as the long-term development and performance of team mates. This view was shared by an experienced international player, who has grown to understand the importance of fuelling, particularly in the context of a tournament with congested fixtures, since working with a full-time nutritionist.

> ***Player 2:*** An endurance runner, they probably know that they have to eat a sh*t load of carbs but I do believe in football we're still not quite switched on with it. We play for 90 minutes, it's a long time. It's not a 100m sprint, you know, it's 90 minutes and I think it's making females understand that, you can still play at a top level of course, 100%, but you can't maintain it for game 1, game 2, game 3, game 4, you know. There's a reason why we get to semi-finals and we can't quite get over the line, you know, it's not a coincidence. People will bring up the 'they're not fit enough', no, that's not the case, we are fit enough, we play in the top league in the world, you know. WSL is one of the most competitive leagues in the world, like, there are other things that we need to be focussing on apart from that. Is it the fact that you're eating salad the day before a game? You know, you've been eating salad for two weeks now on camp, you know, so I think it's just normalising the conversation, making people aware you have to eat, you can't not eat.

Fuelling was also identified as a nutrition priority by the majority of (but not all) coaches (n = 5/9), parents (n = 6/9), sport scientists (n = 5/7) and medical staff (n = 4/5). As expected, all nutritionists (n

= 5/5) identified fuelling as their ‘number one’ performance priority. However, despite such recognition from both players and stakeholders, there were contrasting views and an apparent lack of understanding of what fuelling should look like in practice i.e., what to eat and when, thereby highlighting a gap between knowledge and practice. For example, most players and stakeholders (except for nutritionists) did not understand the importance of consuming higher levels of CHO the day before a game, a day of the week that is often referred to as match day minus one (MD- 1). Rather, there seemed to be a misconception amongst participants that the ‘pre-match meal’ (i.e., the last meal consumed by players before kick-off) was of greater importance than the CHO intake consumed on MD-1. One player astutely recognised the prevalence of misconceptions about match day nutrition amongst her teammates.

> ***Player 5:*** Some of my team-mates, they read this theory, but I have no idea where, where they said eating salad is the new having carbs before a game.

Nutritionists were the only participant group who consistently recognised the importance of CHO intake on MD-1, and they were readily aware that this is an area where player knowledge and implementation is lacking.

> ***Nutritionist 1:*** I haven’t been part of a squad where every single player could genuinely tell you what their consistent MD-1 fuelling plan is.

From their experience, players do not get close to achieving the recommended CHO intake on MD-1, typically cited as ranging between 6–8 $g.kg^{-1}$ BM (Collins et al. 2021).

> ***Nutritionist 2:*** We started to do some lower-level analysis of the players, picked a couple of players out initially, did some analysis and it became quite clear that the carbohydrate intake of the team was likely to be certainly less than 10 g per kilo. In fact, none of them were anywhere near 6 g per kilo.

This confusion surrounding the practices inherent to match day fuelling was particularly apparent in coach interviews. For instance, two coaches appeared to be incorrectly concerned that consumption of high CHO foods on MD-1 may have an adverse impact on performance.

> ***Coach 1:*** They obviously like their toast the night before a game and I’m no expert but I’m sure that’s not the greatest preparation.

In addition to concerns regarding the impact of under-fuelling on performance, several stakeholder groups also extended this discussion to health and wellbeing outcomes. One club doctor (*Medical Staff 5*) provided an example of a player who suffered with secondary amenorrhea, who 'used to have, like, a banana in the morning and the first meal that she had was at about 4 o'clock in the afternoon.' *Player 11* also shared her personal experience of secondary amenorrhea. When she subsequently received nutrition and medical support, she later associated under-fuelling as the cause.

> ***Player 11:*** I was increasing my training load and then I lost my period. I was then like, why have I? And then that made me realise 'oh, I need to focus on nutrition as well as football because it is just as important.

Impaired menstrual health was also reported by *Sport Scientist 7*, stating that 'There's also players who have never actually had a cycle while I've been at the Club'. Furthermore, some medical staff and nutritionists were particularly concerned about the potential impact that under-fuelling for performance could have on chronic low EI and therefore, injury prevalence.

> ***Medical 5:*** They could become lethargic on the pitch, they may not be able to meet the demands of training, the demands of the matches. It could also put them at an injury risk, you know, if they're fatiguing quickly because they're not having enough food, they're not having enough nutritional intake and then the muscles become tired quicker, they start to become tighter and they then run the risk of injury.

Theme two – Carbohydrate confusion, do carbs make me fat?

As an extension of the discussion regarding the impact of under-fuelling, some participants perceived that players may under-fuel daily due to an intentional reluctancy to consume CHO. Some staff members even referred to this as a 'fear of CHOs' and also identified players as being 'carb-phobic'.

> ***Coach 3:*** When players are going through natural growth changes, you see them from a developmental point of view, changing body shape. Sometimes they feel that 'oh well I can't be eating extra carbs because carbs mean fat.'

Three players addressed this directly, all of whom believed that consuming 'too much' CHO makes you gain FM.

> ***Player 4:*** It was quite difficult for me to actually transition into eating, like, more carbs and more calories because I was scared of putting weight back on. Sometimes I just don't want to eat carbs because I know they will make me fat.

This sentiment was also reported by nutritionists, with two participants giving examples of players not wanting to consume a 'protein shake' with added CHO after matches or strength and conditioning sessions. Such practices conflict with the well documented role of post-exercise CHO intake in facilitating muscle glycogen re-synthesis (Burke et al. 2017).

> ***Nutritionist 4:*** The players don't want a mixed protein shake, they just want a protein shake because the mixed protein shake has got too much carbs in and it's, like, 'wow, they're not willing to have carbs after a game, that's pretty scary' I guess . . . The fact that they're worried about some carbohydrate powder in a protein shake because they think it will make them fat is quite a scary thing. And so they might not be recovering quickly or as efficiently because of that.

Despite the importance of CHO intake on MD-1, there was also a perceived reluctance from players to adhere to this strategy.

> ***Sport Scientist 1:*** I've had conversations with players where I'm like 'you need to have carbs at least on match day minus one, making sure you're fuelling for the game ahead' and they're a bit reluctant to want to take on that amount of carbs. Like 'I don't like eating that many carbs, that's not something I do.'

The fact that it is 'not something they do' is also of interest here, as the language suggests a reluctancy to change. As well as being CHO specific, a fear of gaining weight also manifests itself as a general fear of consuming too much food.

> ***Sport Scientist 7:*** This is basically a quote from a player she's 'afraid to eat more', you know, she was shown how much she needed to eat on a training day and she was, like, 'no I don't want to eat that much'. She had concerns.

Staff stakeholders also believe that players are often confused when told to consume more food or CHO, with some staff members believing that players are receiving 'mixed messages around body composition and fuelling' (*Sport Scientist 2*). This confusion was identified further by a goalkeeper coach working with an international senior team. *Coach 9* experienced this following the first appearance of a nutritionist on an international training camp.

> ***Coach 9:*** Working with *National Team*, bringing in the nutritionist and saying, 'well we need to eat more' and, you know, they used to stand on the scales and say 'well I weigh this and

that's my ideal body weight and I've always been that since I as 16 or 17' and then all of a sudden you're asking them to eat more food.

These misunderstandings are also present in parents, with *Sport Scientist 7* being 'asked by a parent if her daughter, aged 18, should go on a low CHO diet.' Such mixed messages, misconceptions, and the 'intentional' reluctance to consume sufficient CHO are all indicative of a culture of CHO confusion, the result of this lack of education has been documented as leading to both negative health and performance outcomes, due to the complex interplay between physiological and psychological components of REDs and the female athlete triad (Langbein et al. 2021).

Theme three – Skinfold culture, body image issues and social media pressure

Themes one and two present a narrative surrounding the role of fuelling as a performance nutrition priority. However, the challenge to fuel whilst also promoting a desirable body composition (and body image) also emerged as a cause for concern amongst participants. Interestingly, over half of the coaches (n = 6/9) interviewed specifically mentioned 'body composition' as an example of how nutrition can affect performance, whereas this thought was not as prevalent amongst other groups e.g. players (n = 3/12), parents (n = 2/9), medical staff (n = 1/5), nutritionists (n = 2/5) and sport scientists (n = 2/7). Coaches appeared to value players presenting with low levels of body fat, in order to optimise their physical performance.

> ***Coach 5:*** I think generally you'd want players to be bit leaner, so have more muscle mass and not as much, erm, body fat percentage just in terms of the physical objectives that it allows them to then accomplish.

In contrast, all other staff members were more concerned with the challenge of players losing too much body fat or not gaining enough BM, with nutritionists identifying the need for players to 'find their sweet spot' (*Nutritionist 4)* when it comes to levels of body fat. Although only three players specifically mentioned 'body composition' as a performance priority, it was 'body image' that presented as a more consistent challenge experienced by players. The consequences of players being consciously aware of how they look (and associated feelings of body dissatisfaction) may potentially present as mental health problems.

> ***Player 4:*** I just feel like with women, weight is a touchy subject . . . .That's just how it's always been and I feel like it will always be this way, just because of the society we live in and especially with, like, all social media and stuff, the last thing you want is to feel is fat.

The assessment of players' body composition is frequently evaluated using a combination of weighing scales (to measure BM) and skinfold callipers (to estimate body fat), often with a frequency of every 4–8 weeks. The perceived pressure to meet body composition targets was an important feature of the discussions surrounding body image. *Player 3* was one of many players (n = 7/12) who reported struggling with the 'skinfold culture'.

> ***Player 3:*** I think for me, personally, it was skinfolds. So, knowing that you're getting your weight checked every 8 weeks, knowing that you were in the red zone, amber, green, it was almost, like, 'well if I'm in red now, how am I going to get into green? The only way to get into green is not eating, eating minimal', like, I think that is the main thing why women players struggle is because we constantly get weight checked and skinfolds.

The challenge to simultaneously fuel whilst also meeting body composition targets was reported as a contributing factor to the transient episodes of under-fuelling that were evident in Themes 1 and 2.

> ***Player 2:*** I feel, as women, we're so conscious about our weight, how we look, how our body comps are, like, it's incredible actually, like when you actually think about it, the stress that people go through when they know that someone's coming in to take their body mass. You can just see it on people, like, some people don't eat the day before because they're so worked up about it and I think then you see what effect it has.

In addition to external pressure to meet objective targets, participants reported that comments from stakeholder groups (e.g. coaches, parents etc.) can also negatively impact a player's perception of their body image.

> ***Coach 4:*** Her mum had made a throwaway comment 'oh you look like one of those East European shot putters' and I think she took this quite bad and worked so hard but ate so little during the break and came back something like 10 kilos underweight.

Participants also discussed the role that social media can play in influencing players' perceptions of body image. Indeed, in accordance with the increasing profile of the women's game, players' personal online following are also increasing, the result of which may manifest as further negative comments akin to 'trolling'.

> ***Sport Scientist 7:*** Pressures on social media, being perceived to have to be a certain way, that comes with it's own remit of pressures. We had a player in the Academy quite recently and she

was quite open about some of the negative comments that have been put her way on social media.

The 'desired ideal' women's body that is often portrayed on social media platforms may also not align to the body composition that is considered conducive to athletic performance. In this regard, medical and sport science staff identified that players may be concerned about putting on *too* much muscle. This was also identified by parents who are aware that their daughters are increasingly conscious of 'looking different' to their friends.

> ***Sport Scientist 5:*** I've also noticed players don't want to look athletic in the gym as well so then you're trying to get them to increase protein and increase muscle mass obviously for performance and injury prevention that you struggle to get them to do, erm, a lot of gym

3.5. Discussion

Using a qualitative approach, the aim of the present study was to explore player and stakeholder perceptions on the role of nutrition in supporting player development and performance. Although 'fuelling' was identified as a critical nutritional priority, our data demonstrate that considerable confusion and misconceptions exists amongst players and stakeholders regarding the theoretical underpinning and practical application of current nutritional guidelines for soccer. Importantly, the application of such guidelines is also hindered by prior beliefs on the perceived impact of CHO on body composition. Furthermore, a 'fear of getting fat' also arose as a result of external pressures from key stakeholders (e.g., coaches, support staff and parents), social media and the culture surrounding measurements of body composition, all of which are likely exacerbated by the lack of professionally accredited nutrition staff overseeing the provision of nutrition support. When taken together, our data provide a platform for which to develop organisational, stakeholder and player-centred educational and behaviour change interventions that strive to promote a positive performance nutrition culture.

To address our aim, we interviewed a cohort of 47 participants comprising individuals actively involved at the highest level of club and international soccer in England. Although we acknowledge that our present sample are limited to those presently working in England, our data provide a novel insight into the current nutritional challenges within the women's game. Many participants, especially players, sports scientists, and nutritionist, identified fuelling as a critical factor for both performance and health. Amongst these participants, discrepancies in theoretical knowledge and practical awareness of strategies manifested in contrasting views on the timing (i.e., MD-1 versus the pre-match meal), quantity of foods required to prepare for match day, particularly regarding the role CHO. The apparent lack of knowledge and common misconceptions (especially in relation to CHO guidelines) also extended to fuelling for training days, where the concerns associated with under-fuelling also manifest as health outcomes associated with the female athlete triad and REDs models e.g. impaired menstrual health, disordered eating, injury risk, underperformance etc. As such, our data support the need for player, parent, and staff education (e.g. coaches) on the importance of fuelling adequately for both physical and mental health as well as performance outcomes (Mountjoy et al. 2018).

With this in mind, the COM-B framework and behaviour change wheel (Michie et al. 2011; Atkins and Michie 2015) provides one such model for which to begin to formulate behaviour change interventions. For example, in those cases where under-fuelling is *unintentional* (Kerr et al. 2006), there were a variety of sources of behaviour that can be made as part of a behavioural diagnosis. In this regard, our data allude to a lack of psychological capability i.e., players and stakeholders are initially unaware of the current nutrition guidelines for soccer (Collins et al. 2021) and/or physical capability (e.g. players lack the basic cooking skills required to prepare the desired food) that may prevent the desired behaviour that is required to consume sufficient daily CHO intake. However, numerous behaviours were reported that relate to a lack of a physical opportunity to engage in optimal nutrition practices, as evident by the lack of on-site food provision described by some players. Such lack of physical opportunity is also likely underpinned by the lack of social opportunity (i.e., cultural norms) associated with the specific environment, as evidenced by language such as '*we would get whatever was left over from the men*' when eating at the training ground, as well as the apparent lack of specialist nutrition provision in terms of professionally accredited staff. These findings appear to agree with sentiments within the professional women's game that there is an *acceptance* of unsatisfactory working conditions (Culvin 2019), with players expecting to be grateful for the opportunity despite this inadequacy (Culvin 2021). When taken together, it is apparent that there are numerous intervention functions (e.g. environmental restructuring, education, modelling, training etc) that could underpin a cultural change in the nutrition provision currently provided to women players, all of which would seek to improve the unintentional under-fuelling that has previously been reported by us (Morehen et al. 2021) and others (Moss et al. 2021). At the very least, an initial starting point could be the mandatory regulation that all professional clubs should employ a full-time professionally accredited sports nutritionist or dietician in order to enhance the overall quality of service provision currently delivered to female players. Furthermore, due to physiological differences between men and women and particularly the importance of normal menstrual function (McNulty et al. 2020), a staff member who has female-specific knowledge would also be beneficial to support and educate all players and staff members. Indeed, the lack of dedicated support staff may result in players seeking education elsewhere (e.g. social media), the result of which likely exacerbates misconceptions surrounding the role of CHO intake on performance and body composition (i.e. 'eating salad is the new having carbs before a game'). The lack of expertise on female specific health amongst staff members may be especially problematic in those instances where players present with symptoms related to the female athlete triad and REDs. Despite the recent increase in professionalism of the women's game in England with the introduction of the WSL in 2018, it is apparent that the provision of specific sport science support services (i.e. nutrition) has not developed in accordance with the progression of players and staff to full-time employment.

In contrast to unintentional under-fuelling, we also report evidence of *intentional* under-fuelling where sentiments surrounding the practice of eating CHO were communicated as 'that's not something I do'. Upon further probing, it became evident that 'CHO fear' exists where players apparently associate CHO intake with 'getting fat'. Such intentional episodes of under-fuelling and fear of getting fat seems to be exacerbated by the frequent assessment of body composition where players are banded in skinfold targets that are classified as red, amber or green. The concern with 'how am I going to get into green' is thus representative of reflective motivation (according to the COM-B model) where the player modifies their behaviour on the belief of what is good or bad. The practice of avoiding CHO intake has also been previously reported in female soccer players in the belief that it may promote a favourable body composition (Culvin 2019, 2021). Although players reported that they understood the benefit of measuring body composition, they did comment on the 'unhelpful' nature of frequency of measurement, setting targets and the lack of application to performance (i.e. how does it affect my performance on the pitch). In consideration of key stakeholders, it is interesting that coaches initially identified body composition as the priority area of where nutrition can affect performance. In this regard, it is noteworthy that players also report incidences where managers/coaches had been issuing BM targets, the result of which is likely to directly impact player's behaviour based on the perceived outcomes surrounding team selection. From a behaviour change perspective, the apparent 'skinfold culture' is therefore representative of an environment where the social opportunity (i.e. cultural norms) to engage in optimal fuelling practices is not aligned to the desired behaviour.

The external pressures associated with social media and both online and stakeholder incidences of body disparagement (e.g. from parents or coaches etc) may also contribute to intentional episodes of under-fuelling. Such issues have been previously reported in weight-sensitive sports (Mosley 2009; Hockin-Boyers et al. 2020). For example, gymnasts who received disparaging comments about their bodies or instructions to lose weight had significantly more disordered eating patterns than those who had not received such comments (Kerr et al. 2006). The rise of social media also results in external pressures 'to look a certain way' and players reported incidences of peers who were 'more obsessed with how they look than their football'. The issue of body image in sport has, of course, been researched extensively and the solutions are likely complex at both an organisational and individual level (Berry and Howe 2000; Ackerman et al. 2020). Nonetheless, it is suggested that player focussed educational strategies should begin during adolescence to promote healthy eating behaviours at a young age (Lieberman et al. 2001; Tiggemann 2001). Additionally, the education of coaches should also be prioritised given the role of the coach in influencing player development (Sabiston et al. 2020; Carson et al. 2021). Such education interventions should also address the heighted pressure arising from social media given that new media formats can result in greater critique of athletic bodies (Kohe and Purdy 2016). Collectively, our data suggest that targeted interventions addressing player's reflective and automatic motivation associated with specific nutritional behaviours may help to reduce feelings of body dissatisfaction and the potential to develop eating disorders. Stakeholder education addressing that 'women's bodies are different to men's' (Clarkson et al. 2020) may also help to improve the cultural norms and practices associated with skinfold assessment and 'generic' target setting. Indeed, carefully monitored assessment of body composition may actually function to *improve* overall player health, owing to the fact that making decisions about weight-loss based on appearance alone can also lead to body dissatisfaction, disordered eating and eating disorders (Griffin and Harris 1996; Rhea 1998).

Despite the novelty of the present data, the present paper is not without limitations. Indeed, we readily acknowledge 'generalisability' as a limitation of the study, given that our sample does not represent *all* elite female soccer players. The use of purposeful sampling requires that the reader does not generalise from the sample, rather they should critically reflect on the relevance of the findings within their context (Smith and McGannon 2017). Furthermore, as all interviews with players aged 16–17 were conducted with a parent present (in order to meet safeguarding guidelines), this may have had an impact on the willingness of these players to share their perceptions and experiences. Lastly, a further limitation was the broad nature of the questioning within study. Although this allowed the interviews to be participant lead, further research should be conducted to explore each of the presented themes in greater depth.

Conclusion

In summary, our data provide a novel insight into the culture surrounding nutrition and body composition within elite women's soccer. Importantly, we observed confusion and contrasting views on the theoretical and practical awareness of nutritional guidelines for soccer. Although unintentional episodes of under-fuelling are likely related to a lack of theoretical knowledge or ability to translate this into practice, intentional incidences of under-fuelling are more complex and appear related to cultural norms and external pressures associated with body composition and body image. When taken together, our data provide a platform for which to develop organisational, stakeholder and player-centred educational and behaviour change interventions that strive to promote a positive performance nutrition culture.

Chapter Four

Study Two

A Qualitative Analysis of Player and Stakeholder Perceptions of Menstrual Health Support within Elite Female Soccer

This paper was published in Science and Medicine in Football (2022):

McHaffie, S. J., Langan-Evans, C., Morehen, J. C., Strauss, J. A., Areta, J. L., Rosimus, C. & Morton, J. P. (2022). Normalising the conversation: a qualitative analysis of player and stakeholder perceptions of menstrual health support within elite female soccer. Science and Medicine in Football, 6(5), 633-642.

The findings from this paper were also presented orally at:

LJMU Football Exchange Women's Network symposium, Liverpool, England, January 2023

Oral presentation at the European College of Sport Sciences (ECSS) 27th annual congress, Sevilla, Spain, July 2022.

4.1. Abstract

Purpose*:* This qualitative study explores player and stakeholder perceptions of menstrual health support in elite female soccer.

Methods*:* Semi-structured interviews were conducted with 47 participants including players (n = 12), parents (n = 9), coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5) and medical staff (n = 5).

Results: Via thematic analysis, data demonstrate that elite female soccer players experience a range of physical and psychological symptoms primarily at the onset of and during menses (as also perceived by stakeholders), with most participants perceiving these symptoms to impact performance. Nonetheless, menstrual health support is perceived as minimal and although players have their menstrual status tracked, they report little understanding as to why or how this information is used. This confusion was also present among stakeholders, often as a result of uncertainty about the evidence supporting the need for menstrual health support. The perceived lack of support may also be reflective of a culture where conversations about the MC are not normalised. Overall, this may result in failure to identify and treat menstrual irregularities despite non-coaching staff members perceiving them to be common amongst players.

Conclusion: These data support the need for individualised support based on the lived experiences of individual players and support staff. Furthermore, our research identifies the need for organisational, stakeholder, and player centred education programmes (led by experts in female athlete health) that create an environment where players receive personalised menstrual health support.

4.2. Introduction

The effects of the distinct phases of the MC on exercise performance are currently a hot topic amongst athletes, support staff, and researchers within elite sport. Although the fluctuations in ovarian steroid hormones (i.e. oestrogen and progesterone) that occur throughout the MC are well characterised (Davis et al. 2017; Landgren et al. 1980; Owen et al. 1975), the impact of such changes on the function of various physiological systems is complex and not yet fully understood (Chrousos et al.1998; Ansdell et al. 2019). Furthermore, the potential impact of such changes on exercise performance is also complicated by the magnitude of physical and psychological symptoms that are experienced at the individual level (Martin et al. 2018). Indeed, although a recent meta-analysis concluded that exercise performance may be trivially reduced in the early follicular phase of the MC (McNulty et al. 2020), the researchers specifically highlighted that a personalised approach should be adopted when managing the impact of the MC on exercise performance. Importantly, the quality of the evidence presented by McNulty et al. (2020) was rated as "low" (due to methodological limitations of the studies included) and measures of exercise performance were limited to markers of endurance or strength capacity, some of which have limited relevance to team-based sports such as soccer.

In relation to soccer (albeit in amateur players), Dos Santos Andrade et al. (2016) reported that hamstring-to-quadriceps peak torque strength ratio was lower during the follicular phase compared with the luteal phase, the outcome of which could lead to increased risk of lower limb injury (Hewett et al. 2008). In addition, Julian et al. (2017) also reported that amateur players' performance in the Yo-Yo intermittent endurance test was reduced during the mid-luteal phase when compared with early follicular phase. In relation to elite level match play, the same researchers recently reported that high-intensity running distance was greater in the luteal phase compared to the follicular phase (Julian et al. 2021). However, it was concluded that interventions at a group or team-based level do not seem necessary to optimise performance, as MC phase does not contribute largely to changes in physical performance in comparison to the potential effects of individual and match variation. With regards to symptomology, our research group (Parker et al. 2021) recently conducted an audit of players in the English WSL and reported that of the 72% of players surveyed who were not currently using hormonal contraceptives, 74% reported negative symptoms with 4% choosing to abstain from training as a result. Furthermore, Reed et al. (2021) also reported that in a cohort of elite players from the WSL, 100% of the group perceived that the MC negatively affected their performance, with the most prevalent occurrence during menses. When taken together, such data suggest that soccer-specific performance may also be negatively affected by the MC and hence, strategies to manage menstrual health support (at an individual level) are therefore warranted.

In addition to understanding the players' lived experiences, an important step towards personalised menstrual health support is to ascertain the current understanding and perceptions of key stakeholders that may be involved in the management and delivery of such processes. Such stakeholders are likely to include coaches, medical doctors, sport science staff, and parents, all of whom can impact the environment and culture around menstrual health support. For example, in a study conducted on elite rugby players, Findlay et al. (2021) emphasised the need for support staff to initiate conversations with female athletes and to "normalise" conversations surrounding the MC. However, Armour et al. (2020) previously reported that female athletes do not readily discuss the MC with their coaches, especially in those instances where the coaches are male, thus highlighting the challenge for practitioners to both support the development of sporting performance whilst also respecting athletes' rights to privacy and control of their own bodies. The athletes in that study also described that their training load was never manipulated as a result of symptoms associated with the MC, despite reporting perceived negative impacts on speed, agility, and strength qualities. Such data clearly highlight the requirement for more aligned thinking between athlete and support staff in order to optimise the management of menstrual health support in an ethical way.

With this in the mind, the aim of the current study was to explore both player and stakeholder perceptions of the menstrual health support currently provided in elite women's soccer. It is anticipated that the present data may serve as a stimulus to better inform the creation and delivery of personalised menstrual health support for players.

4.3. Methods

To explore player and key stakeholder perceptions of menstrual health support, we undertook a qualitative investigation. Qualitative research provides a route to understand the experiences and perceptions of individuals within complex social environments (Sparkes & Smith, 2014). As such, a qualitative approach was deemed an effective way to understand menstrual health experiences across key individuals in elite female soccer (e.g., athletes, parents etc.). The researchers adopted a relativist ontology which recognises that individuals experience their world subjectively (Smith and McGannon, 2018). This position influenced the sampling, data collection, and data analysis procedures that are described below, and which sought to provide a credible, insightful, and transparent account of menstrual health support provided in elite women's soccer.

Sample

To gain multiple detailed insights into the perceptions of menstrual health support, players, parents, and staff in varying roles were purposefully invited to take part in the study. This approach is comparable to the methodology in Study One and previous qualitative explorations in professional sport (Martin et al. 2018; Logue et al. 2021), which value those who experience a phenomenon as best placed to elucidate it, while also enabling the development of a broad understanding of the soccer context in question. The inclusion criteria for the purposeful sample included those above 16 years old and who had experiences of elite female soccer in England within one of the roles (e.g., player, parent, coach etc.). To recruit this sample, some participants were contacted through gatekeepers of their respective governing bodies via an email including details of the study and participant information details. Convenience sampling was also used to contact other participants who met the inclusion criteria. Consistent with the qualitative approach that eschews a-priori sampling size calculations, the sample size was determined by the analysis, with recruitment stopping for each participant group once saturation was experienced within the data i.e., when no new insights were derived from interviews, sampling was ceased. All players (n = 12) competed in elite women's soccer, representing teams in the WSL (n = 9) or The FA Women's Championship (n = 3). Some players also competed at senior (n = 4) and youth (n = 7) international level at the time of the study. All the players regularly experienced menstruation and were excluded if they were currently pregnant or using hormonal contraceptives. Parents (n = 9) were parents or guardians who currently live with an elite female soccer player, aged 16-18 years. Staff members invited to the study all currently work in varying roles in professional female soccer full time, at club level or international level. These roles included technical coaches (n = 9), sport scientists (n = 7), nutritionists (n = 5), and medical staff (n = 5). Together, this sample enabled the generation of in depth and varied understanding of perceptions in elite women's soccer. Ethical approval was granted by the research ethics committee of Liverpool John Moores University (21/SPS/029) and as a condition of this, further details of the participants are not provided to avoid direct identification. All participants provided verbal and written informed consent before completing the interview, including child assent and carer consent forms for those under the age of 18 years.

Data Collection

As part of a larger project, data was taken from semi-structured interviews (36 ± 18 mins in length) that were conducted with all participants using Zoom (Zoom Video Communications, California, USA) and were audio-recorded. These provided accessible and safe spaces for participants to be interviewed and share their experiences and perceptions centred on menstrual health support in elite female soccer. The questions were created with the study aims in mind and were based on previous research (Logue et al. 2021; Armour et al. 2020; Findlay et al. 2020; Okholm et al. 2021; McNulty et al. 2020***).*** The interview was split into three domains: Domain 1) 'Participant background and demographic'; Domain 2) 'Perceived impact of nutrition on performance with an emphasis on priorities and challenges'; Domain 3) 'Female specific performance nutrition priorities and challenges', as detailed in Table 4.1. An 'open ended' (Gall et al. 2003) format was adopted, presenting all questions in a conversational and informal manner, to allow maximum voluntary contribution and detail. For example, questions began with phrases such as, "What are your thoughts on...?" and "In your opinion...?". Following this, naturally occurring probing questions (Gratton and Jones 2004) were asked about the answers provided in order to gain more detail. This format of enquiry allowed participants the liberty to express their experiences and opinions with minimal constraints and to self-navigate towards areas they felt significant (Braun and Clarke, 2013).

Analysis

All interviews were transcribed verbatim and Nvivo10 (QSR International, London, England) was used as a data management and storage tool. The full data set derived from Domain 2 is not presented in the present paper but was included in Study One. Primarily an inductive approach was taken to explore data from Domain 1 and 3 of the interviews, which were directly relevant to the aim of this study. In these domains and as part of the analysis process, the lead author identified meaningful segments of text, which were subject to initial (open) coding (Saldaña, 2021). Once this initial coding was complete, these were revisited as part of a focused process to identify potential themes across the data, and to consider the research aim. Themes were subsequently developed over several iterations by the lead researcher. Through discussion with the research team, these themes were refined in order to provide a credible and trustworthy ‘common thread’ (Sparkes & Smith, 2014), which is presented in the findings to come.

Table 4.1. Player interview guide and aims – Wording adjusted for stakeholders (note, the full data set derived from domain 2 is not presented in the present paper)

Questions	Prompts	Aim
Domain 1: Participant background and demographic		
Can you tell me about your journey as a footballer so far?	Clubs, age started, setbacks, injuries.	Understand their background and experience.
How are training and matches going at the moment?	Club schedule, international schedule, any challenges.	Understand their history in terms of standard and training schedule.
Can you tell me about what kind of support you currently get from staff?	Size of staff team, sport science, nutrition, part/full time, internal/external.	Understand the level of support they have had and responsibility for nutrition.
Domain 2: Perceived impact of nutrition on performance - priorities and challenges		
Have you received much nutrition advice throughout your career so far?	Who from? Was it useful? Method of support.	Understand their experience of nutrition support.
Has your attitude towards nutrition or nutrition knowledge changed over time?	What has impacted this?	Understand their perceptions of the importance of nutrition.
What are your thoughts on nutrition and whether it impacts performance?	What areas? To what extent? Matches, training?	Understand what areas they perceive nutrition to impact and why.
Can you tell me about you approach to these areas of performance?	Strategy in place? Optimal? Barriers?	Understand their level of knowledge and practice.
Have you experienced any nutrition challenges?	When? Why? Areas of performance?	Understand what nutritional challenges they face and why.
Is there any support you have received to overcome these challenges that has been helpful?	Why? What else would be helpful?	Understand what they perceive to be helpful.
Domain 3: Female specific performance nutrition priorities and challenges		
Do you think any of the priorities previously mentioned are more of a challenge because you are female?	If so, why? Physiological or cultural?	Understand if their previous perceptions are female specific.
Do you think contraceptive status or the menstrual cycle impacts performance?	Their status? Why? Tracking, area of performance.	Understand if they perceive/experience a performance impact of the menstrual cycle.
Do you think this impacts your nutrition at all?	Positively or negatively? Appetite? Intentional?	Understand if and how nutrition habits/needs are impacted.
In your opinion, is support in this area is necessary?	Any experience? What is helpful? Who should be responsible?	Understand what they think support should look like in reality.

Rigour

In order to ensure credible and transparent perceptions of support practices in elite women's soccer, several procedures were undertaken. These procedures aspired to add rigour, whilst maintaining a coherent qualitative focus on understanding the subjective and multiple perspectives of the participants (Sparkes & Smith, 2009; Smith & McGannon, 2017). For example, interviews were conducted by a researcher trained in qualitative methods and experienced as a nutritionist in women's soccer. Mindful of their own subjectivities, interview questions were examined by a critical friend to ensure they were not leading. Pilot interviews were conducted with two players and three staff members to ensure questioning and probing were accessible to participants. The wording of some questions was adjusted following these trial interviews. Through the sample, a range of views from players, parents, and staff were gathered. A critical friend (Smith & McGannon, 2017) who is detached from elite sport was also used to check and challenge data analysis, theme generation, and the presentation of selected quote. The role of the critical friends is 'not to "agree" or achieve consensus, rather to encourage reflexivity by challenging each other's' construction of knowledge (Cowan & Taylor, 2016). Consistent with this, the critical friend challenged the coding process and themes were refined over time to provide a credible account of these participants' experiences.

4.4. Results and Findings

Following data synthesis and analysis, four themes were established that present a narrative of participants' perceptions and experiences of menstrual health support within women's soccer. These themes are presented below, with player and stakeholder quotes presented verbatim to support the narrative.

Theme One – Symptomology is not "one-size-fits-all".

When initially questioned about the impact of the MC on performance, all players began by discussing symptoms in the few days before and during menses and reported a perceived negative impact on performance. Stomach cramps were reported more frequently than other symptoms (n = 9/12):

> ***Player 9:*** I feel like when I first come on it when I get cramps, I can't really run with cramps at all.

A range of other symptoms were also identified and reported by players, including sickness (n = 6/12), low energy levels (n = 5/12), tiredness (n = 5/12), muscle aches (n = 4/12), headaches (n = 4/12), lessened co-ordination (n = 3/12) and menstrual flooding (n = 3/12). Variability was also apparent in the severity of players' symptoms, with some players reporting that symptoms were perceived to be minor and manageable and others reporting severe symptoms, such as fainting and vomiting.

> ***Player 5:*** I am in a lot of pain some days and it is really tough but then some players might not even struggle, it might just kind of come up to their time of the month and they'll be fine.

Psychological symptoms were also identified by players (n = 7/12) that manifested as stress, lethargy, irritability, fragility, worry and low mood.

> ***Player 10:*** I think it is energy levels and I think it's also, like, you're probably more, like, stressed. I know I'm more stressed and more emotional, when I'm on my period, so I think it definitely impacts on the mental side of the game.

Symptoms of the MC were also reported to have a perceived impact on nutrition habits due to changes in appetite, with all participant groups sharing first or second hand experiences of nutritional habits being impacted by mood. A wide range of changes to habits occurred, with some players consuming greater amounts of varying food groups while others had less of an appetite, both of which could have a subsequent impact on training or match day performance.

> ***Player 2***: I could eat anything if I'm honest, like crisps, chocolate. I could probably sit on the sofa and eat a whole bag of Doritos and not even think about it. I think it's not just the what you want it's literally how much of it you could eat.

> ***Player 3:*** Obviously it's in your head that you might have pains so you want to comfort eat or whatever it is and I think it's in your head as well that when you, you've ate bad and you've gone on to the pitch you kind of, like, I know for me personally if I've eaten bad leading up to a game I go on the pitch thinking 'I'm gonna perform bad because I haven't had this in me, this, this, this', like, that's in your head as well.

Stakeholders also perceived that players experience a wide range in both the type and severity of physical symptoms. Although psychological symptoms were commonly reported by the players surveyed, this was less common amongst stakeholders (n = 6/35) with the majority of psychological symptoms being reported by parents (n = 4/9), who also identified stress, lethargy, irritability, fragility, worry and low mood.

> ***Parent 3***: I think she is definitely more tired beforehand, erm, and a little bit more irritable and maybe a little bit more fragile emotionally, erm, and I guess that often on the first day she can be a bit uncomfortable. So, I would think she probably wouldn't perform as well just before and on the first day.

As a consequence of the physical symptoms described previously, players and stakeholders (n = 36/47) reported that training and match day performance could be negatively affected in their opinion. This was primarily as a result of discomfort, due to the varying symptoms previously mentioned.

> ***Player 3***: I often just feel sick, like I could throw up at any time, so it makes training difficult when it is really bad.

> ***Parent 9***: I mean obviously if she wasn't feeling up to anything then she wouldn't attend training if things were that bad. She does suffer quite a lot with her period pains and things like that. It physically makes her be sick because that's what she's like. So on them sort of days if it was that bad then she would miss training.

Amongst all participants, the psychological symptom most commonly related to reduced training or match day performance was worry of fear of flooding or a lack of control of menses. Wearing white shorts as part of match or training kit heightened this worry and often led to distraction from performance.

> ***Player 3***: Like having white shorts on for example. The men would never have to think 'oh I've got white shorts on, what if something happens?'. Whereas women, it's constantly in your mind then I think that has an effect on your performance as well because you don't want to overstretch and then if you don't overstretch you might get injured. There's just so many things in your head that you have to think about when it's the time of the month.

Some stakeholders (n = 8/26) suggested a potential link between menstruation and injury risk, particularly regarding anterior cruciate ligament (ACL) injuries. A lack of co-ordination and the potential subsequent impact on injury prevalence was identified by both medical staff, sport scientists and parents.

> ***Parent 5***: She always used to say when she first started her periods that it didn't feel like her leg was connecting quite right to her brain, it was like there was an imbalance there. I was worried that injuries could occur more. I always seem to think that sometimes that goes hand in hand.

However, this notion was challenged by two medical staff members, one of whom believes that a lack of sport science support, alongside the increasing physical demands of the game is a more likely cause of higher rates of ACL injuries in female soccer players, rather than a particular phase of the MC.

> ***Medical 1:*** The culture that these players are living within has as much of an influence and arguably a lot more. Rather than the biological difference that might be due to their menstrual cycle changes and ligament laxity… So I find that quite fascinating, it's something that I feel quite passionate about, I think we're seeing early evidence that the more professional the sport and the longer the players have been in that profession, the ACL risk goes down pretty rapidly.

Three coaches did not perceive a link between MC symptoms and performance. Although they identified symptoms, they acknowledged that they have not witnessed a negative impact of these symptoms on performance.

> ***Coach 4:*** I probably haven't directly, to be honest. I don't know if we've just got a very well-educated group of girls who have got it under control. I've never really noticed a huge difference I must admit, definitely not.

In summary, the type and severity of physical symptoms experienced by players were inconsistent, with each player reporting indivdualised symptoms. As such, the perceived impact of MC symptoms on performance varied greatly. The perceived impact of MC symptoms on performance was acknowledged by most stakeholders, with the exception of three coaches. Furthermore, some staff members acknowledged that the MC may impact susceptibility to injury, whilst participants across all groups identified an impact on appetite, which may subsequently impact performance.

Theme Two – Confusion about the purpose of tracking menstrual status

The players also discussed the support they routinely receive to manage any perceived negative consequences associated with the MC. However, it was MC tracking per se (as opposed to support that is provided as a result of tracking) that was most commonly described. Regarding tracking, this data was typically collected as part of a daily wellness questionnaire collected by a club. For example, players "ticked a box" to say if they are currently menstruating, with the option of listing symptoms. However, amongst those players who are at clubs where this is tracked, most were confused about the purpose.

> ***Player 5:*** We just do a wellness form in the morning and we literally just tick if we are on or if we aren't and if we are on, what sort of symptoms we were having and that. That was it but nothing has ever been altered. So, if you ticked 'yes' there nothing is altered.

Although most players (n = 8/12) described having their MC tracked as part of a daily wellness questionnaire, some players (n = 4/12) had never experienced this at their club. One player identified this as frustrating, because she perceived that her MC impacts her performance.

> ***Player 8:*** No-one kind of really knows which obviously can never really help. Sometimes you can be having a bad session because of it and they can just think it's an off day, or a couple of off sessions.

One of the reasons that this group of players didn't perceive that MC tracking data is used to inform decisions, is that it is often not followed up with them individually, with *Player 3* describing data as being "*collected for the sake of it*". This frustration was something that *Player 3* had experienced at three different WSL clubs.

> ***Player 3:*** No, I think they're very poor with women. Every single club that I've been to, they track it. I know at *Current Club* now we do, it's similar to at *Previous Club* where you did your wellbeing, and you'd say 'are you on your period? Yes, no, whatever …', 'how many days have you been on?' but what actually happens next? Yeah, people are asked the question, but it's never followed through. I've never had a further conversation of 'oh you're on your period now, what, how do you feel?' or 'what, has it impacted?... What can we actually do about it? Nobody train while they're on their period? Do you know what I mean? I just don't know what comes next because I've never had that conversation.

Rarely, some players (n = 3/12) did share their experience of individual training load being manipulated based on menstrual status. This typically occurred following an "in-person" conversation, as opposed to being solely a result of data collected as part of daily wellness questionnaires. Interestingly, players who experienced this were very positive about the impact.

> ***Player 7:*** Generally, once we get to training, they ask us about it more in detail and then if they thought there was something that they thought you couldn't handle they'd probably decrease your load slightly, which is really helpful.

Only two players described tracking their menstrual status individually and they both used the same mobile phone application, designed primarily for the purpose of adapting nutrition to the MC. *Player 1* spoke about the perceived positive impact this had had on her performance, whereas *Player 2* was sceptical but used it as all players at the club are asked to do so.

Player 1: I log my menstrual cycle on an app and I think that that has really raised my awareness and stuff with regards to nutrition as in how nutrition and certain types of foods can help me during different phases and how that can then benefit your training.

Player 2: We've been educated to not eat certain meats in different phases. I, personally, don't ever feel a difference between eating chicken or steak. When I'm not supposed to eat steak, you know, I personally don't feel the difference.

Interestingly, all nutritionists that were interviewed shared similar views to *Player 2*, holding a belief that more research needs to be done before tailoring nutrition support to different phases of the MC. Nutritionists described the importance of educating players to listen to their bodies and not having a one-size-fits-all approach.

Nutritionist 4: The app might say 'eat this at this time in your menstrual cycle', which is fine but the evidence, isn't there for that for me… At the moment I haven't seen strong evidence to say 'this helps at that point'. It could say try and eat more oily fish at this time or take some fish oils, which anecdotally might help but for me I haven't really seen anything. I've seen newspaper articles around 'we've done this and eat different around the menstrual cycle' and I'm just like, well, what does that actually mean? What do you actually do to eat differently in the menstrual cycle? How much more of those foods are you seeing any benefit of or is it a kind of placebo?

Similarly, even those who were responsible for tracking the menstrual status of players (typically sport scientists) were often unsure of the purpose. For example, one sport scientist admitted to tracking menstrual status, despite believing that there is not adequate evidence that modifications based on menstrual status has a performance benefit.

Sport Scientist 6: It may have some influence on performance, but I look at it like what can we do about it? There's nothing, well, the way I see it, practically there's not a lot or there's next to nothing that you can do.

Although those who are responsible for tracking wellness data (typically sport science staff) were aware of the menstrual status of players, other staff members shared that they were often unaware of the this. Therefore, it is unlikely to be used for modulation of training load, nutrition practise, or further sport science support.

Coach 8: So they do a wellbeing questionnaire every morning and it's tracked in that respect but I'm, I would need to check with the sports scientists.

Contrary to menstrual status, contraceptive status was often not tracked by teams at all, with only two staff members (both medical staff) stating that they were aware of players' contraceptive status, with little understanding of whether it impacted performance.

Medical staff 2: It's such a difficult area to answer because I think there's still so many questions around, how contraception impacts women's performance, as it is still really only just being addressed.

Overall, data was often collected to track the menstrual status of players because it is thought to be important. However, a lack of understanding as to how this should be practically applied, (due to a lack of credible high-quality research) resulted in this data being collected but not being used to inform any performance decisions. This frustrated players and coaching staff who believed that more should be done to support players, although sport scientists, nutritionists and medical staff were generally not convinced that there is enough research for decisions to be made based on menstrual status, despite tracking it. However, some players (25% of the players sampled) shared a positive experience of having their training load adjusted, as a result of a one-to-one conversation with a staff member (i.e., individualised adjustments), which was greatly valued.

Theme Three – The MC is a taboo topic of conversation

Despite some players (n = 3/12) reporting perceived benefits from conversations about their menstrual status, other players reported having never discussed their MC with a staff member. Furthermore, of those who said they would discuss it, this was often infrequent and only initiated if necessary.

Player 10: I probably wouldn't talk to anybody at the Club. I'd probably talk to my mum first. At the Club, I mean I'd probably mention it to a coach but it would just generally be, like 'oh I'm having a bad day'.

Player 8: I've got quite a good relationship with my coaches so if anything was needed to be brought up I'd feel more than comfortable to bring it up, erm, obviously only if it was absolutely necessary.

Although it wasn't common, *Player 2* spoke positively about improved menstrual health support at her club as a direct result of conversations being normalised "from the top", with the head coach, who is female, making a concerted effort to drive a change in culture.

Player 2: It's a very open conversation that we have at *Club* and I think that's quite rare in a female sports place where you could go to someone and say 'oh my God, I'm a week late, what's going on, what do I need to do?' and, you know, there's always that feedback…It took, it did take a few months to kind of know that you were comfortable having that conversation… I feel *Head Coach* changed a lot of the views to do with menstrual cycle at *Club*, you know." … I think definitely having a woman drive it is really, really good and I think then it helps everyone else get on board with what's going on.

In the above example, the coach led in normalising the conversation and in challenging the sport science team to ensure players had necessary support, as opposed to providing the players with support herself. The comment about the importance of a woman driving the conversation was reflected in other player interviews. Half of the player sample (n = 6/12) reported they would be more likely to discuss female specific health with a female staff member, as they know that they are more likely to be able to relate to how they are feeling.

Player 8: We've got two female physios and a male physio and the S&C coach is female as well, so it's quite nice to have obviously female coaches to talk to as well. I think female coaches is a lot easier. It's quite easy to talk to them about it because obviously they can relate, whereas the male coaches are still a bit more, a little bit more difficult but are still not unmanageable.

However, other players (n = 4/12) who were typically older, were more concerned with their relationship and trust built with the staff member, irrespective of their gender.

Player 12: We do have a female coach but I'm not that comfortable with her, I'm more comfortable with *male coach*

Like players, stakeholders described the MC as a "taboo topic of conversation". Nonetheless, despite this reluctancy to converse about the MC, stakeholders consistently addressed the need for this culture to be changed.

Coach 3: I do think we've gotta be more open about talking about. I think female health and being comfortable as a multi-disciplinary team talking about it, players talking about it. At the end of the day it's, it's not like it's not happening. It's happening and I'm generalising but people get a little bit, like, 'oh should we talk about that?' and, like, we talk about your receiving skills and being able to run and being able to jump, so it's just part of the bigger picture that makes up you as a person and a player.

Staff members also shared mixed experiences regarding reasons for the perceived reluctancy of players to discuss their MC and associated symptoms. Some staff members reported that younger players are less likely to engage in conversations about the MC, particularly if they are struggling with symptoms. However, others felt that this was more dependent on the gender of the staff member, perceiving players to be more likely to speak to a female member of staff.

***Sport Scientist** 7*: Some people still a little bit, erm, not sensitive, I can't think of the right word, erm, insecure, you know, they don't wanna talk about it, it's, it's their thing, erm, especially being a guy coach as well they might not be comfortable speaking to a male about that.

Two coaches also perceived that players sometimes do not mention their symptoms to coaches, as they are concerned about giving the coach a reason to not select them, although this was not mentioned by players.

Coach 4: I think they're always worried that 'I might not get picked, he'll leave me out', especially when I rotate the team so much, they think 'well, does he only need one little excuse to leave me out?'

Although it didn't seem to be a taboo topic of conversation between staff members, these discussions were centred around the need for support, rather than performance, with staff members giving a wide range of answers when asked who should be responsible for menstrual health support. The lack of an individual taking the lead on normalising these conversations could be one of the primary underlying reasons for this culture.

Coach 5: I think if you've got a nutritionist it's ideally them but I don't know whether the whole, you know, like in our case it's the physio because she's female, who deals with a lot of that so I don't know, it's probably not an issue if it goes through a female first maybe and it's organised with the nutritionist.

Nutritionist 4: I just think at the moment women are not well supported in that side of things because teams are under-resourced from a doctor point of view or a medical point of view and, and I'm not blaming anyone at club because they've got so many things to do, a sports scientist has got 12 different things to do and he can't be monitoring everyone's period and putting a gym session together for 30 players and downloading GPS and loading the waters on the coach and making sure they're all getting gels and making sure that they're all taking their protein shakes. They've got so many things to do that you, you can't do them all well.

As mentioned in theme 2, players found it helpful when decisions were made based on conversations about any symptoms they were experiencing. However, these conversations didn't tend to happen between players and staff members. This was potentially due to nervousness, particularly when sharing this personal information with a male member of staff or a principle of exercising their right not to discuss it. Further reasons for this reluctancy may have been a lack of understanding of potential performance implications or a frustration at the lack of support despite having their MC tracked.

Theme Four –Mixed experiences and concerns about menstrual irregularities

Experiences and perceptions of menstrual irregularities were varying between participant groups, including differing levels of concern about irregularities. For instance, sport science staff (n = 3/7), medical staff (n = 5/5) and nutritionists (n = 5/5) were particularly concerned about players not having regular menses, given that secondary amenorrhea and oligomenorrhea are clinical conditions that are an element of the female athlete triad (De Souza et al. 2014) and potential symptoms of relative energy deficiency in sport (REDs). REDs is defined as impaired physiological function including, but not limited to, metabolic rate, menstrual function, bone health, immunity, protein synthesis, cardiovascular health caused by relative energy deficiency (Mounjoy et al. 2018).

> ***Medical Staff 4***: It's common and, er, getting the erratic cycles, erm, missing periods for several months at a time, that's what we're picking up.

Secondary amenorrhea was also identified as a challenge by one parent who shared her experience of her daughter not having regular menses. She also reported being anxious about not understanding if what their child was experiencing was normal or common. *Parent 8*'s daughter had been diagnosed with secondary amenorrhea by a doctor external to the club and would have valued learning from the experience of others.

> ***Parent 8:*** When she was, what, 13-14, something like that, erm, when, you know, like, her period suddenly stopped and I spoke to, I work in the medical profession and I spoke to a doctor saying 'should I be worried about this? It would be helpful for us to know whether there's girls in the First Team, in the Women's Super League in exactly the same situation as her. We just aren't aware of that and that's not for us to know because it would be confidential and everything else, but we don't know if there's anybody else in her squad or her team that is in the same situation and has come through the other side of it. So, I don't think it's talked about.

This parent's concern was perceived to be a result of the lack of discussion mentioned in theme 2, combined with inadequate support from the club. Concerns from sport science, nutrition and medical staff were particularly related to players not mentioning or reporting it. Several examples were given of this, with *Nutritionist 5* discussing an extreme example, where he perceived that under-fuelling resulted in extreme weight loss and secondary amenorrhea.

> ***Nutritionist 5:*** So obviously I already knew that she'd lost 10 kilos and when I looked into her diet I thought 'this isn't a very high calorie content'. Just to confirm it I got her to do a 2 day "snap and send" food diary. The total calorie intake was, like, 1,500 each day. So, I think that was just an instant red flag to me really. So then I just posed the question about the menstrual cycle, 'when was the last time you'd had a period?' and she said she hadn't had a period for at least 6 months.

In contrast to the concerns noted above, some players demonstrated an acceptance of menstrual irregularity. For example, *Nutritionist 4,* worked with a player who was not concerned about menstrual irregularities, as she felt it improved performance.

> ***Nutritionist 4:*** For me she just wasn't ready to listen, she was saying things like 'ah, actually I think not having a period during the World Cup is quite handy'.

> **Medical Staff 2**: A big part of it is to educate them all about the myth that they believe in when it comes to the menstruation, and I don't know where the myth, came about that when you train it's normal to have some sort of menstrual irregularities.

The only two players who identified menstrual irregularities as a concern, had previous personal experience of this situation. *Player 11* was diagnosed with secondary amenorrhea but now has a regular cycle, which she attributed to a lack of understanding of nutrition.

> **Player 11**: Since I was increasing my training load and then I lost my period it was then, like, why have I and then is it because the mind and my body and then that made me realise 'oh, I need to focus on nutrition as well as football because it is just as important'.

It is important to note, however, that "under-fuelling" may not always be the cause of an irregular cycle, with *Nutritionist 4* acknowledging that they too misunderstood the factors that influence secondary amenorrhea.

> ***Nutritionist 4:*** 18 months down the line she then did kind of begin to get her period back to what was normal and from us looking back as a reflection piece it was probably much more stress related than anything else. This player obviously had surgery, worried about the World Cup, was having knock backs in her rehab etc… For me the, the outcome to take home was it

was probably much more stress related than anything else but I was as guilty as anyone of going 'oh, you're not eating enough.'

This theme highlights both concerns and a simultaneous lack of awareness regarding menstrual irregularities. This could be as a result of limited menstrual health support and education (theme 2) and conversations about menstrual health not being normalised (theme 3). However, the primary reason for the concern and lack of awareness within these participants may be the limited research on menstrual health in athletes and confusion over whose responsibility it is to support menstrual health in practice. This situation may reflect the wider status of menstrual health research and support in general.

4.5. Discussion

Using a qualitative approach, the aim of the present study was to explore player and stakeholder perceptions of menstrual health support in elite women's soccer. Participants reported a wide range of physical and psychological symptoms that vary in severity and that were most commonly experienced in the few days before and at the onset of menses. Additionally, most participants perceived that these symptoms impacted training and match day performance. However, despite such perceived negative impacts, menstrual health support was deemed minimal or perceived to be solely related to data collection (i.e., MC tracking) that rarely impacts decision making within the multi-disciplinary team of support staff. Such practices may be a result of confusion amongst staff as to whether anything can or should be adjusted based on the menstrual status of players (i.e., a lack of high-quality research data and/or knowledge on the topic itself). Furthermore, many described the MC as a taboo topic of conversation, despite some players experiencing the benefit of individual conversations about symptoms. This lack of support and education may also result in menstrual irregularities not being identified or treated. When taken together, our data provide insights into player and stakeholder experiences that can aid the development of organisational, stakeholder, and player centred educational programmes that strive to improve menstrual health support.

Our finding that all players within this sample reported negative symptoms is similar to data from Read et al. (2021), who reported that 93 and 100% of female soccer players experience negative symptoms pre-menses and during menses, respectively. The commonality of stomach cramps was consistent with recent findings from elite athletes in a variety of sports (Bruinvels et al. 2020; Brown et al. 2020; Heather et al. 2021) as well as soccer, the latter reported by our research group (Parker et al. 2021). Perceptions of the impact of stomach cramps on performance are supported by studies that have demonstrated reductions in neuromuscular control and aerobic performance (Lebrun et al. 1993), leg strength and aerobic capacity (Chantler et al. 2009) and maximal anaerobic performance (Giacomoni et al. 2000) in women with period pain or premenstrual syndrome. The concerns surrounding heavy menstrual bleeding reported here has also been identified in female trampoline gymnasts (Stewart et al.

2010) and female rugby players (Findlay et al. 2020) who also reported that wearing white shorts heightened this anxiety. Although women often choose to change clothing in order to conceal menstruation (O'Flynn et al. 2006), this is sometimes not possible for elite soccer players. Teams avoiding the use of white shorts during training and matches may be a helpful initial step that could be taken in order to prevent such anxiety.

The overall perception from participants that players receive inadequate menstrual health support may be a result of a lack of research on which to base this support (McNulty et al. 2020). However, the social environment may also have a part to play, given that the MC was frequently described as a taboo topic of conversation, a notion also reported previously (Santer et al. 2008; Findlay et al. 2021). Although it is well documented that there are benefits to coaches addressing the wellbeing of their athletes (Becker et al. 2000), this does not seem to be reflected when it comes to menstrual health support, which may be because coaches do not see this as their responsibility. However, previous research suggests that coaches have shown willingness to be educated on the MC, especially when considering the subsequent potential adjust training loads (Clarke et al. 2021). The gender of the coach was important to some players when engaging in conversation about the MC, which is reflective of findings in other sports (Armour et al. 2020). Furthermore, the coach's experiences of players being reluctant to talk to them was shared by most staff members, so this doesn't seem to be unique to the staff member's specific role. Rather, more clarity is needed within the multidisciplinary team to establish whose role this is, with many staff members identifying *each other* rather than *themselves* as being responsible for menstrual health support. At a higher level, clarity from governing bodies on who they expect to be responsible for this support is needed so as to ensure that menstrual health support does not fall under the responsibility of someone where it is outside the scope of their expertise.

The overall lack of clarity between staff results in less communication with players which, in turn, could result in players being reluctant to address this in conversation with staff members. Staff education regarding menstrual irregularities and the associated consequences is also important due to the prevalence of primary and secondary amenorrhea in elite athletes (De Souza et al. 2014). Whilst the purpose of this study was not to identify the presence of menstrual dysfunction, the identification of the presence or potential consequences of an irregular MC from participants was lacking. This limited view of identification and concern from some participants for menstrual irregularities demonstrate a clear need for education, as secondary amenorrhea can cause negative health consequences (Gordon et al. 2010; Meczekalski et al. 2008; Meczekalski et al. 2010), as outlined in the female athlete triad (De Souza et al. 2012) and REDs (Mounjoy et al. 2018) models. In both cases of players within this study personally experiencing menstrual irregularities, they attributed the solution to this be a better understanding of nutrition and an increase in dietary intake, as has been reported previously in exercising women (De Souza et al. 2021). In this regard, it is noteworthy that our research group recently identified a prevalence of LEA in elite female soccer players (Morehen et al. 2022) as well as a perception that under-fuelling is commonplace, as a result of "CHO fear" and body image issues, as presented in Study One. Given our findings that some players experience changes in appetite at the onset of and during menses, this further emphasises the importance of individual specific menstrual health support, due to the potential knock-on effects for health and performance. Importantly, various factors can result in secondary amenorrhea, including a variety of diseases, genetic abnormalities, and stress (Viswanathan et al. 2011). Therefore, it is critical to understand if this lack of identification from players, parents and coaches is due to insufficient knowledge regarding the adverse effects of amenorrhea, a lack of awareness as to the commonality, or apathy towards the condition due to amenorrhea removing the inconvenience of menstruation and its associated symptoms.

There were several limitations to this study. Firstly, all measures were self-reported meaning that these data are subjective rather than objective. Furthermore, the occurrence of only one cycle was required for players to participate in the study, which means that a participant may not have gained extensive experience of the challenges associated with the MC. Although the topic of the MC is personal, all interviews were a one-off occurrence and as such, further interviews may have resulted in more detailed findings given that participants may have become more comfortable in the (virtual) presence of the interviewer. Additionally, the fact that the principal investigator is male may have also limited participants' openness during the research process. In addition, the experiences of those participants who did not choose to take part may have been valuable, given they may have not felt comfortable discussing this topic for a significant reason. The interviews were not conducted at any particular phase of the cycle and their perceptions may have been influenced by their experience that particular day. This is important, as pain intensity recall reduces when it is not being experienced at present (Robinson et al. 2002). The fact that all player participants were elite soccer players is a strength of this study, particularly as there was a range in the age of the player participants (16-30 years old) and clubs they represented. This is important, as the experience of being an elite female soccer player is variable between clubs. Furthermore, the range of staff roles was a strength, as well as the inclusion of parents of younger players (aged 16-17 years), in order to understand perceptions amongst a broad range of stakeholders.

In summary, our data provides a novel insight into the experiences and perception of elite female soccer players and key stakeholders regarding menstrual health support. These findings identify a lack of menstrual health support (i.e., tracking data without using it to influence practice, the existence of a taboo culture where MCs and menstrual irregularities are not discussed), despite a need for individualised support due to varied symptomology. This lack of support and awareness of the negative health implications of an irregular MC is underpinned by a culture where conversations about the MC are not common place. Therefore, our data identifies the need for organisational, stakeholder, and player centred education programmes so as to create an environment where players receive credible and personalised menstrual health support.

Chapter Five

Study Three

Assessment of Dietary Practices and Physical Loading of Adolescent Female Soccer Players during an Intensive International Training and Game Schedule

This paper was published in Nutrients (2023):

McHaffie, S. J., Langan-Evans, C., Strauss, J. A., Areta, J. L., Rosimus, C., Evans, M. & Morton, J. P. (2023). Under-Fuelling for the work required? Assessment of dietary practices and physical loading of adolescent female soccer players during an intensive international training and game schedule. Nutrients, 15(21), 4508.

Findings from this paper were also presented orally at:

The European College of Sport Sciences (ECSS) 28th annual congress, paris, France, July 2023.

Liverpool John Moores Women's Physiology and Nutrition Symposium, Liverpool, England, August 2023.

5.1. Abstract

Previous studies demonstrate that "under-fuelling" (i.e., reduced CHO and EI in relation to recommended guidelines) is prevalent within adult female soccer players, the consequence of which may have acute performance and chronic health implications. However, the dietary practices of adolescent female soccer players, a population who may be particularly at risk for the negative aspects of LEA, are not well documented. Accordingly, we aimed to quantify EI and CHO intake, physical loading and estimated EA in elite national team adolescent female soccer players (n = twenty-three; age, 17.9 ± 0.5 years) during a 10-day training and game schedule comprising two match days on day six (MDa) and nine (MDb). The players self-reported their EI via the remote food photography method, whilst the physical loading and associated exercise energy expenditure were assessed via GPS technology. The relative CHO intake was significantly greater (all $p < 0.05$) on the day before the first match (MD-1a) (4.1 ± 0.8 $g \cdot kg^{-1}$), on the day before the second match (MD-1b) (4.3 ± 1.1 $g \cdot kg^{-1}$), MDa (4.8 ± 1.2 $g \cdot kg^{-1}$) and MDb (4.8 ± 1.4 $g \cdot kg^{-1}$) in comparison to most other days (6 $g \cdot kg^{-1}$) for intensive training and game schedules. These data provide further evidence for the requirement to create and deliver targeted player and stakeholder education and behaviour change interventions (especially for younger athletes) that aim to promote increased daily CHO intake in female soccer players.

5.2. Introduction

In the last decade, there has been a substantial growth in female soccer participation (FIFA, 20230, the result of which has likely translated to increased professionalism at the elite level of the sport. Such growth is underpinned by the increased strategic investment from local, continental and national governing bodies (UEFA, 2024). The professionalism of the women's game has also contributed to the inevitable rise in the provision of staffing at professional clubs, including medical and sport science support (UEFA, 2019). Importantly, however, the evidence base to support the delivery of sport science and medicine services is not nearly comparable to the men's game and hence, there have been multiple calls within the academic community for a strategic and targeted approach to research that seeks to improve the health and performance of female players (Nassis et al. 2022). This is especially the case for the research base that supports the provision of an evidence-based sports nutrition programme, where the energetic requirements of elite female soccer players are now only beginning to be understood.

Indeed, we (Morehen et al. 2021) and others (Dasa et al. 2023) have recently reported the direct assessment of adult players' EE, as assessed using the gold standard DLW technique. Such reports document absolute EEs of 2693 ± 432 and 2918 ± 322 $kcal \cdot day^{-1}$ in a cohort of English (international competition) and Norwegian (domestic competition) players, respectively. Notwithstanding the potential for dietary under-reporting, it is noteworthy that both studies also highlighted that players' self-reported EI was below recommended values such that LEA (LEA; as classified according to published values < 30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$) was estimated to occur in 23 (Morehen et al. 2021) and 88% (Dasa et al. 2023) of players on training days. Such data also agree with the prevalence of LEA that was reported in English players playing in their respective domestic league (Moss et al. 2021). Such high prevalence of LEA is especially concerning owing to the potential negative consequences of chronic LEA, as documented in the in both the female athlete triad (Nattiv et al. 2023) and relative energy deficiency in sport (REDs) (Mountjoy et al. 2018) models. It is acknowledged, however, that the thresholds to distinguish LEA are based on short-term laboratory interventions of consistent daily EEE and EI, which is not always applicable to the 'real world' athlete, given that an athlete's daily EA is not likely constant (Burke et al. 2018; Taylor et al. 2022). In this way, there is the possibility that the prevalence of LEA amongst female team sport athletes may have been over-estimated.

In considering the potential reasons underpinning the previously reported dietary practices (especially in relation to sub-optimal daily CHO intake), Study One provided some significant insight. Importantly, we reported a culture of 'CHO fear' whereby players (as also 'told' by stakeholders) reported consciously under-consuming (or avoiding) dietary CHO intake due to perceived pressures surrounding body composition and body image, as mediated by coach pressure and social media influences. When considered this way, the need for education of both players and stakeholders becomes readily apparent, the timing of which should likely be targeted to younger players as they transition through the performance pathway from adolescence to adulthood. Indeed, the adolescent player may be particularly susceptible to the negative aspects of sub-optimal EIs when considering the energy cost of growth and maturation (Malina et al. 2021). With this in mind, there is a clear need to extend the study of dietary practices to the adolescent player, to provide a more complete evaluation of the nutritional practices within the women's game. The assessment of dietary practices surrounding players' habitual CHO intake is especially important in the context of considering the role of CHO availability for muscle metabolism and soccer specific performance. Indeed, recent assessment of the metabolic demands of female match play using muscle biopsies established that that 80 and 70% of type I and type II muscle fibres were classified as empty or almost empty immediately after a game (Krustrup et al. 2022). Furthermore, there is evidence that low CHO intake may also have a negative impact on technical performance (Russel et al., 2012).

Accordingly, the aim of the present study was to quantify the energy (and CHO) intake, physical loading and estimated EA of elite adolescent female soccer players. To this end, we studied a cohort of players participating in a 10-day training and game schedule who were representing their national team. Similar to adult players, we also hypothesised that players would present with dietary practices that are representative of 'under-fuelling' for the work required. However, in order to consider for the potential of dietary under-reporting, we also report unadjusted and adjusted estimation of EA as based on the correction factor recently reported by Dasa et al., (2023).

5.3. Methods

Participants

Twenty-three (n = 2 goalkeepers and n = 21 outfielders) female soccer players (mean ± SD: age: 17.9 ± 0.5 y, BM: 61.6 ± 6.1 kg, stature: 168 ± 5 cm) representing the same national team at the under (U) 18 age group, volunteered to take part in the study. Participant characteristics categorised by playing position are represented in Table 5.1. Written informed parental/guardian consent and player assent were obtained for participants ≤17 years old, and participants ≥18 years old provided their own consent. Ethical approval was granted by Liverpool John Moores University (22/SPS/027).

Table 5.1. Baseline participant characteristics.

	Goalkeepers (n = 2)	Defenders (n = 8)	Midfielders (n = 5)	Attackers (n = 8)	Whole Squad (n = 23)
Age (years)	16.5 ± 0.7	16.4 ± 0.5	16.4 ± 0.5	16.4 ± 0.7	17.9 ± 0.5
Stature (cm)	169 ± 2.8	172 ± 4.2	165 ± 6.4	166 ± 4.5	168 ± 5
BM (kg)	62.8 ± 4.8	60.4 ± 4.6	59.1 ± 8.2	64 ± 6.9	61.6 ± 6.1
FFM (kg)	46.0 ± 4.1	46.0 ± 3.4	43.5 ± 5.3	46.6 ± 4.5	45.7 ± 4.2
FM (kg)	16.8 ± 0.7	14.4 ± 2.5	15.6 ± 3.5	17.4 ± 3.5	15.9 ± 3.1
Body Fat %	26.8 ± 0.9	23.8 ± 3.0	26.2 ± 3.2	27 ± 3.4	25.7 ± 3.3

Study Design

All players took part in a 10-day international training camp, comprising 5 training days, 3 rest days and 2 match days. Match days occurred on days 6 and 9, therefore the last 5 days could be considered as a “congested fixture’ period. All days are defined relative to the first (a) or second (b) match day (i.e., MD-5, MD-4, MD-3, MD-2, MD-1a, MDa, MD+1a, MD-1b, MDb and MD+1b). Both matches were at “home” against other nations and an overview of the training and game schedule is shown in Table 5.2. During the 10-day period, all players self-reported energy and macronutrient intake and physical activity whilst pitch-based training and match load was measured using GPS technology. Bioelectrical impedance analysis (BIA) was also used to assess daily BM, body composition and body water. All players were available for selection for both matches, with no injuries preventing any participation within the study.

Table 5.2. An overview of the training and game schedule.

	Match Day −5	Match Day −4	Match Day −3	Match Day −2	Match Day −1	Match Day	Match Day +1	Match Day −1	Match Day	Match Day +1
09.00	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**	**Breakfast**
10.00	Rest	Rest	**Gym**	Rest	Rest	Rest	Rest/Recovery	Rest	**Breakfast**	Rest
11.00	**Training (pitch)**	**Training (pitch)**	Rest/Education	**Training (pitch)**	**Training (pitch)**	**Pre-match meal**	Rest/Recovery	**Training (pitch)**	**Prep and warm up**	Rest
12.00	**Training (pitch)**	**Training (pitch)**	Rest/Education	**Training (pitch)**	**Training (pitch)**	Rest	Rest/Recovery	**Training (pitch)**	**Match**	**Lunch**
13.00	Snack	Snack	**Lunch**	**Snack**	**Snack**	**Prep and warm up**	**Lunch**	**Snack**	**Match**	Players depart
14.00	**Lunch**	**Lunch**	Rest/Meeting	**Lunch**	**Lunch**	**Match**	Rest/Recovery	**Lunch**	**Snack**	Players depart
15.00	Rest/Education	Rest	Rest/Meeting	Rest/Education	Rest/Education	**Match**	**Gym**	Rest/Education	**Post-match meal**	Players depart
16.00	Rest	Rest	Rest/Meeting	Rest	Rest	**Snack**	**Snack**	Rest/Education	Rest	Players depart
17.00	Rest	Rest	Rest/Meeting	**Gym**	Rest	**Post-match meal**	Rest/Education	Rest	Rest	Players depart
18.00	Rest	Rest	Rest/Meeting	Rest	Rest	Rest	Rest/Education	Rest	Rest	Players depart
19.00	**Dinner**	**Dinner**	**Dinner**	**Dinner**	**Dinner**	Rest	**Dinner**	**Dinner**	**Dinner**	Players depart
20.00	Rest	Rest/Education	Rest/Education	Rest/Education	Rest	Rest	Rest	Rest	Rest	Players depart
21.00	**Snack**	**Snack**	**Snack**	**Snack**	**Snack**	**Snack**	**Snack**	**Snack**	**Snack**	Players depart
22.00	Rest	Rest	Rest	Rest	Rest	Rest	Rest	Rest	Rest	Players depart

Pre-data collection education

Six days prior to commencing the data collection period, an initial online education session was held for all staff members who would be in attendance, in order to inform them of the rationale and study protocol. Three days later, an additional education session was held online for all players and a representative parent/guardian where the primary focus was to introduce and educate the players on the RFPM. Players arrived "on-site" one day prior to the start of data collection and also took part in a further education session where an 'in-person' demonstration of the RFPM method was completed by the lead researcher.

Bioelectrical Impedance Analysis

BM and composition was assessed via BIA (MC-980MA PLUS; Tanita Corp., Tokyo, Japan) in the fasted state each morning. This measurement tool uses a single frequency current of 50 kHz (single frequency BIA [SF-BIA]) and an eight-contact electrode system and was used to assess BM (kg), body fat percentage, FM (kg), FFM (kg), water mass (kg) and water percentage (%) and RMR. The BIA machine provides an value for RMR based on the body composition, age and gender of the participant. Players wore the same training kit and removed shoes and jewelry for the BIA assessment, which was conducted at the same time each day for all players, between 8AM and 8:45AM. All scans were performed in the fast state prior to consumption of food and fluid intake at breakfast.

Quantification of Training and Match Load

Training and match load were measured using GPS technology (Apex, Statsports, Newry, Northern Ireland), with units worn by all players, excluding goalkeepers, for all pitch-based training sessions and matches. The GPS unit was placed inside a custom-made manufacturer provided vest (Apex, STATSports, Newry, Northern Ireland) that was held on the upper back between both scapulae, allowing exposure of the GPS antennae to acquire a clear satellite connection. Variables measured include duration (mins), distance (m), maximum velocity (MV) (m/s), accelerations (> 3 $m{\cdot}s^{-1}$), decelerations (> 3 $m{\cdot}s^{-1}$) and time spent in three different speed zones: Zone 1 (3.46-5.28 m.s^{-1}), Zone 2 (5.29-6.25 m.s^{-1}) and Zone 3 (≥ 6.26 m.s^{-1}). These categories are commonly used within this population, as established by Park et al (2019).

Quantification of Physical Activity Data

Self-reported physical activity was quantified throughout the 10 days using a self- reported activity diary on a Microsoft Form (Microsoft, Washington, United States). Each participant was sent a link to this form at two time points throughout the day. Participants were instructed to provide a short description of their physical activity (e.g., 'walking' or 'watching TV') and RPE for 30-minute periods throughout the day, outside of scheduled activities, such as meal times, team meetings and training. Each entry was then automatically logged on a Microsoft Excel Spreadsheet (Microsoft, Washington, United States), with each activity converted into metabolic equivalent task (MET) to provide an estimation of EE and then assigned one of the following intensity thresholds based upon the EE value; ‘very light’, ‘light’, ‘moderate’, ‘heavy’, ‘very heavy’ (Butte et al. 2018). The purpose of this was to establish whether any additional physical activity (e.g. gym sessions) needed to be accounted for as EEE, when estimating EA.

Quantification of Energy and Macronutrient Intake

Self-reported energy and macronutrient intake was quantified throughout the ten-day period, using the RFPM (Martin et al. 2012). This method has previously been validated in adolescent team sport athletes (Costello et al. 2017) and used by our group to evaluate self-reported energy and macronutrient intakes in male academy soccer players (Dasa et al. 2022; Loucks et al. 2011). As the lead researcher was present for the entire training camp, reminders were able to be made easily in person throughout the data collection period. As well as in-person reminders, physical prompts were placed in the dining area to remind players. Importantly, other staff members were asked to remind players to take their photos during different meal times, in order to reduce the monotony of receiving these reminders from the same source.

As per the protocol, participants were instructed to take two images, at 90 and 45 degrees of any food or drink they consumed throughout the ten days, including all meals and snacks. A third image was also taken of any leftovers, if required. These images were sent to the principal investigator via the phone application Threema (Threema GmbH, Pfäffikon, Switzerland) and a female member of staff was present within each of these group chats, as well as the player and lead researcher. Participants were also instructed to send a brief description of the food items that they consumed. The lead researcher constructed two portions (small and large) of each of the foods available, prior to the arrival of players and staff members for meal times. These were weighed and photographed, providing images to compare to during the analysis process, ensuring more accurate analysis of portion size. Descriptions of foods and drinks consumed before, during and after training and matches were also sent, as players did not have access to their phones at this time. Some players brought their own snacks to the training camp; however, all meals and multiple snacks were provided to players throughout each day and an outline of timings can be viewed in Table 5.2, within the schedule. During training and matches, players were also provided with sports drinks if desired, in addition to water, and post training and match snacks were also provided (e.g., protein bars, fruit, cereal bars, whey protein etc.). Once throughout the training camp, every player completed a dietary recall, to check for any missed data. This also provided an opportunity to the lead researcher to feedback on the quality of their data provision and to provide any additional education if needed.

Energy and macronutrient intake were analysed by a Sport and Exercise Nutrition register (SENr) accredited practitioner using the dietary analysis software Nutritics (Nutritics, v5, Dublin, Ireland) With energy, CHO and protein intake quantified as kilocalories (kcal) and grams, respectively, in both absolute and relative (to each player's BM) terms. During the analysis period, comparisons were made between the photos taken by the players to those of the weighed portion sizes, in order to increase accuracy of estimations. To ensure reliability of energy and macronutrient intake data, a second SENr nutritionist also analysed a sample of food diaries chosen at random (n = 5, equating to 50 days of entries in total), with inter-rater reliability was determined via an independent t-test. No significant differences were observed between estimations for energy (P = 0.96, 95%CI −156 to 38), CHO (P = 0.11, 95%CI −31 to 3), protein (P = 0.14, 95%CI −12 to 1) and fat (P = 0.13, 95%CI −8 to 3). Furthermore, adjusted EI was calculated by increasing self-reported EI by 22%, in at attempt to account for the underreporting that has previously been documented in a comparable sample population previously (Dasa et al. 2023). This 22% estimation of underreporting by Dasa et al. was calculated by comparing self-reported reported intake to the calculated EI, as inferred from assessment of EE (using the DLW technique) and negligible changes in BM.

During Exercise Energy Expenditure

For field-based sessions, the GPS devices with individualised player descriptives inputted provided a value for EEE, which was subsequently increased by 10.7%, based on recent data which demonstrated that this GPS system underestimates EEE within this population (Mara et al. 2015). For gym-based sessions, EEE was estimated based on the activity diaries, with values corrected for everyone, using RMR data from the BIA machine, whereby energy expended for RMR during the session was subtracted from the estimation of EEE.

Estimation of Low Energy Availability and Adjusted Low Energy Availability

EI and EEE throughout the 10-day period was used to calculate EA (EA = (EI – EEE) / FFM)) (Owen et al. 2016) for all outfield players. To allow for comparison with previous literature in female soccer players (Morehen et al. 2021; Dasa et al. 2023; Moss et al. 2021), EA was categorised as optimal, (> 45 kcal.kg FFM^{-1}.day^{-1}), reduced (30-45 kcal.kg FFM^{-1}.day^{-1}) and low (< 30 kcal.kg FFM^{-1} day^{-1}). Adjusted EA was calculated using the same equation, with adjusted EI inputted.

Statistical Analysis

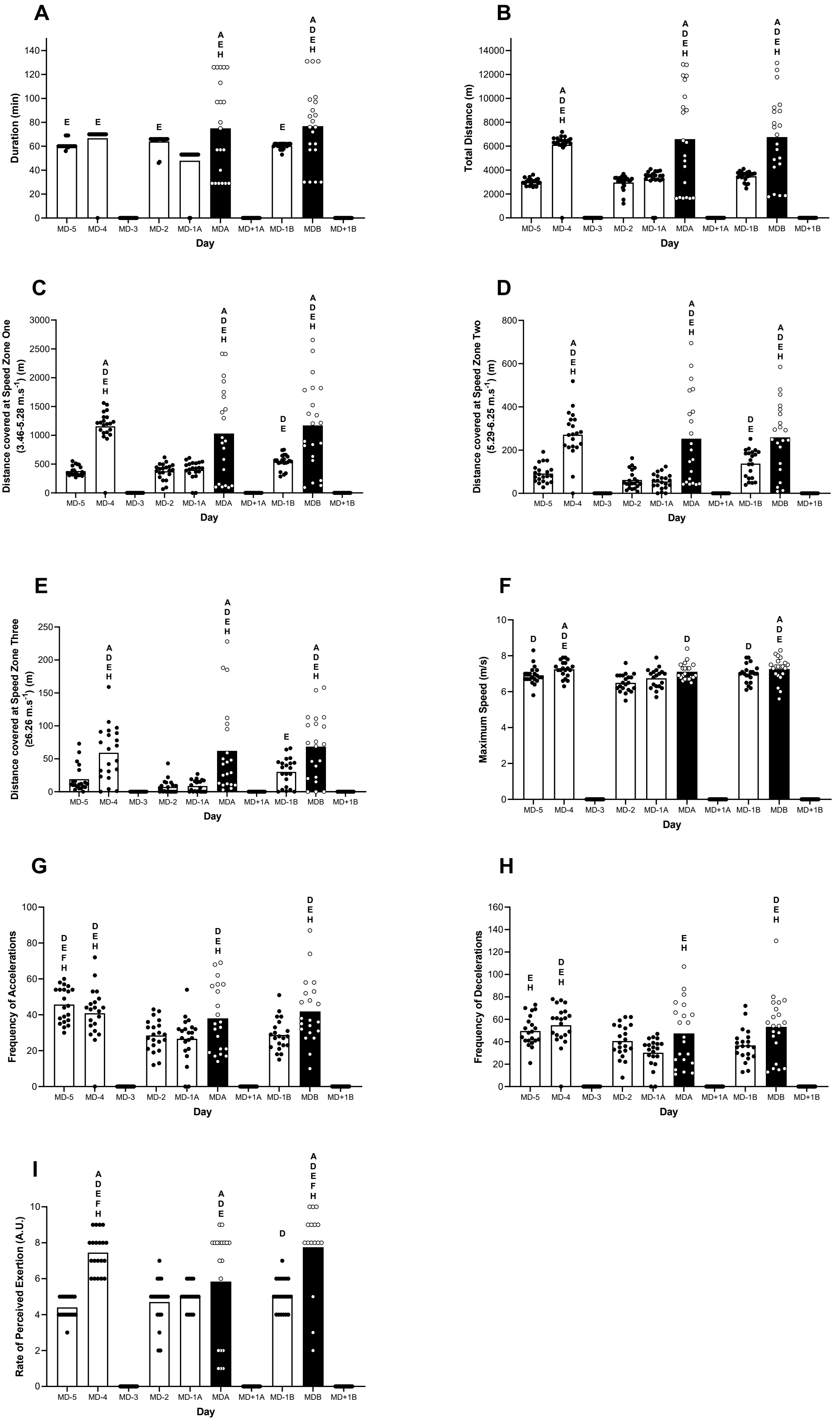
All data were initially assessed for normality of distribution using Shapiro-Wilk's test and outliers using box plots. To determine differences between days in absolute and relative energy and macronutrient intake, BIA and GPS data, a one-way between groups analysis of variance (ANOVA) was used. Where significant main effects were present, LSD post-hoc analysis was conducted to locate specific differences (level of significance set at P < 0.05). Ninety-five % confidence intervals for the difference are also presented. All statistical analyses were completed using SPSS (version 26; SPSS, Chicago, IL) where $P < 0.05$ is indicative of statistical significance. All data are presented as mean ± SD.

5.4. Results

External Load

External loading variables are presented for all outfield players (n = 21) across all training sessions and games. Figure 5.1 displays the training and match load metrics for all days, including duration, TD, distance covered within specific speed zones, maximum speed, accelerations and decelerations. No "pitch based" training sessions occurred on MD-3, MD+1a or MD+1b.

Significant differences were observed between days for all variables (all $P < 0.05$) and pair-wise comparisons are denoted in Figure legends. When considered together, data are suggestive of the traditional approach to micro-cycle periodization within soccer, such that volume (i.e., duration and TD) and intensity (i.e., high-intensity distance, maximal speed and accelerations and decelerations) are greater on MD-4 and a gradual daily reduction is evident as proximity to the first game increases (e.g., MDa). Mean daily EEE during the ten-day period was 442 ± 486 $kcal \cdot day^{-1}$.



A
Duration (min)
B
Total Distance (m)
C
Distance covered at Speed Zone One (3.46-5.28 m.s-1) (m)
D
Distance covered at Speed Zone Two (5.29-6.25 m.s-1) (m)
E
Distance covered at Speed Zone Three (≥6.26 m.s-1) (m)
F
Maximum Speed (m/s)
G
Frequency of Accelerations
H
Frequency of Decelerations
I
Rate of Perceived Exertion (A.U.)
MD-5
MD-4
MD-3
MD-2
MD-1A
MDA
MD+1A
MD-1B
MDB
MD+1B
Day

Figure 5.1. An overview of external loading throughout the 10-day period. Pitch-based training and match's (A) duration, (B) total distance, (C) distance at speed zone one (3.46–5.28 $m \cdot s^{-1}$), (D) distance at speed zone two (5.29–6.25 $m \cdot s^{-1}$), (E) distance at speed zone three (≥6.26 $m \cdot s^{-1}$), (F) maximum speed, (G) frequency of accelerations, (H) frequency of decelerations and (I) rate of perceived exertion. Black bars represent match days. A is significantly higher than MD5, B is significantly higher than MD-4, C is significantly higher than MD-3, D is significantly higher than MD-2, E is significantly higher than MD-1a, F is significantly higher than MDa, G is significantly higher than MD+1a, H is significantly higher than MD-1b, I is significantly higher than MDb and J is significantly higher than MD+1b, all $p < 0.05$.

Energy and Carbohydrate Intake

Players' self-reported daily energy and CHO intake is presented in Figure 5.2. Unadjusted absolute (Figure 5.2A) and relative (Figure 5.2C) daily EI displayed significant differences between days (both $P < 0.001$; see Figure legend for pair-wise comparisons) such that mean values of 2053 ± 486 kcal·*day*$^{-1}$ (range: 1697 - 2413 kcal·*day*$^{-1}$) and 33.6 ± 8.4 kcal.kg.day^{-1} (range: 27.9 – 39.4 kcal.kg.day^{-1}) were reported, respectively.

When accounting for potential dietary under-reporting, a similar pattern of nutritional periodisation was evident for both adjusted absolute (Figure 5.2B) and relative EI (Figure 5.2D) with significant differences between days (both $P < 0.001$; see Figure legend for pair-wise comparisons). However, mean absolute and relative EI values were now increased to 2505 ± 490 kcal·day^{-1} (range: 2070 - 2944 kcal·*day*$^{-1}$) and 40.9 ± 9.1 kcal.kg.day^{-1} (range: 34 – 48.1 kcal.kg.day^{-1}), respectively.

Both absolute (Figure 5.2E) and relative (Figure 5.2F) CHO intake also displayed significant differences between days (both $P < 0.001$; see Figure legend for pair-wise comparisons). The most prominent difference was reported as greater relative CHO intake on the days before the game (4.8 ± 1.1 g·kg^{-1} and 4.3 ± 1.1 g·kg^{-1}, reported on MD-1a and MD-1b, respectively) and game days (4.8 ± 1.2 g·kg^{-1} and 4.8 ± 1.4 g·kg^{-1}, reported on MDa and MDb, respectively) when compared to the remaining training and rest days. No formal calculation of adjusted CHO intake was conducted owing to the difficult of attributing potential under-reporting of EI to a specific macronutrient.

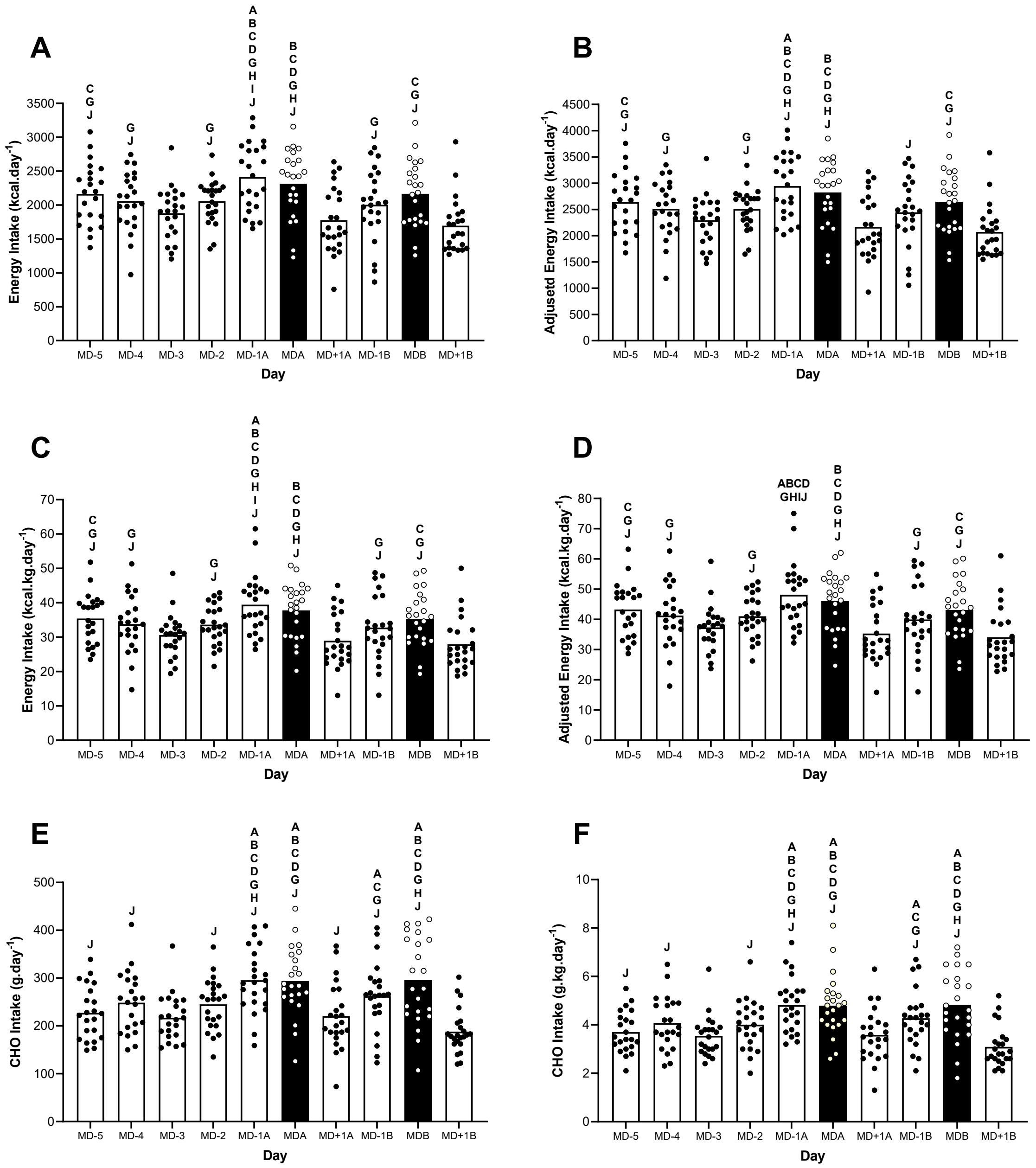


Figure 5.2 An overview of energy and CHO intake throughout the 10-day period. (A)absolute EI, (B) adjusted absolute EI, (C) relative EI, (D) adjusted relative EI, (E) absolute CHO intake and (F) relative CHO intake. A denotes significantly higher than MD-5, B denotes significantly higher than MD-4, C denotes significantly higher than MD-3, D denotes significantly higher than MD-2, E denotes significantly higher than MD-1, F denotes significantly higher than MDa, G denotes significantly higher than MD+1a, H denotes significantly higher than MD-1b, I denotes significantly higher than MDb and J denotes significantly higher than MD+1b, all $P < 0.05$.

Body Composition

Changes in BM, body composition and body water are presented in Figure 5.3. Although FM displayed no changes between days (Figure 5.3 C, P = 0.113), all other variables displayed significant fluctuations throughout the 10-day period (all P < 0.05).

In relation to BM, significantly greater values were observed on MDa (61.9 ± 6.3 kg) and MDb (61.9 ± 6.2 kg) compared with MD-5 (61.4 ± 6.3 kg; 95% CI = 0.2 to 0.6 kg; P < 0.001, 95% CI = 0.1 to 0.6 kg; P = 0.002, respectively), MD-4 (61.8 ± 6.5 kg; 95% CI = 0.04 to 0.5 kg; P = 0.021, 95% CI = 0.02 to 0.5 kg; P = 0.037, respectively) and MD-2 (61.6 ± 6.3 kg; 95% CI = 0.1 to 0.6 kg; P=0.003, 95% CI = 0.1 to 0.5 kg; P = 0.007, respectively). BM was also significantly higher on MDa than on MD-3 (61.8 ± 6.4 kg; 95% CI = 0.01 to 0.5 kg; P = 0.038) and significantly higher on MD+1b (61.8 ± 6.2 kg) than on MD-5 (95% CI = 0.002 to 0.5 kg; P = 0.048).

Body fat percentage was significantly higher on MD-5 (25.6 ± 3.3 %), MD-4 (25.6± 3.2 %), MD-3 (25.7 ± 3.3 %), MD-2 (25.7 ± 3.2 %), MD-1b (25.8 ± 3.2 %) and MDb (25.8 ± 3.4 %) than on MD+1b (25.2 ± 0.7 %) (all P < 0.05).

FFM was significantly higher on MDa (46.1 ± 4.1 kg) and MD+1b (46.1 ± 4.1 kg), than on MD-5 (45.6 ± 4.2 kg), MD-4 (45.9 ± 4.2 kg), MD-3 (45.8 ± 4.2 kg), MD-2 (45.7 ± 4.1 kg) and MD-1b (45.7 ± 4.0 kg) (all P < 0.05).

Water mass and water percentage were both significantly lower on MD-5 (33.0 ± 2.9 kg and 54.0 ± 3.3 %, respectively) than every other day (all P < 0.05). Water mass was also significantly higher on MDa (33.7 ± 0.6 kg) than on MD-2 (33.4 ± 3.0 kg; 95% CI = 0.002 to 0.5 kg; P = 0.048). It was also significantly higher on MD+1b (34 ± 2.9 kg) than on MD-2 (33.4 ± 3.60kg; 95% CI = 0.002 to 0.5 kg; P = 0.048) and MD-1b (33.4 ± 2.9 kg; 95% CI = 0.002 to 0.5 kg; P = 0.048). Water percentage was significantly higher on MD+1b (54.7 ± 2.8 kg), than on MD-2 (54.3 ± 2.5 kg; 95% CI = 0.002 to 0.5 kg; P = 0.048), MD-1b (54.3 ± 2.7 kg; 95% CI = 0.002 to 0.5 kg; P = 0.048) and MDb (54.3 ± 2.7 kg; 95% CI = 0.002 to 0.5 kg; P = 0.048).

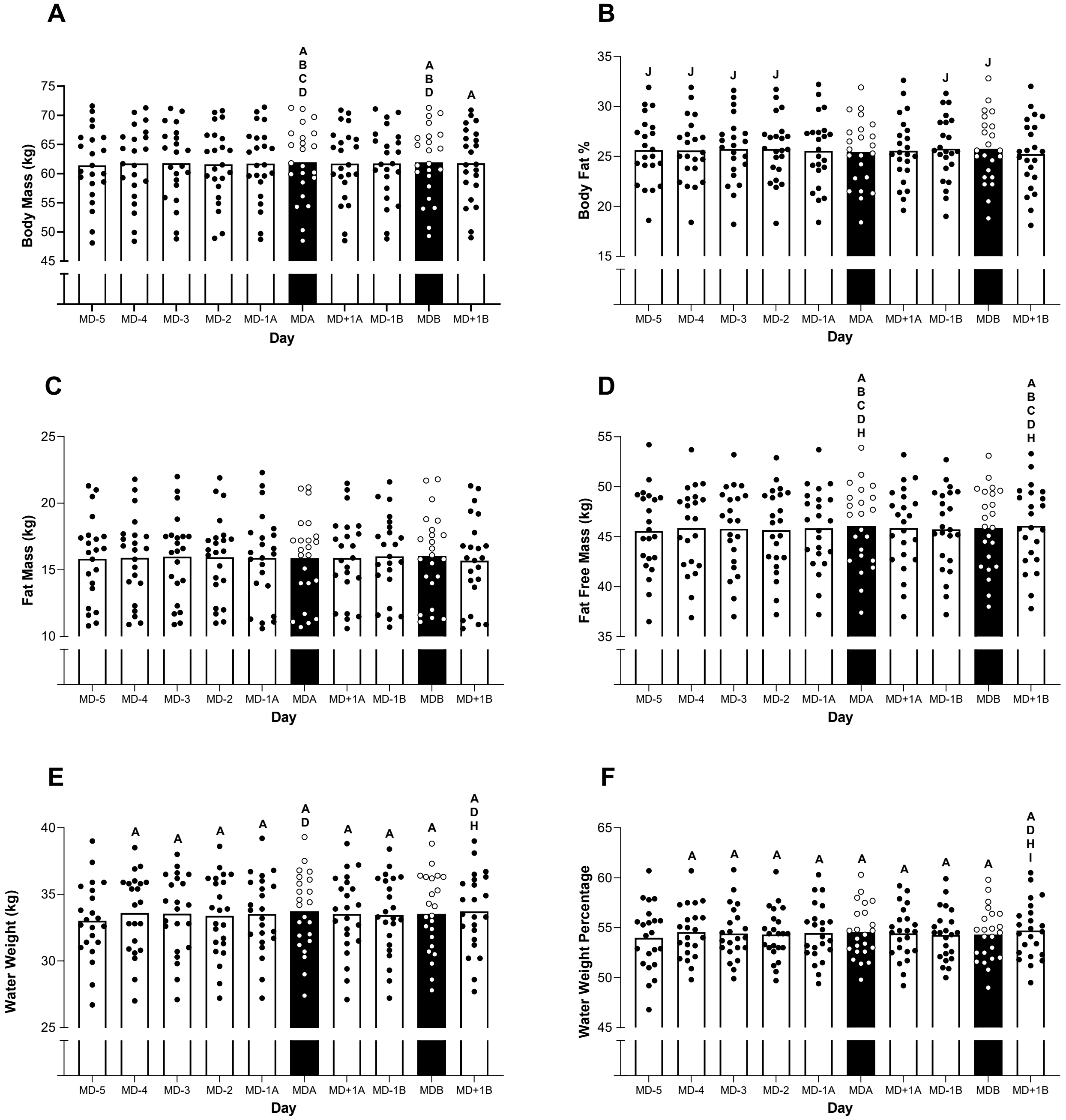


Figure 5.3. An overview of BIA data throughout the 10-day period. (A) BM, (B), body fat percentage, (C) FM, (D) FFM, (E) water mass and (F) water mass percentage. A denotes significantly higher than MD-5, B denotes significantly higher than MD-4, C denotes significantly higher than MD-3, D denotes significantly higher than MD-2, E denotes significantly higher than MD-1, F denotes significantly higher than MDa, G denotes significantly higher than MD+1a, H denotes significantly higher than MD-1b, I denotes significantly higher than MDb and J denotes significantly higher than MD+1b, all $P < 0.05$.

Estimated Energy Availability

Estimated daily EA throughout the 10-day period and mean daily EA for the entire 10-day period is presented in Figure 5.4. Both unadjusted and adjusted daily EA (see Figure 5.4 A and C, respectively) showed a significant difference between days ($P<0.05$) with pair-wise comparisons denoted in the Figure legend.

Unadjusted mean daily EA was 34 ± 12 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$ within outfield players (see Figure 5B), with a prevalence of 2 players (9%) in optimal EA, 13 (57%) players in reduced EA and 6 players (34%) in LEA. However, when EI was adjusted for potential under-reporting, the prevalence of LEA changed considerably such that 8 (38%), 12 (57%) and 1 (5%) players now presented with optimal, reduced and LEA, respectively (see Figure 5 B and D, respectively).

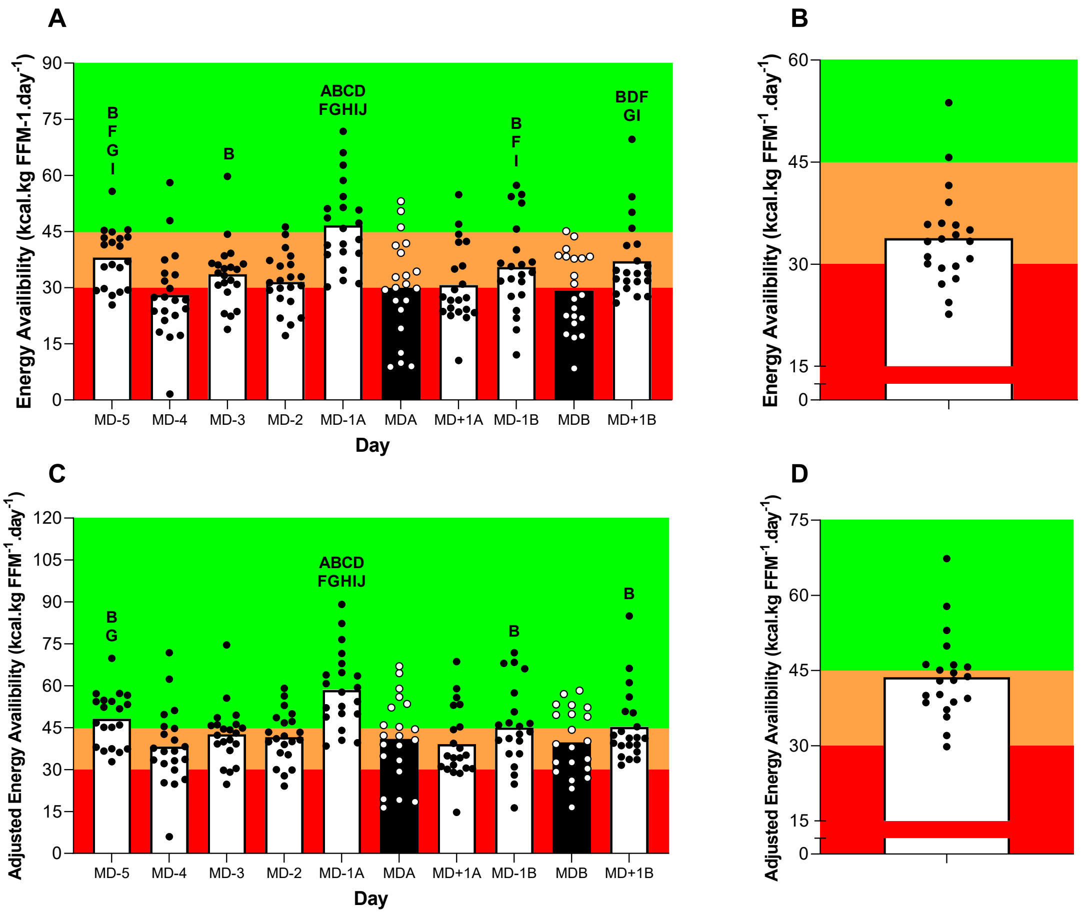


Figure 5.4. An overview of EA and adjusted EA throughout the 10-day period. (A) EA across 10 days, (B) average daily EA, (C) adjusted EA across 10 days and (D) average daily adjusted EA. A denotes significantly higher than MD-5, B denotes significantly higher than MD-4, C denotes significantly higher than MD-3, D denotes significantly higher than MD-2, E denotes significantly higher than MD-1, F denotes significantly higher than MDa, G denotes significantly higher than MD+1a, H denotes significantly higher than MD-1b, I denotes significantly higher than MDb and J denotes significantly higher than MD+1b., all $P < 0.05$. Colours represent optimal, (> 45 kcal.kg FFM−1.day^{-1}), reduced (30-45 kcal.kg FFM−1.day^{-1}) and low (< 30 kcal.kg FFM−1 day^{-1}) categories of EA.

5.5. Discussion

On the basis of recent reports of under-fuelling, LEA (Morehen et al. 2021; Dasa et al. 2023; Moss et al. 2021) and the culture of CHO fear amongst adult professional female soccer players reported within Study One, we aimed to extend our study of the habitual dietary practices of female players to an adolescent population. In studying a cohort of elite players who were training and competing for their national team over a 10-day period, we assessed self-reported EI, physical loading and estimated EA. Although the thresholds of distinguishing LEA amongst athletic populations (under real world free living conditions) remain the topic of intense investigation, our data are in agreement with previous reports from adult players (Morehen et al. 2021; Dasa et al. 2023; Moss et al. 2021) that are suggestive of LEA (n = 6, i.e., 34% of players presented with LEA). However, when accounting for potential dietary under-reporting (Dasa et al. 2023), the pattern of LEA changes substantially such that only one player was now categorized as LEA (albeit it using thresholds derived from laboratory-based research models). When considering the issues of under-reporting alongside the problems associated with distinguishing LEA, such data suggest that the 'true' prevalence of LEA amongst female team sport athletes may be over-estimated within the literature. Nonetheless, evaluation of daily CHO intakes is still suggestive of 'under-fuelling for the work required', as based on the assessment of daily CHO in relation to published recommendations for intakes during congested fixture schedules (i.e. the last 5 days of assessment where two games were played).

To address our aim, we studied players throughout a national 'training camp' environment during which players trained and resided at the same hotel. Importantly, the training and game schedule comprised the traditional microcycle approach that is inherent to soccer where a game is usually preceded by four or five training days. In this regard, evaluation of external loading prior to game one (i.e., MDa) demonstrates the typical periodisation of training load that has previously been reported in both adult female (Owen et al. 2016) and male players (Collins et al. 2021). Indeed, we observed that the highest volume (e.g., duration and TD) and intensity of training (e.g., distance covered within speed zone 3, maximal speed and number of accelerations and decelerations) typically occurred at four days prior to MDa. In the subsequent days, training load displayed an apparent tapering of volume and intensity, likely a conscious decision by the coaching team to promote player readiness for the upcoming game. The rest of the data collection period could be considered to more closely resemble a congested fixture schedule whereby two games were played in a four-day period. As such, the two-day period between games presented as an initial day rest day and a second day of reduced training load. Although it is difficult to compare markers of training intensity between studies (owing to the variety of speed thresholds used in the literature), it is noteworthy that the average training and MD TD reported here (3789 ± 1375 and 6667 ± 3764 m, respectively) is lower than our previous report from adult players (4838 and 6837 m, respectively), who were also participating in a similar international training and game schedule (Morehen et al. 2021). Unfortunately, we are unable to provide any insight as to whether this is a conscious and planned approach to training that takes into account the adolescent nature of the players and/or whether this population is physically unable to attain the same makers of volume and intensity as adult players. It is important to note that match day values include the warmup and all players, including unused substitutes, so this value is heavily impacted by squad sizes across match days.

In relation to self-reported EI, we observed similar absolute values 2053 ± 486 $kcal·day^{-1}$ (range: 1697 - 2413 $kcal·day^{-1}$) as to that reported previously by our group (Morehen et al. 2021) (1923 ± 357 $kcal.day^{-1}$, range: 1639 - 2172) and others (Dasa et al. 2023; Moss et al. 2021) (2274 ± 450 $kcal·day^{-1}$ and 2124 ± 444 $kcal·day^{-1}$, respectively) when assessing adult players competing at both international and domestic level. On the basis of evaluations of EEE, we subsequently report a mean estimated EA of 34 ± 12 $kcal·kg^{-1}$ $FFM·day^{-1}$ such that 9, 57 and 34 % of players could be classified in optimal, reduced and LEA, respectively. Such prevalence of LEA agrees favorably with that reported by Moss et al. 2021, where 23% of adult players playing in the Women's Super League of England were categorized with LEA over a 5-day period (in both cases EEE was quantified via GPS). However, our data are substantially lower than our previous reports from adult players also competing at international level, where we reported 88% of players to have LEA (Morehen et al. 2021). Such differences between studies are likely due to methodological differences given that our previous approach to quantify EEE was based on assessments of 'activity energy expenditure' that was derived from insights from DLW assessment of TDEE. In this way, the prevalence of LEA was likely to be over-estimated.

We readily acknowledge the difficulties of accurately quantifying EA owing to the technical challenges of accurately assessing both EI and EEE. Indeed, the field is further complicated in that categorization of LEA (as < 30 $kcal·kg^{-1}$ $FFM·day^{-1}$) is based on laboratory studies with homogenous patterns of EI and exercise related expenditure (Burke et al. 2018). In contrast, athletes living under free living conditions typically present with daily variations in training volume and intensity (and hence EEE), albeit EI may not be adjusted accordingly (Taylor et al. 2022). Additionally, the field is perhaps most complicated by dietary under-reporting and as such, the potential for symptoms associated with the female athlete triad and REDs may be over-interpreted within the team sport literature. Indeed, a recent study employing DLW to assess TDEE in a cohort of adult Norwegian players (Dasa et al. 2023) reported a discrepancy between EE (2918 ± 322 $kcal·day^{-1}$) and self-reported EI (2274 ± 450 $kcal·day^{-1}$) of approximately 22%. In applying the same correction factor to the data presented here (considering that BM did not decrease during the study period), we were able to highlight an adjusted mean EI of 2505 ± 490 $kcal·day^{-1}$ and an adjusted EA of 44 ± 14 $kcal·kg^{-1}$ $FFM·day^{-1}$. In this way, the pattern of LEA changes substantially such that only one player now presents with LEA. Clearly, further assessments of TDEE in adolescent players (using the DLW method) are now justified to provide further insights on the prevalence of LEA amongst team sport athletes.

It is difficult to provide an adjusted assessment of daily CHO intake owing to the difficulty of attributing dietary under-reporting to a specific macronutrient. However, even when considering the potential of under-reporting of CHO intake, our data are still suggestive of elite female soccer players under-consuming CHO in relation to recommended guidelines. Indeed, the latest Union of European Football Associations (UEFA) expert group statement on 'nutrition for football' recommends at least 6-8 $g\cdot kg^{-1}$ be consumed daily during periods of congested fixtures and intense training schedules (Collins et al. 2021). Additionally, it is well documented that high CHO intakes should be consumed on the day before and after match play, to load and recover muscle glycogen stores, respectively. Indeed, although we observed some evidence supporting some principles of CHO loading (e.g., increased BM on both match days that may be potentially reflective of increased glycogen storage), the reported daily CHO intake still falls short of recommended values. Although these guidelines are generic and not specific to female players, recent assessments of the metabolic demands of female match play using muscle biopsies further demonstrate the importance of CHO availability given that 80 and 70% of type I and type II muscle fibers were classified as empty or almost empty immediately after a game (Krustrup et al. 2022). When considered this way, it is likely that the majority of the players studied here commenced both games with sub-optimal muscle glycogen stores, the result of which could compromise both physical (Krustrup et al. 2022) and technical (Russell et al. 2012) elements of performance. Indeed, of the total daily dietary assessments completed in this study (i.e., 230), there were only 19 (8%) accounts of a player reporting a daily CHO intake >6 $g\cdot kg^{-1}$. Furthermore, although the concept of CHO periodization is gaining increased acceptance as a targeted nutritional strategy for adult athletes (Fernandes et al. 2020), it is unlikely that such periodization should be recommended here when considering the adolescent nature of the players and the intensive demands of the training and game schedule.

We were unable to ascertain the likely reasons for the apparent under-consumption of CHO intake reported here and whether this was a conscious or unconscious decision by players. In using a qualitative methodology to explore the nutrition culture within the women's game (inclusive of both adult and adolescent players), we reported in Study One that players may under-fuel due to a lack of awareness of nutrition guidelines and hence, do not readily appreciate the importance of CHO for football development and performance. However, notwithstanding the need for increasing education amongst players and stakeholders, we also reported incidences of intentional under-fuelling due to perceived pressures surrounding body composition assessment and body image issues. In considering such insights through the lens of behavioural change models such as the COM-B framework (Mitchie et al. 2015; Atkins et al. 2015), it is apparent that the social opportunity (i.e., cultural norms) is not yet conducive to permit the repeated nutritional behaviours that could be considered representative of a positive nutrition and fuelling culture. As such, there is a need for further multi- and inter-disciplinary research that addresses the barriers and enablers to improve the provision of nutrition services within the women's game. The need for targeted education is especially relevant here given the adolescent nature of the players and the potential to instill sound nutritional habits and behaviours as they transition to adulthood and the professional game.

As with all dietary assessment studies, the present study is not without limitations. Indeed, the present paper is based one team only and our data cannot be generalized to other female soccer teams. Furthermore, and as alluded to previously, inferences around EA and sub-optimal CHO intakes are largely based on laboratory studies where in the context of the latter, current recommendations are largely based on male athletes. The present study did also not evaluate the effects of players' habitual dietary practices on associated performance metrics, fatigue indices or any symptomology associated with the REDs or female athlete triad models. When considered this way, it is clear that a strategic approach to further research is now required to more accurately inform the creation of evidence based nutritional guidelines for this population.

Conclusion

In summary, the present data provide the first report to assess the habitual dietary practices of a cohort of adolescent players currently playing at the highest level of the game (i.e., international standard). Although we acknowledge the potential for dietary under-reporting, our data are still suggestive of players under-fuelling for the work required. This is especially the case in relation to total daily CHO intake during times of intense training and competition.

Chapter Six

Study Four

Energy Expenditure, Intake and Availability in Female Soccer Players via Doubly Labelled Water: Are we Misdiagnosing Low Energy Availability?

This paper was published in Experimental physiology (2024):

McHaffie, S. J., Langan-Evans, C., Strauss, J. A., Areta, J. L., Rosimus, C., Evans, M. & Morton, J. P. (2024). Energy expenditure, intake and availability in female soccer players via doubly labelled water: Are we misrepresenting low energy availability? *Experimental physiology*.

6.1. Abstract

Female soccer players have been identified as presenting with LEA, though the prevalence of LEA may be overestimated given inaccuracies associated with self-reporting dietary intakes. Accordingly, we aimed to quantify TDEE via the DLW method, EI (EI) and energy availability (EA). Adolescent female soccer players (n = 45; 16 ± 1 years) completed a 9–10 day 'training camp' representing their national team. Absolute and relative TDEE was 2683 ± 324 and 60 ± 7 $kcal·kg^{-1}$ FFM, respectively. Mean daily EI was lower ($P < 0.01$) when players self-reported using the RFPM (2047 ± 383 $kcal.day^{-1}$) over a 3-day period versus DLW derived EI estimates accounting for BM changes (2545 ± 518 $kcal·day^{-1}$) over 7–8 days, representing a mean daily Δ of 499 ± 526 $kcal·day^{-1}$ and 22% error when using the RFPM. Estimated EA was different ($P < 0.01$) between methods (DLW: 48 ± 14 $kcal·kg^{-1}$ FFM, range: 22–82; RFPM: 37 ± 8 $kcal·kg^{-1}$ FFM, range: 22–54), such that prevalence of LEA (<30 $kcal·kg^{-1}$ FFM) was lower in DLW compared with RFPM (5% vs. 15%, respectively). Data demonstrate the potential to significantly underestimate EI when using self-report methods. This approach can therefore cause a misrepresentation and an over-prevalence of LEA, which is the underlying aetiology of 'relative energy deficiency in sport' (REDs).

6.2. Introduction

In 2023, the International Olympic Committee published their most recent consensus statement on 'relative energy deficiency in sport' (REDs), defined as 'a syndrome of impaired physiological and psychological functioning caused by exposure to problematic (prolonged and/or severe) LEA (Mountjoy et al., 2023a). Although it is suggested that REDs may occur in both female and male athletes (Ackerman et al., 2019), the study of LEA (which is the underlying aetiology of REDs) is more prominent in female athletes as a result of the historical assumption that this syndrome exclusively impacted female athletes (Nattiv & Lynch, 1994). However, in recognising that LEA may compromise other physiological symptoms beyond that of bone health and menstrual function (De Souza et al., 2019; Nattiv et al., 2021), it is now acknowledged within the latest REDs consensus statement that 'REDs may present as decreased energy metabolism, reproductive function, musculoskeletal health, immunity, glycogen synthesis and cardiovascular health, the result of which is associated with impaired well-being, increased injury risk and decreased sports performance in both male and female athletes' (Mountjoy et al., 2023a).

In considering that LEA is an exposure variable at the centre of the REDs health and performance conceptual models (that when problematic may result in various deleterious symptoms outlined in the REDs model), it is unsurprising that REDs is most frequently studied in the context of those athletes that routinely present with high TDEE and/or sub-optimal EI (e.g., gravitational, weight-categorised and aesthetic sports). In addition to the aforementioned sports and our own findings withing Study Three, a growing body of literature also suggests that LEA is evident in female soccer players (Dasa et al., 2023; Morehen et al., 2021; Moss et al., 2021; Reed et al., 2014). For example, in categorising LEA using traditional laboratory derived classifications of <30 $kcal{\cdot}kg^{-1}$ $FFM{\cdot}day^{-1}$ (Loucks & Thuma, 2003; Loucks et al., 1998), we reported a high prevalence of LEA in both international standard adult (Morehen et al., 2021) and adolescent (Study Three) female soccer players of 88% and 34%, respectively. It is acknowledged, however, that the adoption of a cut-off point of <30 $cal{\cdot}kg^{-1}$ $FFM{\cdot}day^{-1}$ is grounded in short-term laboratory studies (Ihle & Loucks, 2004; Loucks et al., 1998; Loucks & Thuma, 2003), with recent real-life clinical investigations challenging the appropriateness of a singular, universal threshold in free-living athletes (Burke et al., 2018; Deutz et al., 2000; Fahrenholtz et al., 2018). Indeed, recent research reveals considerable variations in the EA values that are linked to adverse health and performance outcomes across individuals, sex and diverse bodily systems (De Souza et al., 2022; Lieberman et al., 2018; Salamunes et al., 2024).

In considering that EA is calculated as the difference between dietary EI and EEE expressed relative to the individual's FFM (Loucks et al., 2011), the cause of LEA in female soccer players has been largely attributed to sub-optimal EI (Dasa et al., 2023; Morehen et al., 2021; Moss et al., 2021). This assertion is based on the observation that the habitual training volume and associated TDEE of such players is relatively comparable to male soccer players (Anderson et al., 2017) and moreover, is not considered excessive when compared with female endurance athletes (Heydenreich et al., 2017; Schulz et al., 1992). Furthermore, in using a qualitative research methodology, within Study One we also reported a culture of 'CHO fear' amongst female soccer players, where such athletes may intentionally practice periods of deliberate 'under-fuelling' due to a fear of gaining body fat and perceived external pressure from staff members and social media. Notwithstanding these recent data, it is also important to adopt a more critical lens when evaluating the true extent of LEA in female soccer players (Parker et al., 2022). Indeed, it is well documented that assessment of dietary intake has known limitations including conscious or unconscious under-reporting (Gemming et al., 2014; Livingstone & Black, 2003; Martin et al., 2012; Rollo et al., 2016; Thompson et al., 2010) alongside both intra- and inter-coder error when evaluating dietary records (Stables et al., 2021), especially in the context of the recently popularised RFPM. Accordingly, when we applied a recently published correction factor (22%) to account for potential dietary under-reporting in female soccer players (Dasa et al., 2023), we observed that the prevalence of LEA (albeit defined as <30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$) was reduced from 34% to 5%, within Study Three.

To overcome such methodological limitations, an alternative method for measuring EI is to utilise the DLW technique (as the gold standard method to directly assess TDEE in free living conditions) alongside measuring changes in BM over a known duration (de Jonge et al., 2007; Pieper et al., 2011; Tarnowski et al., 2023). In this way, the DLW method can be used to calculate EI and reduce the error associated with self-reporting dietary intake (Capling et al., 2017; Poslusna et al., 2009). Although we also acknowledge that inaccuracies exist beyond EI when measuring EA (e.g., surrounding the definition of 'exercise', assessment of EEE and measurement of FFM; Areta et al., 2021), the use of DLW-derived estimates of EI is still likely to lead to a more accurate evaluation of the true prevalence of LEA in this population. This consideration gains added significance since research employing DLW has been conducted to a lesser extent in female athletes compared to male athletes. This disparity is noteworthy especially since female athletes seem to be more adversely affected by LEA, in comparison to male athletes (Areta et al., 2021; Koehler et al., 2016).

With this in mind, the aim of the present study was to utilise the DLW method to quantify TDEE, EI and EA in female soccer players. In using the largest total sample size studied to date (n = 45), we assessed a cohort of international adolescent female soccer players during which they took part in an extended training camp where they completed a training and game schedule representing their national team. We specifically hypothesised that EA would be significantly greater when calculated from DLW-derived assessments of EI versus those estimates of EI derived from the RFPM.

6.3. Methods

Ethics approval

The study was conducted according to the Declaration of Helsinki and was approved by the University Ethics Committee of Liverpool John Moores University (22/SPS/027). All experimental procedures and associated risks were explained to players and written informed consent provided, with parental/guardian consent and player assent also obtained for participants <18 years old.

Participants

Forty-five female international soccer players competing at international under 17 (U17s) (n = 17) and under 19 (U19s) (n = 28) level volunteered to take part in the study. Participant characteristics categorised by squad and as a whole sample cohort are presented in Table 6.1.

Table 6.1. Participant characteristics. Mean age, stature, BM, FFM, FM and percent body fat values are presented according for each squad and as a whole sample. Predicted RMR was calculated according to Roza & Shizgal (1984).

	Under 17s (n = 17)	**Under 19s (n = 28)**	**Whole Sample (n = 45)**
Age (years)	16.4 ± 0.4	17.9 ± 0.5	17.4 ± 0.4
Stature (cm)	168.4 ± 6.1	168.0 ± 5.9	168.1 ± 6.0
BM (kg)	60.3 ± 8.4	61.1 ± 6.0	60.8 ± 7.0
FFM (kg)	46.1 ± 5.2	44.3 ± 4.9	45 ± 5.1
FM (kg)	14.9 ± 5.0	16.8 ± 3.7	16.1 ± 4.3
Body Fat %	23.9 ± 6.1	27.3 ± 4.4	26.1 ± 5.4
Predicted RMR (kcal·day^{-1})	1457 ± 92	1457 ± 70	1457 ± 79

Overview of study design

Data were collected from participants during an international training and match fixture camp, lasting 10 days (U17s) and 9 days (U19s), respectively. The U17s camp featured three match days, four training days and three rest days, whilst the U19s camp comprised two match days, five training days and two rest days, as outlined in Tables 6.2 and 6.3. Tables 6.2 and 6.3 also detail the external load of each camp, presented as daily values coded relative to the match days (e.g., MD−1 is the day before the match) and total values. The DLW technique was used to measure TDEE throughout the data collection period. During each camp, all the players self-reported their dietary intake using the RFPM on MD−1, MD and MD+1, and EI was also calculated based on the DLW derived assessment of TDEE, in combination with changes in BM (Tarnowski et al., 2023). Pitch-based training and match load were measured using GPS technology. EEE was estimated using GPS technology and RPEs for on-pitch and gym-based strength and conditioning sessions, respectively. FFM data were derived using the DLW technique and in combination with EI (using both methods) and EEE data was used to calculate EA.

Table 6.2. An overview of external loading throughout the 10-day period of the Under 17s training and fixture period. Daily and overall pitch-based training and match duration (min), distance (m), distance at speed zone one (m), distance at speed zone two (m), distance at speed zone three (m), frequency of accelerations (AU) and frequency of decelerations (AU).

	MD-2	MD-1	MD	MD+1	MD-1	MD	MD+1	MD-1	MD	MD+1	Mean Total
Duration (min)	76 ± 3	70 ± 0	69 ± 40	0	73 ± 4	79 ± 32	0	62 ± 0	82 ± 0 41	0	512 ± 77
Distance (m)	6184 ± 457	4721 ± 386	6326 ± 4014	0	4308 ± 435	6995 ± 3031	0	3932 ± 318	7650 ± 4740	0	40116 ± 8786
Distance covered at Speed Zone One (3.46-5.28 m·s^{-1}**) (m)**	930 ± 218	691 ± 81	998 ± 746	0	699 ± 129	1025 ± 520	0	594 ± 139	1301 ± 1030	0	6238 ± 2001
Distance covered at Speed Zone Two (5.29-6.25 m·s^{-1}**) (m)**	358 ± 263	213 ± 169	229 ± 276	0	296 ± 214	234 ± 204	0	193 ± 133	368 ± 403	0	1890 ± 1416
Distance covered at Speed Zone Three (≥6.26 m·s^{-1}**) (m)**	74 ± 47	22 ± 13	66 ± 50	0	48 ± 45	88 ± 68	0	34 ± 29	157 ± 126	0	488 ± 257
Frequency of Accelerations (>3m·s^{-1}) (AU)	40 ± 10	43 ± 10	34 ± 0 23	0	44 ± 11	38 ± 16	0	38 ± 10	44 ± 25	0	281 ± 69
Frequency of Decelerations (>3m·s^{-1}) (AU)	48 ± 13	50 ± 11	39 ± 30	0	45 ± 9	48 ± 23	0	39 ± 9	53 ± 35	0	321 ± 89

Table 6.3. An overview of external loading throughout the 9-day period of the Under 19s training and fixture period. Daily and overall pitch-based training and match duration (min), distance (m), distance at speed zone one (m), distance at speed zone two (m), distance at speed zone three (m), frequency of accelerations (AU) and frequency of decelerations (AU).

	MD-2	**MD-1**	**MD**	**MD+1**	**MD-3**	**MD-2**	**MD-1**	**MD**	**MD+1**	**Mean Total**
Duration (min)	88 ± 26	79 ± 6	120 ± 30	0	106 ± 24	113 ± 19	83 ±35	92 ± 59	0	680 ± 91
Distance (m)	4197 ± 1656	4092 ± 1417	8401 ± 309	0	5320 ± 1307	4875 ± 1207	3994 ± 1851	5129 ± 4064	0	36,009 ± 5836
Distance covered at Speed Zone One (3.46-5.28 $m \cdot s^{-1}$**) (m)**	509 ± 274	445 ± 288	1328 ± 691	0	602 ± 201	559 ± 283	430 ± 324	897 ± 862	0	4770 ± 1573
Distance covered at Speed Zone Two (5.29-6.25 $m \cdot s^{-1}$**) (m)**	111 ± 134	119 ± 164	273 ±178	0	135 ± 117	171 ± 134	132 ± 190	165 ± 139	0	1106 ± 632
Distance covered at Speed Zone Three (≥6.26 $m \cdot s^{-1}$**) (m)**	48 ± 86	35 ± 43	126 ± 182	0	78 ± 146	79 ± 150	80 ± 165	62 ± 80	0	509 ± 651
Frequency of Accelerations (>3$m \cdot s^{-1}$**) (AU)**	29 ± 12	45 ± 17	56 ± 18	0	40 ± 15	33 ± 11	41 ± 20	31 ± 27	0	276 ± 60
Frequency of Decelerations (>3$m \cdot s^{-1}$**) (AU)**	35 ± 18	43 ±16	64 ± 24	0	49 ± 20	34 ± 13	39 ± 20	37 ± 35	0	301 ± 84

Quantification of external training and match load

Training and match load were measured using GPS technology (Apex, STATSports, Newry, UK), with units worn by all outfield players (n = 40) for all the pitch-based training sessions and matches. The GPS units were placed inside custom-made manufacturer-provided vests (Apex, STATSports), which were positioned on the players' upper-back between both scapulae, allowing the exposure of the GPS antennae to acquire a clear satellite connection. Variables measured included session duration in minutes (min), distance covered in metres (m), frequency of accelerations (an increase in speed of >3 m s−1), frequency of decelerations (a decrease in speed of <3 m s−1) and time spent in three different speed zones: zone 1 (3.46−5.28 m s−1), zone 2 (5.29−6.25 m s−1) and zone 3 (≥6.26 m s−1). These categories are commonly used within this population, as established by Park et al. (2019).

During Exercise Energy Expenditure

For pitch-based sessions, GPS devices with individualised player descriptives inputted provided gross EEE values, which were subsequently increased by 10.7%, based on recent data demonstrating that this GPS system underestimates EEE within this population (Dasa et al., 2022). Gross EEE values for pitch-based sessions were converted into net EEE using RMR estimations based on the updated Harris–Benedict equation (Roza & Shizgal, 1984), whereby the energy expended for RMR during the session and TEF (assumed to be 10%) were subtracted from the estimation of gross EEE, resulting in a value of net EEE. For gym-based sessions, EEE was estimated based on the timing of each individual session, the participant's RPE and the content of each session. Using these data, each gym session could be converted into a MET for the assigned period (Butte et al., 2018), allowing an estimation of EEE for each individual session. Physical activity level (PAL) was also determined by dividing the TDEE by RMR.

Measuring of energy expenditure using the DLW technique

TDEE (kJday^{-1}) was estimated using the DLW technique (Lifson & McClintock, 1966). This method has been previously validated on multiple occasions by comparison to simultaneous indirect calorimetry in humans (Speakman, 1997). A pre-dosing urine sample was collected during the evening of day zero, to estimate background isotope enrichments for each individual. Participants were weighed and then dosed orally by drinking a weighed quantity of mixed isotopes provided by the University of Aberdeen in a sealed bottle. This single bolus oral dose was weighed to four decimal places of deuterium (2H2) and oxygen (18O) stable isotopes in the form of water (2H218O), with a desired enrichment of 10% 18O and 5% 2H2 using the calculation:

where 0.65 is the approximate proportion of the body comprised of water, DIE is the desired initial enrichment (DIE = 618.923 BM (kg) − 0.305) and IE is the initial enrichment (100,000 parts per million) (Speakman, 1997), dosed according to BM two weeks prior to the national training camp. To ensure the whole dose was administered, participants were observed consuming each bolus, and each glass vial was refilled with additional water, which players were asked to consume. Time of dosing and urine sample were recorded throughout the study period. Urine samples were collected on the morning of day 1, approximately 12 h post-dose, to obtain the initial isotope enrichments, following total body water equilibrium (Speakman, 1997). Further urine samples (2nd void of the day) were collected daily until the last day of the training camp. In addition, daily samples were also collected from a non-dosed individual of the team, to adjust for variations in the background level of the isotopes, which may have occurred when travelling to a new country during the early stages of the study. All urine samples were collected by the participants in a 100 ml urine pot, before being immediately transferred into 1.5 ml cryovials. All samples were then kept frozen (−17.8°C) and then transported on dry ice, until subsequent analysis. Analysis of the isotopic enrichment of urine was performed blind, using a Liquid Isotope Water Analyser (DLT-100, Los Gatos Research, California, USA) (Berman et al., 2013). Initially the urine was vacuum distilled (Nagy et al., 1993), and the resulting distillate was used for analysis. Samples were run alongside five lab standards for each isotope and international standards to adjust for daily machine variation and correct delta values to parts per million. Daily isotope enrichments were loge converted after adjusting for the background fluctuations, and the elimination constants (Ko and Kd) were calculated by fitting a least squares regression model to the loge-converted data. The back extrapolated intercept was used to calculate the isotope dilution spaces (No and Nd). A two-pool model, specifically Speakman (1997), was used to calculate rates of CO_2 production.

Assessment of energy intake using the remote food photography method

Self-reported energy and macronutrient intake was quantified on three days. These days corresponded with MD−1, MD and MD+1 for the U17s (days 5, 6 and 7) and U19s (days 2, 3 and 4), measured using the RFPM (Martin et al., 2012). Although this methodology has been questioned with regards to its accuracy when assessing EI (Capling et al., 2017), these data were collected for comparison to the DLW assessment of EI and to provide insights into macronutrient intake. As the lead researcher was present for the entire training camp, reminders were made in person throughout the entire data collection period, alongside physical prompts being placed in the dining area to further enhance compliance. As per the protocol, participants were instructed to take two images, at 90° and 45° of any food or drink they consumed throughout the three days, including all meals and snacks. A third image was also taken of any leftovers, if required. These images were sent to the lead researcher via the mobile telephone application Threema (Threema GmbH, Pfäffikon, Switzerland). Participants were also instructed to send a brief description of the food items that they consumed, including quantities, brands and food types. The lead researcher constructed two portions (small and large) of each of the foods available, prior to the arrival of players and staff members for meal times. These were weighed and photographed, providing detail to compare to during the analysis process, for a more accurate overview of portion size. Descriptions of foods and drinks consumed before, during and after training and matches were also recorded, as players did not have access to their phones at this time. Some players brought their own snacks to the training camp; however, all meals and multiple snacks were provided to players throughout each day, including during training matches. Once throughout the training camp, every player completed a dietary recall, to check for any missed data. Energy and macronutrient intake were analysed by a SENr accredited practitioner using the dietary analysis software Nutritics (Nutritics, v5, Dublin, Ireland), with energy and CHO intake quantified as kcal and grams, respectively, in both absolute and relative (to each player's BM) terms. To ensure reliability of energy and macronutrient intake data, a second SENr nutritionist also analysed a sample of food diaries chosen at random (n = 5, equating to 15 days of entries in total), with interrater reliability determined via an independent Student's t-test. No significant differences were observed between estimations for energy (P = 0.96; 95% CI: −156 to 38) and CHO (P = 0.11; 95% CI: −31 to 3) intake.

Assessment of energy intake using the doubly labelled water method

EI was calculated using the DLW method through the adjustment of TDEE for changes in energy stores, as outlined previously by Schulz et al. (1992). This was measured from day 1, up until the MD−1 before the last MD of camp 1 (day 8) and camp 2 (day 7). This time period was selected given BM is influenced to a greater extent by fluctuating muscle glycogen levels and total body water after an MD−1 and MD, due to CHO loading, in-game nutritional practices, as well as the demands of match play (Bergström et al., 1967). BM (SECA, model 875, Class III, Hamburg, Germany) was collected daily when players were in a fasted state prior to breakfast on all days, between 08.00 and 08.45 h, immediately following the participants' first urine pass of the day. Maintaining consistency in the timing of BM data collection was crucial for minimizing potential errors associated with daily fluctuations in BM levels, thereby reducing measurement variability. Players wore the same training kit and removed their shoes and any jewellery. The equation used was: EI ($kcal \cdot day^{-1}$) = TDEE ($kcal \cdot day^{-1}$) + change in energy stores (kcal in grams of body fat + kcal in grams of FFM change). As outlined by Schulz et al. (1992), this was estimated with the assumption that two-thirds of change in BM was metabolic and one-third was water, and that three-quarters of the change in metabolic mass was FM and one-quarter was FFM. For participants who lost BM, it was assumed 9 kcal g−1 of FM and 1 kcal g−1 of FFM and for BM gain, the assumption was 13.2 kcal g−1 of FM and 2.2 kcal g−1 of FFM (Forbes et al., 1986; Pullar & Webster, 1977; Spady et al., 1976).

Assessment of energy availability

EA for all outfield players was calculated using the formula EA = (EI − EEE)/FFM (Loucks et al., 1998), with FFM values established from the DLW method. This calculation was performed twice, first using EI data obtained via the DLW method, and second by employing the RFPM, to facilitate a comparison between these methodologies in measuring EA. Despite ongoing debates about the appropriateness of universal EA thresholds (Burke et al., 2018), this study classified players into categories of optimal EA (> 45 kcal·kg^{-1} FFM day^{-1}), reduced EA (30–45 kcal·kg^{-1} FFM·day^{-1}) and low EA (< 30 kcal·kg^{-1} FFM·day^{-1}) to allow for comparative analysis with previous research on female soccer players (Dasa et al., 2023; Morehen et al., 2021; Moss et al., 2021) and our own findings in Study Three. This categorization was employed alongside the presentation of raw EA values calculated by both methods, to provide a comprehensive assessment of energy status.

Statistical analysis

All data were initially assessed for normality of distribution via a visual inspection of histograms and a Shapiro–Wilk test. To determine differences between days in absolute and relative energy and macronutrient intake, EA and positional differences in TDEE, a univariate one-way between groups analysis of variance (ANOVA) was used. Where significant main effects were present, Fisher's least significant difference post hoc analysis was conducted for pairwise comparisons. Ninety-five percent confidence intervals (95% CI) for the differences are also presented. External training load, TDEE, TDEE relative to BM and TDEE relative to FFM were compared between U17 and U19 players using an independent Student's t-test and changes in BM within squads were analysed using a paired sample t-test. The strength of association between DLW and RFPM EI measurements was assessed using Pearson (r) correlation analysis, employing the following criteria to explain the relationship of association: trivial <0.1, small 0.1–0.29, moderate 0.3–0.49, large 0.5–0.69, very large 0.7–0.89 and almost perfect 0.9–1.00 (Hopkins et al., 2009). To assess the validity of the RFPM, we evaluated its accuracy by calculating the percentage error in EI measurements taken with RFPM, using EI measured by the DLW method as the reference standard. The percentage error was determined by comparing the observed values from RFPM to the true values obtained from DLW. Additionally, the percentage difference between these two methods was calculated to further quantify discrepancies in measurement accuracy. Least squares regression was also used to assess validity, where DLW EI was regressed against RFPM EI measurements (Hopkins et al., 2009). Fixed bias was assessed by determining whether the intercept for the regression was different from zero and proportional bias was deemed present if the slope of the regression line was different from one. Random error was quantified using standard error of the estimate (SEE) from the regression. Predictive accuracy of each equation for individuals was calculated and evaluated based on the mean of 95% prediction interval (95% PI) for each regression equation. However, it is important to note that the literature currently lacks a universally accepted error rate for EI measurements, which limits the context for direct comparison of our findings. Relationships between daily EE and BM, FFM, stature, age, TD and total duration, as well as EB using both methods of measuring EI were also assessed using Pearson's correlation. All statistical analyses were completed using SPSS Statistics (version 26; IBM Corp., Armonk, NY, USA) where $P < 0.05$ is indicative of statistical significance. All data are presented as means ± SD.

6.4. Results

External loading patterns during both training camps

For illustrative purposes, an overview of outfield players' external loading patterns for those players partaking in the U17s training camp (n = 15) and U19s training camp (n = 25) are presented in Tables 6.2 and 6.3, respectively. When comparing the 7 days of 'exercise' completed on both training camps, there was a significant difference in total duration of time 'on pitch' ($P < 0.01$) during the U19s camp (680 ± 93 min) compared with the U17s camp (512 ± 80 min; 95% CI: −227 to −110 min). However, there were no significant differences between camps for cumulative TD (U17s: 40,116 ± 9095 m; U19s: 36,009 ± 5957 m; 95% CI : −701 to 8915 m; P = 0.09), TD in speed zone 2 (U17s: 1890 ± 1466 m; U19s: 1106 ± 646 m; 95% CI: −58 to 1627 m; P = 0.07), distance in speed zone 3 (U17s: 488 ± 266 m; U19s: 509 ± 665 m; 95% CI: −385 to 345 m; P = 0.91), frequency of total accelerations (U17s: 281 ± 69; U19s: 276 ± 60; 95% CI: −37 to 47; P = 0.81) or frequency of total decelerations (U17s: 321 ± 92; U19s: 301 ± 86; 95% CI: −39 to 78 m; P = 0.5). In contrast, U17 players completed more accumulative distance (6238 ± 2071 min) in speed zone 1 versus U19 players (4770 ± 93 m; 95% CI: 284–2652 m; P = 0.02).

Total daily energy expenditure

When comparing U17 and U19 players, there were no significant differences between mean absolute TDEE (U17s: 2671 ± 375 $kcal·day^{-1}$; U19s: 2689 ± 288 $kcal·day^{-1}$; 95% CI: −186 to 225 $kcal·day^{-1}$; P = 0.85; Figure 1a), TDEE relative to BM (U17s: 44 ± 5 $kcal·kg^{-1}$ $BM·day^{-1}$; .U19s: 44 ± 4 $kcal·kg^{-1}$ $BM·day^{-1}$; 95% CI: −2 to 3.5 $kcal·kg^{-1}$ $BM·day^{-1}$; P = 0.60; Figure 1b), TDEE relative to FFM (U17s: 58 ± 6 $kcal·kg^{-1}$ $FFM·day^{-1}$; U19s: 61 ± 7 $kcal·kg^{-1}$ $FFM·day^{-1}$; 95% CI: −0.1 to 7.7 $kcal·kg^{-1}$ $FFM·day^{-1}$; P = 0.06; Figure 1c) and PAL (U17s: 1.8 ± 0.2; U19s: 1.8 ± 0.2; 95% CI: −0.1 to 0.1; P = 0.79; Figure 1d). Given that there was no difference in TDEE and PAL between squads, when all players were pooled, TDEE was 2683 ± 324 $kcal·day^{-1}$ (range: 1871–3262 $kcal·day^{-1}$; Figure 6.1e). Additionally, no significant differences were apparent when comparing TDEE between goalkeepers (2777 ± 232 $kcal·day^{-1}$), defenders (2651 ± 403 $kcal·day^{-1}$), midfielders (2707 ± 267 $kcal·day^{-1}$) and attackers (2659 ± 349 $kcal·day^{-1}$) (all $P > 0.05$) (Figure 6.1f).

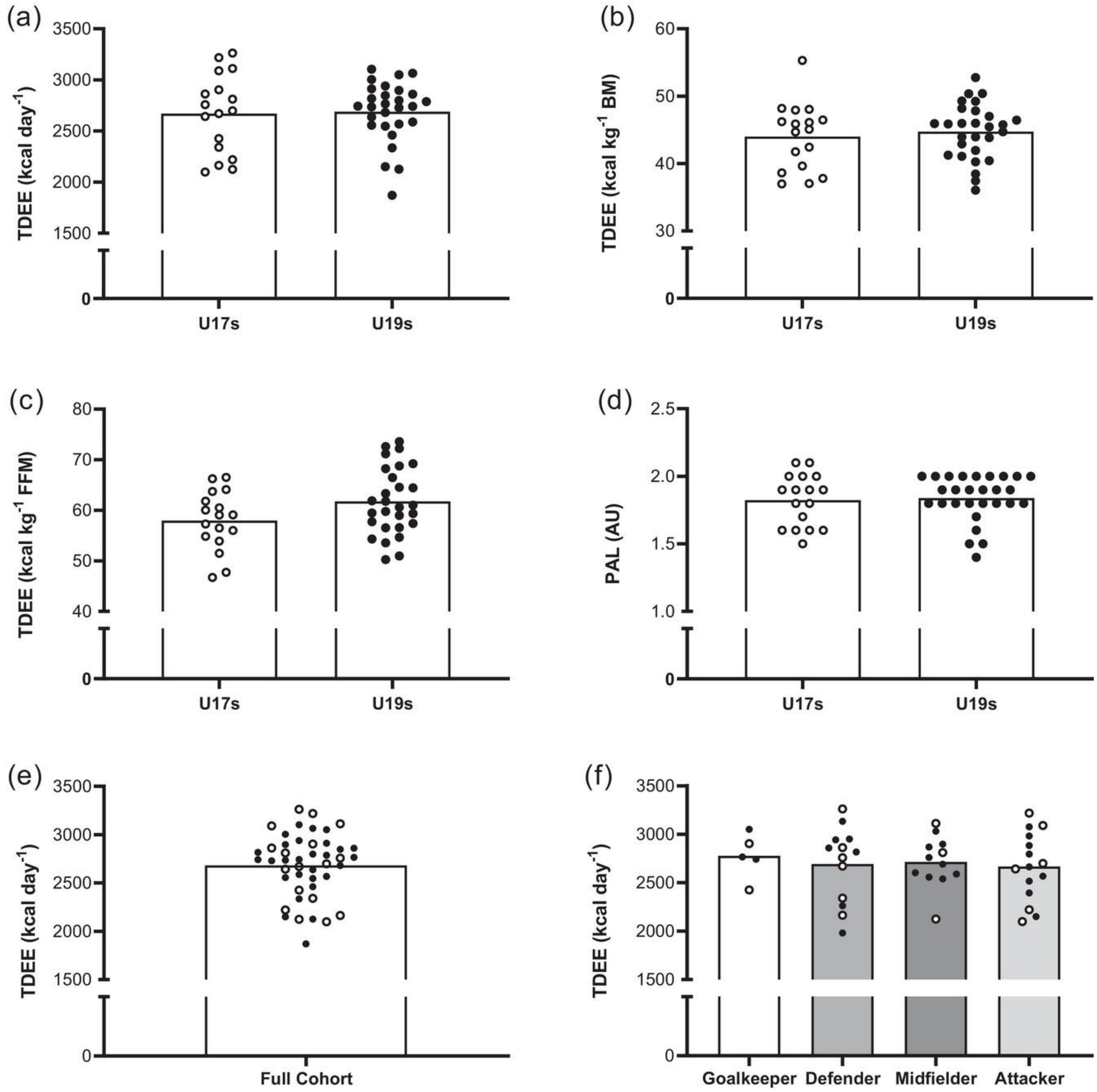


Figure 6.1. (a) Absolute TDEE, (b) TDEE relative to BM, (c) TDEE relative to FFM, (d) PAL, (e) TDEE of the entire cohort (*n* = 45), and (f) TDDE in each playing position. All individual circles represent an individual player, with open circles representing U17s (*n* = 17) and filled circles representing U19s (*n* = 28).

Relationship of factors to TDEE

There was a significant large positive relationship between TDEE and BM (r = 0.56; 95% CI: 0.37–0.72; P < 0.01) (Figure 2a), FFM (r = 0.69; 95% CI: 0.52–0.82; P < 0.01) (Figure 6.2b) and stature (r = 0.56; 95% CI: 0.32–0.73; P < 0.01) (Figure 6.2c). However, there was no significant relationship between TDEE and age (r = 0.13; 95% CI: −0.17 to 0.41; P = 0.39) (Figure 6.2d), TD (r = 0.20; 95% CI: −0.12 to 0.48; P = 0.21) (Figure 6.2e) or total duration (r = 0.14; 95% CI: −0.18 to 0.3; P = 0.40) (Figure 6.2f).

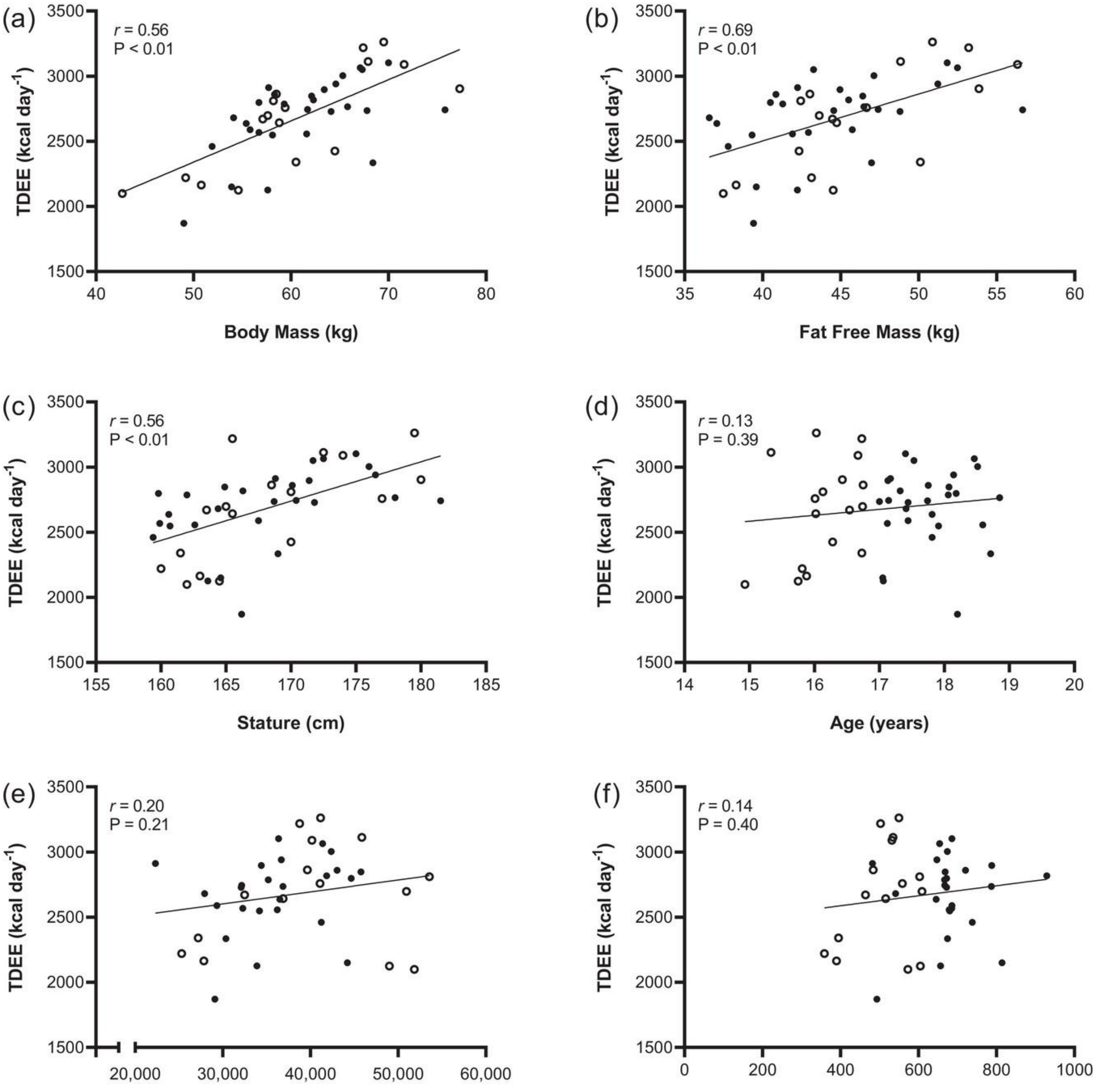


Figure 6.2. The relationships between TDEE and (a) BM, (b) FFM, (c) stature, (d) age, (e) TD, and (f) total duration (*n* = 45 for a–d; *n* = 40 for e, f). All individual circles represent an individual player, with open circles representing U17s (*n* = 17) and filled circles representing U19s (*n* = 28).

Self-Reported Energy and Carbohydrate intake via the Remote Food Photography Method

Mean daily EI (n = 45) using the RFPM was 2047 ± 383 kcal·day^{-1}. There was no significant difference in absolute EI between MD−1 (2126 ± 531 kcal·day^{-1}) and MD (2073 ± 463 kcal·day^{-1}; 95% CI: −206 to 314 kcal·day^{-1}; P = 1.00) or MD+1 (1941 ± 528 kcal·day^{-1}; 95% CI: −75 to 445 kcal·day^{-1}; P = 0.26). There was no significant difference in absolute EI between MD and MD+1 (95% CI: −129 to 391; P = 0.67) (Figure 3a). There were also no significant differences in EI between MD−1, MD or MD+1 when analysed relative to BM (35 ± 8.6 kcal·kg^{-1} day^{-1}, 34.2 ± 7.8 kcal·kg^{-1} day^{-1} and 31.9 ± 8.3 kcal·kg^{-1} day^{-1}, respectively; all P > 0.05) (Figure 6.3b). Total CHO intake was significantly lower on MD+1 (213 ± 63 g day^{-1}), in comparison to both MD−1 (265 ± 67 g day^{-1}; 95% CI: 18–86 g day^{-1}; P < 0.01) and MD (254 ± 67 g day^{-1}; 95% CI: 7–74 g day^{-1}; P = 0.012) (Figure 6.3c). Relative to BM, CHO intake was also significantly lower on MD+1 (3.5 ± 1 g·kg^{-1} day^{-1}), in comparison to MD−1 (4.4 ± 1.1 g·kg^{-1} day^{-1}; 95% CI: 0.3–1.4 g·kg^{-1} day^{-1}; P < 0.01) and MD (4.2 ± 1.1 g·kg^{-1} day^{-1}; 95% CI: 0.1–1.2 g·kg^{-1} day^{-1}; P = 0.01) (Figure 6.3d).

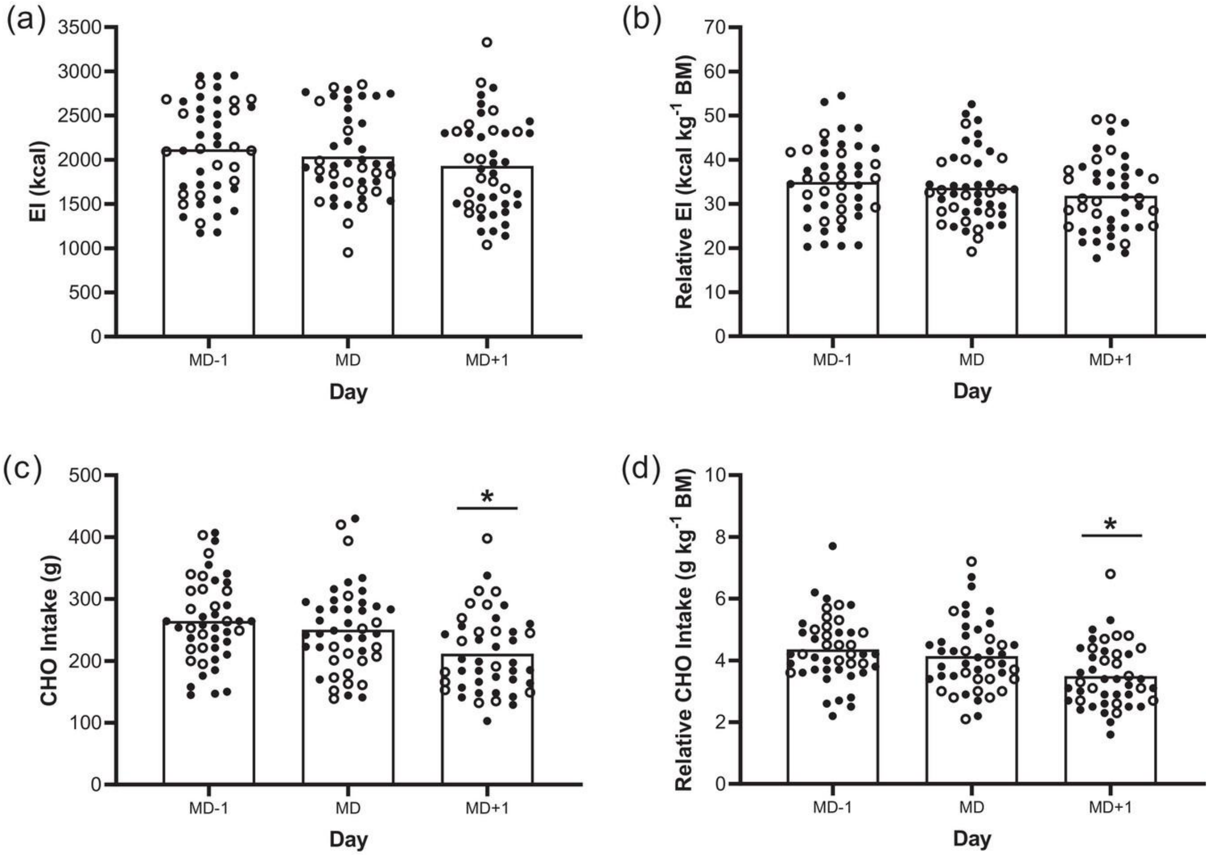


Figure 6.3. Absolute (a) and relative (b) EI and absolute (c), and relative (d) CHO intake across the 3-day assessment period (*n* = 45 for all variables). All individual circles represent an individual player, with open circles representing U17s (*n* = 17) and filled circles representing U19s (*n* = 28). *Significant difference between days (*P* < 0.05).

DLW derived energy intake versus RFPM

The mean daily EI using the RFPM of 2047 ± 383 $kcal \cdot day^{-1}$ was significantly lower than EI estimated using the DLW technique (2545 ± 518 $kcal \cdot day^{-1}$; $P < 0.01$), representing a mean daily Δ of 499 ± 526 $kcal \cdot day^{-1}$. This corresponds to a 25% difference between methods and a 22% error when using the RFPM, as calculated where the DLW method is assumed as the true value (Figure 4a and Table 6.4). There was a significant moderate positive correlation between the DLW and RFPM EI measurements ($r = 0.34$; 95% CI: 0.06–0.58; $P = 0.02$). However, the random error associated with each measurement was relatively large at 498 $kcal \cdot day^{-1}$, with the 95% PI for the RFPM EI method being 1026 (2051) $kcal \cdot day^{-1}$. The RFPM EI method demonstrated the presence of both unacceptable fixed (1595; 95% CI: 782–2408) and proportionate (0.46; 95% CI: 0.07–0.86) biases, highlighting under and overestimation of values versus the DLW EI method (Figure 6.4b). This discrepancy between methods was reflected when converted to EB, as there was no significant correlation between mean daily EB when calculated using the RFPM (−634 ± 434 $kcal \cdot day^{-1}$), in comparison to the DLW technique (−135 ± 417 $kcal \cdot day^{-1}$; $r = 0.24$; 95% CI: 0.06–0.50; $P = 0.11$) (Figure 6.4c). During the DLW derived EI assessment period there was a significant change in BM, with BM decreasing from Day 0 (61.3 ± 7.5 kg) to Day 7/8 (61.0 ± 6.5 kg; 95% CI: 0.1–0.4; $P < 0.01$) (Figure 6.4d).

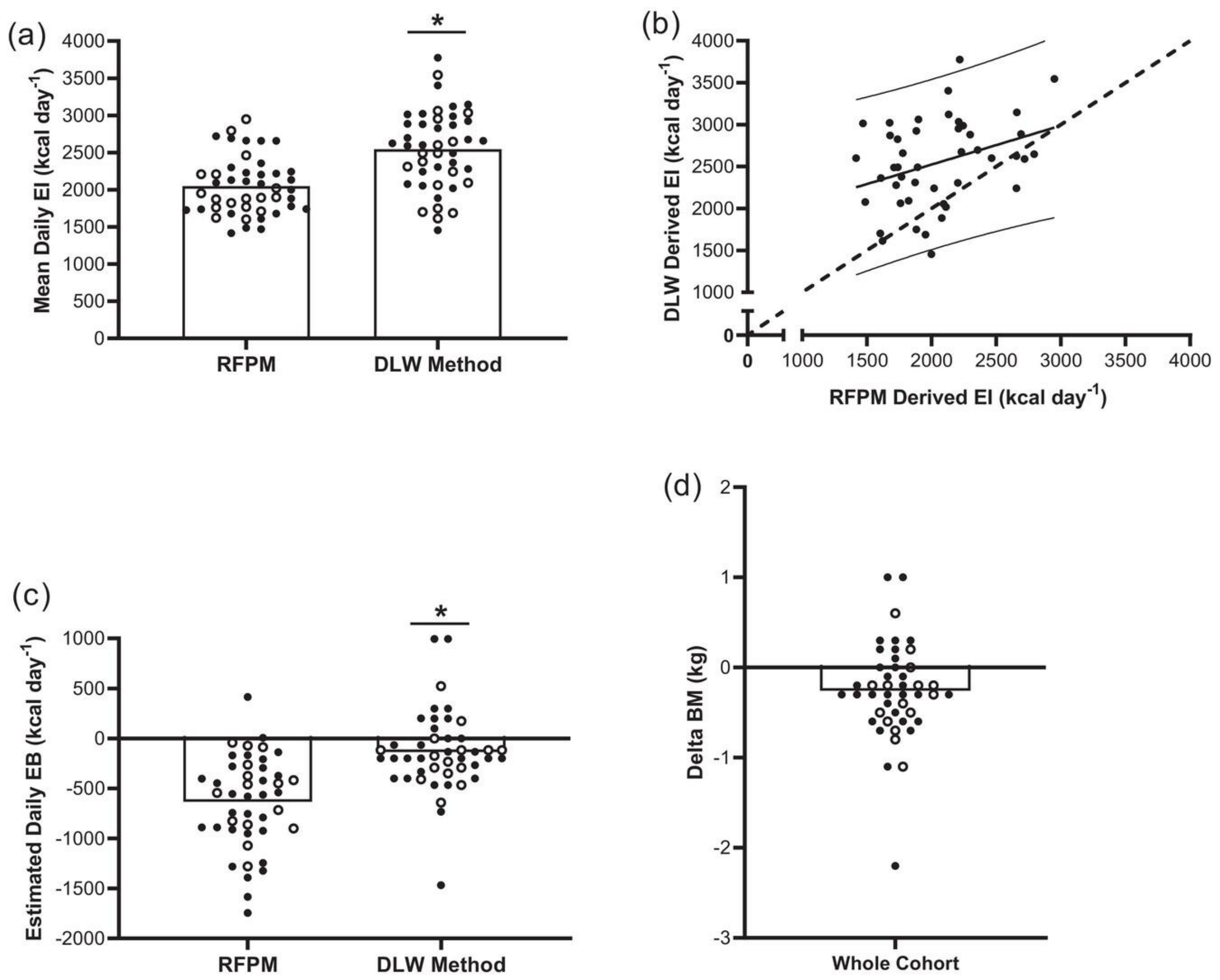


Figure 6.4. (a) Estimated daily EI using the RFPM and DLW method, (b) change in BM during the DLW derived EI assessment period, (c) estimated EB using the RFPM and DLW method, and (d) the strength of association between DLW and RFPM EI measurements (n = 45 for all variables). All individual circles represent an individual player, with open circles representing U17s (n = 17) and filled circles (n = 28) representing U19s. *Significant difference between methods (P < 0.05).

Player	Baseline BM (kg)	BM change (kg)	TDEE (kcal·day^{-1})	EI (RFPM) (kcal·day^{-1})	EI (DLW) (kcal·day^{-1})	ΔEI: DLW minus RFPM (kcal·day^{-1})	Percent difference (%)	Percent Error (%)
Player 1	64	1	2781	2218	3776	1558	52.0	41.3
Player 2	54.6	1	2409	2130	3404	1274	46.0	37.4
Player 3	67.5	0.6	3022	2949	3544	595	18.3	16.8
Player 4	80.1	0.3	2687	2692	2887	195	7.0	6.8
Player 5	57.9	0.3	2625	1882	2924	1042	43.4	35.6
Player 6	63.6	0.3	2689	2243	2988	745	28.5	24.9
Player 7	66.5	0.2	2921	2132	3120	988	37.6	31.7
Player 8	59.3	0.2	2628	1737	2827	1089	47.7	38.5
Player 9	60.6	0.2	2136	1873	2310	437	20.9	18.9
Player 10	57.2	0.1	2922	1677	3021	1345	57.2	44.5
Player 11	74	0	3035	2210	3035	825	31.4	27.2
Player 12	62	0	2880	2299	2880	581	22.4	20.2
Player 13	54	0	2242	2657	2242	-415	17.0	18.5
Player 14	67.3	-0.1	3214	2660	3147	487	16.8	15.5
Player 15	51.1	-0.1	2373	2203	2306	103	4.6	4.5
Player 16	56.9	-0.2	2497	1608	2363	756	38.1	32.0
Player 17	68.2	-0.2	3177	1898	3061	1163	46.9	38.0
Player 18	58.6	-0.2	2609	1892	2492	600	27.4	24.1
Player 19	51	-0.2	2178	1760	2062	302	15.8	14.6
Player 20	60.7	-0.2	3070	2208	2953	745	28.9	25.2
Player 21	49.2	-0.2	2226	1823	2093	270	13.8	12.9
Player 22	55.9	-0.3	1925	1882	1750	-132	7.3	7.5
Player 23	78.5	-0.3	2691	2356	2697	341	13.5	12.6
Player 24	66.1	-0.3	2825	1470	3014	1544	68.9	51.2
Player 25	64.3	-0.3	2897	1739	2491	752	35.6	30.2
Player 26	63.4	-0.3	3214	2657	2625	-32	1.2	1.2
Player 27	55.1	-0.3	2442	2020	2242	222	10.4	9.9
Player 28	58.6	-0.3	3070	1679	2870	1191	52.4	41.5
Player 29	52.1	-0.3	2479	1726	2279	553	27.6	24.3
Player 30	58.5	-0.4	2880	2793	2647	-146	5.4	5.5
Player 31	56.5	-0.4	2858	2719	2591	-128	4.8	4.9
Player 32	57.5	-0.5	2782	1710	2490	780	37.1	31.3
Player 33	57.8	-0.5	2669	1768	2377	610	29.4	25.6
Player 34	64.5	-0.5	2387	2093	2054	-39	1.9	1.9
Player 35	43.3	-0.6	2052	1603	1702	99	6.0	5.8
Player 36	70.6	-0.6	3059	1778	2659	881	39.7	33.1
Player 37	68.6	-0.6	2287	2080	1887	-193	9.7	10.2
Player 38	63	-0.6	3001	1416	2601	1185	59.0	45.6
Player 39	70	-0.7	3009	2464	2601	137	5.4	5.3
Player 40	67.7	-0.7	3140	2230	2674	443	18.1	16.6
Player 41	62	-0.7	2485	2112	2019	-93	4.5	4.6
Player 42	55	-0.8	2081	1622	1614	-8	0.5	0.5
Player 43	56.3	-1.1	2811	1487	2077	591	33.1	28.4
Player 44	59.1	-1.1	2329	1953	1687	-266	14.6	15.8
Player 45	69.3	-2.2	2923	1999	1456	-543	31.4	37.3
Mean ± SD	**61.3 ± 7.4**	**-0.3 ± 0.5**	**2680 ± 343**	**2047 ± 383**	**2545 ± 518**	**499 ± 528**	**25 ± 18**	**22 ± 14**

Table 6.4. Individual data including BM at baseline, change in BM during the DLW derived EI assessment period, TDEE during the DLW derived EI assessment period, EI measured using the RFPM assessment period, estimated EI using the DLW method, delta difference between both EI methods, percent difference and percent error with the DLW method assumed to be the true value.

Estimated Energy Availability

Mean daily EA was significantly higher ($P < 0.01$) when using EI data derived from the DLW technique (48 ± 14 kcal·kg^{-1} FFM·day^{-1}), in comparison to using EI data derived from the RFPM (37 ± 8 kcal·kg^{-1} FFM·day^{-1}). When using the RFPM, there was a prevalence of 7 (18%), 27 (68%) and 6 (15%) players in a state of optimal EA, reduced EA and LEA, respectively. In contrast, when the DLW method was employed, 23 (58%) players were in a state of optimal EA, 15 (38%) reduced EA and only 2 (5%) in a state of LEA.

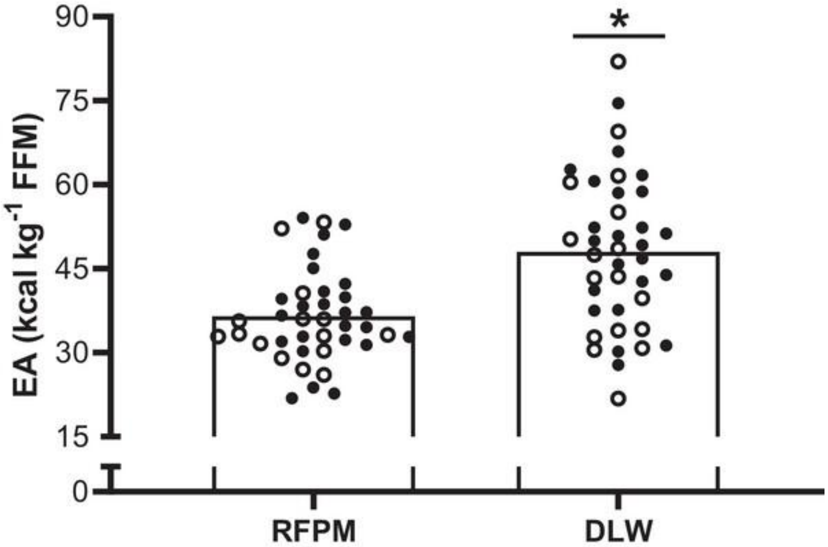


Figure 6.5. Mean daily EA calculated using the RFPM and DLW method for all outfield players (n = 40). All individual circles represent an individual player, with open circles representing U17s (n = 15) and filled circles representing U19s (n = 25). *Significant difference between methods (P < 0.05).

6.5. Discussion

In using the DLW method, the aim of the present study was to quantify TDEE, EI and EA of female adolescent soccer players. Confirming our hypothesis, these data demonstrate that DLW-derived estimates of EI were significantly greater than estimates derived from the RFPM. Accordingly, the prevalence of players categorised with LEA (albeit as classified from historical laboratory-based values) was significantly reduced when using DLW-derived estimates of EI (58% optimal, 38% reduced and 5% low) compared with participants' self-reporting dietary intake (18% optimal, 68% reduced and 15% low). From a practical perspective, the present data not only extend our understanding of the daily energy requirements of female soccer players training and competing at an international standard, but also provide greater methodological rigour to further evaluate the prevalence of LEA in this population of athletes. In that sense, our data offer caution to both researchers and practitioners alike, supporting recent recommendations that LEA should not be used directly as a REDs diagnostic tool (Ackerman et al., 2023).

To address our aim, we sampled the largest cohort of female players studied to date (n = 45), as assessed in a 'training camp' environment during which they also played competitive games representing their national team. In relation to TDEE, we report a mean absolute and relative expenditure of 2683 ± 324 $kcal·day^{-1}$ and 45 ± 4 $kcal·kg^{-1}$ day^{-1}, respectively (Figure 6.1a,b). The present data compare favourably with our previous observations from adult players (from the same national team) where absolute and relative TDEE was 2693 ± 432 $kcal·day^{-1}$ and 43 ± 6 $kcal·kg^{-1}$ day^{-1}, respectively, as reported over a similar time course of data collection (Morehen et al., 2021). Such similarity between age groups is not surprising when considering the comparable values for total BM and FFM of the players studied here (60.8 ± 7 and 45.0 ± 5.1 kg) and those from our previously studied adult cohort (62.1 ± 4.7 and 43.2 ± 3.4 kg). In this regard, it is noteworthy that the TDEE reported here was also positively correlated with players' BM, FFM and stature, as opposed to crude markers of training volume, such as TD or training duration (Figure 2).

In using the RFPM to examine players' self-reported EI during a 3-day assessment period, we report a mean absolute EI of 2047 ± 511 $kcal·day^{-1}$ (range: 1456–3776 kcal). Such data also compare favourably with our previous assessments of both adult (Morehen et al., 2021) and adolescent players in Study Three, where mean absolute EI was 1923 ± 232 and 2053 ± 486 $kcal·day^{-1}$ during a 4-day and 10-day assessment period, respectively. However, when the DLW method (and changes in BM over the initial 7–8 days of training) was used to derive estimates of EI, we observed considerable discrepancy between methods (Figure 6.4a,b). When examined at group level, our data demonstrate a mean difference of 499 + 526 $kcal·day^{-1}$ between methods, thus representing a percentage difference and percentage error of 25% and 22%, respectively. The error reported here also compares well with that identified in recent studies conducted on Dutch (Brinkmans et al., 2024) and Norwegian (Dasa et al., 2023) female soccer players where an error of 22% and 20% was reported, respectively. Whilst we acknowledge the limitation of obtaining dietary records over a 3-day period (as opposed to the similar time course where DLW and BM was used), our data provide further evidence in support of the inaccuracies of utilising the RFPM to make inferences on absolute EI within real world environments. This is especially apparent when considering the large range of variance between methods when examined at an individual participant level (Table 6.4). Although the potential sources of error in both retrospective and prospective assessment methods have been frequently documented (Capling et al., 2017; Gemming et al., 2014; Livingstone & Black, 2003; Martin et al., 2012; Poslusna et al., 2009; Rollo et al., 2016; Thompson et al., 2010), the use of the RFPM has become particularly popularised within the field of sport nutrition research and applied practice. In addition to errors associated with both participant (e.g., reporting of food ‘leftovers’, failure to report snacks and drinks, etc.) and researcher burden (e.g., provision of frequent daily prompts), it is noteworthy that a large proportion of error is also likely attributable to the ability of the coder to estimate portion sizes and/or ‘hidden’ ingredients such as oil used within the cooking process. Indeed, we previously reported that applied sport nutrition practitioners (n = 48) can under-estimate the energy content of meals by approximately 10%, with individual variation between coders ranging from −47% to +18% (Stables et al., 2021). Such data collectively demonstrate the possibility of both intentional and unintentional under-reporting by participants but also considers the methodological challenges inherent in accurately measuring dietary intake. Our data also reflect recent research over a longer period of time, that also identified interindividual variance and considerable differences between direct and indirect assessment of EB (Müller et al., 2023).

In accordance with the reported differences in EI between methods, it follows that the pattern of EA reported within the present cohort of players is also dependent on the methodological approach (Figure 5). Indeed, the prevalence of players categorised with low, reduced and optimal EA (albeit as classified from historical laboratory-based values of <30, 30–45 and >45 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$, respectively) was significantly different when using DLW derived estimates of EI (58%, 38% and 5%, respectively), compared with participants’ self-reporting dietary intake (18%, 68% and 15%, respectively), notably resulting in lower prevalence of LEA. When considering the present data in the context of previous reports of LEA (as estimated using self-reported methods) from elite female soccer players representative of both international standard adult (88%) and adolescent players (34%), as well as within domestic level competition in Norway (23% and 36% on training and match days, respectively) (Dasa et al., 2023) and England (23%) (Moss et al., 2021), it is suggested that the prevalence of LEA within female soccer players and athletes as a whole may have been overestimated within the literature. In this regard, the present data should therefore serve as a caution to both researchers and practitioners alike, given the potential to underestimate EA and inflate the incidence of LEA if a given EA threshold is used, especially in those instances where they may present with symptoms outlined within the conceptual health and performance REDs models that may not be attributable to LEA in the first instance (Mountjoy et al., 2023a; Parker et al., 2022). Our data also support the notion that direct assessment of EI should not be used within free living situations to calculate EA, as recently highlighted by Brinkman’s et al. (2024).

Additionally, it should also be noted that this field is further complicated in that the categorisation of LEA (as <30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$) is typically based on laboratory studies with homogeneous patterns of EI and exercise-related expenditure (Burke et al., 2018). In contrast, athletes living under free-living conditions (such as those studied here) typically present daily variations in training volume and intensity (and hence EEE), albeit we acknowledge that athletes may not always adjust their EI in accordance with fluctuations in training load, as identified in Study Three. Therefore, the findings of this study further the argument against using universal categories to define LEA (i.e., <30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$) (De Souza et al., 2022; Lieberman et al., 2018; Salamunes et al., 2024), given the discrepancy in values, depending on the method used to measure EI. In addition to EI, the methodology used to measure EEE and FFM may also result in variable outcomes (Ackerman et al., 2023), and challenges exist surrounding the definition of 'exercise' (Areta et al., 2021). Although the present study is advantageous in that we studied an elite athlete cohort in free living conditions, it is noteworthy that measurement error associated with RMR (i.e., prediction equations were used as opposed to true measurement), EEE (a correction factor was employed) and BM (we acknowledge that daily hydration status was not measured to verify that changes were not due to small changes in total body water content) can all collectively influence estimated PAL and EA values. As such, we also present supplementary data in Supporting information Tables S1 and S2 to demonstrate how a change in RMR (±10%) and BM (±1%; this value was chosen as all players did not show any day-to-day variation greater than 1%) can affect estimates of PAL and EA. When taken together, it is apparent that there is a definitive need for further research in multiple athletic cohorts, using longitudinal research designs, and with valid assessments of RMR, EEE, total body water content and EI, in order to allow for a more rigorous evaluation of the prevalence of LEA within both female and male athletes.

From a practical perspective, the assessment of TDEE also provides further evidence to formulate population and sport-specific nutritional guidelines. Indeed, on the basis of a recommended daily protein intake of 1.6 $g \cdot kg^{-1}$ (Morton et al., 2018) and daily fat intake equivalent to 30% of EI (Collins et al., 2021), it can be estimated that daily CHO intakes for the players studied here are likely in the region of 5 $g \cdot kg^{-1}$. That said, although such daily CHO intakes are likely sufficient to support daily training requirements, it is also suggested that CHO intake be increased to at least 6–8 $g \cdot kg^{-1}$ on the day before match play, on match day itself and on the day after match play, so as to promote sufficient muscle glycogen storage for performance and recovery. However, consistent with previous assessments of self-reported dietary intake (also using the RFPM) in adolescent within Study Three and adult (Morehen et al., 2021) international soccer players, as well as elite players at club level (Brinkmans et al., 2024; Dasa et al., 2023; Moss et al., 2021), we also acknowledge that players' habitual CHO intakes are not sufficient to promote match play performance and recovery. Indeed, only one participant studied here self-reported a mean daily CHO intake >6 $g \cdot kg^{-1}$ during the 3-day period surrounding match play. Notwithstanding the error associated with self-reporting estimates of energy and CHO intake (as previously discussed), our data are still in support of the assertion that female players are likely 'under-fuelling for the work required' (i.e., match play), as reported in Study Three. The reasons for this may be due to a lack of awareness of nutritional guidelines and/or deliberate and intentional behaviours based on CHO fear, body image challenges and misconceptions surrounding body composition, as reported in Study Three. In this regard, our data provide further rationale for the formulation of player and stakeholder specific education and behaviour change interventions that aim to promote a positive nutrition culture within the women's game.

In summary, the present data provide the first report to assess TDEE of female adolescent soccer players competing at an elite international standard and is the largest DLW study conducted in female athletes to date. Importantly, the use of the DLW method also allowed for a comparison between DLW derived estimates of EI and those estimates of EI derived from the RFPM. We conclude that the use of the latter method significantly underestimates EA within this population particularly when universal thresholds are applied.

Chapter Seven

Synthesis of Findings

This chapter aims to summarise the findings of the thesis in relation to the original objectives outlined in Chapter 1. It begins with a summary of the key findings, followed by a general discussion focusing on how the data derived from this study has contributed to our understanding of the nutritional requirements of elite female soccer players. Finally, the practical implications, limitations, and recommendations for future research are outlined.

7.1. Achievement of Thesis Aims and Objectives

The primary aim of this thesis was to determine energy requirements and nutritional practices of elite female soccer players, using a mixed methods approach.

This was achieved through the following objectives:

1. The aim of Study One was to qualitatively explore player and stakeholder perceptions of nutrition practices in support of female soccer players' development and performance (Chapter Three).
2. The aim of Study Two was to qualitatively explore player and stakeholder perceptions of menstrual health support within elite female soccer (Chapter Four).
3. The aim of Study Three was to quantify energy intake, carbohydrate intake, physical loading and estimated energy availability in elite international female soccer players during a 10-day training and game schedule comprising two match days. (Chapter Five).
4. The aim of Study Four was to quantify total daily energy expenditure (via the doubly-labelled water method), energy intake and energy availability in elite international female soccer players during a training and game schedule (Chapter Six).

The outcomes of this thesis were therefore to:

3. Inform sport nutrition guidelines for women's soccer.
4. Inform education and behaviour change strategies that aim to improve nutrition culture and dietary practices within women's soccer.

Objective 1: To qualitatively explore player and stakeholder perceptions of nutrition practices in support of female soccer players' development and performance (Chapter Three).

Data from Study One demonstrate that considerable confusion and misconceptions exist amongst players and stakeholders regarding the theoretical underpinning and practical application of meeting energy requirements. As such, it is perceived that players 'under-fuel', which is likely caused by misunderstandings about the impact of carbohydrate intake on body composition, a fear of weight gain and the associated impact upon body image. The 'carbohydrate fear' that is experienced by players is exacerbated by external pressures arising from social media, key stakeholders (e.g., coaches) and the skinfold culture surrounding measurement of body composition. Such cultural issues are amplified by the lack of full-time professionally accredited nutritionists overseeing the provision of nutrition support. Indeed, the infrastructure supporting the women's game (e.g. staffing resource, on-site food provision, player education programmes, etc.) was considered incomparable to the men's game. When taken together, our data provide a platform for which to develop organisational, stakeholder and player centred education and behaviour change interventions that strive to promote a positive performance nutrition culture within the women's game.

Objective 2: To qualitatively explore player and stakeholder perceptions of menstrual health support within elite female soccer (Chapter Four).

Study Two demonstrates that elite female soccer players experience a range of physical and psychological symptoms primarily at the onset of and during menses (as also perceived by stakeholders), with most participants perceiving these symptoms to impact performance. Nonetheless, menstrual health support is perceived as minimal and although players have their menstrual status tracked, they report little understanding as to why or how this information is used. This confusion was also present among stakeholders, often as a result of uncertainty about the evidence supporting the need for menstrual health support. The perceived lack of support may also be reflective of a culture where conversations about the menstrual cycle are not normalised. Overall, this may result in failure to identify and treat menstrual irregularities despite non-coaching staff members perceiving them to be common amongst players. These data support the need for individualised support based on the lived experiences of individual players and support staff. Furthermore, our research identifies the need for organisational, stakeholder, and player centred education programmes (led by experts in female athlete health) that create an environment where players receive personalised menstrual health support.

Objective 3: To quantify energy intake, carbohydrate intake, physical loading and estimated energy availability in elite international female soccer players during a 10-day training and game schedule comprising two match days. (Chapter Five).

Within Study Three, players self-reported their energy intake via the remote food photography method, whilst the physical loading and associated exercise energy expenditure were assessed via global positioning system technology. The relative carbohydrate intake was significantly greater (all $p < 0.05$) on the day before the first match (MD-1a) (4.1 ± 0.8 g·kg^{-1}), on the day before the second match (MD-1b) (4.3 ± 1.1 g·kg^{-1}), MDa (4.8 ± 1.2 g·kg^{-1}) and MDb (4.8 ± 1.4 g·kg^{-1}) in comparison to most other days (6 g·kg−1) for intensive training and game schedules. Furthermore, we identified that prevalence of LEA may have been previously overestimated within this population, as prevalence was significantly lower when adjust energy intake values for potential underreporting. These data provide further evidence for the requirement to create and deliver targeted player and stakeholder education and behaviour change interventions (especially for younger athletes) that aim to promote increased daily carbohydrate intake in female soccer players.

Objective 4: To quantify total daily energy expenditure (via the doubly-labelled water method), energy intake and energy availability in elite international female soccer players during a training and game schedule (Chapter Six).

Study Four aimed to quantify total daily energy expenditure via the doubly-labelled water method, energy intake and energy availability. Adolescent female soccer players (n = 45; 16 ± 1 years) completed a 9–10 day 'training camp' representing their national team. Absolute and relative total daily energy expenditure was 2683 ± 324 and 60 ± 7 $kcal·kg^{-1}$ FFM, respectively. Mean daily energy intake was lower ($P < 0.01$) when players self-reported using the remote food photography method (2047 ± 383 $kcal·day^{-1}$) over a 3-day period versus doubly labelled water derived energy intake, accounting for body mass changes (2545 ± 518 $kcal·day^{-1}$) over 7–8 days, representing a mean daily Δ of 499 ± 526 $kcalday^{-1}$ and 22% error when using the remote food photography method. Estimated energy availability was different ($P < 0.01$) between methods (doubly labelled water: 48 ± 14 $kcal·kg^{-1}$ FFM, range: 22–82; remote food photography method: 37 ± 8 $kcal·kg^{-1}$ FFM, range: 22–54), such that prevalence of low energy availability (<30 $kcal·kg^{-1}$ FFM) was lower in doubly labelled water compared with remote food photography method (5% vs. 15%, respectively). Data demonstrate the potential to significantly underestimate energy intake when using self-report methods. This approach can therefore cause a misrepresentation and an over-prevalence of LEA, which is the underlying aetiology of REDs.

7.2. General Discussion of Findings

In summary, this thesis used a mixed methods approach to assess nutritional practices and energy requirements of elite female soccer players. To meet daily energy requirements, data demonstrate that total daily carbohydrate intake should at least be equivalent to 5 $g·kg\ BM·day^{-1}$. However, the nutrition culture within the women's game may not always be conducive to optimal fuelling practices, owing to challenges associated with social opportunity (e.g. social media, comments, etc.) and reflective motivation, all of which are aligned around player and stakeholder perceptions of optimal body composition. Despite previously observation of low energy availability within this population, the data also demonstrate that prevalence of low energy availability is likely over-estimated primarily because of inaccuracies associated with dietary assessment methods. When taken together, this thesis provides a platform for which to formulate targeted education and behaviour change strategies for players, stakeholders and practitioners alike.

Nutrition Culture

Prior to the completion of Study One, the nutrition culture within elite female soccer was yet to be explored. Furthermore, in contrast to Studies 3 and 4, Study One and 2 data collection was not exclusive to adolescent soccer players, rather the culture within elite female soccer as a whole was explored. Although direct measurement of EI within senior players has previously displayed concerning results, with regards to low CHO intake in comparison to guidelines (Morehen et al. 2021; Moss et al. 2021; Dasa et al. 2023), the potential reasons for this were yet to be explored. In addition, findings within other sports demonstrate that a lack of sufficient CHO intake was directly related to an environment where body composition is a prioritised outcome and athlete's perceive CHO intake to results in increased FM (Kerr et al. 2006; Jankauskiene and Pajaujiene 2012; Beckner and Record 2016; Hyatt and Kavazis 2019). Therefore, given the potential severity of the underlying reasons for low CHO intake and EI based on findings in other sports and the impact of low CHO intake and EI on performance and health, it was important to explore this for the first time within elite female soccer.

In completing this study, we provide foundational insights into the nutrition culture within elite female soccer, highlighting several key issues that had not previously been explored. The qualitative data revealed that low CHO intake among players could be attributed to a combination of knowledge gaps, environmental constraints, and social pressures. Players and stakeholders displayed significant misconceptions about CHO intake and its relationship to both body composition and performance, reflecting a broader misunderstanding of the nutritional demands of elite sport. Inadequate CHO intake, as noted in the literature, has serious implications, including increased risk of the Female Athlete Triad and REDs, with adverse effects on menstrual health, energy levels, and overall performance (Mountjoy et al., 2023). Our findings echo these concerns and underscore the critical need for education initiatives targeted at players, staff, and even parents, aimed at addressing the knowledge deficit and encouraging optimal fuelling strategies.

Furthermore, the environmental limitations within elite female soccer were evident in the lack of infrastructure to support good nutritional practices. Players reported restricted access to appropriate food at training facilities and an overall lack of professional nutritional guidance. This shortfall aligns with broader critiques of the professional women's game, which, despite increased professionalism (e.g., the introduction of the WSL in 2018), has not seen a commensurate improvement in support services, such as nutrition (Culvin, 2019; Culvin, 2021). The cultural norms within this environment, where players feel secondary to their male counterparts, only exacerbated the issue. This environment often forces players to seek nutrition advice from less reliable sources, such as social media, which frequently perpetuates harmful myths surrounding CHO and body composition, further complicating their ability to make informed decisions.

Perhaps most striking was the social pressure exerted by coaches and staff regarding body composition targets. Despite acknowledging the potential value of measuring body composition, players were frustrated by the overemphasis on BM and skinfold measurements, and the lack of connection to performance outcomes. This emphasis often led players to adopt counterproductive behaviours (e.g., reducing CHO intake) to meet arbitrary targets, driven by the belief that these would affect team selection. Such findings reflect a skinfold culture, where the social opportunity to engage in optimal nutrition practices is not aligned with what is needed to fuel performance, highlighting a disconnect between performance-driven nutrition and body composition-based directives.

Crucially, these qualitative findings set the stage for Studies 3 and 4, which sought to quantify EI, expenditure, and availability. While Study One highlighted the psychosocial barriers to adequate nutrition and provided rich context for understanding why players struggle with CHO intake, Studies 3 and 4 aimed to establish whether these perceptions were reflected in reality, based on quantitative assessment. Together, these studies paint a comprehensive picture of the nutrition culture within elite female soccer, identifying both behavioural and structural challenges that must be addressed to optimize player health and performance.

Menstrual Cycle Support

Prior to the completion of Study Two, menstrual health support within female soccer was a largely unexplored area. However, findings from a range of sports, including trampoline gymnastics (Stewart et al. 2010), rugby (Findlay et al. 2020), and soccer (Read et al. 2021), have highlighted that MC related challenges significantly affect female athletes. In completing this study, we identified similar themes, revealing a critical need to address menstrual health support within elite female soccer. All players within the sample reported negative symptoms associated with their MC, including stomach cramps and heavy menstrual bleeding. These symptoms are consistent with prior studies, such as those by Read et al. (2021), who found that 93-100% of female soccer players experience negative symptoms pre- and during menses, and by Bruinvels et al. (2020), who reported the prevalence of stomach cramps among elite athletes. The impact of these symptoms on performance, particularly stomach cramps, is well-documented, with research showing reductions in neuromuscular control, leg strength, aerobic capacity, and maximal anaerobic performance (Lebrun et al. 2013; Chantler et al. 2009; Giacomoni et al. 2000). These findings emphasize the importance of recognizing and managing MC symptoms to maintain optimal performance. The concerns surrounding heavy menstrual bleeding, especially in relation to wearing white shorts, were consistent with findings in other sports (Findlay et al. 2020; Stewart et al. 2010). This anxiety, unique to athletes in highly visible sports like soccer, often leads women to change their clothing to avoid embarrassment (O'Flynn 2006). However, this is not always feasible in elite soccer, where kit regulations may prevent players from opting for more concealing attire. A potential first step in reducing this anxiety could be for teams to avoid white shorts during training and matches, creating a more supportive environment for female athletes.

A significant finding from this study was the perception of inadequate menstrual health support among players, which reflects the broader lack of research available to inform such support (McNulty et al. 2020). Moreover, the social environment in soccer may exacerbate this issue, with the MC often regarded as a taboo topic of conversation. This echoes prior findings across different sports, where female athletes reported hesitancy to discuss menstrual health openly (Santer et al. 2008; Findlay et al. 2020). Despite the well-documented benefits of coaches addressing the wellbeing of their athletes (Becker 2009), this study found that menstrual health is often overlooked or deemed outside the purview of coaches. Many coaches do not view menstrual health as their responsibility, though some have expressed willingness to be educated on the subject, especially regarding the potential for adjusting training loads (Clarke et al. 2021).

Notably, gender dynamics also play a role in this lack of support. Some players indicated that the gender of the coach influences their comfort in discussing menstrual health, a sentiment that mirrors findings from other sports (Armour et al. 2020). Furthermore, it was evident that coaches were less likely to acknowledge the impact of the MC on performance compared to other stakeholders. This underscores the need for targeted education for coaches to foster a more supportive and informed environment for female athletes. A critical theme emerging from the study was the need to normalise conversations around menstrual health within the team environment. The lack of clarity among staff regarding whose role it is to provide primary menstrual health support contributes to a communication breakdown, leaving many players hesitant to initiate such conversations. Interestingly, while coaches perceived that players might fear negative consequences (e.g., being left out of team selection) if they raised menstrual health concerns, the players themselves did not share this apprehension. This misalignment points to the need for better communication channels between staff and players to address menstrual health openly and without stigma. This implementation of a mandatory female athlete health lead within professional female soccer clubs would help to enable this.

The findings from this study have important implications for EA, which was measured in Studies 3 and 4. Tracking the MC can be a critical tool in identifying symptoms of REDs, as menstrual irregularities are a primary indicator of LEA. Ensuring that players and staff understand the connection between nutrition, menstrual health, and performance is vital. Regular tracking and open discussions around menstrual health can serve as an early warning system for detecting REDs and implementing appropriate interventions to protect both the health and performance of female soccer players.

Physical Demands

Prior to Study Three, little was known about the physical demands placed on adolescent female soccer players at international level. Most existing research focused on adult male and female players, with minimal data on the training and match demands experienced by youth players. Study Three and Study Four address this gap by providing comprehensive data on the training loads and match loads of elite adolescent female soccer players, shedding light on the physical demands of an international training camp.

In Study Three, training loads were periodised in the days leading up to the first match day (MDa), following a common strategy used in professional soccer. The highest training volume and intensity were observed four days before the match (MD-4), with significant tapering in the final days before matches. Specifically, the average TD covered in training on MD-4 was 3789 ± 1375 meters, with notable high-intensity actions such as maximal speed and accelerations peaking on this day. This tapering should ensure that players are physically prepared for the demands of competition, allowing adequate recovery time before match day. Across all match days in Study Three, the average distance covered by players was 6785 ± 1754 meters. This reflects the increased physical demands of competitive match play compared to training loads earlier in the week. Players were required to engage in more high-intensity activities, including sprints, accelerations, and decelerations, throughout each match. Importantly, this data includes all squad members, including unused substitutes, which can lower the overall average match distance covered. Nevertheless, it offers a comprehensive view of the physical load experienced by the entire squad throughout an international training camp.

In Study Four, further analysis of training and match loads reinforced these findings. The training load data from Table 1 in Study Four revealed similar periodisation, with peak training distances observed on MD-4 and tapering observed in the two days leading up to the match. In both studies, players faced multiple matches within a short time frame, and the data showed that physical demands remained high across these fixtures, with players often covering similar distances and engaging in comparable levels of high-intensity activity from match to match.

In conclusion, these findings demonstrate that training is periodised to prepare players for the increased intensity of match play. This emphasises a potential need for EI and CHO to be periodised, given the varying demands day to day. Comparable demands to data collected at senior level also highlights the need for effective recovery protocols to ensure players can maintain performance levels across multiple games.

Energy Expenditure

Study Four provided the first detailed analysis of EE in female adolescent soccer players using the DLW method. This gold-standard approach allowed for precise measurement of TDEE over the course of the study, capturing the energy demands experienced by players in real-world conditions. The findings from Study Four revealed a mean TDEE of 2683 ± 324 kcal/day. Similarly to TL and ML, energy expenditure findings were comparable to data reported within adult female soccer players during an international training camp, where TDEE values were reported as 2693 ± 432 kcal/day (Morehen et al., 2021). The similarity in EE between adolescent and adult players may reflect the comparable BM and FFM between the two groups, as well as the physical demands placed on them during intense training and match play. The fact that players' mean TDEE was comparable to that of adult players also suggests that adolescent soccer players are subjected to significant physical demands during both training and competition, requiring careful EI management to meet their expenditure.

Study Four further demonstrated that TDEE was closely related to body composition. Players with greater BM and FFM tended to have higher EE. This finding highlights the role that individual physiological characteristics play in determining EE. It also suggests that TDEE is not solely dependent on the volume or intensity of training but is significantly influenced by players' body size and muscle mass. For instance, players with higher FFM are likely to expend more energy at rest and during physical activity, contributing to their overall higher energy requirements, which is a critical consideration for adolescent players, given the vast range in rates of maturation. While the average TDEE provided a valuable baseline, Study Four also highlighted notable individual variability in TDEE, with some players expending significantly more energy than others. The reported TDEE range was 2301 to 3107 kcal·day^{-1}, indicating that even within a relatively homogenous group of elite adolescent soccer players, energy demands can vary substantially from player to player. This variability is crucial for understanding how EE must be individually assessed and managed, particularly in the context of nutrition planning and recovery strategies. Players who have higher energy demands may require more tailored nutritional support to meet their energy needs and ensure optimal performance. Furthermore, it highlights the importance of individualised nutrition strategies and presenting nutritional guidelines relative to BM or FFM.

Although Study Four did not specifically break down EE by training and match days, the data still provide important insights into the overall energy demands experienced by players. Given the high-intensity nature of soccer matches, where players engage in sprints, accelerations, and decelerations, it is likely that TDEE would be higher on match days compared to training days. The use of DLW across the study period, which encompassed both training and match days, gives an accurate reflection of the average daily energy expenditure for players over the course of a competitive period but it is important to be aware of potential daily variation in demands and the subsequent impact on nutritional requirements. Understanding the high TDEE of adolescent female soccer players has important implications for recovery and performance. Players with consistently high TDEE may face challenges in meeting their energy needs through diet alone, particularly if EI is not closely monitored or adjusted to match the demands of training and competition. Ensuring that players are consuming sufficient calories to meet their EE is crucial for maintaining EB, which is essential for recovery, injury prevention, long-term performance and the prevention of potential LEA and the related symptoms.

Overall, the findings from Study Four provide critical insights into the EE of elite adolescent female soccer players. The use of the DLW method offers a more accurate assessment of TDEE for the first time within this population, highlighting the significant energy demands placed on these athletes during periods of intense training and competition, which are similar to their adult counterparts. These findings underscore the need for individualised nutrition and recovery strategies to ensure that players can meet their energy needs and maintain optimal performance and health.

Energy Intake

Accurately assessing EI is critical in understanding whether athletes meet the energy demands imposed by their training and competition schedules. Both Study Three and Study Four attempted to measure EI in adolescent female soccer players using self-reported methods. However, the findings from Study Four cast significant doubt on the legitimacy of these self-reported measures, particularly considering the discrepancy between self-reported EI and total daily EI derived from DLW. In Study Three, EI was recorded over a 10-day period using self-reported food diaries, with a mean reported EI of 2053 ± 486 $kcal \cdot day^{-1}$. Similarly, Study Four utilised a 3-day RFPM, which yielded a comparable mean intake of 2047 ± 511 kcal/day. While these self-reported EI values are consistent between the two studies, both methodologies rely on self-reporting, which has inherent limitations, particularly the tendency for underreporting (Gemming et al., 2014; Thompson et al., 2010).

The DLW-derived EI in Study Four provided a far more accurate assessment of actual EI, revealing a mean EI of 2505 ± 490 $kcal \cdot day^{-1}$. This discrepancy between self-reported EI and DLW-derived EI highlights potential underreporting of EI in both studies and within previous research. The difference (approximately 450 to 500 $kcal \cdot day^{-1}$) indicates that athletes were likely consuming far more than they reported. This underreporting is a common phenomenon in athletes, especially in adolescent populations, due to factors such as misjudging portion sizes, social desirability, and forgetting to log certain meals (Livingstone & Black, 2003), as also acknowledged in a study by Brinkmans et al. (2024).

Given the high physical demands placed on these athletes, accurately assessing EI is crucial for understanding whether they are achieving EB or facing the risk of LEA. This underreporting becomes particularly problematic when evaluating athletes' overall nutritional status. If EI is systematically underestimated, it could lead to inappropriate conclusions about energy deficiencies, potentially resulting in misguided nutritional interventions or the misdiagnosis of LEA and REDs. These findings emphasise the need for more accurate and objective methods of assessing EI in athletes. While self-reported methods such as food diaries and photographic logs are useful in some settings, they are prone to significant errors, particularly in adolescent athletes who may be more susceptible to body image concerns and dietary pressures. DLW-derived EI offers a more reliable approach to assessing true caloric intake, enabling more precise evaluations of EA.

Carbohydrate Intake

CHO is vital for fuelling high-intensity intermittent efforts typical of soccer. Both Study Three and Study Four revealed that the players' CHO intake consistently fell below recommended guidelines, which suggest that athletes should consume 6-8 $g \cdot kg\ BM^{-1}$ during periods of intense training and match schedules (Burke et al., 2001). In Study Three, CHO intake remained low throughout the 10-day assessment period, which is concerning given the energy requirements of soccer. The insufficient CHO intake reported in Study Three was similarly observed in Study Four, where players also failed to meet the necessary CHO consumption levels. The insufficient CHO intake, combined with high energy demands, puts players at risk of early fatigue and reduced performance, as their glycogen stores are likely not being replenished adequately. This issue of low CHO intake reflects a broader trend observed in female soccer players and other team sports, where misunderstanding about the role of CHO in fuelling performance leads to inadequate consumption (Culvin, 2021). However, as previously mentioned, it is possible that CHO intake was underreported within these studies due to underreporting, however, even when account for potential underreporting of ~20%, players would still consistently fall short of guidelines of 6-8g·kg FFM, which is recommended during congested fixture periods.

Study One sheds light on potential reasons for the low CHO intake reported within studies 3 and 4, as it highlights a cultural issue within female soccer regarding CHO fear, with many players reporting actively avoiding CHO due to concerns about weight gain. This behaviour was driven by misconceptions such as "carbohydrates make you fat," which persisted among the players. These dietary misconceptions are compounded by external pressures, including body composition targets and frequent skinfold measurements, which reinforced the belief that lower CHO intake would result in more favourable body composition scores. As a result, players may engage in intentional CHO restriction, despite the critical role of CHO in maintaining energy levels and fuelling both training and match performance. Studies 1, 3 and 4 identify a critical need for nutritional education interventions to address these misconceptions. Players must understand the importance of consuming adequate CHO to fuel their bodies for the demands of soccer. Nutrition interventions should aim to dispel myths about CHO intake and body composition, ensuring that athletes are aware of the performance benefits of consuming the right amount of CHO at the right times.

Lastly, accurate assessment of EE allows for the creation of population-specific nutritional guidelines. Based on the recommended daily protein intake of 1.6 g·kg·day^{-1} (Morton et al., 2018) and a daily fat intake equivalent to 30% of energy intake (Collins et al., 2021), it can be concluded that recommended daily CHO intakes for the players studied here should be in the region of 5 g·kg^{-1}. While this intake is probably adequate to meet daily training demands, it is recommended to increase carbohydrate intake to at least 6–8 g·kg·day^{-1} on the day before, the day of, and the day after match play to support optimal muscle glycogen storage for performance and recovery.

In conclusion, the findings from Study Four raise significant concerns about the validity of self-reported EI in both Study Three and Study Four. The DLW-derived EI data clearly showed that self-reported methods underestimated EI by about 22%, highlighting a significant underreporting issue. Given the importance of maintaining EB for performance and health, more objective measures of EI, such as

DLW, are needed to accurately assess athletes' nutritional status in the future. However, even when accounting for underreporting, CHO intake failed to meet optimal levels which are recommended during congested fixture periods (6-8 $g \cdot kg^{-1}$). Additionally, the widespread CHO fear observed in Study One provides a potential reason for this and emphasises the importance of nutrition education, in ensuring that athletes meet their dietary requirements, particularly for CHO.

Energy Availability

In Study Three, mean estimated EA was reported as 34 ± 12 $kcal \cdot kg$ $FFM \cdot day^{-1}$, with 34% of players classified as having LEA and 57% showing reduced EA but not falling into the LEA category. These findings align with previous studies that reported a high prevalence of LEA in female soccer players (Dasa et al., 2023; Morehen et al., 2021; Moss et al., 2021). However, these values were based on self-reported EI and GPS-derived EEE, methods that often struggle with accuracy due to common underreporting of dietary intake. Study Four introduced a more accurate approach by using DLW, a gold-standard method for measuring TDEE and indirectly, EI. The findings revealed a significant underestimation in self-reported EI by approximately 22%, meaning that players were likely consuming more than they had reported. This discrepancy between self-reported EI and DLW-derived EI suggested that the prevalence of LEA in Study Three (and likely other similar studies) was overreported. When recalculating EA using DLW-derived data, the number of players classified as having LEA dropped significantly from 18% to 5%. This highlights the critical importance of using more accurate methods like DLW to assess EA, especially in female soccer players, where underreporting of intake is common. Overestimating the prevalence of LEA could lead to misdiagnosis and unnecessary interventions, underscoring the need for objective measurements in both research and practice.

7.3. Practical Applications

Study One

Practically, Study One has deepened our understanding of the nutritional culture and environment within elite female soccer. The findings underscore the critical need for comprehensive nutritional support to foster a cultural shift and enhance education, which in turn could mitigate some of the challenges reported by players. For instance, it is evident that various intervention strategies, such as environmental restructuring, education, modelling, and training, could be pivotal in transforming the current nutritional provisions for women players. These interventions aim to address the issue of under-fuelling, which was later quantified in Studies 3 and 4. A fundamental step towards this goal could involve mandating that all professional clubs employ a full-time, professionally accredited sports nutritionist or dietician to elevate the quality of nutrition services provided to female athletes.

Moreover, addressing the complexities of body image challenges faced by players requires a multifaceted approach at both the organisational and individual levels (Berry and Howe 2000;

Ackerman et al. 2020). Our findings support previous recommendations that educational initiatives focused on players should commence during adolescence, promoting healthy eating behaviours from a young age (Lieberman et al. 2001; Tiggemann 2001). Additionally, prioritizing the education of coaches is crucial, given their significant influence on player development (Sabiston et al. 2020; Carson et al. 2021). These educational interventions should also tackle the increased pressure from social media, as emerging media formats often intensify scrutiny of athletic bodies (Kohe and Purdy 2016), which is only going to become more of a challenge as the sport continues to grow. Collectively, our data suggest that targeted interventions aimed at influencing players' reflective and automatic motivations related to specific nutritional behaviours could help reduce body dissatisfaction and the risk of developing eating disorders. Educating stakeholders on the differences between male and female bodies (Clarkson et al. 2020) may also contribute to improving cultural norms and practices related to skinfold assessments and generalized target setting. Indeed, carefully monitored assessments of body composition might enhance overall player health, as decisions based solely on appearance can exacerbate body dissatisfaction, disordered eating, and the development of eating disorders (Griffin and Harris 1996; Rhea 1998).

Study Two

The findings of Study Two offer critical insights into the management of menstrual health among elite female soccer players, highlighting several practical applications that could enhance both player well-being and performance. Firstly, the practice of avoiding white shorts during training and matches could serve as a simple yet effective measure to alleviate anxiety related to menstruation, a concern commonly reported by female athletes (O'Flynn, 2006). This initial step, however, should be part of a broader strategy aimed at fostering an environment where menstrual health can be openly discussed and normalised.

Our data suggest that players benefit from environments where issues surrounding menstruation are addressed openly, with both athletes and staff members being educated on the subject. To this end, the development and delivery of educational programs focused on menstrual health is crucial. It is essential that governing bodies provide clear guidance on who is responsible for delivering this support, ensuring that it does not fall under the purview of individuals lacking the necessary expertise. Although the present study does not define what optimal support should look like, it is evident that such support should be personalized, conversational, and responsive to the individual experiences and symptoms of each athlete.

In addition, while menstrual tracking at both the team and individual levels (e.g., through mobile applications) can be useful for assessing the timing of menstruation, it is the individualised follow-up conversations and potential interventions that players value most. These discussions are particularly important in light of the high prevalence of secondary amenorrhea among elite athletes (De Souza et al. 2014). The lack of concern or identification of menstrual irregularities among some participants highlights a critical need for education, as conditions such as secondary amenorrhea can lead to serious health consequences, as outlined in the Female Athlete Triad (De Souza et al. 2021) and REDs (Mountjoy et al. 2023) models.

Interestingly, players who experienced menstrual irregularities in this study attributed their improvement to a better understanding of nutrition and an increase in dietary intake, findings that align with previous research on exercising women (De Souza et al. 2021). This underscores the importance of individualised menstrual health support, particularly given that some players reported a loss of appetite at the onset of and during menstruation, which can negatively impact both health and performance. Given the potential for secondary amenorrhea to result from various factors—including diseases, genetic abnormalities, and stress (Viswanathan and Eugster 2011)—it is imperative to address the apparent gaps in knowledge and awareness among players, parents, and coaches. Understanding whether this lack of identification stems from insufficient knowledge, a lack of awareness, or a perceived convenience of amenorrhea due to the removal of menstruation's associated symptoms is essential for developing effective educational interventions.

Studies 3 and 4

The combined findings from Studies 3 and 4 offer valuable insights into the nutritional strategies and methodologies appropriate for elite female soccer players, particularly with respect to CHO intake and EA.

Carbohydrate Requirements:

Although daily CHO intakes of approximately 5 $g \cdot kg^{-1}$ were recommended for this population based on our EE findings, it is advisable to increase this intake to 6-8 $g \cdot kg^{-1}$ on the day before match play, on match day itself, and on the day after match play. This adjustment is crucial to ensure adequate muscle glycogen storage, which is necessary for optimal performance and recovery. Although we did not measure muscle glycogen levels, 5 $g \cdot kg^{-1}$ is based on mean daily EE within Study Four, however the study encompassed numerous training, match and rest days.

Energy Availability and Methodological Considerations:

Study Four highlights significant discrepancies in the estimation of EI and, consequently, EA when comparing different methodological approaches. The data indicate that the prevalence of LEA among elite female soccer players may have been overestimated in the literature, particularly when self-reported dietary intakes are used. For instance, while self-reported data suggested a lower prevalence of LEA, the more accurate DLW method revealed a higher incidence. This finding underscores the importance of cautious interpretation of EA data and suggests that relying solely on self-reported methods may lead to an underestimation of EA and an overestimation of LEA, potentially misinforming both research and practice. Given these methodological considerations, it is recommended that direct assessments of EI not be used in free-living conditions to calculate EA, as this can lead to erroneous conclusions. Instead, practitioners should consider more robust and validated methods, such as DLW, when assessing EA in elite athletes and symptoms must also be considered when screening for LEA and REDs, as recommended in the latest consensus statement (Mountjoy et al. 2023).

The latest REDs consensus statement emphasizes a shift toward a more symptom-led approach to assessing and diagnosing Relative Energy Deficiency in Sport (Mountjoy et al., 2023). This approach acknowledges that relying solely on objective thresholds for LEA (such as the traditional 30 $kcal \cdot kg\ FFM \cdot day^{-1}$ cut-off) may overlook athletes who are suffering from the effects of energy deficiency but who do not fall below this numerical threshold. Instead, the consensus recommends evaluating a range of clinical symptoms, including menstrual disturbances, bone health issues, impaired immune function, and psychological symptoms, alongside objective measures of EI and EE. The symptom-led approach claims to allow practitioners to identify athletes experiencing REDs even if their EA falls above the traditionally accepted threshold for LEA, however, it must not be assumed that LEA is directly causing the symptom in question, as isolating the purported effects of LEA from the myriad of other potential causes of REDs symptoms is experimentally challenging. While the DLW method provides a more accurate assessment of energy availability, some athletes may still experience symptoms of REDs despite not meeting the strict LEA threshold. This highlights the need to assess subjective symptoms in addition to relying solely on numerical values to make clinical decisions, although diagnosis of REDs based solely on symptoms is also problematic, therefore a multifaceted approach is necessary. A recent review brings into question the REDs model and the reliability of a symptom led approach to REDs and LEA diagnosis (Jeukendrup et al. 2024). It is evident that even in the more extensively researched areas, many questions remain unanswered, particularly regarding the causal relationships between LEA and its associated symptoms or clinical manifestations. The evidence supporting other symptoms (those not covered here) is even less convincing, which is understandable given that the model is still in its early stages, and conducting longitudinal studies is time-consuming, complex, and likely costly. While the focus should be on clinical evidence, such evidence is limited and, in some cases, unavailable. Despite this, diagnostic tools based on symptoms are being developed and implemented. A model is a simplified representation of real-world phenomena, designed to capture and explain physical, biological, or sociological aspects by referencing established and widely accepted knowledge. While models are essential tools in biomedical research, they require testing to validate their accuracy. In this process, it is often found that the model is incomplete or even flawed, necessitating adjustments or replacement with a more accurate model. REDs is a model (Mountjoy et al. 2014) and like any other model it needs to be scrutinized and improved. Therefore, an approach that accounts for symptoms (whilst measuring

EA) is need but the purpose needs ultimately to be to find the cause of the symptoms, rather than trying to prove that LEA is the cause of REDs, such as the recently proposed Athlete Health and Readiness Checklist (Jeukendrup et al. 2024), which is applicable within a real-world setting. Findings within this thesis reinforce the idea that assessing for REDs should involve a holistic evaluation that includes both objective measures like EA and a detailed assessment of an athlete's overall health status, in order to seek a cause, rather than the REDs model (or any model) being the starting point. Addressing LEA may be beneficial in many cases, but assuming that symptoms are always due to insufficient energy intake relative to exercise could limit or divert attention from exploring other potential causes for these symptoms. This narrow focus may overlook other contributing factors that could be equally important in understanding their development.

Furthermore, if LEA were the sole cause of REDs symptoms, treatment would be straightforward, simply increasing energy intake or reducing energy expenditure. In reality, numerous underlying dietary and psychological factors influence eating behaviour, and in most cases, these factors are the primary cause. It is not just about "calories," as the definition of LEA suggests, but rather a more complex interplay of behavioural and psychological elements and Study One contributes to a greater understanding of these elements within female soccer.

General Nutritional Guidelines and Educational Interventions:

The findings also align with Study One and reinforce the need for targeted education and behaviour change interventions aimed at promoting a positive nutrition culture within women's soccer. Despite the recommendations for increased CHO intake surrounding match play, our data reveal that players frequently do not meet these guidelines, with many under-fuelling relative to the demands of match play. This under-fuelling may stem from a lack of awareness of nutritional guidelines, or from intentional behaviours influenced by misconceptions about CHO intake, body image concerns, and fears surrounding body composition, as identified in Study One. To address these issues, it is crucial to develop player and stakeholder-specific educational programs that not only disseminate accurate nutritional information but also work to shift attitudes and behaviours towards a healthier approach to diet and performance. By fostering an environment that encourages adequate fuelling and dispels myths around CHO intake, these interventions can help to enhance both the health and performance of elite female soccer players.

Nutrition and Female Athlete Health Support Structure in Soccer Clubs

The overarching practical recommendation from all studies within this thesis is the critical need for comprehensive nutritional and female athlete health support tailored specifically to elite female soccer players. Effective provision in these areas is fundamental to addressing persistent issues such as under-fuelling, energy availability concerns, menstrual health challenges, and overall player wellbeing. Study

Two especially highlighted the importance of incorporating specialised female athlete health expertise into the support system, underscoring the necessity for knowledgeable professionals who can provide individualised, evidence-based menstrual health care. Considering the wide variability in financial and resource capacities among soccer clubs globally, a single, standardized model of athlete support is neither feasible nor practical. Therefore, this thesis recommends that clubs adopt minimum support structures adapted to their specific budgetary and operational contexts. Two distinct models are proposed:

Recommended High-Resource Model

This model is aimed at well-funded clubs with extensive budgets, typically operating in top-tier professional environments (e.g., Women's Super League in England). It prescribes a full-time, multidisciplinary support team to provide holistic care addressing the physical, mental, and social dimensions of player health and performance:

Head of Nutrition: Oversees all nutritional strategies and integrates nutrition within overall athlete management frameworks.

First Team Nutritionist: Deliver continuous, tailored nutritional guidance to senior players.

Academy Nutritionist: Deliver continuous, tailored nutritional guidance to academy players.

Female Athlete Health Lead (Full-Time Sport Scientist): Develops and implements a dedicated Menstrual Health Support Strategy as part of a broader Female Athlete Health and Wellness framework. This role coordinates closely with the club doctor, physical performance coaches, sport psychologists, clinical psychologists, lifestyle and wellbeing coaches, and other relevant staff to ensure comprehensive care.

Club Doctor: Collaborates with the Female Athlete Health Lead in decision-making regarding menstrual and general health matters.

External Specialists: Access to experts in eating disorder support and other specialty fields remains essential to provide specialised care when necessary.

Recommended Low-Resource Model

This model targets clubs with more limited financial and human resources but still employing full-time female professional players (e.g., Women's Super League Two in England). It emphasizes the efficient use of available personnel while maintaining core support and referral mechanisms:

Dedicated Full-Time Nutritionist: Recognised as the minimum requirement to provide consistent, evidence-based nutritional guidance appropriate for full-time female athletes.

Female Athlete Health Lead (Club Doctor or Sport Scientist): This role is an additional responsibility rather than a dedicated expert position. The lead's focus is on identifying concerning menstrual or health-related symptoms, offering general advice, and referring complex or high-risk cases to external specialists as needed. Regular menstrual cycle and symptom monitoring should be incorporated into athlete wellbeing assessments using accessible tools. Appropriate training should be provided by the league or governing body to enable the lead to recognize "high-risk" incidences. Additionally, the lead is responsible for organising educational sessions delivered by external experts at the team or club level. **External Expert Support**: Clubs must facilitate access to specialised professionals in menstrual health, eating disorder management, and other related fields on an as-needed basis. Importantly, the governing league or body should ensure that this external expert support is available and accessible as part of their duty of care to athlete welfare.

By adopting these minimum recommended differentiated support systems, clubs can more effectively optimise player health, mitigate risks related to low energy availability and menstrual dysfunction, and foster positive cultural and behavioral changes around nutrition and female athlete health. This scalable approach allows smaller or less resource-rich clubs to progressively enhance their support structures over time, promoting equity and improved welfare across women's soccer.

7.4. Limitations

While the studies conducted in this thesis have contributed novel data to our understanding of elite female soccer players, each study within this thesis had specific limitations that should be acknowledged.

Qualitative Study Protocol Design

While the qualitative studies within this thesis provide valuable insights into the areas of nutrition and menstrual health support among elite female soccer players, several limitations of the study protocol must be acknowledged.

Generalisability

A primary limitation across both studies is the issue of generalisability. The use of purposive sampling, although essential for capturing in-depth and context-specific data, limits the extent to which the findings can be applied to a broader population. The sample in each study was composed exclusively of elite female soccer players, and the results may not reflect the experiences of all individuals within this group or beyond. Readers are encouraged to critically reflect on the relevance of these findings within their own contexts, rather than generalizing them broadly (Smith and McGannon, 2017). However, unlike Studies 3 and 4, adult players were represented within this study, as well as players at club level.

Influence of Interview Context

In both studies, the presence of certain contextual factors during interviews may have influenced participants' willingness to share openly. All interviews with younger players (aged 16-17) were conducted with a parent present to adhere to safeguarding guidelines, which could have impacted the depth of disclosure from these participants. Additionally, within both studies, the one-off nature of the interviews may have limited participants' comfort and openness, as repeated interactions might have fostered greater trust and more detailed sharing. This perhaps had a greater impact on Study Two, given the personal nature of the topic of discussion.

Questioning and Topic Breadth

The broad nature of the questioning within both studies allowed the interviews to be participant-led, which was advantageous in exploring a wide range of topics. However, this approach also emerged as a limitation, as it may have prevented a deeper exploration of specific themes. Further research is recommended to investigate the themes of studies 1 and 2 in greater detail.

Subjectivity and Representation of Menstrual Experiences (Study Two)

In Study Two, all data were self-reported, which introduces an element of subjectivity regarding experience as no MC data was tracked. Furthermore, the study included only participants who menstruated regularly, meaning that any challenges related to menstrual irregularities were based on participants' perceptions of others' experiences or past experiences rather than current, personal challenges. This limitation may have constrained the depth and accuracy of insights into menstrual irregularities, as the study did not directly capture the experiences of those currently facing irregular MCs.

Timing and Recall Bias (Study Two)

Another limitation specific to Study Two is the timing of interviews relative to the participants' MCs. Interviews were not conducted at any specific phase of the cycle, which means that participants' perceptions and recall might have been influenced by their immediate experience on the day of the interview. Pain intensity recall, for instance, is known to diminish when not being experienced in the moment (Robinson et al., 2002).

6. Researcher Characteristics

Finally, in Study Two, the fact that the principal investigator was male may have influenced the openness of participants during interviews. This is an important consideration, especially given the sensitive nature of discussing menstrual health, which may have led some participants to withhold certain information.

Quantitative Study Protocol Design

While the quantitative studies within this PhD research provide valuable contributions to understanding EE, EI and EA among elite female soccer players, several limitations related to the study design and methodology must be acknowledged.

Generalisability

A common limitation across both studies is the issue of generalisability. All data were collected within a single national team, albeit from different squads, which limits the extent to which the findings can be generalized to the wider population of elite female soccer players. The unique characteristics and conditions of this specific team may not fully represent the experiences or practices of other teams or athletes in different contexts. For example, differences in coaching approaches, training routines, dietary practices, and organisational frameworks across various clubs could affect the results seen in each study.

Accuracy of Dietary Assessment Methods

Both studies highlight the inherent challenges in accurately assessing dietary intake and EA in free-living conditions. In Study Three, the quantification of EA was complicated by the technical difficulties of accurately assessing both EI and EEE. The potential for under-reporting of dietary intake, which is a common issue in such studies was however addressed within both studies by adjusting data for potential underreporting (Study Three) and in directly estimating underreporting within Study Four. Based on the findings of Study Four, the limitations of using the RFPM were evident, particularly in the context of accurately measuring absolute EI. The study identified a mean difference of 499 $kcal \cdot day^{-1}$ between methods, with substantial variability at the individual level. This variance underscores the challenges inherent in accurately capturing dietary intake data, especially in real-world environments where participant reporting errors and researcher estimation errors are significant factors, which will have a knock-on effect on EA values.

Limitations in Measuring Energy Availability

Both studies grappled with the complexities of measuring and interpreting EA, particularly in athletes living under free-living conditions. The categorization of LEA as <30 $kcal \cdot kg^{-1}$ $FFM \cdot day^{-1}$, which is typically based on controlled laboratory studies, may not be directly applicable to athletes with varying daily training volumes and dietary practices. This limitation is exacerbated by the use of prediction equations for RMR and correction factors for EEE, which may introduce further inaccuracies. In Study Four, the absence of daily hydration status measurements also added uncertainty to the interpretation of BM changes, which could influence estimated EA and PAL values.

Absence of Performance and Symptomology Data
Neither study evaluated the effects of players' habitual dietary practices on performance metrics, fatigue indices, or symptoms associated with LEA. This omission limits the ability to draw conclusions about the practical implications of the observed dietary behaviours on athletic performance and health outcomes. Future research should aim to incorporate these measures to provide a more comprehensive understanding of the relationship between dietary intake, EA, and athlete performance.

Methodological Challenges in Assessing Exercise Energy Expenditure (Study Four)
In Study Four, the methodology used to measure EEE posed additional challenges. The study relied on correction factors and prediction equations, which, while necessary, introduce potential sources of error. Furthermore, the study acknowledges the challenges in defining "exercise" in a consistent manner, as daily variations in training intensity and volume complicate the assessment of EEE. These methodological issues highlight the difficulty in applying universal categories for LEA in free-living athletes and call for more nuanced approaches to assessing EA in diverse athletic populations.

7.5. Recommendation for Future Research Directions

Recommendation One
Insights derived from Study One provide practical insights that have direct implications for creating behaviour change interventions and educational frameworks. However, although this study was coded according to a behaviour change framework, a cultural theory was not incorporated. In order to effectively explore the culture, a framework such as Bourdieu's Connected Concepts of Habiteus and Doxa Practices would provide a theoretical lens to more effectively evaluate how nutritional culture influences the nutritional habits of elite female soccer players, as recently incorporated within a study in elite men's soccer (Foo et al. 2024). Furthermore, due to the broad nature of the questions asked within Studies One, themes could have been explored in far greater detail. Therefore, further research should look to explore each of the themes in greater detail, specifically with the aim of understanding the experience of players who do encounter body image challenges due to the prevalence and potential severity of these challenges. A greater understanding of the nutritional culture and underlying causes of body image challenges will help to fine tune education interventions with the purpose of providing the necessary support to players from adolescence.

Recommendation Two
Insights derived from Study Two provide practical insights that have direct implications for improving menstrual health support. Given the identified lack of menstrual health support, the development of an educational framework with the aim of increasing knowledge within this area is recommended, focussing on the insights from this study and similar qualitative studies within elite sport. Furthermore,

a follow-up could study could measure the impact of the previously mentioned intervention or framework at the elite level.

Recommendation Three

Given the flaws discussed within Studies One and Two in measuring LEA using self-reported EI, future studies should look to report levels of absolute EI and EA using the DLW method, similarly to Study Four but over a longer period. This would allow for the identification of periods where players are at greater risk of LEA., as well as the prevalence of long-term LEA.

Recommendation Four

Lastly, although Studies Three and Four within this thesis measured EA, symptoms of LEA were not measured. Given that LEA is the underlying aetiology of REDs and that the latest REDs consensus statement (Mountjoy et al. 2024) recommends a symptom led approach to assessing REDs, long term measurement of symptoms related to LEA (and indeed REDs) should be measured at the elite level. However, it must be acknowledged that REDs diagnosis by symptoms alone is a flawed concept. Therefore, a recommended framework for this research is to use the eight components of the 'Athlete Health and Readiness Checklist' (Jeukendrup et al. 2024). This broad approach encompasses symptoms related to REDs, without assuming that REDs exists, prioritising the most appropriate treatment for the athlete.

7.6. Closing Thoughts

In summary, this thesis used a mixed methods approach to assess nutritional practices and energy requirements of elite female soccer players. To meet daily energy requirements, data demonstrate that total daily carbohydrate intake should at least be equivalent to 5 $g \cdot kg^{-1}$. However, the nutrition culture within the women's game may not always be conducive to optimal fuelling practices, owing to challenges associated with social opportunity (e.g. social media, comments, etc.) and reflective motivation, all of which are aligned around player and stakeholder perceptions of optimal body composition. Despite previously observation of low energy availability within this population, the data also demonstrate that prevalence of low energy availability is likely over-estimated primarily because of inaccuracies associated with dietary assessment methods. When taken together, this thesis provides a platform for which to formulate targeted education and behaviour change strategies for players, stakeholders and practitioners alike.

Chapter Eight

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