An evaluation of energy requirements and nutritional practices in male academy soccer players: implications for growth, maturation and player development.

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“I have missed more than 9,000 shots in my career. I’ve lost almost 300 games. Twenty-six times I’ve been trusted to take the game-winning shot and missed. I’ve failed over and over and over again in my life. And that is why I succeed.”

Michael Jordan

Abstract

Soccer academies in the EPL and EFL aim to develop players to play for their first team. While transitioning through the development pathway, players experience growth and maturation whilst completing high volumes of pitch-based loading, non-pitch-based work and full-time education. This thesis aims to quantify the acute fuelling and recovery practices of academy players and determine the response of bone (re)modelling markers in the hours before and after pitch-based training. Players (U12-U21 age groups, n=48) self-reported their energy and macronutrient intake (RFPM) in the 4 hours pre- and post-training (Chapter Four). Pre-training CHO intake ranged from 0.8 ± 0.4 $g.kg^{-1}$ (U21) to 1.5 ± 0.9 $g.kg^{-1}$ (U12), post-training CHO intake ranged from 1.6 ± 0.8 $g.kg^{-1}$ (U12) to 0.9 ± 0.5 $g.kg^{-1}$ (U14) highlighting sub-optimal fuelling and recovery practices. In using doubly labelled water academy players (n=8, U13) displayed greater daily energy expenditure over 14-day period (ACAD: 3380 ± 517 $kcal.d^{-1}$, NON-ACAD: 2641 ± 308 $kcal.d^{-1}$; $p < 0.05$) compared to their non-academy counterparts (n=6, U13) (Chapter Five). To determine the response of high (TRAIN HIGH; 1.5 $g.kg^{-1}$, 60 g, 1.5 $g.kg^{-1}$ and 1.5 $g.kg^{-1}$ consumed at 08:00, during training, 12:30 and 13:30, respectively) and low CHO availability (TRAIN LOW; 0 $g.kg^{-1}$) upon markers of bone (re)modelling (Chapter six) players completed two trials separated by one week, preceded by a REST trial. AUC for βCTX and PINP was greater ($p < 0.01$ and $p = 0.03$) in TRAIN LOW compared to TRAIN HIGH. Utilising the COM-B framework, players, parents and staff members highlighted a lack of understanding of acute nutritional requirements and a lack of opportunity to consume food and drink, as barriers to optimal nutritional intake (Chapter 7). Data presented provides the first assessment of the acute nutritional practices of academy soccer players using both quantitative and qualitative methodologies.

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Declaration

I declare that the work within this thesis, is unless otherwise stated entirely my own. All attempts have been made to ensure that the work of others which has contributed to this thesis breaches no copyright laws and is appropriately cited and referenced within the text.

Publications and presentations

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

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Abbreviations

18O (Heavy oxygen)

2H (Heavy hydrogen / deuterium)

Aca (Albumin Adjusted Calcium)

AEE (Activity Energy Expenditure)

ANOVA (Analysis of Variance)

AUC (Area Under the Curve)

BMC (Bone Mineral Content)

BPM (Beats Per Minute)

Ca (Calcium)

CHO (Carbohydrate)

CI (Confidence Interval)

CM (Centimetres)

CO_2 (Carbon dioxide)

CTX (C-Terminal Telopeptide)

CV (Coefficient of Variation)

DIE (Desired Initial Enrichment)

DLW (Doubly Labelled Water)

DXA (Dual-Energy X-Ray Absorptiometry)

EDEE (Exercise Daily Energy Expenditure)

EDTA (Ethylenediaminetetraacetic Acid)

EE (Energy Expenditure)

EI (Energy Intake)

ENMO (Euclidean Norm Minus One)

EPL (English Premier League)

EPPP (Elite Player Performance Plan)

FA (Football Association)

FC (Football Club)

FFM (Fat-Free Mass)

FP (Foundation Phase)

GH (Growth Hormone)

GIP (Glucose-Dependent Insulinotropic Polypeptide)

GLP-1 (Glucagon-Like Peptide-1)

GPS (Global Positioning System)

HR (Heart Rate)

HSR (High-Speed Running)

IDP (Individual Development Plan)

IE (Initial Enrichment)

IGF-1 (Insulin-Like Growth Factor-1)

IL-6 (Interleukin-6)

ISAK (International Society for the Advancement of Kinanthropometry)

Kcal (Kilocalories)

KG (Kilograms)

KJ (Kilojoules)

KM (Kilometres)

LEA (Low Energy Availability)

LTAD (Long-Term Athlete Development)

MD (Match Day)

MDT (Multidisciplinary Team)

MET (Metabolic Equivalent of Task)

MVPA (Moderate to Vigorous Physical Activity)

NEAT (Non-Exercise Activity Thermogenesis)

O_2 (Oxygen)

PA (Physical Activity)

PAS (Percentage of Adult Stature)

PDP (Professional Development Phase)

PHV (Peak Height Velocity)

PINP (Procollagen Type I N-Terminal Propeptide)

PTH (Parathyroid Hormone)

PWV (Peak Weight Velocity)

RED-S (Relative Energy Deficiency in Sport)

RMR (Resting Metabolic Rate)

RQ (Respiratory Quotient)

RPE (Rating of Perceived Exertion)

SD (Standard Deviation)

SENr (Sports Exercise Nutrition Register)

TD (Total Distance)

TDEE (Total Daily Energy Expenditure)

UEFA (Union of European Football Associations)

U (Under)

$\dot{V}CO_2$ (Carbon Dioxide Production)

$\dot{V}O_2$ (Oxygen Consumption)

VO_2 (Volume of Oxygen)

YDP (Youth Development Phase)

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player's mean intake. a denotes significant difference from U12, b denotes significant difference from U13, c denotes significant difference from U14, d denotes significant difference from U15/16, e denotes significant difference from U18, and f denotes significant difference from U21 (all $p < 0.05$).

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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 in order to provide the rationale for the aims and objectives of this thesis.

Background

In England there are 89 soccer academies across the English Premier League (EPL) and Football League (EFL) (Premier League, 2022) with the aim of recruiting and developing players by improving their technical, tactical, psychosocial and physical capabilities (Wrigley et al., 2012). Twenty years after joining Aston Villa Football Club's (FC) academy, in the summer of 2021 Jack Grealish was sold to Manchester City FC for £100 million, an English record transfer fee. Two years later this record was broken by a second academy graduate, following the transfer of Declan Rice from West Ham United to Arsenal FC. Whilst underlining the potential successes of academy programmes, both transfers further emphasised the importance of academies to produce players to feed a club's respective first team (Elferink-Gemser et al., 2012) therefore omitting the requirement for significant investment in transfer fees.

The development of youth soccer players is multidimensional and shaped by the Elite Player Performance Plan (EPPP), a combined framework produced by the Football Association (FA), EFL and EPL. The EPPP was introduced in 2011, three years prior to Grealish making his senior debut, with the aim of modernising youth development in English Football by producing a world leading academy system (Premier League, 2011). Indeed during the 2012/13 season youth players from European leagues received twice as much formal coaching as their English counterparts (Premier League, 2022). Twelve years on, there have been more than 500 home-grown debutants in the Premier League, with more than 75% of professional contracts in the EPL and EFL currently held by home grown players, placing English under (U) 21 players as the most financially valuable, globally (Premier League, 2022).

English Premier League and Football League soccer academies can be grouped into four classifications; Category One (n = 26, highest level), Category Two (n = 18), Category Three (n = 41) and Category Four (n = 4), depending upon factors including academy facilities and staffing provision (Carney et al., 2022). Category One academies have greater staffing provision exemplified through the number of full-time nutritionists, and also greater resource than lower ranked academies (i.e., food and drink provision) yet even between Category One academies provision is inconsistent (Carney et al., 2022). Category One academies may recruit players as young as eight years old into the Foundation Phase (FP: under 9 - 11 years old). Thereafter which players progress through the academy system to The Youth Development Phase (YDP: under 12 - 16 years old) and Professional Development Phase (PDP: under 17 - 21 years old) where they are exposed to a formalised and structured coaching programme, non-football activity (i.e. video analysis or yoga) and full-time education (Hannon et al., 2020). As players progress through the academy system they may be enrolled on part-time, full-time or hybrid programmes depending upon factors including academy category, staffing provision and education provision. This decision will likely have an impact upon the pitch-based load which players are exposed to, their daily and weekly education and soccer schedule, their daily energy expenditure and as such energy and macronutrient requirements.

As players progress through chronological age groups, growth and maturation results in increases in body mass (~ 30 kg), stature (~ 25 cm) and fat-free mass (~ 23 kg) coinciding with increases in resting metabolic rate (~ 400 kcal.d^{-1}) between the ages of twelve and eighteen (Hannon et al., 2021b, Hannon et al., 2020). During this time academy players are exposed to increases in training load, both through increases in exercise duration and total distance (Hannon et al., 2021a). While academy players fail to match training intensity of adult players, pitch-based volume is comparable to that of their adult counterparts (Anderson et al., 2016b, Malone et al., 2015). When taken together increases in resting metabolic rate and progressions in training load lead to increases in total daily energy expenditure (TDEE) throughout the development pathway of ~ 750 $kcal.d^{-1}$ between U12 and U18 players (Hannon et al., 2021b). Accordingly resultant total daily energy expenditures of academy players being comparable to (and in some cases) greater than their first team counterparts (Anderson et al., 2017). Investigations into the total daily energy expenditure (~ 3600 $kcal.d^{-1}$) of elite men's first team football is well documented (Anderson et al., 2017). Research using gold standard methodologies (*i.e.,* the doubly labelled water) with elite participants (*i.e.,* those from a Category One academy) in academy soccer however is limited to one club (Hannon et al., 2021b). This presents a clear need to further investigate the total daily energy expenditure of academy soccer players considering the additional energetic demands of pitch based training and physical activity attributable to the busy daily lives of academy soccer players compared to adolescents not enrolled in academy programmes.

Such high daily energy expenditure presents a need for academy players to achieve optimal intake of energy and macronutrient intake through the training week, yet academy soccer players often fail to consume sufficient energy and carbohydrate (Hannon et al., 2021b). Different methodologies highlight a range in estimated daily energy intake of academy players between 1900 – 3300 $kcal.d^{-1}$ throughout the training week (Russell and Pennock, 2011, Briggs et al., 2015, Hannon et al., 2021b, Naughton et al., 2016). Most recently in using the RFPM Hannon et al. (2021b) showed that energy intake of academy players increases in a hierarchical fashion with U12/13 players (2659 ± 187 $kcal.d^{-1}$) consuming less energy than U15 players (2821 ± 338 $kcal.d^{-1}$) and U18 players (3180 ± 279 $kcal.d^{-1}$) respectively. Despite suggesting that academy players often present with an energy deficit, data provides little context to the timing and totality of energy and macronutrient intake with reference to pitch-based training.

Indeed given the need for optimal carbohydrate to support physical and technical performance during training (Russell and Pennock, 2011, Briggs et al., 2015, Pueyo-Arias, 2024) and to optimise recovery post-training (North et al., 2022) it is important to better understand the habitual fuelling practices of academy soccer players. Specific reference should be given to the acute period before, during and after pitch-based training and with reference to additional activities (i.e., schooling) associated with enrolment on a full-time academy programme.

A lack of sufficient energy and macronutrient intake through the training week or "under-fuelling" is associated with reductions in performance during immediate and subsequent training sessions (Collins et al., 2021). Repeated under-fuelling presents a risk of low energy availability (LEA, often defined as <30 kcal.kg FFM^{-1}.day^{-1}) to youth soccer players. The associated negative implications of LEA and relative energy deficiency in sport (RED-S) are multifaceted and include reduced bone mass accrual and an increased risk of stress fractures (Mountjoy et al., 2023). Consistent under-fuelling coupled with high training load may provide rationale for the high prevalence of bone stress injuries to the pelvis, lower back, sacrum and knee in soccer academies from England, Europe and South America (Hall et al., 2020). While research in adult populations suggests that commencing exercise with low carbohydrate availability increases bone (re)modelling through increased bone resorption markers (Sale et al., 2015), and high carbohydrate availability attenuates bone turnover in elite runners (de Sousa et al., 2014) conclusions are drawn from tightly controlled laboratory conditions, often in adult populations, with little ecological validity due to the different mechanical demands of soccer training and match play. To better understand the effects of habitually commencing training with low carbohydrate availability, further research is required to understand the effects of soccer specific training to markers of bone formation and resorption and the implications of low and high carbohydrate availability pre-, during and post-training within this population at a vital phase of skeletal development.

Despite data highlighting that academy players on occasion fail to achieve optimal energy and macronutrient intake (Hannon et al., 2021) with theoretical links between performance and health, specifically markers of bone remodelling, there is very little qualitative data highlighting the reasons behind such nutritional practices. Despite an increase in nutrition research within academy soccer (Hannon et al., 2020, Hannon et al., 2021a, Carney et al., 2023), quantitative data remains from a relatively small sample size. Such information provides little insight into the reasons underpinning nutritional choices of academy soccer players and the athlete's physical and social environment which influences their behaviour (Bentley et al., 2019b). Limited qualitative data suggests factors such as nutritional knowledge, food preparation skills and food provision at training grounds (Carter et al., 2022) or a lack of free time around training (Carney et al., 2024) are key barriers to optimal energy and macronutrient intake in academy soccer players. In this instance qualitative research clearly demonstrates that failure to achieve nutritional guidelines is a complex interaction between multiple factors within the busy daily lives of an academy soccer player. The application of theoretical models such as the COM-B model which seek to assess an athlete's capability, opportunity and motivation towards completing a specific behaviour provides context behind an athlete's nutritional intake (Michie et al., 2011). Further research utilising such models is required to understand the biological (i.e., appetite or taste), physical (i.e., access to provision), psychological (i.e., mood), cognitive (i.e., knowledge), social (i.e., family and peers) and cultural and economic variables (i.e., food provision) which present as barriers and enablers to optimal nutritional intake for academy soccer players in the acute period before and after training. When taken alongside quantitative data, qualitative insight must seek to facilitate increases in energy and macronutrient intake in the hours before and after training.

1.1 Aims, objectives and hypotheses

The aim of this thesis is to evaluate the energetic requirements and habitual fuelling and recovery practices of male academy soccer players with specific focus upon the acute period pre-, during and post-training. In addition, the physiological effects of high and low carbohydrate availability upon acute regulation of bone turnover markers will also be assessed, before conducting a qualitative exploration of the potential barriers and enablers to optimal nutritional practices in academy players in the acute period before and after training.

This will be achieved through the following objectives:

1. Quantification of the acute fuelling and recovery practices of male academy soccer players through the Youth and Professional Development Phases of a Category One academy pre-, during and post-training. Acute fuelling and recovery practices will be evaluated using the Remote Food Photography Method in the four hours before, during and after training. This objective will be achieved through the completion of study 1 (Chapter 4).
2. Quantification of the energy expenditure, external training load and physical activity levels of academy soccer players compared with age matched non-academy players. Total daily energy expenditure will be quantified using the doubly labelled water method. This objective will be achieved through the completion of study 2 (Chapter 5).
3. Quantification of the effects of a soccer specific training session and the role of carbohydrate availability upon markers of bone (re)modelling in academy soccer

players. Bone (re)modelling will be assessed through aliquots of blood plasma and serum. This objective will be achieved through the completion of study 3 (Chapter 6).

4. A qualitative analysis of the barriers and enablers to achieving optimal energy and macronutrient intake in the acute period pre- and post-training in academy soccer players. Qualitative data will be collected from players, parents and staff members using semi-structured interviews. This objective will be achieved through the completion of study 4 (Chapter 7).

It is hypothesised that academy players will on occasion fail to consume optimal energy and carbohydrate intake, especially within players from younger age groups due to constraints of travel, education and lack of nutrition provision compared to their older counterparts. Indeed it is hypothesised that academy players will display total daily greater energy expenditure values compared to non-academy players, underlining the need for players to achieve optimal energy and macronutrient intake. The downstream effect of sub-optimal carbohydrate intake pre-, during and post-training is hypothesised to have a negative impact upon acute bone (re)modelling which may present a risk of skeletal injury.

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 An Overview of English Premier and Football League Academies

Historically the lack of emerging youth talent across UEFA federations and the reluctance to invest in youth soccer programmes became a point for concern for national soccer federations (Relvas et al., 2010). The continued globalisation of European soccer paired with increasing revenues at first team level (i.e., through broadcasting rights) further facilitated the increased buying and selling of players (Relvas et al., 2010). Such phenomena created concern that teams would lose their identity (i.e., a lack of eligible national players) and that potentially talented youngsters would not get to play within their local community, leading to the development of 'the home-grown rule' (Downward et al., 2014). In efforts to reduce such losses in England, the Premier League in tandem with the FA introduced the Elite Player Performance Plan (EPPP) to English soccer academies. Stimulated by a rise in the global success of the EPL but a reduction in the success of homegrown players and national teams over the last two decades, the EPPP was designed with the vision of developing a world leading academy system and technically excellent players.

The EPPP aims to add value to player development throughout all age groups from U9 – U21 across a multi-disciplinary platform including physical, technical, tactical and psychological development (Premier League, 2022). As presented in Table 1 the introduction of the EPPP is cited as a success by the Premier League in a number of key areas relating to on pitch performance and off pitch development. While aiming to enhance player development upon its conception, success of the EPL has also facilitated areas including work force development and financial investment. To this end since the introduction of the Elite Player Performance plan in the 2012 / 2013 season more than 1,860 homegrown players have featured in the Premier League and more than £4billion in revenue has been raised from the transfer of academy graduates across the EPL and EFL (Premier League, 2022). Thus arguably achieving the aims previously set out that elite soccer development programmes to aspire to develop players and the individual as a whole either for the first team or to generate income through the sale of marketable assets (Stratton, 2004). Indeed the Premier League adopted a four-corner model aiming to enhance a player's technical, tactical, psychosocial and physical capabilities (Wrigley et al., 2012). The result is a formal three-tiered development system comprising of the Foundation Phase (U9 – U11), Youth Development Phase (U12 – U16) and the Professional Development Phase (U18 – U21). That said, a player may register with a club from U5 and can join at any stage of the pathway depending upon the classification of the respective academy. Opportunity to play more matches, the absence of injury, training, social, personal and cultural influence all impact upon the development of a youth soccer player (Reilly et al., 2000) and given the development pathway to elite adult soccer is characterised by a heightened level of performance expectation with a reduced tolerance to failure (Reilly et al., 2008), the importance of successful long-term development cannot be understated.

2.1.1 Classification and the development phases of English Premier League soccer academies

The classification of academies from Category One (best) to Category Four (worst) is audited annually. Academies are grouped depending upon a number of factors including their vision and strategy, leadership and management, coaching, education, games programme, sports science and medicine provision, player development and progression, talent identification and recruitment, facilities and corporate and financial stability (Premier League, 2011). While Category One, Two, and Three academies all may register players formally at U9 (Category Four academies may only recruit at U17), the provision between each level, notably the training model (i.e. part-time, hybrid or full time), number of coaching hours, investment, performance analysis, facilities, and support staff will increase significantly towards the higher classified academies. In the 2022 / 2023 season there were 25 Category One academies, five more than before the introduction of the EPPP ten years earlier (Premier League, 2022). While Category One academies are required to provide a dictated number of education and coaching hours, with governance dictating the number of coaching roles required across each phase, such a president does not exist for nutrition support. The result is disparity between the nutrition provision (i.e., food and drink provided before and after training) and staffing within academies. As such many lower ranked academies do not have access to full, or part-time staffing support with limited food and drink provision to players (Carney et al., 2022).

2.1.2 Increased sport science and medicine staffing and research support within soccer academies since the introduction of the EPPP

More than 4,000 staff are employed within English soccer academies across all four classification levels. In Category One academies staff form multi-disciplinary teams (MDT) falling into; coaching staff (29%), sport science and medicine (25%), education, player care and safeguarding (7%), performance analysis (6%), talent identification (8%) and academy operations (7%) (Premier League, 2022). The EPPP stipulates that sport science and medicine teams must provide nutrition support as an aspect of each player's individual performance plan (IDP) (Premier League, 2011). The result is an increase in sport nutrition research within this population since its implementation in 2012 (Carney et al., 2022, Carney et al., 2024, Hannon et al., 2020, Hannon et al., 2021a, Hannon et al., 2021b, Hulton et al., 2022a, Naughton et al., 2016, Russell and Pennock, 2011). Despite this however only 64 % of Category One academies employ a nutritionist full time, with no full-time nutritionist employed in Category Two or four academies. The consequence is that nutritional support is often provided by non-specialist support staff (i.e., physiotherapist or sport scientist) who may pass on incorrect or conflictive evidence (Cockburn et al., 2014). Nutrition staffing provision is focused towards players in the PDP with considerably less support for YDP and FP players (Carney et al., 2022) despite compounding effects of rapid growth and maturation (Hannon et al., 2021b) and clear barriers to optimal nutritional intake within these age groups (Carney et al., 2024). To this end there is a clear need to increase the number of accredited nutritionists employed full-time within academy soccer.

Table 1. The benefits of the EPPP to the academy soccer landscape. Adapted from "Ten years of the EPPP, Ten reasons to celebrate." (Premier League, 2022)

1	762 more academy graduates signed professional contracts in the 2021/2022 season compared to the 2011/2012 season.
2	In the 2021/2022 season twice as many match minutes in the English Premier League were completed by English U21 players compared to the 2011/2012 season.
3	By the end of the 2021/2022 season English U21 players were the most financially valuable globally, rising from fifth most financially valuable ten years earlier.
4	By the end of the 2021/2022 season England International youth teams had won four titles in five years, with the men's senior team reaching the final of Euro 2020 (and later Euro 2024). With their female counterparts winning the competition in both 2021 and 2025.
5	By the end of the 2021/2022 season more than £22 million had been invested in workforce development of academy staff.
6	Since 2012/2013 season more than £1.9 billion has been invested into Youth Development soccer.

2.2 Growth and Maturation

Growth refers to the measurable changes in size, physique and body composition of various systems within the body and maturation refers to the progress towards a mature state (Malina et al., 2004a). Changes in body size are outcomes of three underlying cellular processes; 1) an increase in cell number of hyperplasia, 2) an increase in cell size or hypertrophy and 3) an increase in intercellular substances or accretion (Malina et al., 2004a). Development during this time can be termed as biological or behavioural. Biological development refers to the development of stem cells into different cell types, tissues, organs and functional units. Behavioural development relates to the competence in a variety of an individual to adjust to the behaviours which characterise a certain population. The process of growth and maturation is an example of biological development, however the interaction of behavioural development during growth and maturation shapes an individual as they progress through from immaturity to adolescence to adulthood on their journey throughout the academy system. It is biological development which triggers a growth in stature which is highest during the first year of life and slowly declines until the onset of the adolescent growth spurt at the approximate chronological age of twelve to fourteen years old in males, approximately two years later than their female counterparts. At this stage individuals are typically classified as early, on-time or later maturers due to the interaction between their chronological age and their biological maturation.

Given the differences within squads there is a clear need to assess biological maturity age and maturity. There are a number of methodologies which aim to assess the degree of maturation with respect to a player's chronological age grouped as invasive or non-invasive methods.

Invasive methodologies such as assessment of skeletal age provide an accurate assessment of biological maturation (Tanner, 1962) through utilisation of the Greulich-Pyle method (Garn, 1959), Tanner-Whitehouse methods (TW1, TW2 and TW3; Tanner et al. (2001)) and the Kamis Roche equation (Khamis and Roche, 1994). However differences in populations used within the development of such methods lead to discrepancies in results when applying data to youth soccer players (Malina et al., 2007). Regular x-ray protocols such as these which require specialist trained staff are both impractical and exposes individuals to low – level radiation presenting ethical concerns within the youth athlete population (Lloyd et al., 2014). Methods to assess sexual maturation as an individual passes through puberty to full sexual maturity (Tanner, 1962) have been used to determine maturation through ratings of secondary sexual characteristics in comparison to pre-determined stages of physical development known as Tanner stages (Tanner, 1962). Yet the obvious ethical and legal issues of collecting such data result in maturation being inappropriate for youth sport, with non-invasive methodologies and prediction equations most commonly used within academy soccer (Hannon et al., 2021).

Within soccer academies assessments of somatic maturity are the most commonly used methods of assessing biological maturity. Predicting age at peak height velocity (PHV) and predicting adult stature (which later allows for calculation of current percentage of adult stature achieved) are used both in research and practice within academy soccer (Hannon et al., 2021) describing the rate of growth in stature or another body part (Lloyd et al., 2014).

The prediction equation developed by Mirwald and colleagues (2002) utilises body mass, stature, sitting height and estimated leg length by subtracting sitting height from standing height allows for prediction of age at PHV. Originally designed in both male and female caucasian adolescents the Mirwald equation reports mean differences in verification samples of as little as 4 months in boys and an even smaller error margin in girls. Such data provides a maturity offset which when viewed with respect to chronological age will provide coaches and researchers with a predicted age at PHV between ten to eighteen chronological years of age (i.e., -/+ four years from PHV). Despite using two independent cohorts, authors exercise caution when using the model given a bias to underestimate PHV at younger ages and overestimate PHV at older ages. In attempts to reduce bias and error within the Mirward equation, models later proposed by Moore et al., (2015) were validated using existing longitudinal studies yet such models succeeded only in reducing, not eliminating error. With inaccuracies still existing both pre- and post-PHV. As such both equations report systematic bias and their application should be limited to (as is used within practice) to describing group level individuals (i.e., an U13 squad) as pre, circa or post-PHV.

Estimation of predicted adult stature (PAS) and the calculation of current percentage of adult stature allows comparison of players of similar chronological age to their biological maturity. To this end players of the same chronological age may have achieved different degrees of their predicted adult stature, as such the players with greater %PAS would be more biologically mature than those with a lesser %PAS (Lloyd et al., 2014, Malina et al., 2015). A number of equations can be used to determine predicted adult stature, with those developed by Sherar et al., (2005) as shown in figure two and the Khamis and Roche (1994) prediction equation are most commonly used within academy soccer. The Khamis Roche equation (1994) equation uses body mass, stature and mid-parent high to assess predicted adult height with an error or ± 2.2 cm. The need to collect both mother and father’s height however raises methodological concerns given its lack of feasibility (Malina et al., 2007). The Sherar equation is considered advantageous given it accounts for maturity timing, an omission of other prediction equations. Alongside chronological age, body mass, stature and sitting height, the work by Sherar and colleagues takes maturity offset into account without needed mid-parent height. Utilising a greater sample size than other prediction equations, work by Sherar et al., boasts 95% prediction intervals of ± 5.35 cm in boys when predicting adult height. While unable to provide a direct assessment of an individuals growth relative to their PHV, in academy soccer it is common that both the Mirwald and Sherar equations are used in tandem to provide assessments of growth and maturation to key stakeholders both objectively to assess injury risk or subjectively often to account for technical or physiological changes in an individual's game.

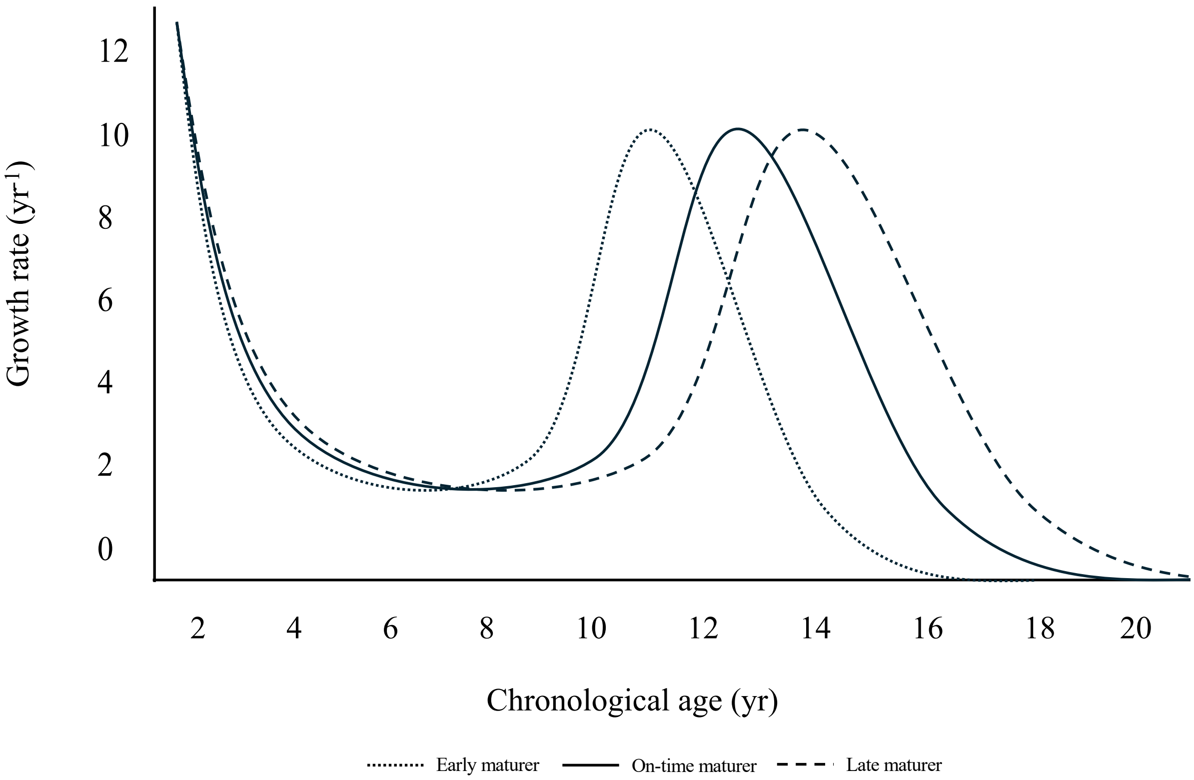

Figure 1. Adapted from Sherar et al., (2005) showing typical growth curves of an early, on time and later maturer.

2.2.1 An overview of growth and maturation; sexual, skeletal and somatic maturation

Growth and maturation is an interaction of genes, hormones, nutrients and the environment in which the individual lives (Malina, Bouchard and Bar-Or, 2004) resulting in many anatomical, physiological and metabolic changes through adolescence. Growth and maturation is spilt into three main paradigms: chronological age, biological age and skeletal age. Chronological age, the time point calculated as the date from birth is used to set school years, grade teams, identify talented individuals and prescribe sessions for individuals (Lloyd et al., 2014). Yet chronological age does not directly correlate with an individual's maturity status. Indeed biological and skeletal maturation refers to the progression towards full maturity within constituent biological systems (Balyi and Hamilton, 2004) and the development of skeletal tissue respectively (Malina, 2011). During adolescence the growth of a player follows a non-linear pattern from birth, with rapid changes occurring in the first two years, followed by steady growth thereafter until a rapid acceleration during puberty before growth once again slows until full adult height is achieved (Philippaerts et al., 2006). The rapid increase in growth around puberty, typically takes place between the ages of 12 – 14 in boys, yet differences in rate of growth can mean that the range at which players achieve PHV can be between 12 – 17 years old (Sherar et al., 2005). The onset of PHV triggers a rise in stature which equates to ~ 7 cm per year, with an initial increase in leg length followed by an increased in trunk length. Following from PHV is a sustained period of weight gain (PWV) whereby adolescent's body weight can increase more than 10 kg per year (Philippaerts et al., 2006). Indeed a variation in genetic and environmental factors ensures that children of the same chronological age can vary by as much as five or six years in skeletal and biological maturity, in a non-linear relationship between stature, body mass and height (Towlson et al., 2021).

2.2.2 Biological development during adolescence

In academy soccer players both stature and body mass increase with age and maturity status (Deprez et al., 2013, Lovell et al., 2015, Malina et al., 2017, Malina et al., 2000). Changes in body size, composition and functional capacities (i.e., strength and power, aerobic capacity) that occur with puberty and the growth spurt in males are well documented (Malina et al., 2004b). The process of growth through adolescence (Malina et al., 2004a) is generally similar through body weight and dimensions of the body, with the exception of subcutaneous fat and fat distribution. Such biological development is linked to physical performance in adolescent soccer players, with differences between early and late maturers becoming more pronounced in early adolescence (Philippaerts et al., 2006). Often favouring selection of early maturers within younger age groups, indeed boys who are advanced in both sexual and skeletal maturity perform on average better than those who are later maturers. To this end several studies have reported that there is a clear selection bias towards players who are older and physically taller (Fleming and Fleming, 2012, Simmons and Paull, 2001). Despite no difference in tactical performance (Borges et al., 2018), the result of which is that fewer 'later maturing' players are represented in soccer teams after the chronological age of thirteen (Philippaerts et al., 2006). The counter to such a phenomenon is that the perceived advantaged gained by early maturing players no longer exists towards the upper Youth Development Phase (Bezuglov et al., 2019).

The classification of player's as early, 'on-time' or late maturers refers to the level (magnitude of change), timing (onset of change) and tempo (rate of change) of biological maturation throughout childhood and adolescence (Lloyd et al., 2014, Malina et al., 2004b). Reference of maturity status is typically commented in reference to peak height velocity. For example an on-time maturer would experience PHV between 13 – 14 years old (Philippaerts et al., 2006). Individuals may be more biologically advanced in relation to their chronological age and be classified as an early maturer or behind their chronological age referred to as a later maturer. Early maturers may experience peak height velocity between the ages of 11 – 13, whereas later maturers would typically experience PHV between the ages of 14 -16 years old (Lloyd et al., 2014, Malina et al., 2004b).

With reference to elite academy soccer players stature and body mass has been shown to increase by ~ 29 cm and ~ 35.5 kg respectively from U12 to U21 age groups (Hannon et al., 2020). During which time adult stature is typically achieved by approximately 16 – 17 years old (Patel et al., 2019). It is therefore not surprising that in an assessment of every registered player of a Category One EPL academy, Hannon et al. (2020) observed differences within all U12 (157 ± 4 cm), U13 (163 ± 6 cm), U14 (173 ± 8 cm) and U15 (176 ± 7 cm) age groups compared to U18 (182 ± 6 cm) and U21 (183 ± 4 cm) age groups. Similarly body mass at U12 (45.5 ± 5.9 kg) and U13 (47.4 ± 5.6 kg) was less that U15 (63.1 ± 7.1 kg), U16 (72.9 ± 7.9 kg), U18 (73.2 ± 8.1 kg) and U21 (80.3 ± 8.8 kg) players. In agreement with previous observations, fat free mass displays considerable differences of ~ 31kg between U12 and U21 players (Hannon et al., 2020) with a smaller incremental rise between U18 and first team players ~ 7 kg (Milsom et al., 2015). Notably the greatest increases in FFM observed in this study were during the transition from U13 to U14 age groups, coinciding with the greatest increases in stature and body mass, at a time when most players were experiencing peak height velocity (Hannon et al., 2020). Such increases in FFM provide reason for increasing in resting metabolic rate by ~ 400 $kcal.d^{-1}$ experienced by Indian youth soccer players (Cherian et al., 2018) and EPL academy soccer players (Hannon et al., 2020) as they progress through the chronological age groups.

2.2.3 Body composition

At the tissue level body composition consists of fat free mass, fat mass and bone tissue (Malina, 2007). With reference to adult male soccer players, links exist between body composition and performance (Sutton et al., 2009), yet caution must be exercised when comparing players of different ages and playing levels. Indeed changes in body composition in youth soccer players are likely to be a result of growth and maturation, rather than cyclical morphological changes and variation as seen in the adult men's game. When comparing the body composition of 367 academy soccer players from U15, U17 and U19 age groups Spehnjak et al. (2021) reported no difference between U17 and U19 players in body composition, however height, body mass, fat free mass and body fat were significantly different within U15 age groups compared to their older counterparts. Older players possessed greater height, body mass and muscle mass, than their younger counterparts who in turn had a greater percentage of body fat. Findings were mirrored by Mala et al. (2023) in a cohort of Portuguese soccer players when comparing U15, U16 and U17 Portuguese soccer players, U17 players presented with greater height and body mass yet lower relative body fat. In a cohort of Croatian soccer players Kovačević et al. (2023) reported U15 age group players had significantly lower body mass, height, and fat free mass than U17 and U19 players, yet presented with a greater percentage body fat. Such data correlates with findings from a Category One Premier League academy. Hannon et al., (2020) reported how growth and maturation increases absolute fat-free mass from U12 (31.6 ± 4.2 kg) to U18 (57.9 ± 6.6 kg), yet there was no difference in absolute fat mass between age groups. as such younger players display a higher percentage of body fat (U12: 22.3 ± 5.7 %) which decreases through the age groups as seen within the U18 age group (U18: 14.4 ± 2.1 %) (Hannon et al., 2020).

2.2.4 Skeletal development

Adolescence is a rapid period of skeletal development essential for the attainment of peak bone mass, during which almost half of all skeletal mass is accrued (Weaver, 2002). Development of bone tissue is dependent upon osteocytes; bone cells which regulate the flow of minerals and nutrients between the matrix and the blood. Bone deposition and bone resorption depends heavily upon osteoblasts and osteoclasts. During puberty a rise in testosterone, growth hormone (GH) and insulin-like growth factor-1 (IGF-I) enhances bone (re)modelling through osteoblastic stimulation (Hock et al., 1988). Downstream increased growth plate activity and increases in muscle mass results in increased accretion and changes in bone growth. Whilst there is very little difference in bone density between boys and girls, peak bone mineral velocity is higher in adolescent males and happens ~ 1.5 years later than in adolescent females, with a longer period of skeletal growth (Cameron et al., 1982)resulting in males typically having longer lower extremities in males compared to females(Vicente-Rodríguez et al., 2006) .The higher rate of bone accrual in adolescent boys is in part a consequence of greater calcium retention which will increase until plateau is achieved (Weaver and Fuchs, 2014). Both IGF-I and dietary calcium are essential in skeletal development, serum IGF-1 is associated with periosteal bone expansion, resulting in greater bone size. As such low IGF-I concentrations and sub-optimal calcium intake may lead to low bone formation resulting in players failing to achieve predicted stature at the onset of PHV, the consequences of which may be irreversible. Failure to achieve peak bone mass at this time as a result of hormonal or lifestyle factors may have implications for both acute skeletal injury and osteoporosis in later life (Weaver, 2002).

Skeletal development in academy soccer players has been shown to be stable up to the age of thirteen, in that skeletal age is equal to chronological age. At this stage at least 25% of total adult bone mineral content is attained in a two-year period (Bailey et al., 2000). The attainment of PHV precedes peak mineral accumulation by approximately seven months, the consequential lag period between bone size and mineral accumulation which makes the skeleton more susceptible to fracture (Weaver and Fuchs, 2014). Post-PHV skeletal age becomes greater than chronological age, a difference which becomes greatest between players aged 15 and 16, with 16% of players already at this age already skeletally mature (Malina et al., 2000). That said, the attainment of peak bone mass is site specific, for example despite maturing early in comparison to other sites, the hip does not fully mature until the ages of 16

– 18 (Matkovic et al., 1994), which may provide rationale for the high incidences of skeletal injury seen at this site within academy soccer players (Hall et al., 2020).

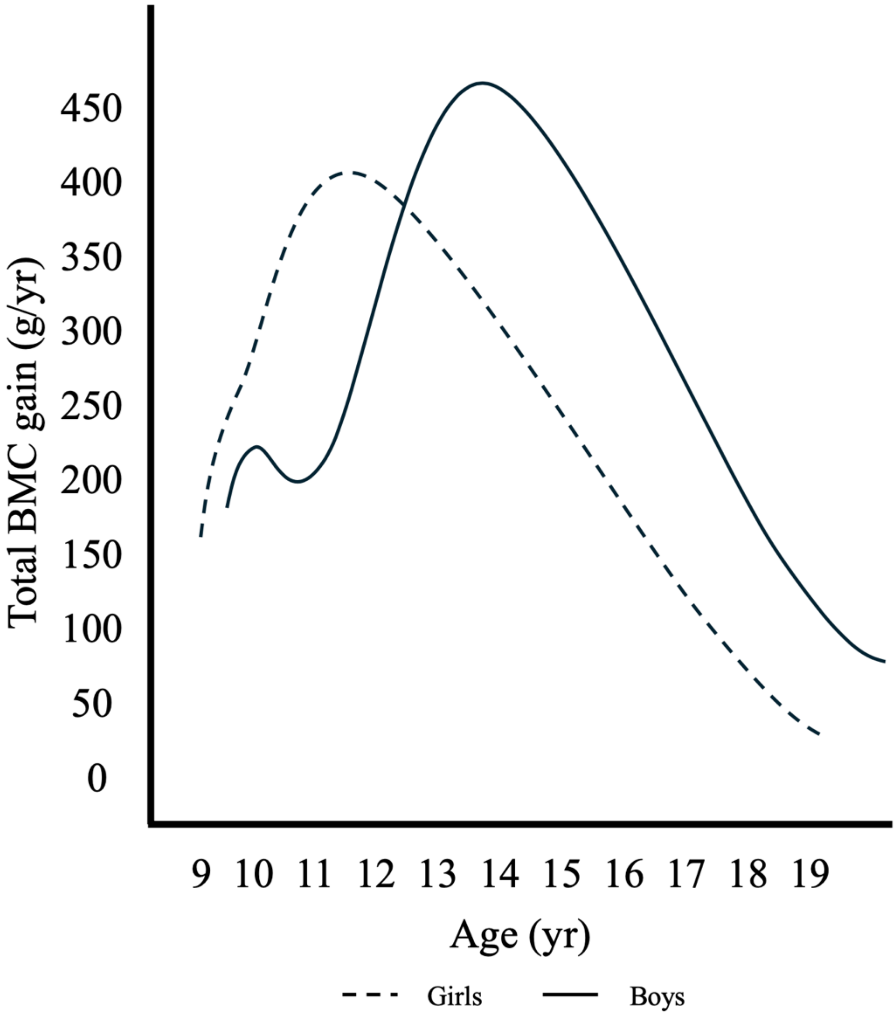

Figure 2. Total body BMC gain in boys and girls from longitudinal DXA data adapted from Bailey et al., 1999. Peak bone mineral content (BMC) gain in boys lags behind that in girls (14.0 vs. 12.5 years) and peak height velocity precedes peak BMC gain (11.8 years in girls vs. 13.4 years in boys).

Weight bearing exercise such as soccer training and match play has been cited as anabolic to bone (Varley et al., 2023) eliciting structural, shape and size changes in youth athletes (Weaver et al., 2002) suggesting that adolescents who partake in regular soccer training and match play may present with greater bone mineral density that their peers. To this end data presented by Bass et al. (1998) suggested that weight bearing sport participation during adolescence would increase BMC by up to 20%. A number which can further be increased if chronic exercise stimulus is experienced prior to the pubertal growth spurt (Vicente-Rodriguez et al., 2003), which may provide rationale for increases in skeletal injury in adolescents who enter academy systems later, or who are signed from lower ranked academies following the adolescent growth spurt. Data sampling adolescents from equivalent Foundation Phase age groups (i.e., U9 – U11) reported increases in bone mineral content in both the neck and lumbar spine following repeated jumping three times per week for one year in comparison to those who completed non weight bearing stretching exercise for the same period (Fuchs et al., 2001). Yet the consequence of rapid skeletal growth of between 7cm and 12cm per year during PHV also aligns to changes in joint stiffness, bone mineral density and imbalances between strength and flexibility contributing to a state of skeletal fragility (van der Sluis et al., 2014). Such changes lead to a rise in injury burden and frequency specifically to the knee, hip and sacrum, specifically non-contact injuries, gradual onset injuries (i.e., Osgood Schlatter disease) (Hall et al., 2020; Read et al., 2018) around rapid periods of growth and maturation (Rommers et al., 2020).

2.2.5 Physiological and metabolic development

Activation of the hypothalamic-pituitary-gonadal axis, particularly an increase in growth hormone, insulin-like growth factor 1, testosterone and thyroid hormones which occur during peak height velocity stimulates an increase in muscle mass (Malina et al., 2004b). Through the academy pathway body mass and in turn fat free mass increases by ~ 30 kg and ~ 23 kg respectively (Hannon et al., 2020). Increases in fat free mass provide rationale for increasing resting metabolic rate observed throughout the academy pathway. (Hannon et al., 2020). A phenomenon observed across both elite and recreational youth soccer players (Łuszczki et al., 2021), the latter observing acute differences pre (1528 ± 191 kcal.d^{-1}), circa (1859 ± 234 kcal.d^{-1}) and post (1940 ± 324 kcal.d^{-1}) PHV. Indeed increased resting metabolic rate at this time further contributes to increases in TDEE regardless of pitch-based training and match loads, providing rationale for the requirement of players to increase their energy and macronutrient intake in response to growth and maturation pressures (Hannon, 2020).

Between the ages of ten and nineteen the cross-sectional area of type I and type II muscle fibres increases almost twenty-fold. Greater FFM and greater absolute tissue volume subsequently contributes to phosphocreatine and glycogen stores increasing by ~ 60% allowing for a greater capacity for endogenous carbohydrate storage Timmons et al., (2007). Therefore more mature academy players will benefit from commencing training with greater levels of muscle and liver glycogen compared to less mature players if optimal carbohydrate intake (6 g.kg) is achieved throughout the training day (Hannon et al., 2021b). Conversely less physically mature players with less endogenous storage capacity have a greater reliance upon exogenous carbohydrate intake (Timmons et al., 2003) and greater oxidation rate of exogenous carbohydrate than players of the same or greater chronological age (Timmons et al., 2007). Taken together data underlines the requirement for optimal acute carbohydrate intake pre-, during and post-training. Youth athletes display a greater level of anaerobic and aerobic fitness than their non-athletic counterparts, with such differences likely as a result of training adaption (Armstrong, 2017), genetics (Simoneau and Bouchard, 1998) and variation in the timing and tempo of biological maturation (Malina, 2017). The development of anaerobic fitness increases with biological maturation (Van Praagh, 2002) with increases in peak power outstripping increases in body mass so that peak power may increase by over 350% from the ages of seven to seventeen, in line with a player's journey from pre-academy soccer (U8) to their first professional contract at aged seventeen.

In a study of most physically immature boys and girls and the most physically mature in line with Tanner reference values (Tanner, 1962), more biologically mature adolescents displayed 32% greater peak VO_2 values and 66% greater peak power than the most immature athletes (Armstrong et al., 2013, Armstrong et al., 2011). Peak VO_2 increases with chronological age from ten – seventeen years old, almost doubling during this time. Compared to their female counterparts the development of aerobic fitness in male athletes is far greater, with gender differences of ~ 50% greater peak VO_2 at the end of adolescence (Armstrong and Welsman, 2019)possibly as a surrogate of greater muscle mass, enhanced venous return and in turn increased in stroke volume subsequently increasing cardiac output. It should be noted however given male athletes typically achieve PHV later than females, there is overlap between maximal aerobic capacity in males and females between the ages of ten and thirteen (Armstrong and Welsman, 2020).

2.3 Energy Expenditure, Physical Activity and the Daily Lives of Academy Soccer Players

2.3.1 Basal Metabolic Rate

Basal metabolism displays very little day to day variation as the amount of energy required to maintain normal homeostatic physiological function at rest (Speakman and Selman, 2003). Accurate assessment of basal metabolism requires the test to be completed within an individual's bed in which they have slept. As such resting metabolic rate, collected in a rested, fasted and thermoneutral state is more commonly used in research and practice (Manore and Thompson, 2000). Energy and macronutrient intake, caffeine, alcohol and acute recent exercise history all impact upon an individual's resting metabolic rate as such any measurement of resting metabolic rate must be collected under standardised conditions (Bone and Burke, 2018). Most recently Hannon et al. (2020) provided the first estimates of resting metabolic rate in EPL academy soccer players using indirect calorimetry. Data from Indian soccer players highlighted how resting metabolic rate increases by approximately 400 kcal.d^{-1} between the ages of ten and thirteen in line with increases in stature, body mass and fat-free mass (Cherian et al., 2018). When investigating data from the EPL Hannon et al. (2020) reported increases in ~ 400 kcal.d^{-1} between the ages of twelve to eighteen. Given the correlation between increasing fat free mass at this time and the basal energetic cost of skeletal muscle authors concluded that increases in FFM as a result of growth and maturation stimulate increases in resting metabolic rate (RMR). Indeed while there was similar RMR values between U15 (1957 ± 128 kcal.d^{-1}), U16 (2042 ± 155 kcal.d^{-1}), U18 (1875 ± 180 kcal.d^{-1}) and U21 (1941 ± 197 kcal.d^{-1}) players, there was significant differences between U12 (1655 ± 195 kcal.d^{-1}), U13 (1720 ± 205 kcal.d^{-1}) and U14 (1846 ± 218 kcal.d^{-1}) age players compared to their older counterparts.

2.3.2 Thermic Effect of Food

In addition to basal metabolic rate, the consumption of energy stimulates an increase in metabolism. The thermic effect of food (TEF) quantifies the amount of energy required to digest, absorb, transport, metabolise and store nutrients following their consumption (Manore and Thompson, 2000). Consumption of a mixed macronutrient diet typical of that reported in academy soccer players (Hannon et al., 2021b) results in a TEF of ~ 10% of total energy intake (Westerterp, 2004). Indeed data presented by Hannon et al. (2021b) suggests that TEF accounts for ~ 280 kcal.d^{-1} in academy soccer players. That said it must be noted that carbohydrates (5 – 10%), protein (20 – 30%) and fat (0 - 3%) contribute small differences in TEF values (Westerterp, 2004).

2.3.3 Activity Energy Expenditure

Unlike the general population, in athletic populations daily activity energy expenditure (AEE) and non-exercise activity thermogenesis (NEAT) are often the greatest and most variable portion of daily TDEE (Westerterp, 2013). AEE accounts for the energy cost of planned exercise related energy expenditure while NEAT relates to energy cost of daily living activity, fidgeting and spontaneous muscle contraction (Levine, 2004). Indeed although no data exists detailing the variation between training, rest and match days in academy soccer players, it would be fair to assume that pitch-based training would stimulate rises in AEE and subsequently TDEE. To this end average daily activity energy expenditure is similar throughout academy age groups with U12 (700 ± 184 kcal.d^{-1}), U15 (724 ± 172 kcal.d^{-1}) and U18 (1033 ± 456 kcal.d^{-1}) players showing little difference (Hannon et al., 2021b). While such data estimating the daily AEE cost of training sessions does not exist, data from injured academy players who were not fit to train displayed significantly less AEE at both U15 (380 kcal.d^{-1}) and U18 (635 kcal.d^{-1}) age groups (Hannon et al., 2021b). In data from the Premier League, a case study from an injured male player displayed comparable total daily energy expenditure to fit outfield players (Anderson et al., 2019a).

2.4 Methods to assess Energy Expenditure

Until recently the prescription of energy and macronutrient guidelines for soccer training and match play in academy soccer players were based upon manipulation of adult guidelines. Indeed assessment of energy expenditure in adult male soccer players had been quantified almost a decade previously with reference to outfielder players (Anderson et al., 2017), goalkeepers (Anderson et al., 2019b) and injured players (Anderson et al., 2019a). More recently assessment also encompassed adult (Morehen et al., 2022) and youth (McHaffie et al., 2024) women's international players however to date only one study has assessed total daily energy expenditure of elite academy soccer players using the gold standard doubly labelled water method (Hannon et al., 2021b). Measurement of whole-body metabolic rate is performed with direct calorimetry, based upon quantification of heat loss or secondly indirect calorimetry based upon the measurement of oxygen consumption, carbon dioxide consumption and urine-nitrogen loss for energy production for carbohydrate, protein and fat. The DLW method is one such indirect measure which is derived from the measurement of carbon dioxide production (Westerterp, 2017). Previous assessments of energy expenditure in both research and practice rely predominantly upon non-calorimetric methodologies as opposed to calorimetric assessments of direct and indirect calorimetry often due to a lack of specialist equipment, technical expertise or opportunity as a result of testing test or time.

2.4.1 Prediction Equations to assess Resting Metabolic Rate

In the absence of specialist equipment prediction equations have been used to calculate RMR. Such measurements provide an estimation which is quick and can be extrapolated across athletes with ease and little to no expertise. Indeed when accounting for variables such as sex, age, body mass and fat free mass (Cunningham, 1980, De Lorenzo et al., 1999, Harris and Benedict, 1918, Wong et al., 2012) prediction equations may be applied to a number of populations to estimate RMR. One population which remains understudied in this area however is elite athletes, as many prediction equations were developed in non-elite populations and therefore underestimate the true RMR (Morehen et al., 2016).

Only two prediction equations exist within academy soccer. Both prediction equations developed by Kim et al. (2015) and Hannon et al. (2020) utilise FFM. Failure of Kim et al., (2015) to use elite participants without differentiation between males and females are both weaknesses which limit the application of the given equation. Given we know that fat free mass of academy soccer players increases year on year and is greater in males than females this equation lacks ecological validity when transferred to academy soccer players from the English Premier League. In contrast Hannon and colleagues (2020) recruited ninety-nine academy elite soccer players from the EPL in an effort to develop a population specific prediction equation. Previously developed prediction equations underestimated the resting metabolic rate of academy soccer players when compared to open circuit indirect calorimetry following an overnight fast of at least 8 hours and omittance from exercise for at least 12 hours as per standardised procedures (Bone and Burke, 2018). In following such procedures Hannon et al. (2020) reported increases in resting metabolic rate with age, as such players from U12 squad presented with lower resting metabolic rate (1655 ± 195 $kcal.d^{-1}$) than those from U15 (1957

± 128 kcal.d^{-1}) and then U18 players (1875 ± 180 kcal.d^{-1}) respectively. When extrapolating the measured resting metabolic rate from this study to previously employed prediction equations, authors reported both fixed and proportional bias. To this end, given that fat free mass was the biggest predictor of resting metabolic rate, accounting for approximately 43% of variation in values, authors developed a population specific equation incorporating fat free mass:

$$\text{RMR (kcal.d}^{-1}\text{)} = 1315 + (11.1 \text{ x FFM in kg})$$

Despite the accuracy and applicability of this novel equation to the population of academy soccer players, the ability to obtain fat free mass (via DXA) within this population is difficult due to both the costs and radiation associated with DXA testing. As such using stepwise linear regression, authors were able to develop a second prediction equation which relies solely upon body mass:

$$\text{RMR (kcal.d}^{-1}\text{)} = 1254 + (9.5 \text{ x body mass in kg})$$

2.4.2 Tri-axial Accelerometery

Tri-axial accelerometers typically worn on the non-dominant wrist or hip provide an assessment of movement in three planes; anterior-posterior, mediolateral and longitudinal to provide assessments of physical activity and AEE. Tri-axial accelerometery succeeds uniaxial and biaxial devices which only provide assessment of movement in one and two planes of movement respectively. Triaxial accelerometers are seen to provide a more thorough assessment of physical activity, particularly in children and adolescents as they are more sensitive to movements such as jumping (Ott et al., 2000) and provide a more accurate assessment of high intensity activity such as running compared to uniaxial and biaxial devices (Rowlands et al., 2008). In research and practice decisions upon selection of devices to use are dependent upon cost, feasibility, size of device, monitoring capacity, memory and ease of use, yet the most common device across adult and youth field based physical activity research is the Actigraph accelerometer (Ridgers and Fairclough, 2011).

When deciding upon the specific method of data collection researchers must consider a number of factors. Namely the position of the accelerometer on the body as while devices should be worn as close to the centre of mass as possible (i.e., hip), devices can also be worn on the wrist, lower back or ankle. Indeed small differences may be reported in the amount of moderate physical activity and moderate to vigorous activity recorded between wearing devices at different positions (Nilsson et al., 2002). A second consideration in research and practice is the data collection sampling period (also known as epoch), duration of data collection, data collection process and participant compliance must also be considered. Currently there is no standardised time for which an accelerometer must be worn to represent a valid day (Corder et al., 2007), yet ten hours per day is typically accepted within adolescents (Andersen et al., 2006, Riddoch et al., 2007) yet as little as three hours (Penpraze et al., 2006) and different wear times for weekend days and weekend days have also been reported (Rowlands et al., 2008). However given the training times and both daily and weekly distribution of training and match play in academy soccer, it is fair to suggest that such short assessment periods would not provide an accurate assessment of physical activity or energy expenditure within this population.

2.4.3 Doubly labelled water

Measure	What does it measure?	Outcome Variable(s)	Dimension of Physical Activity	Strengths	Weaknesses
Self-report	Types of PA and behaviour PA levels	Bouts of PA, Minutes of PA engagement	Frequency, Intensity, Time, Type	Low cost, Low participant burden, Can be used in large population studies, Captures qualitative and quantitative information	Reliability/validity problems, Limited utility with children, Potential recall bias, Misinterpretation of PA due to language/culture
Direct observation	Behaviour PA levels, Frequency of activities, activity points, intensity of activity	Behaviour	Frequency, Intensity, Time, Type	Contextually rich data produced, Comprehensive, Can provide qualitative and quantitative information, Used in a variety of contexts	Time-consuming, High associated costs, High observer and participant burden, Potential for reactivity, Extensive training required
Heart rate	Cardiorespiratory load of PA	Mean heart rate, Time spent at PA intensities (e.g., heart rate reserve percentage)	Frequency, Intensity, Time	Ease of use, Monitor over extended periods, Socially acceptable, Can be used for water-based activities	Expensive, Heart rate affected by other variables, Can be obtrusive, Heart rate response lags behind movement, Monitor discomfort.
Pedometer	Steps, Distance covered*, Energy cost*	Steps	Time	Low cost, Non-invasive, Provides feedback, Little participant burden, Ease of use	Does not assess intensity and patterns of PA, Data loss due to tampering, Potential reactivity, Some models not robust, Some models have poor validity and reliability
Accelerometer	Human movement	Counts per minute, Time spent at PA intensities, Time spent active/inactive, Activity bouts	Frequency, Intensity, Time	Unobtrusive, Large storage and monitoring capacity, Adjustable monitoring periods, Non-reactive	Expensive, Limited assessment of upper-body, water-based PA, and incline walking, Cannot guarantee accurate monitor placement, Time-consuming data handling
Combined heart rate and accelerometer	Heart rate, Human movement	Time spent at PA intensities, Predicted energy expenditure	Frequency, Intensity, Time	Combined measure, Adjustable monitoring periods, Large storage and monitoring capacity.	Expensive, Monitor discomfort, Requires skin preparation for successful monitoring, Can be obtrusive

During its early conception the doubly labelled water method was used solely to determine energy expenditure in animal subjects, with data collection in humans deemed too expensive. During its conception predicted costs of using DLW to sample energy expenditure in humans were approximately 50,000 US dollars (Lifson et al., 1975).Yet seven years later the first assessment of energy expenditure using this method was carried out upon humans (Schoeller and van Santen, 1982). Today DLW is seen as the gold standard method of assessing total daily energy expenditure in *free living* conditions (FAO/WHO/UNU, 2001; (Westerterp, 2017). It is doubly labelled water which is used to most accurately assess energy expenditure in elite male adult (Anderson et al., 2017) and academy soccer (Hannon et al., 2021b) and adult international female (McHaffie et al., 2024) soccer. Work by our research group was the first to utilise doubly labelled water to assess the energy expenditure of twenty-four (U12/13, U15 and U18, all n = 8) Category One academy soccer players over a 14-day period. Interpretation of methodologies outlined by Speakman (1997) employed by Hannon et al., (2021b) provided the basis for the testing protocol outlined in Chapter Five. Indeed both participant characteristics and testing environments reported by Hannon et al., (2021b) were not dissimilar to those from the academy group within this study allowing for replication of the methods to employ DLW. While greater energy expenditure of U13 players was reported Chapter 5 is greater than that previously reported by Hannon et al., (2021b) which is likely attributable to different training schedules, growth and maturation and physical activity, it is important to note one methodological difference within equations used between datasets.

As per previous assessments of indirect calorimetry in adult participants (Speakman, 1997), players provided a baseline urine sample on the evening of day zero, before the commencement of data collection and asked to consume a single dose of DLW calculated according to their body mass. Players were then required to provide a second urine sample the following morning (day 1) between 07:00 – 11:00, allowing for isotope enrichment to be determined once the DLW had achieved equilibrium with total body water. Despite high financial costs DLW provides the ability to assess energy expenditure in free living subjects for up to 20 days (Ainslie et al., 2003) with a much smaller error value of between 2-8% compared to prediction equations (Schoeller and van Santen, 1982) providing the optimal methodology over one or two week training microcycles (Brinkmans et al., 2019). Doubly labelled water provides an assessment of energy expenditure following the ingestion of a bolus dose of deuterium (H) and oxygen (O) in stable isotopes in the form of water by an individual to reach the desired enrichment of 10% O and 5% H in the body using the below equation:

$$\text{dose (mL)} = 0.65 \text{ (body mass, grams) x DIE/IE}$$

where 0.65 is the approximate proportion of the body comprising water, DIE is the desired initial enrichment (DIE = 618.923 body mass, $kg^{-0.305}$), and IE is the initial enrichment (10%) 100,000 ppm. Once the desired dosage has been achieved a decrease in 18O in the bodily water is a measure for H_2O plus CO_2 output and the decrease in 2H is a measure of H_2O output alone, with CO_2 being calculated for the difference (Lifson, 1966). Once ingested isotopes reach an equilibrium within several hours, often overnight (Speakman, 1998) with urine samples being taken on subsequent days allowing for an average estimation of total energy expenditure over the assessment period. During this time isotopes remain in flux with total body water which enhances accuracy of data collected via urine sampling as opposed to alternative collection methods. Despite being cited as the gold standard measure of energy expenditure many assumptions relate to this method (Westerterp, 2017). Including but not limited to 1) that the body water pool size remains constant during the measurement period, 2) that the rates of water and CO_2 flux are constant during the measurement period, 3) that the isotopes label only the water and CO_2 in the body, 4) that the isotopes only leave the body as water and CO_2, 5) that the enrichments of the isotopes leaving the body are the same as those left behind, 6) that isotopes do not re-enter the body once they have left and 7) that the background levels of the isotopes remain constant over the measurement interval (Speakman and Hambly, 2016).

Figure 3. An academy soccer player consumes a dose of DLW for assessment of energy expenditure.

2.4.4 Energy Expenditure in Adolescent and Adult Soccer Players

The energy expenditure of academy and adult soccer players is dependent upon many factors including, fat free mass, on-pitch session demands, strength training, individual daily lives and formal match play frequency and duration (Hulton et al., 2022a). In using the doubly labelled water method, Anderson and colleagues (2019) observed daily energy expenditures of ~ 3566 $kcal.d^{-1}$ across a two-game week, which was comparable to expenditures observed by Japanese professionals (~ 3532 $kcal.d^{-1}$) during a double game week (Ebine et al., 2002). During a similar training and match schedule Brinkmans et al. (2019) reported daily energy expenditures of ~ 3285 $kcal.d^{-1}$ in both outfielders and goalkeepers which although lower than observations from the English and Japanese players, differences in data can be attributed to the inclusion of goalkeepers within this study, given they exhibit much lower daily training load (Anderson et al., 2019b). The nature of soccer specific training schedules and match play makes the accurate assessments of single or multiple day daily energy expenditure difficult. Indeed during a typical week the number of training sessions, rest days and competitive fixtures can vary due to competitional demands or coaching philosophy and as a result there are very rarely two weeks which are the same resulting in large differences in weekly energy expenditure (Anderson et al., 2016a, Hannon et al., 2021a).

In efforts to determine the specific energy requirements of training sessions and single matches authors have employed heart rate data reporting energy expenditure data between adult and U20 soccer players of ~ 1360 kcal (Bangsbo, 1994) and ~ 1540 respectively (Dias Soares et al., 2010). Later Russell and Pennock (2011) employed prediction equations to try and estimate the differences between energy expenditure on rest (~3000 $kcal.d^{-1}$), training (~ 3500 $kcal.d^{-1}$) and match days (~ 3900 $kcal.d^{-1}$) although as with other literature using prediction equations, the data presented here appears to be larger than those presented by studies using doubly labelled water as a consequence of methodological differences.

Within academy soccer to date there remains only one study which has utilises doubly labelled water to provide estimations of energy expenditure (Hannon et al., 2021b). In using open circuit calorimetry authors reported higher resting metabolic rate in the U18 squads (2236 ± 93 kcal.d^{-1}) compared to the U15 (2023 ± 162 kcal.d^{-1}) and U12/13 (1892 ± 211 kcal.d^{-1}) players. Then in accordance with RMR, U18 players also presented a higher total daily energy expenditure over a fourteen-day period (3586 ± 487 kcal.d^{-1}) compared to the U15 (3029 ± 262 kcal.d^{-1}) and U12 (2859 ± 265 kcal.d^{-1}) players. It is worth noting that there was no difference between activity energy expenditure between U18 (1033 ± 456 kcal.d^{-1}), U15 (724 ± 172 kcal.d^{-1}) and U12/13 (700 ± 184 kcal.d^{-1}) squads. Data presented of U18 players is similar to that of previous data from the English Football League (Russell and Pennock, 2011) and elite youth Portuguese players (Martinho et al., 2023). U18 players reported greater daily energy expenditure of Turkish sixteen-year-old academy players ~ 3322 kcal.d^{-1} (Ersoy et al., 2019) partially due to differences in physical characteristics (Hannon et al., 2021b). When comparing U15 players, data presented by Hannon et al., (2021b) was ~ 500 kcal.d^{-1} greater than previous observations from the EFL (Briggs et al., 2015) but similar to observations of age matched Spanish academy soccer players (Iglesias-Gutiérrez et al., 2005). While caution should be used when drawing conclusions between different assessment methodologies and squads of different training and match demands, it is noteworthy that individuals within each squad exhibited mean total energy expenditures which were comparable to that of their first team counterparts (Anderson et al., 2017).

2.4.5 Physical Activity in the Adolescent Athlete

Physical activity is defined as any bodily movement produced by the skeletal muscles that results in energy expenditure (Caspersen et al., 1985). A complex set of behaviours of freely chosen movement types, physical activity may be sub-divided into frequency (how often the activity occurs), intensity (how strenuous the activity is), duration (how long the activity lasts) and type (the form of activity itself) (Sallis and Patrick, 1994). Differing levels of physical activity, including that attained through organised sport contributes to development of healthy, capable and resilient young athletes (Bergeron et al., 2015). In elite soccer academies however, early specialisation and a reduction in participation in free play, informal physical activity and other sports facilitates worry that enrolment on academy programmes may have negative impacts to some of our most talented youth athletes (Bahr, 2014).

Guidelines for health-related physical activity in children recommend at least sixty minutes of moderate to vigorous physical activity per day (Strong et al., 2005), given associations with lower risk of obesity, diabetes, chronic diseases and osteoporosis (Department of Health, 2004). However in 2007 it was reported that only 2.5% of children met such recommendation (Riddoch et al., 2007). As children progress towards PHV participation in physical activity and organised sport declines and sedentary behaviours become more common throughout later teenage years (Dumith et al., 2011). Despite no clear 'gold standard' measure of physical activity within this population due to no comprehensive assessment of cardiorespiratory response, mechanical loading and the behavioural response during physical activity, a number of objective (i.e., accelerometers or heart rate monitors) and subjective methods (i.e., interviews or activity diaries) exist (Ridgers and Fairclough, 2011). In a study of Norwegian, French, Spanish and Greek adolescent boys, authors reported daily moderate to vigorous physical activity was greater in those who participated in organised soccer training compared to those who did not (Wold et al., 2013). Highlighting the possible additional energy demands associated with participation in formal sport in youth athletes compared to their peers. In a study of non-elite adolescent soccer players, Leek et al. (2011)concluded that during soccer training players spend ~ 45% of playing time completing moderate to vigorous activity, which when extrapolated to training times presented by Hannon et al., (2021a) suggests youth soccer players complete ~ 168 minutes of MVPA per week during training. This figure would likely be far greater within an elite population when considering non pitch based activities (i.e., multisport or gym) and physical activity away from training (i.e., physical education).

In a study of elite male youth soccer players Beenham et al. (2017) reported greater tri-axial loading in small-sided games in training compared to match play, with midfielders reporting the greatest level of physical activity per minute, with central defenders the lowest. Indeed to our knowledge there is only one study which explores the physical activity of elite soccer players away from formal training. Johnson et al., (2022) reported that U12, U13/14 and U15/16 players completed fourteen, seventeen and nine different types of activities away from formal training respectively, the most common being school based physical education, physical training, cycling and free play. While authors reported that there was no effect of age upon external physical activity, authors did report the U13/14 age group completed the greatest frequency and intensity of physical activity away from the host club on days without planned training sessions. While support staff may seek to manage the load of training sessions (Salter et al., 2021) or individuals (Abbott et al., 2018), players are subjected to high levels of physical activity both away from and within their respective clubs (i.e., tag, handball, gymnastics and American football) as highlighted in Table 3, the physical loading of which remains unreported. Daily physical activity is far greater than pitch-based training and match play, yet failure to monitor daily acute and weekly accumulative load away from training neglects an important factor which will contribute to greater daily energy expenditure. Failure to account for such increases in TDEE risks sub-optimal nutritional intake, LEA and presents an increased risk to injury at a vital time of growth and development. Further research is required from different academies using a number of methodologies to quantify physical activity away from training as current data is drawn from a single club, notwithstanding bias in player reported subjective ratings of perceived exertion through activity diaries.

Table 3. A sample of a week in the life of an academy soccer player on a full-time programme whilst completing full time education. Adapted from the work of (Hannon et al., 2021a, Hannon et al., 2021b). Players complete full time education, regular physical activity and pitch based and non-pitch-based loading associated with academy soccer programmes.

	MONDAY	**TUESDAY**	**WEDNESDAY**	**THURSDAY**	**FRIDAY**	**SATURDAY**	**SUNDAY**
07:00	Wake up	Wake up	Wake up	Wake up	Wake up	Sleep	Sleep
08:00	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Wake up	Wake up
09:00	Travel to school	Travel to school	Travel to school	Travel to school	Travel to school	Breakfast	Breakfast
10:00	Lesson one	Lesson one	Lesson one	Lesson one	Lesson one	Travel to football	Travel to football
11:00	Lesson two	Lesson two	Lesson two	Lesson two	Lesson two	Football training (pitch)	Travel to fixture
12:00	Lunch	Lunch	Lunch	Lunch	Lunch	Football training (pitch)	Travel to fixture
13:00	Lesson three	Lesson three	Lesson three	Lesson three	Lesson three	Travel home	Play match
14:00	Lesson four (P.E.)	Lesson four	Lesson four	Lesson four	Lesson four	Visit family	Play match
15:00	Lesson five	Lesson five	Travel to football	Lesson five	Lesson five	Visit family	Travel from fixture
16:00	Travel home	Travel to football	Football Education (Analysis)	Travel to football	Travel to boxing gym	Downtime	Travel from fixture
17:00	Homework	Football training (gym)	Football training (multisport)	Football training (gym)	Boxing training	Downtime	Travel home
18:00	Have dinner	Football training (pitch)	Football training (pitch)	Football training (pitch)	Boxing training	Downtime	Homework
19:00	Collect sister from swimming	Football training (pitch)	Football training (pitch)	Football training (pitch)	Travel home	Downtime	Homework
20:00	Travel home	Travel home	Collect brother from rugby	Travel home	Homework	Downtime	Downtime
21:00	Downtime	Downtime	Travel home	Downtime	Downtime	Downtime	Downtime
22:00	Bed	Bed	Bed	Bed	Bed	Bed	Bed

2.4.6 Training and Match Load of Academy Soccer Players

Regular training and match play is an integral part of an academy player's week as depicted in table 3. Athletic or sport specific training is defined as the process of systematically performing exercises to improve physical capabilities and to acquire sport specific skills (Viru and Viru, 2000). When executed appropriately the exercise bout stimulates a physiological response which provides a stimulus for adaptation, it is then the nature, intensity and duration of such stimulus which determines how an athlete responds (Booth and Thomason, 1991). To determine the appropriate nature of such stimulus monitoring of player training and match load is essential to reduce injury risk, determine training prescription and enhance adaptation while reducing the risk of over-training (Malone et al., 2017b, Scott et al., 2013).

The training load which is experienced by academy soccer players can be described as the input variable that is manipulated to elicit a desired training response (Coutts et al., 2018). Training load can then be classified as internal or external. The organisation, duration and quantity of training and match play make up the external load experienced by a player. It is then the psychophysiological responses to such external load which form a player's internal load (i.e., heart rate, blood lactate and RPE) (Impellizzeri et al., 2019, Miguel et al., 2021). Gaining a clear understanding of the training and match load of academy soccer players is essential to provide an understanding of their total daily energy expenditures (Anderson et al., 2017, Westerterp, 2013) and for the formulation of population specific nutrition guidelines (Hannon et al., 2021b). Referring specifically to the quantification of pitch-based volume, intensity and frequency of exercise which provides practitioners with objective data which may inform subsequent energy prescription, assist with decisions around training and match play on a daily basis, as well general player development. Taken together both internal and external load are the greatest determinant of subsequent energy prescription in an applied setting and as such allow for energy and macronutrient prescription.

Despite the extent of knowledge examining the training and match loads of adult soccer players (Anderson et al., 2016a, Anderson et al., 2016b, Brinkmans et al., 2019, Hulton et al., 2022b) data within academy soccer players is limited (Hannon et al., 2020, Hannon et al., 2021a, Hannon et al., 2021b, Varley et al., 2017a, Varley et al., 2023) and while most studies report GPS as an indicator of training load, assessments using variables such as session RPE (Connolly et al., 2024) and a lack of consistency between analysis and reporting make comparisons between data difficult. To develop the quality of GPS data players should be allocated individual units to reduce inter-unit noise and variability, with practitioners regularly carrying out their own variability and reliability checks. Older units or interference with the GPS signals from external factors (i.e., buildings) may create false data against published benchmarks which create false outputs. This is of specific importance within academy soccer as Lovell et al., (2013) reported that the movement patterns conducive with academy soccer such as high-speed running and multi-directional movement increases measurement error. In line with recommendations of Varley et al. (2012) Lovell and colleagues (2013) recommended set sampling rates of 10Hz for most accurate reporting and analysis with units turned on or ‘alarmed’ up to 15 minutes prior to the start of a session to allow units to connect to up to three satellites to establish clear connection for the entirety of the session. Authors further cited practitioners should ensure all units are using the same processing algorithms and firmware to ensure consistent data across a squad (Malone et al., 2017a), with practitioners similarly having a role in data integrity through filtering and cleaning any outliers within training and match data or removing erroneous data points all together (Lovell et al., 2019).

Previously factors influencing the training loads of soccer players have been listed as; phase of the season and player position (Malone et al., 2015) coaching philosophy (Anderson et al., 2016a, Malone et al., 2015), frequency of matches (Morgans et al., 2014), player starting status (Anderson et al., 2016a) and player-specific goals such as manipulation of body composition (McEwan et al., 2020, Milsom et al., 2015) or rehabilitation from injury (Anderson et al., 2019b). However the detailed prescription of pitch-based training is essential to not only enhance player development but also to reduce injury risk (Bowen et al., 2017) while minimising time lost from training (Wrigley et al., 2012).

When comparing weekly pitch-based loading between age groups in academy soccer, physical loading has shown increases in line with chronological age until players reach the Professional Development Phase (Hannon et al., 2021a). Indeed Premier League clubs employ long-term athletic development (LTAD) models to promote gradual improvements in a player's physical capabilities due to measured and incremental increases in their training load (Ford et al., 2011). It should be noted that although aspects of training load are dictated to clubs by the Premier League, the quantity and content of sessions, which can dictate the internal and external load of sessions is at the discretion of each host club. Factors including coaching philosophy (Anderson et al., 2019) and the distribution of training around competition (Hannon et al., 2021a) will also impact upon the actual training loads experienced by academy players. Early studies prior to the introduction of the EPPP in 2011 highlighted total distance and training intensity increased between U14 to U18 age groups (Wrigley et al., 2012). Yet as a consequence of the recommendation to increase pitch-based loading from ~ 600 – 720 minutes up to ~ 720 – 840 minutes in 2011, total distance of academy players has increased further through U12/13, U15 and U18 age groups with players completing 38.3 ± 5.1 km, 53.7 ± 4.5 km and 54.4 ± 7.1km respectively over a two-week period (Hannon et al., 2021a). Such data is comparable (and exceeds) data from elite first team players in both the English Premier League (26 ± 5 $km.wk^{-1}$, Anderson et al., 2019) and Dutch Eredivisie (~ 35 $km.wk^{-1}$, Brinkmans et al., 2019).

Albeit the influence of fixture programming and periodisation of training in relation to congested fixture patterns will likely reduce the load of adult men's training data (Anderson et al., 2016b). When comparing mean accumulative weekly training and match loads of elite Category One academy EPL players over the course of a competitive season (inclusive of pre-season) there was no difference between U12 (329 ± 29 min; 19.9 ± 2.2 km), U13 (323 ± 29 min; 20.0 ± 2.0 km) and U14 (339 ± 25 min; 21.7 ± 2.0 km) players for exercise duration, total distance, mean speed ($m.min^{-1}$), high speed running distance or sprint distance. Exercise duration and total distance were greater in U15 (421 ± 15 min; 26.2 ± 2.1 km), U16 (427 ± 20 min; 25.9 ± 2.5 km) and U18 (398 ± 30 min; 26.1 ± 2.6 km) age groups compared to those of the lower YDP (Hannon et al., 2021b). Similarly there was no difference between U12, U13 and U14 age groups in high-speed running distance or sprint distance. However with reference to high-speed running distance U15 (657 ± 242 m), U16 (749 ± 152 m) and U18 (979 ± 254 m) aged players had a greater HSR than U12 (220 ± 95 m), U13 (331 ± 212 m) and U14 (448 ± 193 m) players with U18 players being greater than U15 players. The same phenomenon exists for sprint distance whereby there was no difference between U12 (6 ± 9 m), U13 (6 ± 27 m) and U14 (21 ± 29 m) players. With U15 (49 ± 98 m) , U16 (95 ± 55 m) and U18 (123 ± 56 m) players all displaying greater sprint distance than U12 players and both U16 and U18 players greater than U13 players. In support of the hierarchical nature of training load in academy soccer Smalley et al. (2021) reported that total distance covered (U21; 9.8 ± 0.7 km, U18; 9.3 ± 1.0 km, U16; 7.9 ± 0.7 km), high speed running meters (U21; 674 ± 164 m, U18; 595 ± 127 m, U16; 455 ± 125m), accelerations (U21; 81 ± 16, U18; 83 ± 11 m, U16; 58 ± 11 m) and decelerations (U21; 91 ± 16, U18; 88 ± 12 m, U16; 62 ± 14 m) were greater in U21 and U18 players compared to their younger U16 counterparts during competitive matches. It should be noted when reporting absolute match data that U21 and U18 players complete a minimum of ninety minutes match play (i.e., two halves of forty-five minutes), greater than eighty minutes completed by U16 players (i.e., two halves of forty minutes). Data reported here of the U18 and U21 players correlates to that of an average week for elite adult players in the EPL (Bowen et al., 2017) suggesting that academy players are capable of replicating the training and match load outputs of their senior counterparts. Whilst capable of completing comparable relative training loads, players within the Youth Development Phase cannot match absolute thresholds set by their Professional Development counterparts. Indeed the step from YDP to PDP is present in both full time and part time models (Hannon et al., 2021a, Taylor et al., 2023). Such differences in absolute speed distance between academy squads are likely a direct result of growth and maturation (Malina et al., 2004b) with maximal speed increasing until as late as 18 months post PHV (Philippaerts et al., 2006). Indeed it is likely that a combination of anatomical growth (i.e., increased leg length), biomechanical (i.e., stride length), and metabolic changes (i.e., larger phosphocreatine stores) along with morphological changes to muscle and tendon and motor skill improvements (Ford et al., 2011, Oliver et al., 2024) influence the differences in such performance metrics between squads.

When comparing data from the same EPL club, weekly training load between academy and first team players suggests that total distance in academy soccer players is greater on MD -4, MD – 2 and MD – 1 compared to their first team counterparts (Morgans et al., 2023). Notably both Morgans et al., (2023) and Hannon et al., (2021a) reported that the second training day of the week produced the greatest total distance. A phenomenon seen in Spanish (de Dios-Álvarez et al., 2024) and English academy soccer players (Johnson et al., 2022), where combined loading of pitch based training and physical activity was greatest on MD - 3 (with no session on MD - 4) which authors attributed due to higher pitch based volumes on that day, although the former was from a small sample of only six sessions. Taken together data from across the training week, data presented by Hannon et al., (2021a) shows that players experience the greatest physical load on match day, while this may correlate to greater total daily energy expenditures, without understanding physical activity and activity away from training (i.e, physical education on a school day) this is not yet understood. Despite the suggestion of periodisation of training load in academy soccer players, a true representation of an adult Premier League loading pattern was only seen in U16 and U18 age groups. To that end such training patterns with total distance, high-speed running meters and sprint distance greatest on MD – 4 with a taper towards MD -1 (Hannon et al., 2021a). Such a pattern suggests as players progress throughout the pathway, they evolve away from technical development in the younger age-groups towards preparation for competition in the older age-groups (Coutinho et al., 2015, Wrigley et al., 2012).

Table 4. Training loads of a ‘typical’ week of a Category One academy soccer players in adapted from work by (Hannon et al., 2021a)

	Accumulative total distance	Average speed	Accumulative high-speed running	Accumulative sprint distance
U18	26.1 ± 2.6 km	66 ± 6 m.min^{-1}	979 ± 254 m	123 ± 56 m
U16	25.9 ± 2.5 km	60 ± 3 m.min^{-1}	749 ± 152 m	95 ± 55 m
U15	26.2 ± 2.1 km	64 ± 6 m.min^{-1}	657 ± 242 m	49 ± 98 m
U14	21.7 ± 2.0 km	61 ± 11 m.min^{-1}	448 ± 193 m	21 ± 29 m
U13	20.0 ± 2.0 km	63 ± 2 m.min^{-1}	331 ± 212 m	6 ± 27 m
U12	19.9 ± 2.2 km	60 ± 3 m.min^{-1}	220 ± 95 m	6 ± 9 m

2.5 Dietary Intake of Academy Soccer Players

Estimation of daily energy expenditure in academy soccer players allowed for the first publication of energy and macronutrient guidelines for academy soccer players (Hannon et al., 2021b). In the same study authors reported that players on occasion, despite exhibiting daily energy expenditures which were comparable to (or exceeded) their first team counterparts (Anderson et al., 2017), players failed to match their energy expenditure with appropriate energy and macronutrient intake (Hannon et al., 2021b).

During a seven-day period Briggs et al., (2015) combined a weight food diary and 24-hour recall to assess energy and macronutrient intake of ten academy soccer players. Authors reported average energy intake of 2245 ± 321 kcal.d^{-1} which when combined with estimations of energy expenditure using accelerometery resulted in a negative energy balance of ~ 311 kcal.d^{-1} over the study period. Indeed authors reported that only on rest days did players exhibit a positive energy balance. Between heavy, moderate, rest and match days authors reported energy intake values of ~ 2390 kcal.d^{-1}, 2210 kcal.d^{-1}, 2330 kcal.d^{-1} and ~ 2150 kcal.d^{-1} respectively with no difference in energy intake regardless of periodisation. Similarly, no difference was reported in carbohydrate intake through the week with a mean intake of ~ 5.6g.d^{-1}. Such data is in contrast with findings from the adult game which shows periodisation of carbohydrate through the training week with respect to match play, with carbohydrate intake increasing from 4.2 g.kg.d^{-1} to 6.4 g.kg.d^{-1} from a training to match day (Anderson et al., 2017). Data presented here was comparable to mean intake values of Italian adolescent soccer players of ~ 2560 kcal.day^{-1} (Caccialanza et al., 2007) and less than that of Turkish academy players, which to date reported the greatest mean energy intake in academy soccer players ~3320 kcal.day^{-1} albeit despite both studies utilising greater sample size, data was collected over a smaller sample period of four and three training days respectively. In a similar study (Martinho et al., 2023) reported mean absolute energy intake of 1929 ± 388 kcal.day^{-1} on a cohort of 15-year-old Portuguese academy soccer players, such findings represent some of the lowest daily intakes reported in academy soccer, partly attributable to relative carbohydrate intakes of ~ 4g.kg.day^{-1}, despite the inclusion of a match day within the five day study period.

In comparison to early estimations of energy intake in academy soccer players, Hannon et al., (2021b) reported higher mean daily energy intakes across U18 (3180 ± 279 kcal.d^{-1}), U15 (2821 ± 338 kcal.d^{-1}) and U12/13 (2659 ± 187 kcal.d^{-1}) players. In contrast to work by Naughton et al. (2016) where no difference was reported between squads for energy intake, Hannon et al., (2021b) also reported significant differences between squads with U18 players consuming more energy that U15 and U12 players, in accordance with increasing TDEE as players progress through the academy pathway. When expressed in relative terms carbohydrate intake of U15 players was similar to that reported by Briggs et al., (2015). While there were little differences in absolute carbohydrate intake between groups, there was variation throughout U12 (7.3 ± 1.0 g.d^{-1}), U15 (5.8 g.d^{-1}) and U18 (4.8 ± 0.6 g.d^{-1}) squads for relative intake. Such a trend was also reported by Naughton et al., (2015) whereby relative carbohydrate intake decreased with age, in that relative carbohydrates for the U13/14 (6.0 ± 1.2 g.d^{-1}), U15/16 (4.7 ± 1.4 g.d^{-1}) and U18 (3.2 ± 1.3 g.d^{-1}) players reported here were less than that reported by Hannon et al., (2021b). Naughton et al., (2015) reported individuals with negative energy balance were evident across all three squads, yet deficit was lower than that reported by Briggs et al., (2015), however caution should be exercised when comparing different assessments of both energy intake and energy expenditure.

Despite emerging knowledge in relation to total energy and macronutrient intake, there is little understanding relating to the timing of food and drink consumption, specifically with reference to training. Indeed early work by Naughton et al., (2015) presented the distribution of energy and macronutrient intake with reference to 'breakfast', 'lunch', 'dinner' and 'snacks'. Authors reported that both absolute and relative energy, and absolute carbohydrate intake was lower at breakfast than lunch and dinner. Data correlates with more recent findings of Martinho et al., (2023) whereby energy, carbohydrate, protein and fat intake are lowest at breakfast compared to lunch and evening meals. Given that sub-optimal nutritional intake at breakfast cannot be compensated for later in the day (Sievert et al., 2019) such findings provide rationale for the emerging theme of players failing to at least match their daily energy expenditure. With reference to both the U18 and U21 squads who often training in the morning (Hannon et al., 2021b) this is particularly concerning given the implications for acute performance (Briggs et al., 2017) although greater research is required to determine the timing of energy and macronutrient intake with reference to pitch based training.

With regards to protein intake, to date only one study has assessed the protein requirements of adolescent soccer players using nitrogen balance methods. Boisseau et al. (2002) suggested intakes of 1.4 - 1.6 $g.kg.d^{-1}$ would be optimal for players aged 13 – 15 years old, a recommendation which is less than has been observed over a training microcycle in their adult counterparts (Anderson et al., 2017). Indeed players from the English Premier League have also been shown to consume greater protein daily across the development pathway (U12/13: 2.5 ± 0.4 $g.kg.d^{-1}$; U15: 2.1 ± 0.3 $g.kg.d^{-1}$; U18: 2.1 ± 0.5 $g.kg.d^{-1}$). With reference to protein distribution, as with energy intake Naughton et al. (2016) reported that protein intake at breakfast was lower than both lunch and dinner, despite total daily intakes which were similar to those reported by Hannon et al., (2021b). The importance of protein intake to support recovery and adaptation as well as its role in producing new tissues during growth and maturation cannot be underestimated and therefore a skewed protein intake, rather than an equal distribution of ~ 30g across the day will lead to reduced muscle protein synthesis, even if absolute protein intake is matched (Mamerow et al., 2014).

Table 5. A summary of energy and carbohydrate intake of academy soccer players of different nationalities and age groups.

Reference	Population (Ethnicity & Age)	Energy (kcal.d^{-1})	Carbohydrate (g.d^{-1})
Ruiz et al., 2005	Spanish academy players U15 (1): 14.0 ± 0.3 yrs U16 (2): 14.9 ± 0.2 yrs U17 (3): 16.6 ± 0.6 yrs	1: 3456 ± 309 2: 3418 ± 182 3: 3478 ± 223	1: 442 ± 45 2: 391 ± 27 3: 392 ± 37
Caccialanza et al., 2007	Italian academy players 16 ± 1 yrs	2560 ± 636	389 ± 39
Russell and Pennock, 2011	English Championship academy players 17 ± 1 yrs	2831 ± 164	393 ± 18
Iglesias-Gutiérrez et al., 2012	Spanish academy players 18 ± 2 yrs	2794 ± 526	338 ± 70
Briggs et al., 2015	English Premier League academy players 15.4 ± 0.3 yrs	2245 ± 321	318 ± 24
Bettonviel et al., 2016	Dutch academy players 17.3 ± 1.1 yrs	2938 ± 465	411 ± 87
Naughton et al., 2016	EPL academy players U13/14 (1): 12.7 ± 0.6 yrs U15/16 (2): 14.4 ± 0.5 yrs U18 (3): 16.4 ± 0.5 yrs	1: 1903 ± 432 2: 1927 ± 317 3: 1958 ± 390	1: 266 ± 58 2: 275 ± 62 3: 224 ± 80
Hannon et al., 2021b	EPL academy players U12/13 (1): 12.2 ± 0.4 yrs U15 (2): 15.0 ± 0.2 yrs U18 (3) : 17.5 ± 0.4 yrs	1: 2659 ± 187 2: 2821 ± 187 3: 3180 ± 279	1: 309 ± 27 2: 325 ± 44 3: 346 ± 28

Urhan and Yildiz, 2022	Turkish academy players U14/U15 (1): 13.9 ± 0.6 U16/U17 (2): 15.8 ± 0.6 U19 (3): 18.3 ± 0.4	1: 2607 ± 318 2: 2626 ± 360 3: 2761 ± 444	1: 290 ± 45 2: 285 ± 55 3: 306 ± 76
Martinho et al., 2023	Portuguese academy players 15.3 ± 0.3	1929 ± 388	245 ± 61

2.5.1 Methods to Assess Energy Intake

Assessment of energy and macronutrient intake remains one of the most difficult practices in sport nutrition, assessment is fraught with error and a lack of reliability within both athletes (Capling et al., 2017) and experienced and in-experienced practitioners alike (Stables et al., 2021). Dietary assessment tools may be 'retrospective' whereby records are typically made post consumption (i.e., food frequency questionnaires or 24 – hour dietary recalls) or 'prospective' where data collection is typically instantaneous (i.e., food diaries or the RFPM). Regardless of methodology there is a trend towards misreporting, specifically misreporting (Gemming et al., 2014) within free-living individuals (Martin et al., 2012). The validity and accuracy of such methods alongside burden to both the practitioner and athlete are often cited as key contributors to error within dietary assessment (Thompson et al., 2010). Variation between assessments of food and drink intake and a lack of validity further weakens the ability to interpret and compare data between studies. To this end the systematic error within such a practice is often overlooked by practitioners and researcher alike (Kirkpatrick and Collins, 2016).

2.5.2 Food diaries

Traditionally within academy soccer written food diaries, with or without the addition of 24-hour recalls have historically been used as assessments of energy and macronutrient intake (Briggs et al., 2015; Caccialanza et al., 2007; Ersoy et al., 2019; Iglesias-Guiterrez et al., 2005; Russel and Pennock; 2011). Although simple in practice a lack of consistency in measurement tools and basic written description (i.e., one small bowl of cereal) make analysis difficult and inaccurate. An evolution of simple written food diaries is the addition of weighed food records which required individuals to weigh whole meals and / or individual items pre- and post-consumption. Despite allowing practitioners to more accurately assess energy and macronutrient content of meals, in addition to greater athlete burden, criticism of such methodologies argue that the practice of weighing food will likely influence athlete behaviour and as a result lead to conscious or unconscious underreporting and a change in eating habits (Goris et al., 2000).

2.5.3 The Remote Food Photography Method

In an attempt to improve reporting accuracy over traditional pen and paper methods, photo-based diaries such as the RFPM developed by Martin and colleagues (2009) became common place in research and practice. Given advancements in modern technologies images can be sent via instant messaging applications (i.e., Whatsapp) with the addition of a time stamp indicating when food and drink was consumed (Costello et al., 2017). The RFPM allows for the assessment of food and drink intake in real time by practitioners through ecological momentary assessment (Boushey et al., 2017). The RFPM (see also ‘Snap ‘n’ Send’) has previously been used in both elite populations in soccer (Anderson et al., 2017), rugby (Morehen et al., 2016) and tennis (Ellis et al., 2023) as well as youth soccer (Hannon et al., 2021b) and youth rugby players (Costello et al., 2017). In addition to reducing participant burden the RFPM has also been cited as a preferred method of dietary analysis by adolescent athletes due to a lack of reliance upon parents or guardians (Boushey et al., 2017). Despite advancements the accuracy of the RFPM remains low, despite error of less than 5% reported by some authors (Cosetllo et al., 2017) our group previously reported an underreporting of ~ 13% and a variance in energy intake estimations in both experienced and inexperienced practitioners of - 47% to + 18% of reference values (Stables et al., 2021). Indeed given the degree of underreporting energy intake increases with greater energy expenditure (Barnard et al., 2002) it is likely in practice the level of error could be greater than reported in the literature. It should be noted that this study presumed all food and drink had been consumed and total intake was lower than that of elite athletes suggesting the ecological validity of the data could be improved. When paired with other traditional methodologies the RFPM may reduce participant burden (Costello et al., 2019), yet further development within this area to improve assessment accuracy is essential to drive practice forwards.

2.6 Low Energy availability and the Associated Risks of Low Energy Availability (LEA)

Historically literature focusing upon low energy availability is linked to female athletes, with consequences of repeated sub-optimal energy intake categorised within the female athlete triad (Torstveit and Sundgot-Borgen, 2005). Despite variation in outcomes it is evident that an imbalance between energy intake and the energy required to support basic homeostatic function affects the male athlete, facilitating the development of the relative energy deficiency in sport (RED-S) paradigm (Mountjoy et al., 2014). RED-S presents itself as the inadequacy of energy to support the range of bodily functions involved in optimal health and performance (Cabre et al., 2022). In adult athletes an energy availability of greater than 45 kcal.kg FFM^{-1}.d^{-1} is recommended to support normal bodily function (Loucks et al., 2011). It is essential that academy soccer players at least achieve energy balance to support health and performance, yet owing to growth and maturation youth soccer players also require energy for the disposition of new tissues compared to their fully mature adult counterparts (Torun, 2005). Taken together it is reasonable therefore to suggest that youth soccer players should regularly achieve an energy availability which is superior to adult recommendations. Chronic periods of energy availability lower than this, or lower than the adult LEA threshold of <30 kcal.kg FFM^{-1}.day^{-1} may result in impaired growth and maturation of tissues and organs, reduced skeletal bone mineral accrual, increased risk of stress fractures, increased risk of osteoporosis later in life, delayed sexual maturation and a suppression of the immune system (Loucks et al., 2011, Mountjoy et al., 2018). It is not uncommon that periods of low EA may be triggered by increases in exercise energy expenditure or a reduction in energy intake (Mountjoy et al., 2014), both of which are risk factors associated with enrolment in an academy soccer programme through progressive increases in training load and correlations between pitch-based performance metrics and TDEE (Hannon et al., 2021b).

While it was previously noted that academy soccer players are at risk of low energy availability (Briggs et al., 2015), accurate assessments of LEA remain problematic, indeed assessing energy availability is cited as one of the most difficult values to quantify in sport nutrition (Burke et al., 2018a). To date there is only one study which has assessed energy availability in academy soccer. Hannon et al. (2021b) reported an inverse relationship with chronological age and energy availability, in line with progressing training load and energy expenditure. Indeed estimated energy availability in the U12/13 age-group (69 ± 10 kcal.kg FFM^{-1}day^{-1}) was greater than the U15 (51 ± 9 kcal.kg FFM^{-1}day^{-1}) and U18 age-groups (41 ± 15 kcal.kg FFM^{-1}day^{-1}). While such findings are greater than an average energy availability of ~ 28.5 kcal.kg FFM^{-1}day^{-1} reported in elite athletes from a variety of sports (Koehler et al., 2013), it would be fair to assume that individuals within squads would display lower daily energy availability. Indeed further research is required to understand the energy availability of players across other academies with different training schedules and degrees of food and drink provision.

2.7 Barriers and Enablers of Optimal Nutrition in Academy Soccer

As evidenced previously there is increasing quantitative evidence that players fail to meet their daily energy expenditure with appropriate energy intake, the reasons underpinning a lack of optimal energy and macronutrient intake remain relatively unknown. In a study of twenty-six sports nutritionists working across elite sport Bentley et al., (2019a) reported to achieve nutritional adherence and optimal energy and macronutrient intake, intervention was required with reference to a player's capability (i.e., nutritional understanding), their opportunity (i.e., ability to consume food and drink) and their motivation (i.e., desire to eat around training). First identified by Michie et al., (2011) the COM-B model recognises that athlete behaviour is an interactive system due to the social and physical environments which players are embedded within. In using such a model (Bentley et al., 2019a) suggested that with reference to the sports nutritionist, barriers and enablers to optimal practice were found at the intrapersonal, interpersonal and nutritional service level, in that perceptions of an athlete's capability and motivation to interact with their social and physical opportunity provide an opportunity to influence a player's behaviour.

Across other sports there is a similar underrepresentation in the research as to the qualitative reasons which underpin the dietary choices of athletes (Bentley et al., 2019b). It is estimated that athletes make approximately 200 choices about their food and drink intake each day (Wansink and Sobal, 2007). In a cohort of male hockey players such choices were influenced by health beliefs, time available to eat, taste, quality, and cost (Smart and Bisogni, 2001). With sport specific factors such as performance, weight and body composition concerns also impacting the energy and macronutrient intake of athletes (Birkenhead and Slater, 2015). Many approaches have been theorised in efforts to understand the reasoning behind food choices of athletes, such as the food choice process which incorporates the influences of past experiences, individual ideas (i.e., expectations), personal factors (i.e., food preferences) and resources (i.e., skills and knowledge) (Furst et al., 1996). Developing upon this early theory eating decisions have also been suggested to be influenced by the environment, location or food choice which is being made (Bisogni et al., 2005, Marshall and Bell, 2004) which will likely be affected if in the presence of others which may influence the amount and type of food consumed (Herman et al., 2003, Vartanian et al., 2008). Carter et al. (2022) evidenced this in the context of academy soccer with players citing that living and eating with parents or host family enabled them to adopt positive nutritional habits, especially if they possessed good nutritional knowledge. Players also commented upon how youth players in the company of their adult counterparts used role modelling to positively impact their nutritional habits.

Indeed in using the COM-B model Carter et al., (2022) evaluated key barriers and enablers to nutritional adherence in academy soccer using a sample of players, nutritionists and coaching staff. A barrier to optimal nutritional practice which is common place across male academy (Carney et al., 2024, Carter et al., 2022) and female youth international soccer (McHaffie et al., 2022) is education and stakeholder understanding. It is well established that level of nutritional knowledge within this population should be improved (Andrews and Itsiopoulos, 2016, Devlin et al., 2017), however establishing strong understanding alone does not correlate to positive nutritional habits. Most recently Carney et al., (2024) reported that while academy players, staff members and parents envisage links between nutrition and performance, individuals showed a lack of understanding as to the role of nutrition in player development, exemplified through a lack of understanding of key nutritional concepts such as increasing energy requirements as players progress through the academy pathway. Additional factors including a lack of dedicated food and drink provision and contact with a full-time nutritionist also present a barrier in the eyes of both coaches, nutritionists and academy soccer players (Carter et al., 2022). Despite seen as an enabler to good practice in elite basketball (Tsoufi et al., 2017), nutrition service provision in academy football remains understaffed and underfunded, especially to players in the Youth and Foundation Phase of their development, and those enrolled in Category Two, Three and Four academies (Carney et al., 2022). Indeed in even in Category One academies only fourteen clubs employed a full-time nutritionist, with many relying upon part-time staff, non-specialised coaching staff (i.e., sport scientists) or interns and students (Carney et al., 2022). Indeed in a recent assessment of sport nutrition knowledge of 360 parents and caregivers of academy soccer players across Category One, Category Two and Category Three clubs, authors reported knowledge to be poor, with only 10% suggesting they had received formal nutritional education, with the internet, family or coaches cited as the main source of nutritional information (Callis et al., 2023) a sentiment echoed in findings of Carney et al., (2024). Ultimately providing a cause for concern given that such sources of information have been shown to be incorrect and have the potential to disseminate harmful and / or conflicting nutritional advice (Cockburn et al., 2014). While clearly impacting upon the level of service which can be provided to players, an additional layer of complexity to this issue highlights that sports nutritionists are most effective at changing behaviour when working full - time with players to build a rapport and gain their trust (Bentley et al., 2019b). It is important to note that even in full – time roles the number of hours which a sport nutritionist is employed does not correlate to direct contact time with players and key stakeholders (Bentley et al., 2019b). To this end approximately 35 % of academy parents and caregivers report that neither their child / dependent nor themselves had access to nutrition support (Callis et al., 2023).

Given the influence of an individual's environment upon their nutrition, it is not surprising that training ground food and drink provision has an impact upon player's ability to adhere to nutritional guidelines (Carter et al., 2022, Shepherd et al., 2006) and a lack of food and drink provision creates a barrier to players achieving optimal energy and carbohydrate intake at this time (Carney et al., 2024). By creating and facilitating increased energy and macronutrient intake sport nutritionists are more likely to facilitate behaviour change (Bentley et al., 2019a). Such a challenge however is not limited purely to the food and drink provision at a host club's training ground. The demand to recruit players from outside of the local area places demands upon 'host families' as well as parents whereby nutritional provision at external accommodation presents as a key enabler, or barrier when players become more independent when living away from home (Heaney et al., 2008). The dietary habits of children in the Foundation and Youth Development Phases are heavily influenced by the parents and caregivers purchasing provision and preparation of food (Iglesias-Gutiérrez et al., 2005), a phenomenon experienced in youth rugby players (Sharples et al., 2021) with a caregivers creating a barrier towards healthy nutritional practice for adolescents (Liu et al., 2023). Even in the context of good theoretical and practical nutritional knowledge by caregivers, a lack of quality and quantity of food and drink to meet the additional demands of the academy soccer compared to other individuals in the household presents a further barrier to players (Carter et al., 2022).

The busy daily schedules of academy players expose individuals to a number of different environments, but such schedules themselves also present a barrier to optimal nutrition. Players from the Youth Development Phase have suggested that they are 'too busy to eat' without 'even having time to think about food' (Carney et al., 2024). Ultimately the factors presented above show the potential barriers and enablers to academy soccer players to achieve optimal energy and macronutrient intake and the roles and responsibilities of key stakeholders to remove such barriers. Commonality between the literature is the call for more dedicated support to parents / caregivers as they are the individuals (certainly within the YDP / FP) who have the most influence over their dependent's nutritional habits (Carney et al., 2024, Carter et al., 2022, Delbosq et al., 2022). Namely through an increase of an individual's capability (i.e., theoretical knowledge) and physical opportunity (i.e., providing time to consume food and drink). Ultimately neglect of the sport nutrition community and key policy makers to provide solutions to those and other barriers to optimal nutritional intake during such a vital phase of growth and maturation and sport specific development may impact health and performance whilst also negatively impacting upon a player's ability to progress towards professional football (Dugdale et al., 2021).

2.8 Injury in Academy Soccer

2.8.1 Typical overview of injury mechanisms

Soccer is associated with high rates of contact and non-contact injuries, in the adult game over twenty years ago player would miss on average 24 days of training and competition per incidence of injury (Hawkins et al., 2001). At the close of the most recent 2024/2025 season across the Premier League more than 21,000 days were lost to injury (ISSPF, 2025), yet less data exists with reference to both the acute and long-term injuries in academy soccer. Reducing injury rates is essential to support player's long term development while minimising risk of injury or long-term health issues in later life (Swain et al., 2018). An assessment of elite youth English soccer players found that injury rates were less than their adult (Price et al., 2004) and their European counterparts who lost 32 days per year (Le Gall et al., 2006) with injury burdens of between 16 to 29 days lost reported across Belgium, Brazil, England, Netherlands, Spain and Uruguay (Materne et al., 2021b). In a cohort of youth Qatari soccer players authors cited contusions, sprains and growth-related injuries as the most common injury mechanisms across 551 youth soccer players aged U9 – U19 (Materne et al., 2021a). In a cohort of English academy soccer players over a four-year period authors reported a total of 603 separate incidences of injury to 190 players with the most common injury sites reported as the thigh, knee ankle and hip and groin (Light et al., 2021). Findings which relate to work of Hall et al., (2020) who report that injuries to the hip, lower back and sacrum typically as a result of overuse are the most common across youth soccer academies.

2.8.2 Growth related injuries in academy soccer

Although limited in comparison to their adult counterparts, existing literature highlights how time-loss injuries in youth soccer peak between the ages of U12 – U16 coinciding with to onset of peak height velocity and rapid growth and maturation. To this end differences in maturation status have been linked to the type, location and severity of injuries experienced by youth soccer players (Le Gall et al., 2007, van der Sluis et al., 2014). In an assessment of injury rate over two seasons Johnson et al., (2022) reported that players classified as circa-PHV were at a greater risk of injury (24.5 injuries per 1000h) compared to those who were pre-PHV (11.5 injuries per 1000h) although the risk was not dependent upon maturation timing. Such data suggests that it is the stage at which a player is with reference to their own growth and maturation, rather than if they are an early, on-time or late maturer which influences their risk of injury. Indeed players in U14 and U15 age groups (who present with chronological ages of 13 and 14) suffer the greatest incidence of injury (Le Gall et al., 2006, Read et al., 2018) at a time coinciding with typical PHV of 13.8 years (Malina et al, 2004). The role of maturation status and injury is multifaceted with a number of factors likely contributing to a player's injury. Indeed while growth and maturation is a growth of all bodily tissues, growth of the body at different rates namely changes in limb length and limb mass stimulate acute periods of coordination and a reduction in technical skill commonly referred to as adolescent awkwardness. Such a lack of coordination can lead to an increase in injury when paired with asymmetries in the lower limb and a loss of neuromuscular control (Read et al., 2018). Moreover an increase in plasticity of connective tissue namely muscle-tendon junctions and bone-tendon junction, ligaments and growth cartilage as well as reduce bone mineral density (Faulkner et al., 2006; Van de Sluis et al., 2014) propose a risk of injury to players enhanced by high training and match loads increasing stress on such structures.

2.9 Implications for sub-optimal nutritional practices upon soccer players

2.9.1 Soccer specific performance

Seminal work investigating the physiology of soccer highlighted the importance of carbohydrate intake for soccer performance following depletion of muscle glycogen stores using muscle biopsy studies (Saltin, 1973). Despite decades of evolving knowledge of the importance of carbohydrate intake upon soccer performance, sub – optimal fuelling practices are commonplace across elite male and female adult and male and female academy soccer. The type, quantity and timing of food, fluids and supplements consumed can influence a player's performance and recovery (Collins et al., 2021). Indeed in the elite adult men's soccer more goals are scored and conceded after 75 minutes of match play have been completed, which is not surprising given that following ninety minutes of exercise almost half of all individual fibres are depleted of glycogen (Krustrup et al., 2006). In the presence of carbohydrate intake however time to exhaustion is delayed and therefore performance capacity increased (Nicholas et al., 1995) with player's possessing a greater ability to execute technical skills to a higher standard which may in turn determine the outcome of the match (Lago-Peñas et al., 2010). To this end despite the many situational impacts upon the result of competitive soccer match play (i.e., home advantage or technical superiority) reductions in fuel availability, impaired cognitive function and dehydration likely all play a role, all of which may be modulated by carbohydrate intake.

In comparing technical skill Russell and Kingsley (2014) concluded that carbohydrate had the ability to maintain soccer specific skills and therefore suboptimal intake of carbohydrate, would lead to a reduction in soccer specific performance. Specifically carbohydrate intake has shown to enhance dribbling speed, coordination, precision and power (Ostojic and Mazic,

2002) and skill execution in both dominant and non-dominant limbs in comparison to no carbohydrate supplementation, with the most prominent differences within the final third of match play (Rodriguez-Giustiniani et al., 2019). A phenomenon mirrored in other sports such as tennis whereby both dominant and non-dominant sides respond positively to carbohydrate intake compared to without (McRae and Galloway, 2012).

2.9.2 Energy and macronutrient intake and the response to bone

Energy availability, the amount of energy available for basic physiological function once exercise energy expenditure has been removed is an essential determinant of bone health. When investigating individuals with varying severities of low energy availability Loucks et al., (2011) reported that individuals with less than 45 kcal.kg LBM.d^{-1} experienced comprised bone development, reduced bone formation and increased bone resorption. In work investigating a chronic combination of sub-optimal carbohydrate intake with high daily energy expenditure such as practices seen on occasion academy soccer (Hannon et al., 2021b) bone formation was compromised (Fensham et al., 2022). If repeated, chronic low energy availability may have negative implications for skeletal development, namely achieving peak bone mass and risks of skeletal injury during such a vital phase of development.

Almost 90% of peak adult bone mass is achieved by the age of 18 (Golden et al., 2014), if achieved and maintained, high levels of peak bone mass in adolescence reduces incidence of fractures and later, osteoporosis (Hereford et al., 2024). However failure to achieve peak bone mass during adolescence cannot be super compensated later in life, therefore the role of optimal nutritional intake alongside the anabolic effect of high levels of physical activity at this time cannot be understated. With specific reference to acute carbohydrate intake there is a strong body of literature which suggests high carbohydrate intake in the hours before, during and after exercise reduces markers of bone resorption (Townsend et al. 2017; Sale et al. 2015; Hammond et al. 2019; de Sousa et al. 2014). When feeding carbohydrate prior to exercise Scott et al. (2011) attenuated pre-exercise βCTX, yet hypothesised that the effect was superseded by the mechanical stress of the exercise bout. To test this theory Sale et al., (2015) provided trained distance runners with carbohydrate pre-, during and post-exercise, reporting that both PINP and βCTX remained suppressed in the hours post-exercise. Therefore consumption of 2 g/kg carbohydrate before pitch-based training and consumption of 60 $g.hr^{-1}$ which may be seen as 'best practice' nutritional intake at this time (Collins et al., 2021) may have ergogenic effects upon markers of bone (re) modelling. Indeed most recently data has extended to investigating the effects of carbohydrate availability over a longer period to assess the response to bone tissue, Fensham et al. (2022) reported that low carbohydrate consumption over a six-day period increased bone (re)modelling markers through both increased bone resorption and reduced bone formation. Mechanistically increased bone resorption under conditions of low CHO availability illudes to the role of IL-6 concentrations which are increased during and after exercise compared to when CHO has been consumed at this time (Starkie et al., 2001). Indeed when reporting attenuated βCTX post exercise highlighted above, authors reported a similar reduction in IL-6 (Sale et al., 2015), strengthened by models highlighting that IL-6 increases osteoclastogenesis and as such increased bone resorption (Kirk et al., 2020). Repeatedly failing to achieve daily carbohydrate intake targets (6 $g.kg^{-1}$) while completing training loads comparable to their adult counterparts (Anderson et al., 2016a, Hannon et al., 2021a, Hannon et al., 2021b) may therefore compromise skeletal development. Taken together it would be fair to assume that both acute and chronic carbohydrate intake will impact markers of bone (re)modelling and sub-optimal nutritional practices may increase the risk of injury during a vital phase of skeletal development.

2.9.3 The acute response of bone to exercise

Bone metabolism is influenced by exercise in both catabolic and anabolic means through various metabolic and mechanical pathways (Dolan et al., 2020, Wherry et al., 2022; Kohrt et al., 2009). Activities which convey higher impact, multidirectional and unaccustomed loading patterns typically relay the greatest positive effect upon bone increasing bone mineral density resulting in greater bone strength (Frederickson et al., 2007). Daily loading through walking, completing menial tasks and the gravitational force at ground level are all seen as osteogenic, along with physical activity such as soccer training (Varley et al., 2023). Amplification of bone (re)modelling makers is typically greater when a response to a given stimuli is catabolic, road cycling for example owing to the lack of physical load (Scofield and Hecht, 2012) stimulates increases in βCTX - a bone resorption marker. Recent meta-analyses suggest that the acute response of bone (re)modelling markers is time sensitive with βCTX peaking almost immediately following commencement of exercise, with PINP and PTH increasing post exercise, illuding to a flux of bone resorption followed by bone formation. Yet changes in bone resorption and formation markers however do not translate meaningful change in bone tissue (Dolan et al., 2022). A criticism of literature investigating the effects of exercise upon bone modelling markers is that typically, investigations occur in the morning, when circulating βCTX concentrations are low following their peak at ~ 05:00 (Qvist et al., 2002). Indeed that the true effect of an acute bout upon bone (re)modelling markers, specifically βCTX is likely greater than reported (Dolan et al., 2020).

The consequence of increased bone resorption following acute exercise remains open to interpretation, data suggests that increased resorption may be essential to stimulate (re)modelling (Roblin et al., 2006; Hadjidakis 2006) and a subsequent rise in bone formation markers underlines the anabolic response to mechanical stimulus if maintained. The counter to increased resorptive activity is that, high frequency of exercise stimulus facilitating large increases in bone resorption may increase the risk of skeletal injury (Herbert et al., 2019).

The response of bone tissue to exercise is influenced by a number of factors including age, genetics and the specific exercise stimulus in which an individual is engaged. The academy soccer player will present with a greater concentration of bone (re)modelling markers and greater bone (re)modelling compared to their adult counterparts as a result of their stage of growth and maturation (Seeman and Delmas 2006). The dynamic and unpredictable nature of soccer specific training sessions and match play will further stimulate a greater response of bone (re)modelling markers in comparison to unidirectional exercise such as running, or to a greater extent, non-weight bearing exercises such as swimming (Gómez Bruton et al., 2016). Bone tissue responds directly to the magnitude, rate, number and direction of activity induced loading as such soccer training and match play which are characterised by their high impact, multidirectional movement and unaccustomed loads with higher carbohydrate availability are widely accepted as providing the optimal osteogenic stimulus (Varley et al., 2023)

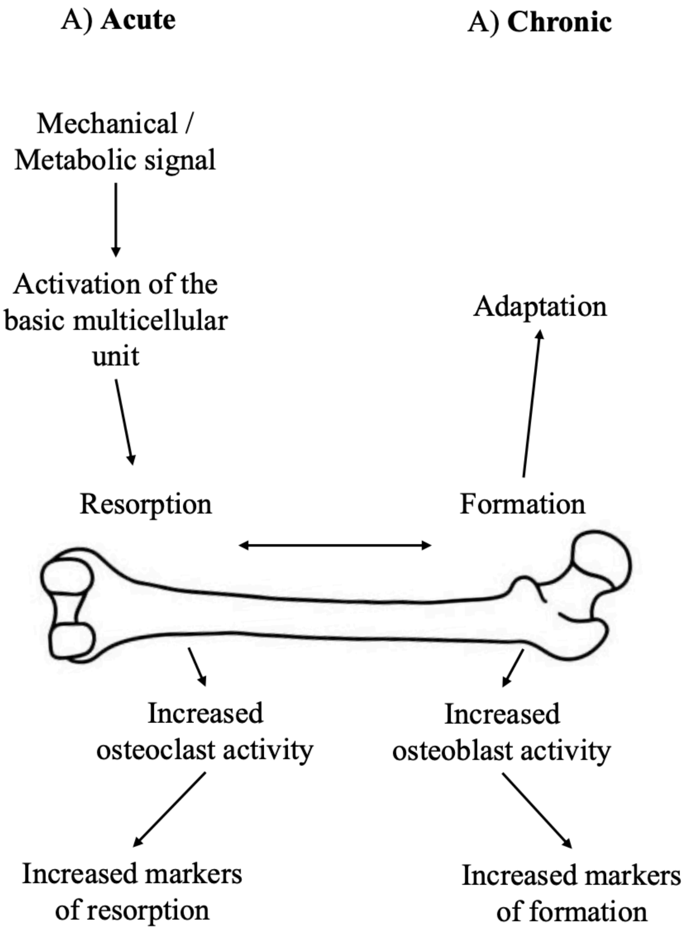

Figure 4. The bone (re)modelling in response to exercise adapted from Dolan et al., (2020). Section A highlights the acute response of a given exercise stimulus, section B highlights the chronic effects of a repeated exercise stimulus.

2.10 Sport Nutrition In Academy Soccer: Summary and Directions for future research

Within the last ten years there has been a significant rise in research within academy soccer. Prior to novel work by Hannon et al., (2021b) the majority of nutrition prescription was drawn from that of their adult counterparts (Anderson et al., 2017). Production of daily energy expenditure values alongside daily and weekly training load data has allowed for the production of daily energy and macronutrient intake guidelines for academy players.

Adherence to such guidelines will enhance training and match play in addition to player health at a vital time of biological and physical development whereby players stature, body weight and fat free mass increases by ~ 25 cm, ~ 30kg and ~ 23kg respectively (Hannon et al., 2020). Such energy expenditure data highlighted how daily energy expenditure increases by ~ 750 $kcal.d^{-1}$ throughout adolescence facilitated by an increase in resting metabolic rate of ~ 400 $kcal.d^{-1}$ during the same period (Hannon et al., 2020).

Despite an increase in quantitative research within this population, data remains limited to that of one club. Further research within academy soccer is required to determine the daily energy expenditures and energy and macronutrient intakes of elite youth soccer players. Despite being governed by the Premier League, soccer academies may determine their own weekly training loads as such it is important to gain a broader understanding of training and match loads and daily energy expenditures within this population. To this end it is not yet understood to what extent pitch-based training stimulates increases in daily energy expenditure compared to age matched adolescents. Despite estimating daily energy and macronutrient intake for the first time within this population, the timing and totality of intake in relation to pitch based training remains unknown. Given that data highlighted how players often display sub-optimal nutritional practices throughout the training week (Hannon et al., 2021b) there is a clear need to assess the response of specific blood markers, particularly those relating to bone (re)modelling at a vital time of skeletal development under conditions of low carbohydrate availability. It is hope that the data presented within the studies listed throughout this thesis will inform acute nutritional guidelines in the hours pre-, during and post-training, outlining the specific recommendations based upon daily energy expenditure data and the response of markers of bone (re)modelling during a vital phase of skeletal development.

Chapter 3

General Methods

The aim of this Chapter is to provide details of common methodologies that were employed in each of the subsequent Chapters (Chapter's 4, 5, 6 and 7). Methodologies that were unique to a specific Chapter are presented in the methods section of that relevant Chapter.

3.1 Ethical approval and location of testing

All experimental procedures and associated risks were explained both verbally and in writing to each player and their parent or guardian, and written informed consent and assent were obtained respectively. All players were informed that they could withdraw from participation at any stage throughout these studies. Ethical approval for all studies in this thesis was granted by the Ethics Committee of Liverpool John Moores University (ethics number: M18SPS037).

All anthropometric assessments (stature, sitting height and body mass), baseline urine samples (Chapter 5) and blood samples (Chapter 6) were collected at the host club's training ground (Aston Villa Training Ground) at Bodymoor Heath, Tamworth, Birmingham. Training load data collection occurred on the grass pitches at Aston Villa's Training Ground (Figure 5). Match load data collection also occurred on the grass pitches at Bodymoor Heath for home games, or at the relevant away teams training facility in the United Kingdom (Finch Farm, Liverpool and Sir Jack Hayward Training Ground, Wolverhampton). For Chapter 5 training load and anthropometric assessments for the non-academy group were carried out at their training ground. Risk assessments were conducted and approved for all testing locations.

Figure 5. Bodymoor Heath training ground. Facilitates encompass training pitches for all Foundation, Youth development and Professional Development Phase players and were the site of data collection for chapters 4, 5, 6 and 7.

3.2 Participant characteristics

Male soccer players from a Category One EPL academy (and grassroots soccer team) volunteered to participate in these studies. Players were categorised according to their respective age-group (U12, U13, U14, U15, U16, U18 and U21) based upon their chronological age. A total of 103 individual players participated in these four studies. A summary of participant characteristics from all three studies can be seen in Table 6. Participant characteristics of each age-group within each study are included in the relevant chapter.

Table 6. Participant characteristics across studies one, two and three. * Data is an average of both academy and non-academy groups. Participant

		U12	U13	U14	U15/16	U18	U21
Study One (Chapter Four)	**(n)**	8	8	8	8	8	8
	Age (years)	11.9 ± 0.1 (11.7 - 12.1)	13.1 ± 0.2 (12.9 – 13.6)	13.9 ± 0.1 (13.8 – 14.2)	15.8 ± 0.3 (15.4 - 16.2)	17.2 ± 0.3 (16.8 – 17.8)	18.6 ± 1.5 (16.4 – 21.1)
	Maturity offset (years)	-1.65 ± 0.3 (-2.1—1.0)	-0.7 ± 0.6 (-1.6 - -0.1)	0.2 ± 0.7 (-0.9 – 1.3)	2.3 ± 0.6 (1.1 – 3.2)	-	-
	PAS (%)	85 ± 1.1 (83.6 – 86.4)	88 ± 2.5 (84.9 – 90.1)	92.1 ± 3.4 (86.7 – 96.3)	99.3 ± 0.6 (98.4 – 100.5)	-	-
	Stature (cm)	154.4 ± 4.3 (148.1- 160.0)	161.9 ± 9.1 (146.1 – 173.0)	168.9 ± 8.6 (154.6 – 176.9)	184.5 ± 5.3 (176.6 – 192.4)	184.5 ± 5.3 (173.0 – 192.5)	186.1 ± 7.2 (178.9 – 195.4)
	Body Mass (kg)	44.6 ± 7 (37.0 – 57.7)	49 ± 7.6 (38.2 – 60.6)	58.1 ± 10 (43.1 – 75.5)	70.3 ± 6.7 (58.0 - 78.9)	70.3 ± 6.7 (61.5 – 91.4)	76.6 ± 7.1 (72.2 – 87.7)
Study Two (Chapter Five)	**(n)**	-	ACAD (8), NON ACAD (6)	-	-	-	-
	Maturity offset (years)	-	-0.6 ± 0.7 (-2.2 – 0.3)	-	-	-	-
	PAS (%)	-	88.9 ± 2.6 (85.2 – 92.6)	-	-	-	-
	Stature (cm)	-	164.3 ± 6.7 (152 - 178)	-	-	-	-
	Body Mass (kg)	-	51.9 ± 5.2 (36.2 – 73.4)	-	-	-	-
Study Three* (Chapter Six)	**(n)**					10	
	Maturity offset (years)	-		-	-	-	-
	PAS (%)	-		-	-	-	-
	Stature (cm)	-		-	-	184.2 ± 7.8 (168.2 – 193.4)	-
	Body Mass (kg)	-		-	-	74.6 ± 9.1 (63.6 - 89)	-

baseline characteristics were not collected as per methods in Study Four (Chapter Seven)

3.3 Anthropometric assessments of stature, sitting height and body mass

Participants removed jewellery and wore only minimal training kit (t-shirt and shorts) for assessments of stature, sitting height and body mass. Participant's body mass (SECA, model-875, Hamburg, Germany), stature and sitting height (SECA, model-217, Hamburg, Germany) were measured to the nearest 0.1 kg, 0.1 cm and 0.1 cm respectively according to the International Society for the Advancement of Kinanthropometry (ISAK) guidelines (Stewart et al., 2011) by an ISAK Level-1 practitioner (PhD candidate). Leg length was subsequently calculated by subtracting sitting height from stature. Two measurements were taken for each anthropometric measure, with a third taken if the first two measures differed by more than 2%. Where two measures were taken, the mean was recorded and if a third measure taken, the median was recorded.

3.4 Calculation of maturity offset and percent of predicted adult stature

In Chapters 4 and 5, somatic maturity (timing) was determined for each participant by calculating maturity offset (Mirwald et al., 2002). This equation estimates the time in years from PHV and is accurate to ± 0.24 years (Mirwald et al., 2002). A maturity offset value was calculated for all players in the U12 - U16 age-groups as this is typically the timeframe in which PHV occurs in youth soccer players (Towlson et al., 2017) and also the age-range in which the equation was developed (Mirwald et al., 2002).

Maturity offset calculation = -9.236 + (0.0002708 × leg length and sitting height interaction) + (-0.001663 × age and leg length interaction) + (0.007216 × age and sitting height interaction) + (0.02292 × weight by height ratio).

In the U12-U15/16 age-groups predicted adult stature (PAS) was calculated using the Sherar equation which is accurate to ± 5.35 cm (Sherar et al., 2005). Current percent of PAS (maturity status) was then calculated using the following equation:

$$(\text{current stature} \div \text{predicted adult stature}) \times 100.$$

3.5 Quantification of training and match load

Pitch based training load was measured using global positioning system (GPS) technology (Vector, Catapult, Melbourne, Australia). Each player was provided with a GPS unit (81 mm x 43 mm x 16 mm) and custom-made manufacturer provided vest (Catapult, Melbourne, Australia) to wear on the upper back between both scapulae during each pitch-based training session and match. Each unit was alarmed to turn on thirty minutes prior to the start of each session to sample absolute; total distance (m), high speed running meters (> 5.5 $m.s^{-1}$), accelerations (> 3 $m.s^{-1}$), decelerations (< 3 $m.s^{-1}$) and relative; meters per minute ($m.min^{-1}$) training metrics at 10 Hz providing a valid and reliable assessment of soccer specific movement (Coutts and Duffield, 2010, Varley et al., 2012). To ascertain if academy soccer players were capable of achieving the training and match intensities of adult EPL players, absolute speed thresholds commonly used within the adult game were deliberately selected (Anderson et al. 2016; Malone et al. 2015). Such metrics align with comprehensive assessments of both male academy (Hannon et al., 2021) and female academy aged international players (McHaffie et al., 2024) providing justification for their inclusion within this body of work. While it is accepted that absolute thresholds have limitations within academy soccer namely when comparing players with different biological and chronological maturation (Gabbett, 2016, Hannon et al., 2021a), individualisation of speed thresholds was deemed inappropriate due to the acute nature of each study – paired with the need for such thresholds to be regularly updated in line with growth and maturation (Philippaerts et al., 2006), a practice which was not common place within the host club.

3.6 Assessment of Energy and Macronutrient Intake

3.6.1 Parent and Player Workshop

Prior to data collection, all participants and parents/guardians were invited to an educational workshop where the study methodology was explained in detail. Players and parents / guardians of players were initially instructed on the rationale for collecting energy and macronutrient intake data and how these analyses can be used to positively impact player health and performance. Participants were shown a video detailing "step-by-step" how to use the RFPM and instructed on additional details to include (i.e. branding, weights and cooking methods). Participants were shown common problems (i.e. difficulty to identify food items or a loss of phone signal) when collecting this data and how to rectify them (i.e. provide ingredients and individual weights or record the time of consumption which could be sent as soon as possible once signal had returned). This workshop was pre-recorded and sent to each parent / guardian along with a written step-by-step guide as a point of reference throughout data collection.

3.6.2 Quantification of energy and macronutrient intake

Self-reported daily energy and macronutrient intake was quantified using the RFPM. 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 professional adult (Anderson et al. 2017) and academy (Hannon et al., 2021b) soccer players.

Participants were instructed to take two images of any food or drink consumed using their smart phone; one at 45 degrees and one at 90 ninety degrees (allowing for a better estimation of portion size than one image alone) and send both images to the principal investigator. Participants were instructed to provide a detailed description of each eating occasion encompassing all ingredients, branding, weights, cooking methods and pre-existing nutritional information from food labels. Post-consumption, participants were required to send a final image detailing any food or drink remaining with weights of anything which had not been consumed. If all food and drink had been consumed participants were permitted to send a message reading "finished" to reduce participant burden. All images were sent using the instant messaging application Threema (Threema GmbH, Pfäffikon, Switzerland). Where food was consumed on-site, the principal investigator was also present at the host club training ground to assist with data collection on behalf of the participant (i.e. self-record images and weights at mealtimes) and make written records of energy and macronutrient intakes, specifically for food and drink provided by the club. A database of any food and drink provided by the host club (e.g. "homemade energy balls") was created by the principal investigator to reduce participant burden.

At the end of data collection, each player completed a dietary recall to highlight any missed data and cross reference data collected by the principal investigator (Capling et al. 2017). During this process the principal investigator clarified all timings, quantities, branding and weights provided by the participant and prompted the participant to recall any missed items. Energy and macronutrient intake was analysed by a Sport and Exercise Nutrition register (SENr) accredited nutritionist, then a sample of data (Chapter 4) and total data (Chapter 5) was analysed by a second (Chapter 4) and two other (Chapter 5) Sport and Exercise Nutrition register (SENr) accredited nutritionists respectively, using dietary analysis software Nutritics

(Nutritics, v5, Dublin, Ireland). For all chapter's energy intake was reported as kilocalories in both absolute and relative terms and macronutrient intake was reported in grams for both absolute and relative terms. For both Chapters 4 and 5 inter-rater reliability of analyses was determined via a one-way analysis of variance (ANOVA).

Chapter 4

Acute fuelling and recovery practices of academy soccer players: implications for growth, maturation, and physical performance.

The aim of this chapter was to quantify the acute fuelling and refuelling practices of academy soccer players (U12 – U21) in the four hours before, during and the four hours after pitch-based training using the Remote Food Photography Method. This study also aimed to assess the physical activity and travel time in the same acute period before and after training.

Sam McHaffie assisted with the data analysis for this study.

Stables, R. G., Hannon, M. P., Costello, N. B., McHaffie, S. J., Sodhi, J. S., Close, G. L., & Morton, J. P. (2022). Acute fuelling and recovery practices of academy soccer players: implications for growth, maturation, and physical performance. Science and Medicine in Football, 8(1), 37–51.

4.1 Abstract

Considering that academy soccer players frequently train in the evening (i.e. 17:00 - 20:00 h), there is often limited time to nutritionally prepare and recover due to schooling, travel and sleep schedules. Accordingly, we assessed the timing and quantity of dietary intake of academy soccer players in the pre - training and post - training period. Over a 3-day in-season training period, male adolescent players (n = 48; n = 8 from under (U) 12, 13, 14, 15/16, 18 and 21 players) from an English Premier League academy self-reported their dietary intake and physical activity levels (via the RFPM and activity diary, respectively) in the four hours before and after training. External training load was also quantified via GPS. Timing of pre-training energy intake ranged from 40 ± 28 mins (U15/U16 players) to 114 ± 71 mins (U18) before training and mean carbohydrate (CHO) intake ranged from 0.8 ± 0.4 $g.kg^{-1}$ (U21) to 1.5 ± 0.9 $g.kg^{-1}$ (U12). Timing of post-training energy intake ranged from 39 ± 27 mins (U14) to 70 ± 84 mins (U21) and mean CHO intake ranged from 1.6 ± 0.8 $g.kg^{-1}$ (U12) to 0.9 ± 0.5 $g.kg^{-1}$ (U14). In contrast to sub-optimal CHO intakes, all age groups consumed sufficient protein intake in the post-training period (i.e. > 0.3 $g.kg^{-1}$). We conclude academy soccer players habitually practice sub-optimal acute fuelling and recovery strategies, the consequence of which could impair growth, maturation and physical performance. Player and stakeholder education and behaviour change interventions should therefore target specific behaviours that lead to increased CHO intake before, during and after training.

4.2 Introduction

The aim of soccer academies is to develop players through improving their tactical, technical, physical and psychosocial capabilities (Wrigley et al., 2012). Ultimately, the end goal is to produce players to represent the first team at the host club or to be sold for financial gain (Elferink-Gemser et al., 2012). As players transition through the academy pathway (i.e., from U12 to U18 age groups), they undergo sustained periods of growth and maturation (Hannon et al., 2020). For example, in a cohort of male academy players from the English Premier League (EPL), we recently observed increases in body mass (~ 30 kg), fat-free mass (~ 23 kg) and stature (~ 25 cm) between the ages of 12 and 18, which coincided with increases in resting metabolic rate of approximately 400 kcal.d^{-1} (Hannon et al., 2020). Furthermore, in accordance with increases in absolute daily training load (i.e. increases in duration and total distance) throughout the development pathway (Hannon et al., 2021a), we also observed significant increases in total daily energy expenditure (~ 750 kcal.d^{-1}) between U12 and U18 players (Hannon et al., 2021b). In some individuals, total daily energy expenditure (as evident in U12, U15 and U18 players) was comparable to or exceeded that previously reported from adult EPL players (Anderson et al., 2017). When taken together, such data clearly demonstrate the requirement for academy soccer players to maintain sufficient energy availability to support the energetic requirements of growth and maturation in addition to daily training activities.

Although nutritional strategies for athletic populations have traditionally focused on meeting "daily" energy requirements, the importance of timing of energy and macronutrient intake is becoming increasingly recognised (Collins et al., 2021). Indeed, the sub-optimal provision of CHO before and/or during training and match play can reduce the performance of technical skills such as passing, shooting and dribbling (Russell et al., 2012) as well as physical performance outputs (Rodriguez-Guistiniani et al., 2019). Additionally, the intake of CHO availability around training can also affect the acute regulation of bone turnover (Sale et al., 2015), thus having relevance for the academy soccer player given the requirement to accrue bone mass and maximise skeletal development during the adolescent years (Costa et al., 2022). The importance of sufficient protein intake in recovery from training is also of importance to stimulate muscle protein synthesis and promote the growth of fat-free mass (Boisseau et al., 2007). Nonetheless, despite the critical importance of timing of energy and macronutrient intake, the practicalities of adequate food consumption are complicated by the logistics and often busy lives of academy players. For example, academy players from the EPL (albeit dependent on age) often train in the evening periods (e.g., 17:00 - 20:00) thereby presenting a limited time-period between the end of the school day (e.g., 15:30) and beginning of training. In this way, the physical opportunity to consume sufficient energy intake in the acute period before training is often limited and moreover, the timing of players' previous food intake may have been limited to that consumed at school mealtimes (e.g., 12:00 - 13:00). Given the time required to transport players to and from training, the acute fuelling and recovery practices of academy players may also occur in their parent's or guardian's cars, local bus or train for example, thus presenting as an additional practical challenge to actively plan and consume meals. When considered this way, it is readily apparent that nutritional education programmes for both players and stakeholders (e.g., parents, coaches, support staff etc.) should align on the technical knowledge and practical execution of strategies to ensure sufficient energy and macronutrient intake in the hours before and after training.

Despite the increasing recognition of the role of nutrition in supporting player development (Collins et al., 2021), a recent audit from our research group identified that English soccer academies are often under-resourced in relation to the quality and extent of service provision that is currently offered to players (Carney et al, 2022). This lack of resource was evidenced by a lack of full-time accredited nutrition staff delivering player and stakeholder education as well as a lack of on-site food provision before and after training. Moreover, it was also identified that players in the Foundation and Youth Development Phases (i.e. U9 - U11 and U12 - U16, respectively) receive significantly less support than players from the Professional Development Phase (i.e. U18-U21). These findings are consistent with recent observations of Carter et al., (2022) who report that nutritional knowledge, training venue food provision and access to an accredited nutritionist are key enablers for optimal nutritional practices for academy soccer players. Although a more focused service provision towards the latter phase appears aligned with potential progression to the first team, the apparent lack of provision in the earlier phases is especially concerning given that the transition throughout such phases coincides with peak rates of growth and maturation. As such, there is a definitive requirement to better understand the nuances of the habitual nutritional practices of academy players at varying stages of the academy pathway.

With this in mind, the aim of the present study was to quantify the acute fuelling and recovery practices of male academy soccer players. To this end, players across the academy pathway (i.e., U12 to U21) were assessed for energy and macronutrient intake in the four hours before, during and after training over a three-day assessment period from a typical in-season training microcycle. Additionally, external training load was monitored (via GPS monitoring) and players also completed physical activity diaries (when not training) to assess physical activity patterns across the assessment period. We hypothesised that all age-groups would report sub-optimal fuelling and recovery practices, the prevalence of which would be greater in the younger playing squads.

4.3 Methods

4.3.1 Participants

Forty-eight (n = 43 outfield and n = 5 goalkeepers) male soccer players from a Category One English Premier League soccer academy volunteered to participate in this study. Participants of different chronological and biological ages were non-randomly allocated into groups depending upon their chronological age-group (U12, U13, U14, U15/16, U18 and U21). Written informed parental/guardian con- sent and player assent were obtained for participants ≤ 16 years old, and participants ≥ 17 years old provided their own consent. Ethical approval was granted by Liverpool John Moores University.

4.3.2 Study Design

In a cross-sectional design, self-reported energy and macronutrient intake, pitch-based training load and physical activity data was collected over two (U12 - U16) or three (U18 - U21) in-season training days. Data was collected in the four hours pre-, during and four hours post-training. Data were collected during an in-season period between October and December 2021. During this time, all players continued with their usual education, training and match schedules. An overview of the on-pitch training schedules of each age group is displayed in Table 8 where data collection days are highlighted in bold.

4.3.3 Baseline measures

Players underwent assessments of stature, sitting height, body mass in accordance with the procedures outlined in section 3.3. For participants in the Youth Development Phase (YDP; U12 - U15/16), somatic maturity was determined by calculating maturity offset (Mirwald et al, 2002) and predicted adult stature (PAS) and the current percentage of adult stature achieved (%PAS) (Sherar et al., 2005) was also collected as per procedures outlined in section 3.4.

Table 7. A comparison of age, maturity offset, current percentage of predicted adult stature (PAS), stature and body mass between youth soccer players (U12 – U21) age groups (n = 48) from a Category One English Premier League Academy

	U12	U13	U14	U15/16	U18	U21
n	8	8	8	8	8	8
Age * (years)	11.9 ± 0.1[bcdef] (11.7 - 12.1)	13.1 ± 0.2 [adef] (12.9 – 13.6)	13.9 ± 0.1[adef] (13.8 – 14.2)	15.8 ± 0.3[abcef] (15.4 - 16.2)	17.2 ± 0.3[abcdf] (16.8 – 17.8)	18.6 ± 1.5[abcde] (16.4 – 21.1)
Maturity offset * (years)	-1.65 ± 0.3[cd] (-2.1—1.0)	-0.7 ± 0.6[d] (-1.6 - -0.1)	0.2 ± 0.7[a] (-0.9 – 1.3)	2.3 ± 0.6[ab] (1.1 – 3.2)	-	-
PAS (%) *	85 ± 1.1 [bcd] (83.6 – 86.4)	88 ± 2.5 [acd] (84.9 – 90.1)	92.1 ± 3.4 [abd] (86.7 – 96.3)	99.3 ± 0.6[abc] (98.4 – 100.5)	-	-
Stature * (cm)	154.4 ± 4.3 (148.1- 160.0)	161.9 ± 9.1 (146.1 – 173.0)	168.9 ± 8.6[a] (154.6 – 176.9)	184.5 ± 5.3[abc] (176.6 – 192.4)	184.5 ± 5.3[abc] (173.0 – 192.5)	186.1 ± 7.2[abc] (178.9 – 195.4)
Body Mass * (kg)	44.6 ± 7 (37.0 – 57.7)	49 ± 7.6 (38.2 – 60.6)	58.1 ± 10[a] (43.1 – 75.5)	70.3 ± 6.7[ab] (58.0 - 78.9)	70.3 ± 6.7[abc] (61.5 – 91.4)	76.6 ± 7.1[abc] (72.2 – 87.7)

* denotes significant difference between squads (main effect, $p < 0.05$). [a] denotes significant difference from U12, [b] denotes significant difference from U13, [c] denotes significant difference from U14, [d] denotes significant difference from U15/16, [e] denotes significant difference from U18, and [f] denotes significant difference from U21 (all $p < 0.05$). Data are presented as means ± SD with range displayed in parentheses.

Table 8. An overview of pitch-based training, gym and match schedules for each squad. Data collection was completed on days in bold.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
U12	Gym 15:45 – 16:15 Pitch-based training 17:00 – 19:00	**Pitch-based training 17:30 – 19:30**	OFF	**Pitch-based training 17:30 – 19:30**	OFF	Gym 9:45 – 10:15 Pitch-based training 10:30 – 12:30	Match 11:00 (kick-off)
U13	OFF	**Pitch-based training 17:30 – 19:30**	Gym 15:00 – 15:40 Pitch-based training 17:00 – 19:00	**Pitch-based training 17:30 – 19:30**	OFF	Gym 9:45 – 10:15 Pitch-based training 10:30 – 12:30	Match 11:00 (kick-off)
U14	OFF	**Pitch-based training 17:30 – 19:30**	Gym 15:45 – 16:25 Training 17:00 – 19:00	**Pitch-based training 17:30 – 19:30**	OFF	Gym 9:45 – 10:15 Pitch-based training 10:30 – 12:30	Match 11:00 (kick-off)
U15/16	**Pitch-based training 17:30 – 19:30 Gym 19:30 – 20:00**	Pitch-based training 10:30 – 12:00 Gym 14:15 – 15:00	OFF	**Pitch-based training 17:30 – 19:30**	OFF	Match 12:00 (kick-off)	OFF
U18	**Pitch-based training 10:30 – 12:00**	**Pitch-based training 10:30 – 12:00 Gym 14:15 – 15:00**	OFF	**Pitch-based training 10:30 – 12:00 Gym 14:15 – 15:00**	Pitch-based training 10:30 – 12:00	Match 12:00 (kick-off)	OFF
U21	**Pitch-based training 10:30 – 12:00 Gym 15:00 – 16:00**	**Pitch-based training 10:30 – 12:00 Gym 15:00 – 16:00**	OFF	**Pitch-based training 10:30 – 12:00**	Match 19:00 (kick-off)	Training / Recovery 10:30 – 12:00	OFF

4.3.4 Quantification of training load

Pitch based training load was measured using global positioning system (GPS) technology (Vector, Catapult, Melbourne, Australia) in accordance with the procedures outlined in section 3.5. Start time, end time and therefore duration of sessions were not manipulated for the purpose of this research to maintain ecological validity. Moreover session content was determined by technical coaches who were external from the host club and periodised as part of a longer-term coaching curriculum within the host club and to satisfy the match demands of each week. To that end the research team had no influence over the training design however sessions typically followed the following structure; warm up, possession practice, technical practice and small or larger sided games.

4.3.5 Quantification of energy and macronutrient intake

Self-reported energy and macronutrient intake was quantified during the four hours prior to training, during training and the four hours post-training using the RFPM as outlined in section 3.6.2.

Prior to data collection, all participants and parents/guardians were invited to an educational workshop where the study methodology was explained in detail as detailed in section 3.6.1 of this thesis.

YDP players (U12 – U16) were provided with pre-training snacks and cold post-training food options (e.g. cereal bar, fruit and chicken wrap, pasta pot, flapjack, fruit juice and milkshake). During training, players from the PDP were also given the opportunity to consume CHO (e.g. sports drinks) and/or plain water ad libitum. At the end of each two- or three-day data collection phase, each player completed a dietary recall to highlight any missed data and cross reference data collected by the principal investigator (Capling et al., 2017). During this process, the principal investigator clarified all timings, quantities, branding and weights provided by the participant and prompted the participant to recall any missed items. Energy and macronutrient intake was analysed by a SENr accredited nutritionist using dietary analysis software Nutritics (Nutritics, v5, Dublin, Ireland). Energy, CHO and protein intake was quantified as kilocalories and grams respectively in both absolute and relative (to each player's body mass) 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 = 10, equating to 30 days of entries in total). Inter-rater reliability was determined via an independent t-test. No significant differences were observed between researchers for energy (p = 0.95, 95% CI - 202 to 49), CHO (p = 0.09, 95%CI - 40 to 1), protein (p = 0.09, 95%CI -14 to 1) and fat (p = 0.11, 95%CI -13 to 1).

4.3.6 Quantification of physical activity

Self-reported physical activity was quantified in the four hours before training and the four hours after training using a self-reported activity diary on a smartphone application designed by the principal investigator (Glide, California, United States). Each participant was sent a link to download the application prior to the start of the study. At fifteen-minute intervals during each four-hour period, participants were instructed to provide a short description of their physical activity (e.g. 'walking the dog', 'travelling' or 'watching TV') and rating of perceived exertion (RPE) and submit these via the smartphone app. Each entry was then automatically logged on an online Google sheet (Google, California, United States) and exported to Microsoft Excel (Microsoft, Washington, United States) by the principal investigator. Each activity entry was then converted into metabolic equivalent task (MET) to provide an estimation of energy expenditure and then assigned one of the following intensity thresholds based upon the energy expenditure value; “very light”, “light”, “moderate”, “heavy”, “very heavy” (Butte et al., 2018).

4.3.7 Statistical analysis

All data were initially assessed for normality using the Shapiro Wilk test. Baseline characteristics between groups was assessed via a one-way between groups analysis of variance (ANOVA). To determine differences in absolute and relative energy and macronutrient intake between age-groups, data were also assessed using a one-way between-groups ANOVA. 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.

4.4 Results

4.4.1 Baseline characteristics

Player characteristics including age, maturity offset, percent of PAS, stature and body mass are presented in Table 7. All of the aforementioned parameters were significantly different between squads (all main effects, $p < 0.05$) with specific pair-wise comparisons.

4.4.2 Self-reported physical activity levels, energy and macronutrient intake in the four hours before training

Pre-training physical activity levels.

Physical activity levels in the four hours before training is displayed in Table 9. No differences were observed between squads for the time engaged in *very light* (p = 0.35), *moderate* (p = 0.31), *heavy* (p = 0.49) or *very heavy* (p = 0.15) activity. In contrast, there was a significant difference in time spent engaged in *light* (p = 0.02) activities. Players in the U15/16 squad reported more time spent in *light activity* when compared with the U18 (p = 0.02; 95% CI, 24 to 104) and U12 players (p < 0.01; 95% CI, 20 to 106). There was also a significant difference in travel time to training between squads (p < 0.05). U18 players spent less time (16 ± 4 min) travelling to training than all YDP players (U12: 38 ± 19 min, 95% CI, -37 to -7, p < 0.01; U13: 33 ± 19 min, 95% CI, -35 to 0, p = 0.04; U14: 32 ± 19 min, 95% CI, -33 to -2, p = 0.03; U15/16: 34 ± 11 min, 95% CI, -34 to -2 , p = 0.03) players. U21 players also spent less time (21 ± 4 min) travelling to training than U12 players (95% CI, -33 to -1, p = 0.04).

Table 9. Time spent completing very light, light, moderate, heavy, and heavy physical activities as well as travel time to training in the four hours before training. * denotes significant difference between squads (main effect, $p < 0.05$). All data was collated using physical activity diaries converted using METs. [a] denotes significant difference from U12, [b] denotes significant difference from U13, [c] denotes significant difference from U14, [d] denotes significant difference from U15/16, [e] denotes significant difference from U18, and [f] denotes significant difference from U21 (all $p < 0.05$). Data are presented as means ± SD.

	U12	**U13**	**U14**	**U15/16**	**U18**	**U21**
Very Light (e.g. sleep and travel to training)	165 ± 46	160 ± 50	156 ± 36	118 ± 60	145 ± 77	130 ± 64
Light * (e.g. completing homework)	35 ± 34	61 ± 53	67 ± 33	98 ± 56 [ae]	34 ± 32	64 ± 72
Moderate (e.g. brisk walk)	27 ± 36	10 ± 21	45 ± 8	15 ± 20	26 ± 28	22 ± 20
Heavy (e.g. jogging)	10 ± 17	12 ± 23	0	10 ± 12	26 ± 55	27 ± 42
Very Heavy (e.g. boxing gym training)	8 ± 15	0	0	3 ± 12	19 ± 33	18 ± 26

Timing of pre-training energy, CHO and protein intake

The timing of energy, CHO and protein intake within each squad is displayed visually in Figures 7-9 (pre-training data are displayed *left* of the grey shaded area which represents the timing and duration of training). With the exception of the U18 and U21 players, all squads trained in the evening period. Energy intake was consumed in closer proximity to the start of training in the U15/16 squad (16:50; - 40 ± 28 mins) compared to the U12 (15:59; - 91 ± 77 mins), U13 (15:51; - 99 ± 63 mins), U14 (15:46; - 104 ± 56 mins), U18 (08:36; - 114 ± 71 mins) and U21 (08:51; - 99 ± 52 mins) squads (all $p < 0.01$). There was a significant difference ($p = 0.01$) between squads in the frequency of eating occasions before training. U18 players had more eating occasions (1.9 ± 0.9) than U12 players (1.5 ± 0.5; 95%CI 0.1 to 1.0, $p < 0.05$). U15/16 players displayed fewer eating occasions (1.0 ± 0.3) than U21 (1.7 ± 0.9; 95% CI -1.2 to -0.7, $p = 0.03$), U18 (95% CI -1.4 to -0.4, $p < 0.01$) and U14 (1.9 ± 0.4; 95% CI -1.4 to -0.4, $p < 0.01$) players.

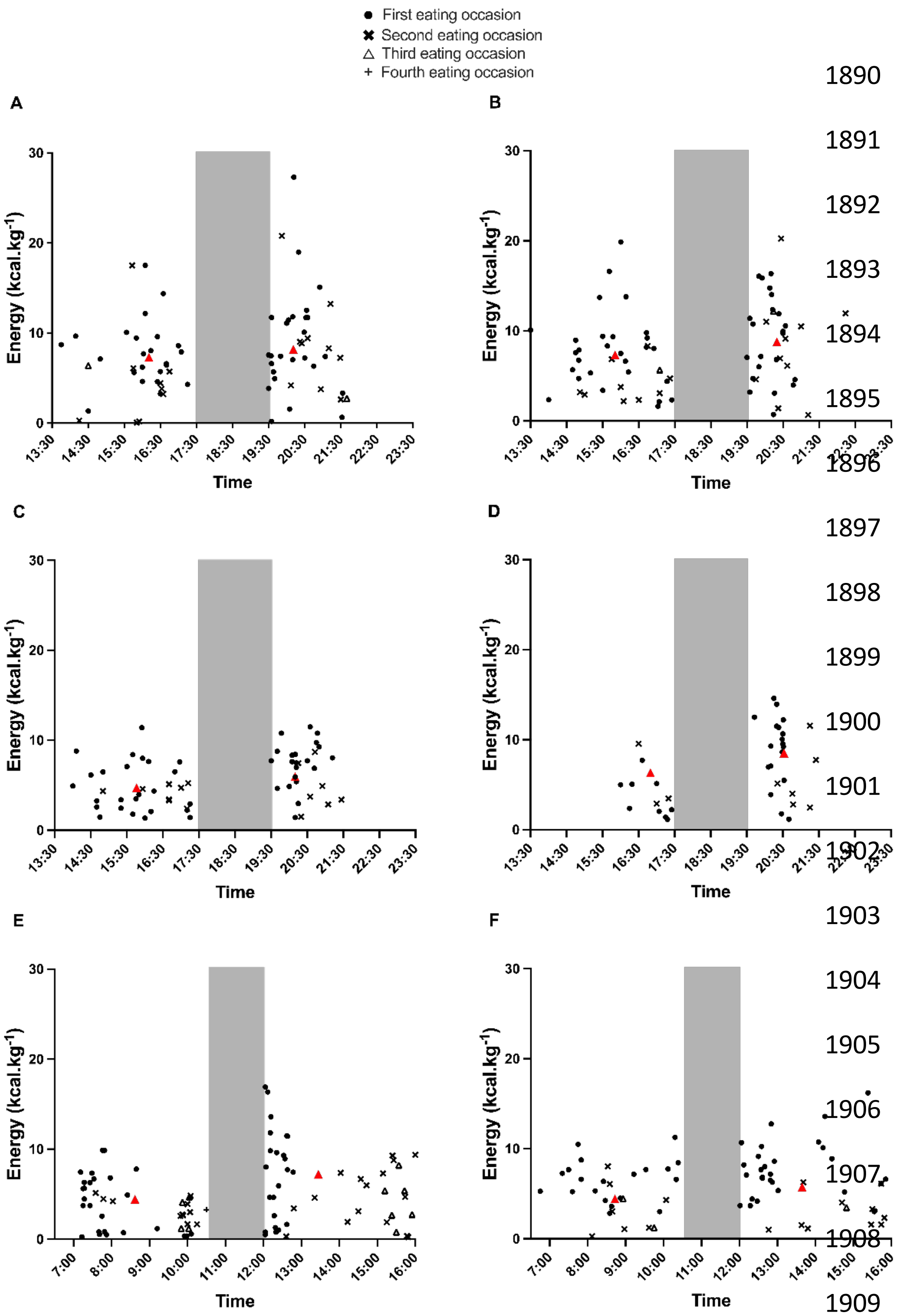

Figure 6. The distribution of relative energy intake pre- and post-training across three in season training days in (A) U12, (B) U13, (C) U14, (D) U15/16, (E) U18 and (F) U21 players. On pitch training is represented by the grey shading. Mean energy intake and mean eating time pre- and post- training is displayed in red.

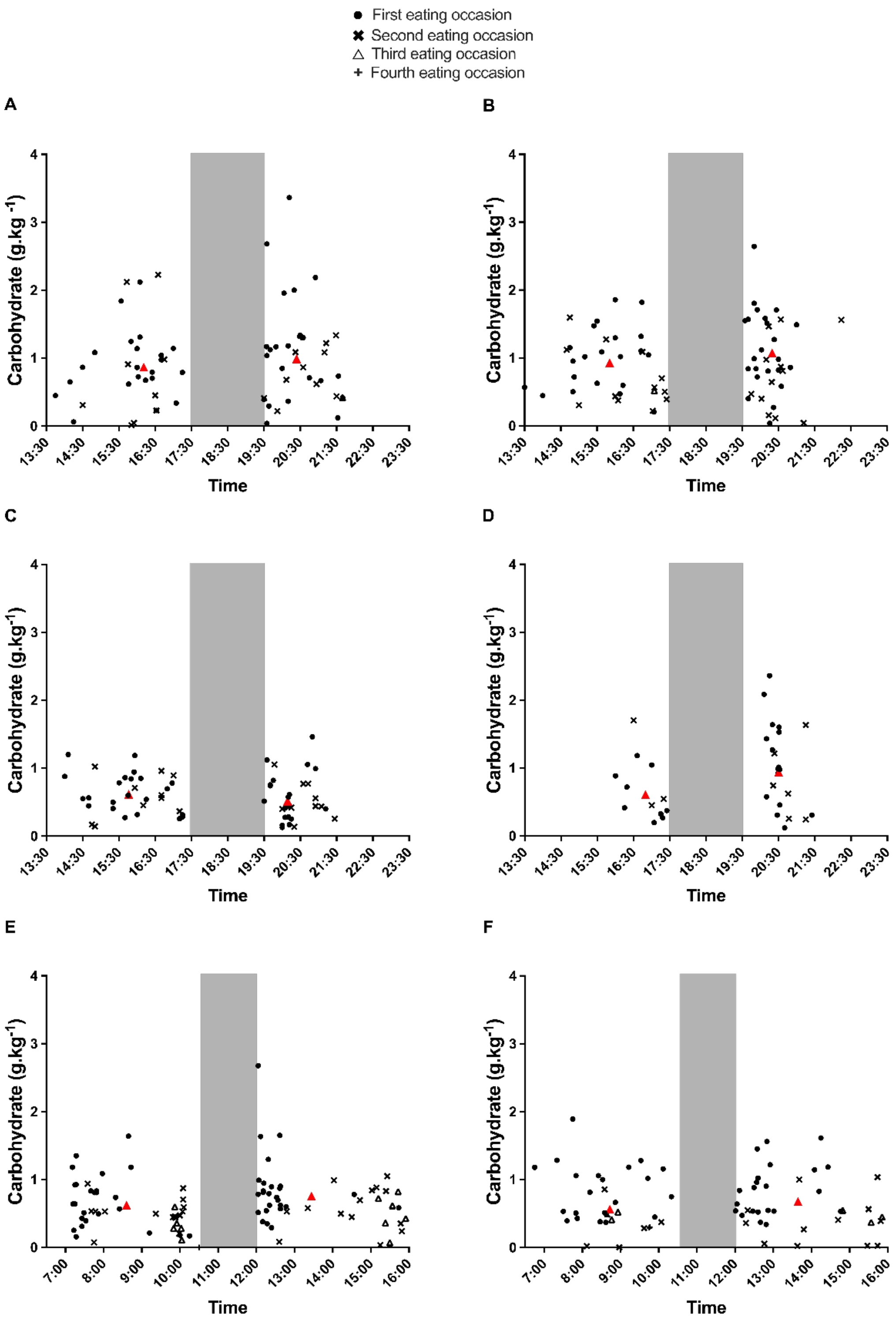

Figure 7. The distribution of relative carbohydrate intake pre- and post-training across three in season training days in (A) U12, (B) U13, (C) U14, (D) U15/16, (E) U18 and (F) U21 players. On pitch training is represented by the grey shading. Mean energy intake and mean eating time pre- and post- training is displayed in red.

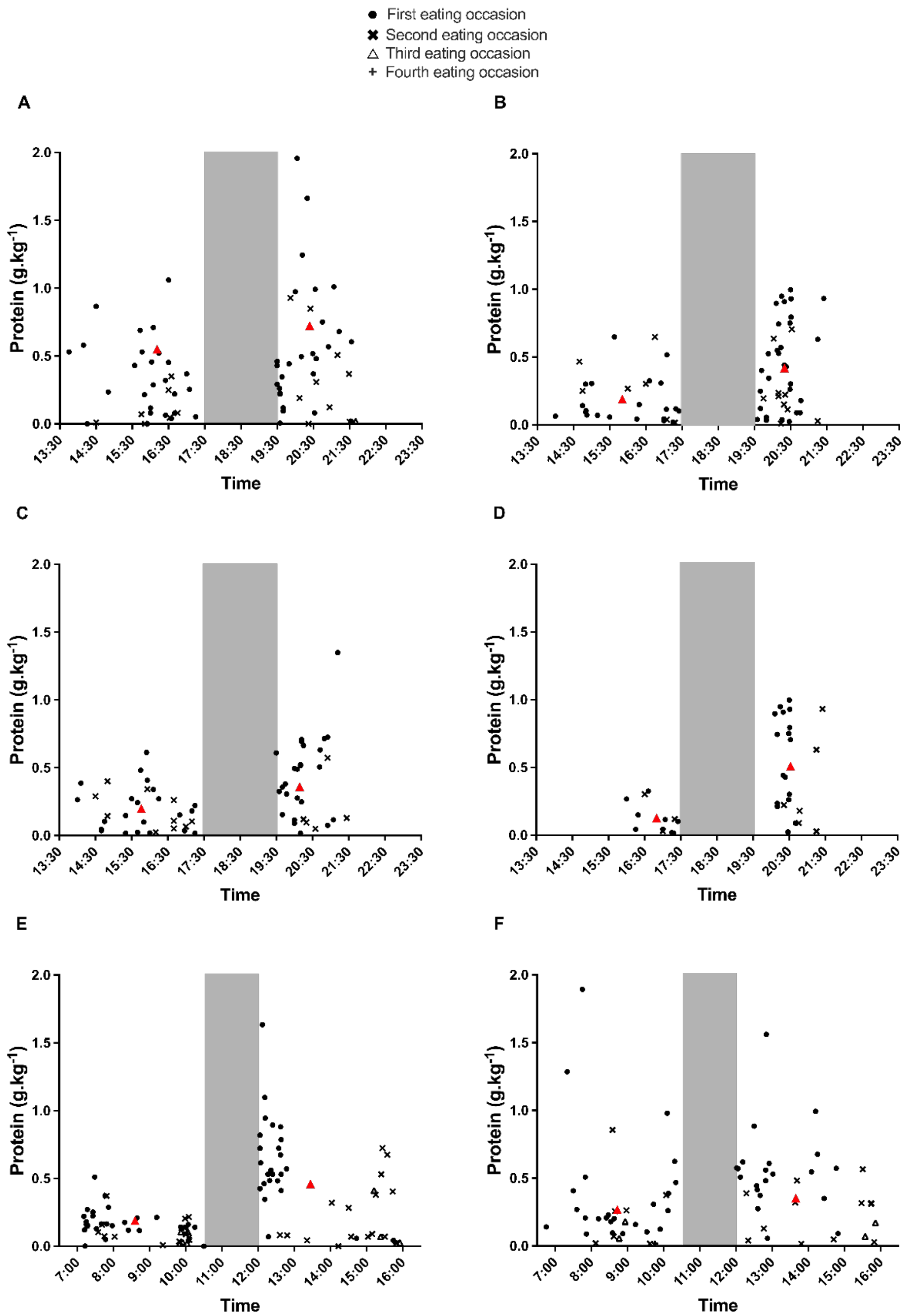

Figure 8. The distribution of relative protein intake pre- and post-training in (A) U12, (B) U13, (C) U14, (D) U15/16, (E) U18 and (F) U21 players. On pitch training is represented by the grey shading. Mean energy intake and mean eating time pre- and post- training is displayed in red.

Quantity of pre-training energy, CHO and protein intake

The quantity of energy, CHO and protein intake within each squad is displayed in Figure 10 A-C. Relative EI was greater in U12 (11 ± 6 kcal.kg^{-1}) and U13 (11 ± 7 kcal.kg^{-1}) players when compared to U15/16 (7 ± 8 kcal.kg^{-1}, 95% CI: 1 to 7, p = 0.02; 95%CI: 1 to 8, p = 0.02, respectively) and U21 players (7 ± 3 kcal.kg^{-1}, 95%CI: 0 to 7, p = 0.03, 95% CI: 0 to 7, p = 0.04 respectively) (see Figure 10A).

Relative CHO intake in the U12 (1.5 ± 0.9 g.kg^{-1}) and U13 (1.5 ± 1.0 g.kg^{-1}) players were greater than the U14 (0.9 ± 0.5 g.kg^{-1}, 95%CI: 0.2 to 1.0, p < 0.01; 95%CI: 0.1 to 1.0, p = 0.01, respectively), U15/16 (0.8 ± 0.8 g.kg^{-1}, 95%CI: 0.2 to 1.0, p = 0.02; 95%CI: 0.2 to 1.1, p < 0.01, respectively) and U21 (0.8 ± 0.4 g.kg^{-1}, 95%CI: 0.2 to 1.0, p = 0.01; 95%CI: 0.2 to 1.0, p < 0.01, respectively) players (see Figure 10B).

Relative protein intake was greater in U12 (0.5 ± 0.5 g.kg^{-1}) compared to the U15/16 (0.3 ± 0.3 g.kg^{-1}, 95%CI: 0 to 0.4, p = 0.05) and U18 players (0.3 ± 0.1 g.kg^{-1}, 95%CI: 0 to 0.4, p = 0.05) . Relative protein intake in the U13 (0.5 ± 0.5 g.kg^{-1}) players was also greater than U15/16 (95%CI: 0.1 to 0.5, p = 0.04) and U18 (95%: 0.1 to 0.5, p = 0.04) players (see Figure 10C).

4.4.3 External training load

Mean external training load metrics for the three-day data collection period are displayed in Figure 9. Total distance (TD) was greater in the U12 (6057 ± 1494m) than the U21 (4878 ± 1171 m, 95%CI: 58 to 2305, p = 0.03) players (see Figure 9A). Additionally, TD in the U15/16 (6162 ± 1165 m) players was greater than the U18 (5099 ± 1160 m, 95%CI: 57 to 2069, p = 0.03) and U21 players (95%CI: 320 to 2248, p < 0.01).

Average meters per minute per session was significantly greater in the U14 (68 ± 9 m.min^{-1}, 95%CI: 1 to 31, $p = 0.03$), U15/16 (81 ± 12 m.min^{-1}, 95%CI: 16 to 42, $p < 0.01$), U18 (79 ± 15 m.min^{-1}, 95%CI: 13 to 41, P < 0.01) and U21 (75 ± 17 m.min^{-1}, 95%CI: 9 to 37, $p < 0.01$) players compared to the U12 (53 ± 27 m.min^{-1}) players (see Figure 9B). Metres per minute was also greater in the U15/16 players compared to the U13 players (69 ± 8 m.min^{-1}, 95%CI: 2 to 28, $p = 0.01$).

High-speed running meter (HSR) was significantly greater in the U21 players (262 ± 164 m) compared to U14 (73 ±39 m, 95%CI: 84 to 295, $p < 0.01$), U13 (95 ± 76 m, 95%CI: 65 to 269, $p < 0.01$) and U12 players (60 ± 50 m, 95%CI: 87 to 299, $p < 0.01$) (see Figure 9C). HSR meters was greater in the U18 players (251 ± 162 m) compared to the U14 (95%CI: 70 to 287, $p < 0.01$), U13 (95%CI: 51 to 262, $p < 0.01$) and U12 (95%CI: 74 to 291, $p < 0.01$) players. HSR meters in the U15/16 players (195 ± 118 m) was greater than U14 (95%CI: 19 to 225, $p = 0.01$), U13 (95%CI: 1 to 199, $p < 0.05$) and U12 (95%CI: 24 to 229, $p = 0.01$) players.

The frequency of accelerations per session were greater in U21 (48 ± 19) and U18 players (48 ± 20) compared to U15/16 (28 ± 14, 95%CI: 9 to 32, $p < 0.01$; 95%CI: 9 to 33, $p < 0.01$, respectively), U14 (18 ± 9, 95%CI: 17 to 44, $p < 0.01$; 95%CI: 17 to 45, $p <0.01$, respectively) and U12 (20 ± 11, 95%CI: 15 to 41, $p < 0.01$; 95%CI: 15 to 42, $p < 0.01$, respectively) players (see Figure 9D). Frequency of accelerations in the U13 (40 ± 14) players was also greater than those in the U15/16 (95%CI: 0 to 25, $p = 0.048$), U14 (95%CI: 8 to 37, $p < 0.01$) and U12 players (95%CI: 6 to 34, $p = 0.01$). The frequency of decelerations per session in the U21 (40 ± 21, 95%CI: 1 to 33, $p = 0.03$), U18 (44 ± 24, 95%CI: 4 to 36, $p < 0.01$) and U15/16 (39 ± 18.1, 95%CI: 1 to 31, $p < 0.05$) players were greater than U12 players (28 ± 11) (see Figure 9E).

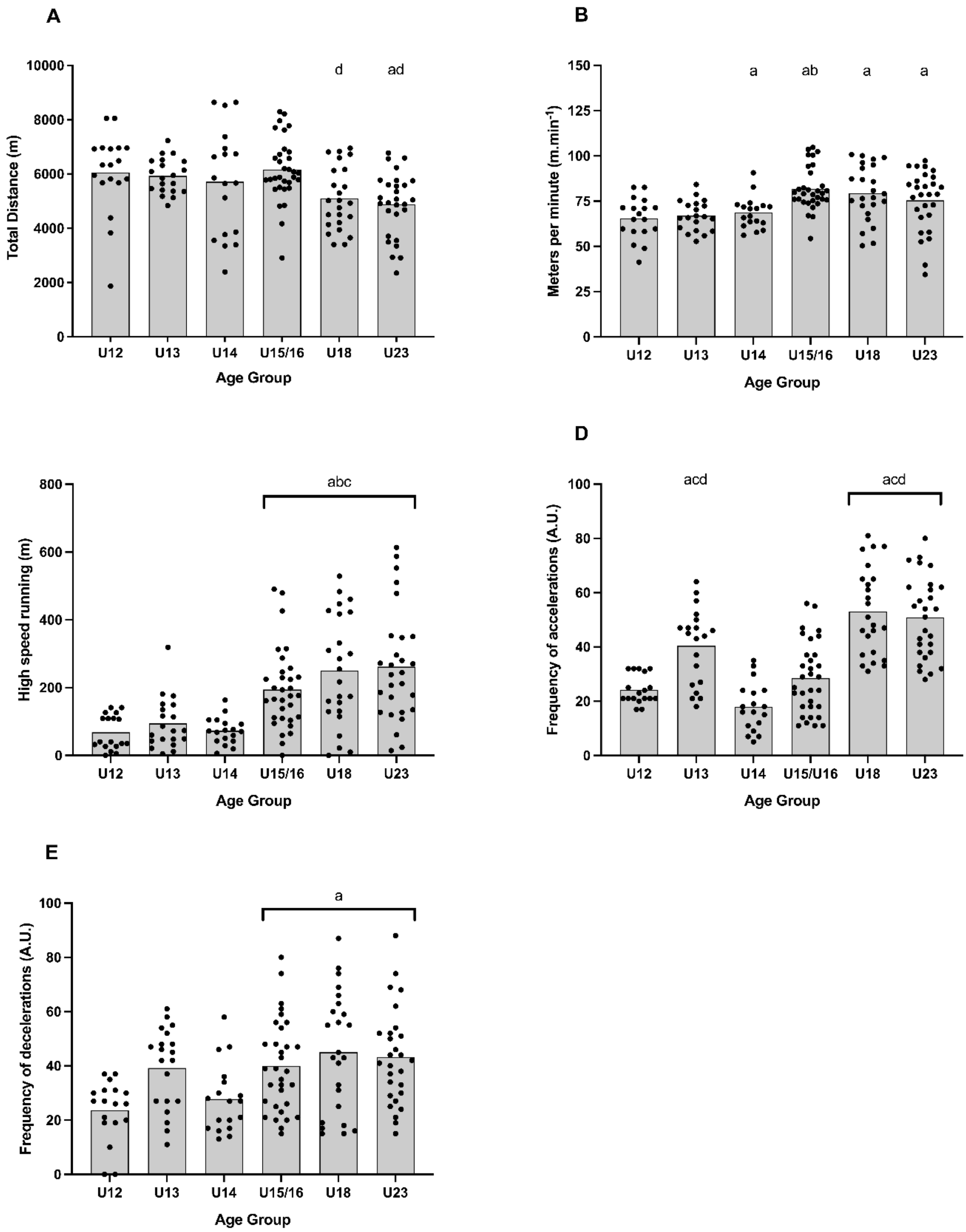

Figure 9. Overview of training duration and external load characteristics. (A) Total distance (B) average meters per minute (C) high speed running distance (D) accelerations and (E) decelerations across U12, U13, U14 (mean data compiled from n=3 training sessions) and U15/16, U18 and U21 (data compiled from n=4 training sessions) in-season training sessions. [a] denotes significant difference from U12, [b] denotes significant difference from U13, [c] denotes significant difference from U14, [d] denotes significant difference from U15/16, [e] denotes significant difference from U18, and [f] denotes significant difference from U21 (all $p < 0.05$).

4.4.4 Self-reported physical activity levels, energy and macronutrient intake in the four hours after training

Post-training physical activity levels

Physical activity levels in the four hours after training are displayed in Table 10. In contrast to reported physical activity levels in the pre-training period, much more variation between squads was evident in post-training activity levels. Specifically, significant main effects were observed between squads for time spent completing *moderate* ($p = 0.02$) and *heavy* ($p = 0.01$) activities. U21, U18 and U12 players completed more *moderate* activities than U15/16 (95%CI 14 to 57 min, $p < 0.01$; 95%CI 9 to 55 min, $p < 0.01$; 95%CI 10 to 57 min, $p < 0.01$) and U13 (95%CI 14 to 56 min, $p < 0.01$; 95%CI 9 to 53 min, $p < 0.01$; 95%CI 10 to 57 min, $p < 0.01$) players. U21 players also completed more *heavy* activities than U15/16 (95%CI 25 to 102 min, $p < 0.01$), U14 (95%CI 14 to 115 min, $p = 0.01$), U13 (95%CI 25 to 100 min, $p < 0.01$) and U12 players (95%CI 15 to 98 min, $p < 0.01$).

There was a significant difference in travel time post training ($p < 0.05$). U21 players spent less time travelling home (21 ± 10 mins) from training than U12 players (38 ± 20 mins, 95%CI, -32 to 2, $p = 0.03$). U18 players (17.1 ± 2.5 mins) spent less time travelling home from training than U14 (34 ± 23 mins, 95%CI, -32 to -1.4, $p = 0.03$), U13 (34 ± 19, 95% CI, -34 to -1, $p = 0.04$) and U12 players (95%CI, -36 to -5, $p = 0.01$).

Table 10. Time spent completing very light, light, moderate, heavy, and very heavy physical activities in the four hours after training. * denotes significant difference between squads (main effect, $p < 0.05$). All data was collated using physical activity diaries converted using METs. [a] denotes significant difference from U12, [b] denotes significant difference from U13, [c] denotes significant difference from U14, [d] denotes significant difference from U15/16, [e] denotes significant difference from U18, and [f] denotes significant difference from U21 (all $p < 0.05$). Data are presented as means ± SD.

	U12	**U13**	**U14**	**U15/16**	**U18**	**U21**
Very Light (e.g. sleep and travel from training)	170 ± 37	179 ± 48	139 ± 40	177 ± 41	130 ± 76	95 ± 80
Light (e.g. completing homework)	30 ± 29	58 ± 51	48 ± 22	58 ± 30	37 ± 36	23 ± 49
Moderate * (e.g. brisk walk)	35 ± 34[bd]	2 ± 8	24 ± 32	1 ± 4	33 ± 31[bd]	34 ± 40[bd]
Heavy * (e.g. jogging)	8 ± 20	2 ± 8	0	1 ± 4	24 ± 37	60 ± 98[abcd]
Very Heavy (e.g. boxing gym training)	9 ± 16	0	0	0	26 ± 76	20 ± 25

Timing of post-training energy, CHO and protein intake

The timing of energy, CHO and protein intake within each squad is displayed visually in Figures 1-3 (post-training data are displayed *right* of the grey shaded area which represents the timing and duration of training). In contrast to pre-training, there was no difference in the timing of EI between groups in relation to the proximity of finishing training (U12: 20:24, + 56 ± 39 mins; U13: 20:20, + 50 ± 34 mins; U14: 20:09, + 39 ± 27 mins; U15/16: 20:23, + 53 ± 25; U18: 13:26, + 54 ± 91 mins; U21: 13:40, + 70 ± 84 mins).

The frequency of eating occasions post-training was significantly different between squads ($p < 0.01$). Specifically, U21 and U15/16 players displayed 1.9 ± 0.6 and 1.8 ± 0.2 eating occasions, respectively, greater than 1.5 ± 0.3 in the U13 squad (95%CI 0.5 to 0.9, $p = 0.03$; 95%CI 0.0 to 0.8, $p < 0.05$ respectively). Players in the U18 squad had greater eating frequencies (2.2 ± 0.4) than all players in younger squads; U15/16 (95% CI 0.1 to 0.8, $p = 0.02$), U14 (1.5 ± 0.2, $p < 0.01$, 95%CI 0.4 to 1.2), U13 (1.5 ± 0.3 $p < 0.01$, 95%CI 0.5 to 1.2) and U12 (1.6 ± 0.3, $p = 0.01$, 95%CI 0.3 to 1.1).

Quantity of post-training energy, CHO and protein intake

The quantity of energy, CHO and protein intake within each squad is displayed in Figure 10D-F. Relative post-training EI was greater in U18 players (15 ± 5 $kcal.kg^{-1}$) compared to U14 (9 ± 4 $kcal.kg^{-1}$, 95%CI: 3 to 9, P < 0.01), U15/16 (11 ± 3 $kcal.kg^{-1}$, 95%CI: 1 to 7, $p < 0.01$) and U21 (11 ± 5 $kcal.kg^{-1}$, 95%CI: 1 to 7, $p = 0.01$) players (see Figure 10D). Relative EI was also greater in both the U12 (12 ± 6 $kcal.kg^{-1}$) and U13 players (13 ± 7 $kcal.kg^{-1}$) compared to the U14 (95%CI: 0 to 6, $p = 0.04$, 95%CI: 1 to 7, $p < 0.01$) and U15/16 squads respectively (95%CI: 0 to 6, $p = 0.04$, 95%CI 2 to 8, $p < 0.01$).

Post-training relative CHO intake was greater (all $p < 0.01$) in the U12 (1.6 ± 0.8 $g.kg^{-1}$), U13 (1.6 ± 0.8 $g.kg^{-1}$), U15/16 (1.3 ± 0.6 $g.kg^{-1}$) and U18 (1.6 ± 0.6 $g.kg^{-1}$) age groups compared to U14 (0.9 ± 0.5 $g.kg^{-1}$, 95%CI: 0.4 to 1.0; 95%CI: 0.4 to 1.0; 95%CI: 0.3 to 1.1, 95%CI 0.1 to 1.0; 95%CI 0.4 to 1.0) respectively. Post training CHO was also greater in U12 (95%CI 0.3 to 1.0, $p < 0.01$), U13 (95%CI 0.3 to 1.0, $p < 0.001$) and U18 (95%CI 0.3 to 1.1) squads compared to U21 players (all $p < 0.01$) (see Figure 10E).

Post-training protein intake was greater (all $p < 0.01$) in U18 players (1.0 ± 0.6 $g.kg^{-1}$) compared to all squads (U12, 0.8 ± 0.4 $g.kg^{-1}$, 95%CI: 0.1 to 0.5; U13, 0.5 ± 0.4 $g.kg^{-1}$, 95%CI: 0.3 to 0.7; U14, 0.6 ± 0.3 $g.kg^{-1}$, 95%CI: 0.3 to 0.7; U15/16, 0.8 ± 0.2 $g.kg^{-1}$, 95%CI: 0.1 to 0.5 and U21, 0.6 ± 0.3 $g.kg^{-1}$, 95%CI: 0.2 to 0.7). Relative protein intake in the U12 age group was greater compared to the U13 squad (95%CI 0.0 to 0.4, $p < 0.05$) (see Figure 10C).

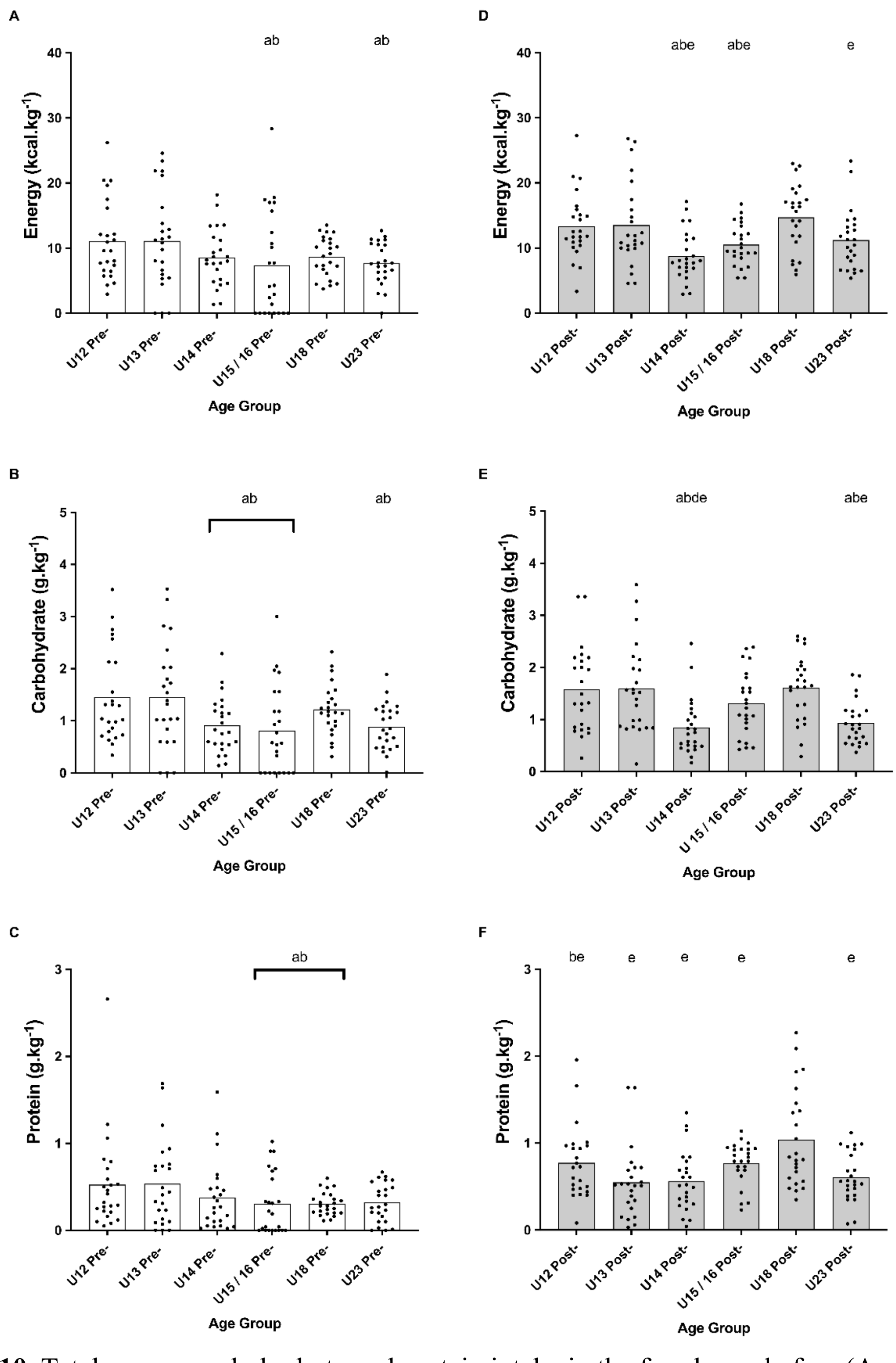

Figure 10. Total energy, carbohydrate and protein intake in the four hours before (A - C) and after (D - F) training. Mean values are represented by solid bars, black circles represent each player's mean intake. [a] denotes significant difference from U12, [b] denotes significant difference from U13, [c] denotes significant difference from U14, [d] denotes significant difference from U15/16, [e] denotes significant difference from U18, and [f] denotes significant difference from U21 (all $p < 0.05$).

4.5 Discussion

In considering the limited time available to nutritionally prepare and recover from academy soccer training sessions (e.g. constraints associated with schooling, travelling and sleep schedules etc), the aim of the present study was to quantify the acute fuelling and recovery practices of male academy soccer players. To this end, we assessed dietary intake and self-reported physical activity levels in the four hours before, during and after training over three days of an in-season training microcycle. Although players readily achieve sufficient protein intake, our data demonstrate that academy players (from across the academy pathway of U12-U21) under-consume CHO both before and after training. Given the well documented role of energy and CHO availability in promoting both physical performance (i.e. training intensity) and development (i.e. growth and maturation), the present data suggest that nutritional education programmes for academy players and key stakeholders (e.g. parents, coaches etc.) should target behaviour change strategies that specifically promote sufficient quantity and timing of CHO intake before, during and after training.

Although we acknowledge that our data are compiled from one EPL Category One academy only, it is noteworthy that the training and game schedule studied here is representative of the typical academy schedules within England (see Table 8) and is similar to that studied previously by our group when monitoring players from other Category One academies (Brownlee et al., 2018, Enright et al., 2015, Hannon et al., 2021a, Naughton et al., 2016). As such, players from the Youth Development Phase (i.e. U12-U16) trained in the evening periods between 17:30 and 19:30 whereas players from the Professional Development Phase (i.e. U18-U21) trained in the morning period between 10:30 and 12:00. In considering the timing of training within both phases in combination with their daily lives (i.e. afternoon schooling and morning routines, respectively), it is unsurprising that we observed little differences in the intensity of self-reported pre-training activity between age-groups (see Table 9). Indeed, the majority of time was spent engaging in activities classified as very light (e.g. sleeping, watching television, travelling), light (e.g. doing homework) or moderate (e.g. walking).

Although we observed marked individual variation in both the timing (see Figures 6-8) and quantity (see Figure 10) of pre-training energy and macronutrient intake, it is noteworthy that the habitual fuelling patterns reported here are likely sub-optimal in relation to preparing for the energetic demands of the upcoming training session. Indeed, this was especially evident for CHO where both the mean reported intakes of ~ 1 $g.kg^{-1}$ and sub-optimal intakes in individual players (see Figure 7 and 11B) is less than the recommended intake of 1-3 $g.kg^{-1}$ in the 3-4 hours before soccer-specific activity (Collins et al. 2021). It is therefore likely that players (as evident within in all age groups) commenced training with sub-optimal muscle and liver glycogen stores as previously reported within individual academy players (Hannon et al., 2021b), the result of which may impair physical performance and development.

Unfortunately, the present study did not ascertain the potential reasons underpinning the apparent prevalence of under-fuelling, though considering such reasons through the lens of behaviour change models such as the COM-B framework (capability, opportunity, motivation and behaviour) and behaviour change wheel may afford some insight (Michie et al. 2011). For example, Carter et al., (2022) reported some player and stakeholders (e.g. parents or host families) may lack the psychological capability (i.e. awareness of nutritional guidelines) and/or physical capability (ability to plan and prepare appropriate meals and snacks) appropriate for an academy soccer player presenting a barrier to players consuming optimal energy and macronutrient intake pre- and post-training. Such lack of capability may be exacerbated by the lack of both social opportunity (i.e. scheduling of training in close proximity to finishing school) and physical opportunity (i.e. the requirement to consume sufficient energy intake whilst travelling to training) to actually engage with the necessary nutritional practices. In contrast to our hypothesis, however, it is noteworthy that U18 and U21 players also reported sub-optimal pre-training CHO intakes, despite the fact that players from the Professional Development Phase spent less time travelling to training and typically receive more educational support (i.e. capability) and on-site food provision (i.e. opportunity) than younger players (Carney et al., 2022). In such instances as highlighted by Bentley et al., (2019) the role of a players' automatic motivation (i.e. emotions and impulses towards consuming carbohydrate before training) and their reflective motivation (i.e., evaluations of fuelling and plans for recovery post-training) may therefore need to be assessed in order to bring about the necessary change. Indeed, in a cohort of female soccer players (encompassing both youth and adult players), we recently observed that players describe a culture of "carbohydrate fear" where players consciously under-consume CHO in the belief that excessive CHO intake leads to gains in fat mass (McHaffie et al. 2022). To this in end, continuation of the qualitative exploration of potential factors underpinning the dietary practices of soccer players reported here appears warranted, with specific focus on the acute fuelling and recovery practices of academy players.

The external training metrics reported here (see Figure 9) are comparable to that previously reported by our group (Hannon et al., 2021a, Hannon et al., 2021b), as assessed from academy players that were also playing within another Category One academy from the EPL. Interestingly, we observed that players of the Youth Development Phase (i.e. U12-U16) tended to complete more total distance during training when compared with players from the Professional Development Phase (i.e. U18-U21) (see Figure 9A). In keeping with our previous approach (Hannon et al., 2021a), we deliberately chose to report absolute speed thresholds (i.e. high-speed running) that are typically used within the adult game. When considered this way, our data further demonstrate that academy soccer players from the Youth Development Phase are not capable of achieving the same absolute physical loading patterns as adult players (e.g. high-speed running, average speed, frequency of accelerations and decelerations etc.) until they are physically mature (Anderson et al., 2022). In contrast, the U18-21 players studied here produced external training load metrics (see Figure 9 B-F) that are comparable to elite adult players (Anderson et al. 2022).

When considering the external training demands (i.e. 1.5 and 2 hours for U18-U21 and U12-U16 players, respectively), it is noteworthy that players did not report consuming any form of CHO during training (though it is noted that the host club only provided access to CHO during training for the U18-U21 players). Given the ergogenic effects of CHO feeding during soccer-specific activity on both physical (Rodriguez-Guistiniani et al., 2019) and technical performance (Currell et al., 2009, Russell et al., 2012), our data suggest that academy players would likely benefit from the consumption of 30 - 60 g of CHO per hour, in accordance with recommended guidelines (Collins et al. 2021). Additionally, the provision of CHO during training may also exert positive influences on bone turnover (de Sousa et al., 2014; Sale et al., 2015), especially in those instances where individual players have "under-fuelled" in the four hours before training. As alluded to previously, both players and stakeholders (e.g. coaches) should therefore be educated on the requirement to consume CHO during training so as to inform behaviour change strategies (e.g. scheduled "fuel" breaks during training) that result in the desired behaviour (e.g. consumption of a specific quantity of CHO at specific time-points during training).

In the four hours after training, self-reported physical activity levels demonstrated distinct differences between groups. For example, U18-21 players reported less time engaged in very light activities and more time engaged in heavy activities when compared with the U12-U16 players. Such data are likely a reflection of the timing of training sessions in that the younger players are returning home after training to commence their sleeping schedules whereas the older players finish training at 12 noon and hence, have more opportunity to engage in further physical activity throughout the remainder of the day. We also observed that PDP players spent less time travelling to and from training, likely as a result of club funded 'host family' accommodation being physically closer to the training ground when compared with homes of the players from the YDP. This point highlights how the type of training programme which players are engaged in (i.e. full-time or part-time) can influence a player's life (i.e. moving into host family accommodation or time spent travelling) thereby potentially impacting their ability to appropriately fuel for and recover from training sessions.

In relation to post-training energy and macronutrient intake, we observed that players within all squads reported recovery practices that could also be considered sub-optimal. For example, although data demonstrate that the majority of players achieved sufficient post-training protein intake of 0.3 $g.kg^{-1}$ body mass (Collins et al. 2021) (see Figure 10 F), we observed CHO intakes that are likely sub-optimal in relation to promoting muscle and liver glycogen re-synthesis (see Figure 10 E). Indeed, it is well documented that rates of muscle glycogen re-synthesis are greatest when CHO is consumed immediately post-exercise (Ivy et al., 1988) and accordingly, post-exercise intakes of ~1 $g.kg^{-1}$ per hour (for several hours) are now recommended to promote muscle glycogen storage (Burke et al., 2011). However, the present data demonstrate that mean post-training timing and quantity of CHO intake across groups ranged between 39 - 70 minutes and 0.8 - 1.6 $g.kg^{-1}$ (see Figure 7 and 9 B, respectively), the majority of which was achieved within one to two eating occasions (see Figure 10). Interestingly, evaluation of mean and individual data from the U21 players highlighted what could be considered as the "poorest" post-training CHO practices (i.e. delayed feeding until 70 minutes after training and mean intakes of only 0.9 $g.kg^{-1}$), this despite the increased physical opportunity (i.e. on-site food provision and time available) to recover in the afternoon period after training. It is acknowledged, however, that U21 players were also restricted to access to the club's canteen facilities until 30 minutes after training, as due to a staggering of access to accommodate players from other squads, a common logistical challenge within professional soccer clubs. In contrast, players from the U12 and U13 players reported the highest relative post-training CHO intakes despite spending significantly more time travelling home from training in the late evening period (up to sixty minutes). When taken together, such data further demonstrate the requirement for targeted player and stakeholder education programmes that result in behaviour change interventions to increase CHO intake in the post-training period.

As with all dietary assessment studies, a limitation of the present data set is the potential for under-reporting from participants, in addition to the measurement error associated with researcher assessment when using the RFPM. Indeed, we recently observed that both experienced and inexperienced nutrition practitioners underestimated total "daily" CHO intake by 54 and 66 g, respectively, as obtained from 2-days of dietary assessment comprising 4 meals per day (Stables et al. 2021). Nonetheless, when considering that we observed no significant differences between two researcher assessments and the potentially smaller margin for error (i.e. 2 x 4-hour assessments as opposed to 2 x 24 h assessments), we consider that the present data are still indicative of sub-optimal fuelling and recovery practices. Furthermore, our assessments were also strengthened by the use of known "in-house" dietary databases, prior training on data collection and the onsite presence of the researcher to assist participants where required.

In summary, we report for the first time the acute fuelling and recovery practices of male academy soccer players from across the academy pathway (i.e. U12 - U21 players). We observed an apparent under-consumption of CHO before, during and after training, the result of which could impair physical performance and development if performed long-term. Future studies should now explore the reasons underpinning the nutritional choices reported here, so as to provide the basis for player and stakeholder education programmes and behaviour change interventions that promotes increased CHO intake. As well as investigate the acute implications of sub-optimal carbohydrate intake upon bone, specifically markers of bone (re)modelling at this vital time of skeletal development given associations between low carbohydrate intake and bone resorption in adult populations.

Chapter 5

Daily energy requirements of male academy soccer players are greater than age-matched non-academy soccer players: A doubly labelled water investigation.

The aim of this chapter was to quantify the mean daily energy expenditure (using doubly labelled water), physical activity, training and match loading and energy and macronutrient intake of academy soccer players compared to their non-elite grassroots counterparts.

Marcus Hannon, Adam Jacob and Oliver Topping, assisted with the data collection for this study. Adam Jacob, Oliver Topping, Lynne Boddy, Catherine Hambly and John Speakman assisted with the data analysis for this study.

Stables, R. G., Hannon, M. P., Jacob, A. D., Topping, O., Costello, N. B., Boddy, L. M., Hambly, C., Speakman, J.R., Sodhi, J.S., Close, G.C. and Morton, J. P. (2023). Daily energy requirements of male academy soccer players are greater than age-matched non-academy soccer players: A doubly labelled water investigation. Journal of Sports Sciences, 41(12), 1218–1230

5.1 Abstract

This study aimed to test the hypothesis that total daily energy expenditure (TDEE) of male academy soccer players is greater than players not enrolled on a formalised academy programme. English Premier League academy (ACAD: n = 8, 13 years, 50 ± 6 kg, 88 ± 3% predicted adult stature, PAS) and non-academy players (NON-ACAD: n = 6, 13 years, 53 ± 12 kg, 89 ± 3% PAS) were assessed for TDEE (via doubly labelled water) during a 14-day in-season period. External loading was evaluated during training (ACAD sessions: n = 8, NON-ACAD sessions: n = 2) and matches (ACAD matches: n = 2, NON-ACAD matches: n = 2) via GPS and daily physical activity was evaluated using triaxial accelerometery. Accumulative duration of soccer activity (ACAD: 975 ± 23 min, NON-ACAD: 397 ± 2 min; $p < 0.01$), distance covered (ACAD: 54.2 ± 8.3 km, NON-ACAD: 21.6 ± 4.7 km; $p < 0.05$) and time engaged in daily moderate-to-vigorous (ACAD: 124 ± 17 min, NON-ACAD: 79 ± 18 min; $p < 0.01$) activity were greater in academy players. Academy players displayed greater absolute (ACAD: 3380 ± 517 kcal.d^{-1}, NON-ACAD: 2641 ± 308 kcal.d^{-1}; $p < 0.05$) and relative TDEE (ACAD: 66 ± 6 kcal.kg.d^{-1}, NON-ACAD: 52±10 kcal.kg.d^{-1}; $p < 0.05$) versus non-academy players. Given the injury risk associated with high training volumes during growth and maturation, data demonstrate the requirement for academy players to consume sufficient energy (and carbohydrate) intake to support the enhanced energy cost of academy programmes.

5.2 Introduction

The apparent success of soccer academies to produce players to represent the first team at the host club or to be sold for financial gain (Elferink-Gemser et al., 2012) is evidenced by the recent report that over 75% of professional contracts in the English Premier League (EPL) and English Football League (EFL) are held by home grown players (Premier League, 2022). As per the EPPP framework, clubs are audited and categorised from Category One (the best) to Four, largely dependent on the extent of support they provide to their players, taking into consideration factors such as productivity rates, training facilities, coaching, education, welfare provision and sport science and medicine support. However, despite the mandate from the EPPP for interdisciplinary specialists in the sports science and medicine team, a recent audit from our group (from all 89 soccer academies across England) reported that the provision of "nutrition related support" is not comparable to the other disciplines of sport and exercise science, perhaps most evidenced by the lack of full-time and professionally accredited staff delivering nutrition related services (Carney et al., 2022).

Nonetheless, emerging data clearly demonstrate the importance of consuming sufficient daily energy intake to support the energetic requirements of growth and maturation alongside the energy cost of increasing training demands. Indeed, the sustained periods of growth and maturation that players experience as they transition through the academy pathway (i.e. from under (U) 12 to U18 age groups) significantly increases both their resting metabolism and total daily energy requirements. In a cohort of male academy players from the EPL, we observed that the increases in body mass (~ 30 kg), fat-free mass (~ 23 kg) and stature (~ 25 cm) between the ages of 12 and 18, coincides with an increased resting metabolic rate of approximately 400 $kcal.d^{-1}$ (Hannon et al., 2020). In accordance with increases in absolute daily training and match load (i.e. increases in duration and total distance) throughout the development pathway

(Hannon et al., 2021a), we also observed significant increases in total daily energy expenditure (~750 kcal.d^{-1}) between U12 and U18 players from a Category One (Hannon et al., 2021b). In some individuals, total daily energy expenditure (as evident in U12, U15 and U18 players) was comparable to or exceeded (i.e. >3500 kcal.d^{-1}) that previously reported from adult players from the EPL (Anderson et al., 2017).

Despite such high training and energetic demands, data from Chapter Four highlights that academy players often "under-fuel" before, during and after training (Stables et al., 2022), likely due to the busy schedules associated with schooling and travelling to and from training, the lack of dedicated resource provision and a lack of education for key stakeholders such as coaches and parents (Carney et al., 2022). Although the negative outcomes associated with sub-optimal fuelling and recovery practices are often considered from a performance perspective, a more concerning outcome is the potential impact upon growth and maturation with a specific risk to skeletal structures. In this regard, data highlights that the most prevalent injury occurring in academy players from England, Europe and South America was growth related injuries in the anatomical location of the knee, lower back, sacrum and pelvis, the prevalence of which was most evident during periods of peak height velocity (Hall et al., 2020).

Although the importance of nutrition in supporting player development is becoming increasingly recognised, we acknowledge that the direct assessment of total daily energy expenditure in academy players is limited to the study of players from a single soccer academy (Hannon et al., 2021b). In this way, our current understanding of the energetic requirements of academy soccer players may not be applicable to players from other academies where the club may have differing training demands and schedules. Furthermore, no researchers have yet quantified the daily energy expenditures of non-academy soccer players and as such, the "energy cost" associated with enrolment in an academy programme is not yet known.

With this in mind, the aim of the present study was to quantify the total daily energy expenditure, external training demands and physical activity levels of academy soccer players when compared with age matched non-academy players. To this end, players from a Category One academy from the English Premier League (n = 8) and players competing at "grassroots" level (n = 8) were assessed for energy expenditure (using the doubly labelled water method), external training load (via GPS technology) and daily physical activity levels (via triaxial accelerometery) during a 14-day in-season data collection period. We deliberately recruited players from the U13 age-groups given that this period is often associated with the highest rate of growth during adolescence (i.e. peak height velocity; (Hannon et al., 2020). We hypothesised that academy players would present with significantly greater total daily energy expenditure than non-academy players, in accordance with the greater training demands associated with formalised coaching programmes.

5.3 Methods

5.3.1 Participants

Sixteen male soccer players (outfield, n = 15, goalkeeper n = 1) volunteered to participate in this study. To satisfy the eligibility criteria of this study, players were enrolled in a Category One academy from the English Premier League (ACAD: n = 8) and aged matched non-academy players participating in "grassroots" standard soccer (NON-ACAD: n = 8). Two players from the non-academy group were later removed from the study due to failure to comply with sample collection. Given the original sample of n=14 this dataset provides a statistical power of 0.72 (G* Power, version 3.1). Participant characteristics are presented in Table 11 and section 3.2.

Table 11. Baseline player characteristics. * denotes significant different between squads (main effect, $p < 0.05$). Data are presented as means ± SD with range displayed in parentheses. (PAS) Predicted Adult Stature.

	Academy	Non-academy
n	8	6
Age (years)	13.4 ± 0.2 (13.1 – 13.6)	13.1 ± 0.5 (12.8 – 13.5)
Maturity offset (years)	- 0.56 ± 0.65 (- 1.4 – 0.3)	- 0.78 ± 0.77 (- 2.2 – 0.0)
Current percent of PAS (%)	88.8 ± 2.7 (85.6 – 92.6)	89.2 ± 2.3 (85.2 – 91.0)
Stature (cm)	165.7 ± 7.2 (155.8 – 178.0)	162.9 ± 6.4 (152.0 – 168.7)
Body mass (kg)	51.2 ± 8.4 (41.2 – 65.9)	52.7 ± 12.4 (36.2 – 73.4)
Fat-free mass (kg)	45.9 ± 8.2 (35.2 – 60.2)	39.6 ± 6.0 (30.7 – 48.8)
Resting metabolic rate ($kcal.day^{-1}$)	1824 ± 90* (1706 - 1983)	1699 ± 45 (1656 - 1779)

5.3.2 Study design

In a cross-sectional design, players were assessed for total daily energy expenditure (TDEE), daily physical activity, and pitch-based loading (comprising both training and game related activity) over a 14-day in-season period displayed in Figure 12. Over the first seven days of the study period players were assessed for self-reported energy and macronutrient intake as detailed in section 3.5. During this time, players continued with their usual schooling, training and match schedules. An overview of the weekly training and match schedules of both groups is shown in Table 11.

5.3.3 Baseline measures

On the evening before day one and after providing a baseline urine sample, players were assessed at baseline for stature, body mass and maturity status as described in section 3.3. Absolute fat mass, percent fat mass and fat-free mass were calculated via hydrometry (Edelman et al., 1952). As the value of deuterium is known, it is possible to calculate total body water to an error lower than 2% (Schoeller et al., 1980). Absolute fat-free mass was then used to calculate resting metabolic rate using the population specific prediction equation developed by Hannon et al., (2021b). The thermic effect of food (TEF) was assumed to be 10% of EI for each individual (Westerterp, 2004) subsequently enabling estimations of activity energy expenditure (AEE; TEE − [RMR + TEF]) and energy availability (EA = EI − AEE/FFM). Somatic maturity, calculation of predicted adult stature (PAS) and current percentage of adult stature achieved (%PAS) we collected in accordance with procedures outlined in section 3.4.

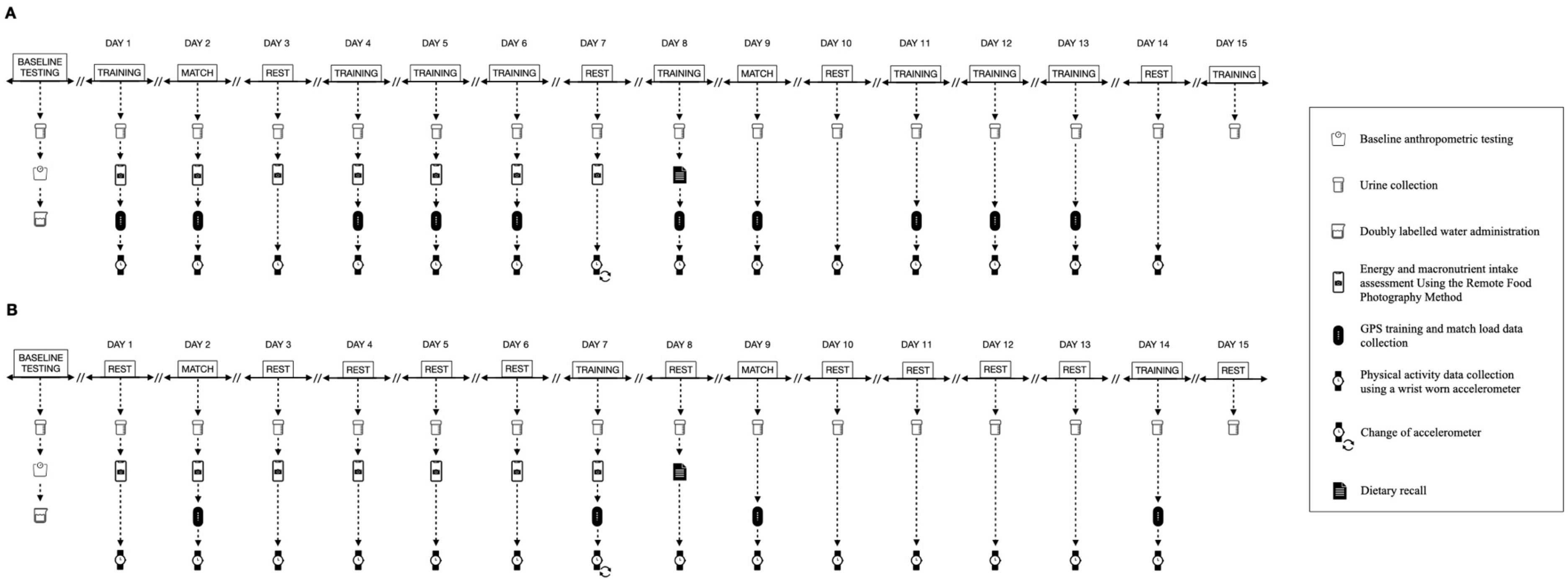

Figure 11 – Schematic overview of the study period for the (a) academy and (b) non-academy group.

5.3.4 Quantification of training load

Pitch based training load was measured using global positioning system (GPS) technology (Vector, Catapult, Melbourne, Australia) in accordance with the procedures outlined in section 3.5.

5.3.5 Measurement of total daily energy expenditure (TDEE) and body composition using the doubly labelled water (DLW) method

Measurement of total energy expenditure over the 14-day study period was quantified using the DLW method as previously used in EPL academy soccer players (Hannon et al., 2021b) as detailed in section 2.3.4.

5.3.6 Quantification of energy and macronutrient intake

Self-reported daily energy and macronutrient intake was quantified using the RFPM as outlined in section 3.6.2. Prior to data collection, all participants and parents/guardians were invited to an educational workshop where the study methodology was explained in detail detailed in section 3.6.1.

Data was collected in week one only as this was determined to provide an accurate sample of training and match days, whilst not being too great a data collection period which may lead to poor data quality and player adherence. At the end of the training week, each player completed a dietary recall to highlight any missed data and cross reference data collected by the principal investigator (Capling et al., 2017). During this process the principal investigator clarified all timings, quantities, branding and weights provided by the participant and prompted the participant to recall any missed items. Energy and macronutrient intake was analysed by a SENr accredited nutritionist, then cross-referenced by two other SENr accredited nutritionists, each analysing 98 days' worth of photo food records to determine the validity of results using dietary analysis software Nutritics (Nutritics, v5, Dublin, Ireland). Energy intake was reported as kilocalories in both absolute and relative terms and macronutrient intake was reported in grams for both absolute and relative terms. Inter-rater reliability of analyses was blinded and determined via a one-way analysis of variance (ANOVA). When comparing energy and macronutrient analysis, there was no significant difference between coders in the academy (energy, $p = 0.99$, CHO, $p = 0.73$, protein, $p = 0.73$, and fat, p = 0.91) or non-academy players (energy $p = 0.89$, CHO $p = 0.81$, protein, $p = 0.88$, and fat, $p = 0.97$).

5.3.7 Quantification of physical activity

Free-living physical activity was assessed using the Actigraph GT9X triaxial accelerometer (Actigraph, Pensacola, Florida), which has been validated against traditional hip-worn accelerometers (Rowlands et al., 2014). The accelerometer was worn on the non-dominant wrist at all times for 7 consecutive days (including during sleep, training and matches, and water-based activities) and initialised to sample physical activity at 30Hz using ActiLife software (ActiLife v6, Actigraph, Pensacola, Florida). To mitigate any changes in behaviour, all data on the watch display was removed apart from the 24-hour time. As the accelerometer battery would not last for the 14-day period, at the end of the first seven days, participants were provided with a second accelerometer for the second half of the study period. All physical activity data was exported using ActiLife software (ActiLife v6, Actigraph, Pensacola, Florida) and stored as raw GT3X files. These were then converted to csv files for analyses using the R software package GGIR (van Hees et al., 2014). GGIR completed autocalibration and wear time identification (>16 hours per day was classed as a valid day), with 10 valid days over the 14-day period necessary to denote valid inclusion (van Hees et al., 2014). The default non-wear setting was used, whereby if invalid data was present, data was replaced by the average at similar time points on different days of the week (Rowlands et al., 2018). Therefore, the outcome variables were based on the complete 24-h cycle (1440 min) for all participants with valid data. GGIR automatically converted triaxial accelerometer signals into one omnidirectional measure of acceleration (ENMO) (van Hees et al., 2013). Average day ENMO values were averaged per five second epoch over each day and expressed in milligravitational units (mg). The distribution of time spent in intensity zones of increasing intensity (0 - 150 mg, 150 - 300 mg, 300 - 450 mg, 450 - 600 mg and > 600 mg) (Rowlands et al., 2018) and time spent completing moderate to vigorous physical activity (> 200mg, MVPA) was calculated. The negative curvilinear relationship between the intensity of physical activity and the time spent at any given activity was calculated to provide a physical activity intensity gradient (IG) for each individual (Rowlands et al., 2018).

5.3.8 Statistical analysis

All data were initially assessed for normality of distribution using the Shapiro-Wilk test. Comparisons between groups in baseline data, energy expenditure, energy intake, training load metrics and physical activity related data were assessed using students t-tests for independent samples, where ninety-five percent confidence intervals (95% CI) for the differences are also presented. Within group comparisons between days for self-reported energy intake were assessed using a one-way General Linear Model. Between group comparisons for self-reported energy and macronutrient intake were also assessed using a between groups one-way general linear model. Additionally, differences in time spent in physical activity threshold zones within each squad were also assessed using a one-way General Linear Model. Relationships between TEE and body mass, stature, RMR, FFM, AEE training and match duration, average speed and total distance were assessed using a Pearson correlation. All data in text, tables and figures are expressed as means and SD with $p < 0.05$ indicating statistical significance. Statistical tests were performed using SPSS for Windows (version 27, SPSS Inc, Chicago, IL).

5.4 Results

5.4.1 Accumulative soccer training and match load

The accumulative training and match load completed by both groups of players is presented in Figure 12. The total duration of activity completed in week one (ACAD: 591 ± 157 min, NON-ACAD: 190 ± 3 min; 95% CI, 260 to 542, $p < 0.05$), week two (ACAD: 506 ± 190 min, NON-ACAD: 205 ± 2 min; 95% CI, 130 to 471, $p < 0.05$) and over the total 14-day assessment period (ACAD: 975 ± 23 min, NON-ACAD: 397 ± 2 min; 95% CI, 557 to 599, $p < 0.01$) was greater in academy players compared with non-academy players (see Figure 12 A). In accordance with a greater exercise duration, the total distance covered in week one (ACAD: 31.2 ± 5.6 km, NON-ACAD: 11.6 ± 2.6 km; 95% CI, 14.3 to 25.1, $p < 0.05$), week two (ACAD: 22.9 ± 3.3 km, NON-ACAD: 10.4 ± 2.4 km; 95% CI, 8.9 to 15.9, $p < 0.01$) and over the 14-day period (ACAD: 54.1 ± 8.5 km, NON-ACAD: 21.6 ± 4.7 km; 95% CI, 24.3 to 40.8, $p < 0.05$) was also greater in academy players compared with non-academy players (see Figure 12 B).

In relation to proxy measures of exercise intensity, average speed was also greater in academy players versus non-academy players (see Figure 12 C), as evident in week one (ACAD: 74 ± 9 $m.min^{-1}$, NON-ACAD: 60 ± 15 $m.min^{-1}$; 95% CI, 0 to 27, $p < 0.05$), week two (ACAD: 71 ± 8 $m.min^{-1}$, NON-ACAD: 55 ± 14 $m.min^{-1}$; 95% CI, 4 to 29, $p < 0.05$) and the 14-day period (ACAD: 72 ± 7 $m.min^{-1}$, NON-ACAD: 57 ± 14 $m.min^{-1}$; 95% CI, 3 to 27, $p < 0.05$).

The accumulative distance completed as high-speed running (i.e. >19.8 $km.h^{-1}$) was also greater in academy versus non-academy players (see Figure 12 D), as was the case for week one (ACAD: 689 ± 307 m, NON-ACAD: 77 ± 76 m; 95% CI, 330 to 893, $p < 0.01$), week two (ACAD: 572 ± 213 m, NON-ACAD: 56 ± 80 m; 95% CI, 315 to 717, $p < 0.01$) and the total 14-day period (ACAD: 1261 ± 454 m, NON-ACAD: 152 ± 149 m; 95% CI, 658 to 1531, $p < 0.01$). As a further marker of exercise intensity, the total number of accelerations (see Figure 12 E) completed in week one (ACAD: 167 ± 46, NON-ACAD: 16 ± 13; 95% CI, 109 to 193, $p < 0.01$), week two (ACAD: 131 ± 24, NON-ACAD: 15 ± 12; 95% CI, 93 to 139, $p < 0.01$) and the 14-day period (ACAD: 299 ± 22, NON-ACAD: 30 ± 10; 95% CI, 211 to 326, $p < 0.01$) and decelerations in week one (ACAD: 166 ± 46, NON-ACAD: 25 ± 16; 95% CI, 97 to 183, $p < 0.01$), week two (ACAD: 121 ± 31, NON-ACAD: 19 ± 16; 95% CI, 72 to 132, $p < 0.01$) and over the 14-day period (ACAD: 286 ± 24, NON-ACAD: 46 ± 12; 95% CI, 175 to 306, $p < 0.01$) were also markedly greater in academy players compared with non-academy players.

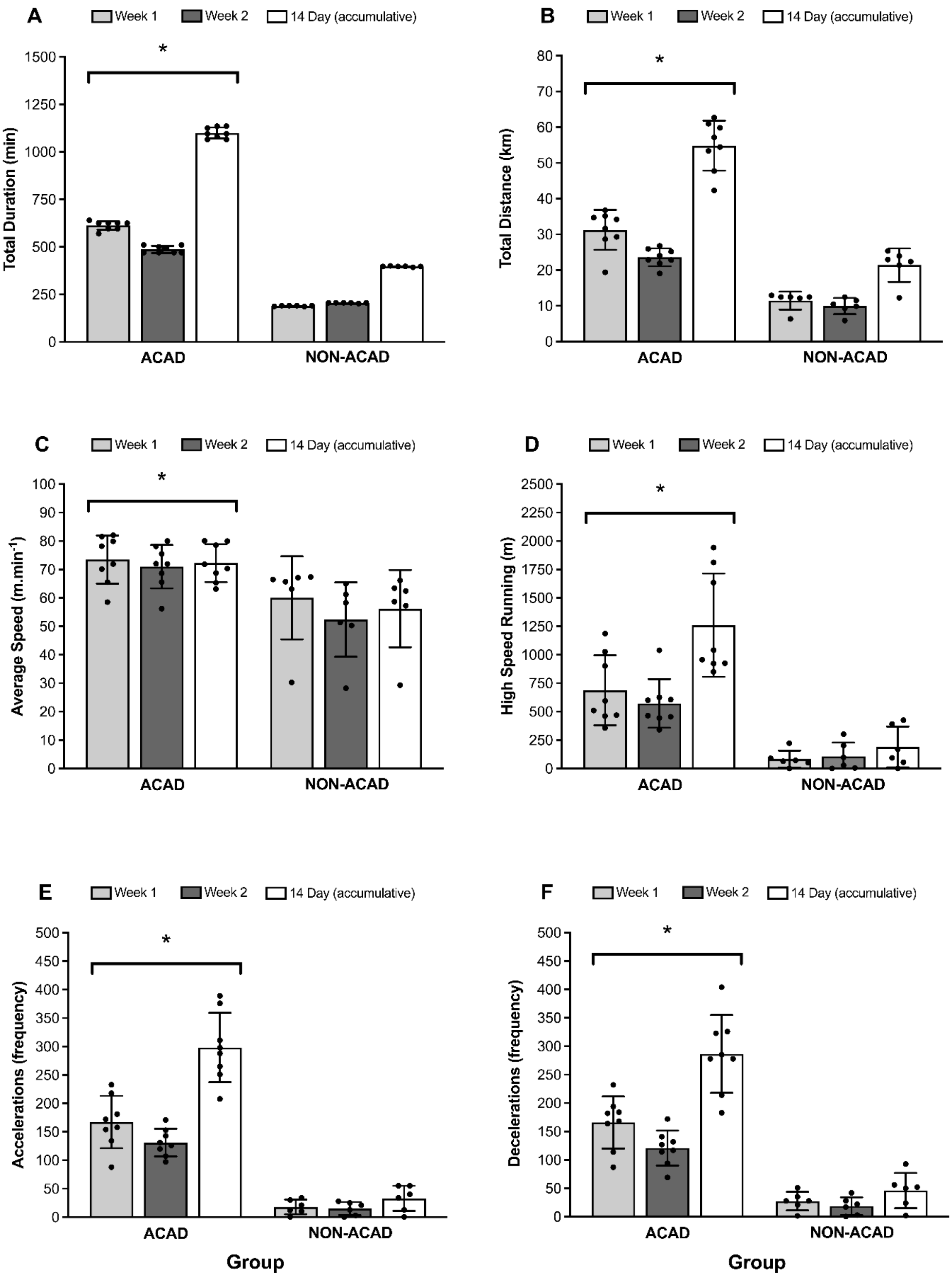

Figure 12. Overview of accumulative training and game duration and external load characteristics. (A) Total duration (B) Total Distance (C) Average Speed (D) Total High-Speed Running (E) Total Accelerations and (F) Total Decelerations across academy training sessions (n=8) and matches (n=2) and non-academy group training sessions (n=2) and matches (n=2). Black dots represent individual data points. *denotes significant difference from the non-academy group for week 1, week 2 and 14-day period, $p < 0.05$.

5.4.2 Daily training and match load

An overview of mean daily loading patterns is presented in Table 11. When comparing mean external loading of matches between playing groups, match duration (ACAD: 62 ± 9 min, NON-ACAD: 92 ± 1 min; 95% CI, 22 to 30, $p < 0.01$) was greater in the non-academy group. Total distance (ACAD: 7.3 ± 0.9 km, NON-ACAD: 4.4 ± 2.0 km; 95% CI, 1.2 to 4.7, $p < 0.05$), average speed (ACAD: 87.1 ± 7.6 $m.min^{-1}$, NON-ACAD: 51.6 ± 23.7 km; 95% CI, 16.3 to 54.6, $p < 0.01$), high-speed running (ACAD: 324 ± 104 m, NON-ACAD: 38 ± 39 m; 95% CI, 188 to 384, $p < 0.01$), accelerations (ACAD: 32 ± 10, NON-ACAD: 9 ± 6; 95% CI, 13 to 32, $p < 0.01$) and decelerations (ACAD: 40 ± 11, NON-ACAD: 12 ± 10; 95% CI, 16 to 40, $p < 0.01$) was greater in academy players versus non-academy players.

No comparisons were made between groups in relation to external loading of training sessions given that training did not occur at comparable time-points in relation to matches and subsequent differences in periodisation. In relation to variations in daily external loading patterns throughout the week in the academy players, significant differences were observed in duration ($p < 0.01$), total distance ($p < 0.01$), average speed ($p < 0.01$), high-speed running meters ($p < 0.01$), accelerations ($p < 0.01$) and decelerations ($p < 0.01$). Pairwise comparisons between days for each of the aforementioned external load variables are presented in Table 12.

Table 12. An overview of pitch-based training and match schedules with GPS metrics for each squad. GPS metrics shown are an average of two in-season microcycles. [a], [b], [c], [d], [e] and [f] denote significant difference from match day (MD) - 1, MD, MD+2, MD-4, MD-3 and MD-2 respectively. [*]denotes significant difference from MD in the non-academy group, [#] denotes significant difference from MD-2 in the non-academy group.

	MD - 1	**MD**	**MD + 1**	**MD + 2**	**MD - 4**	**MD - 3**	**MD - 2**
Academy	Saturday 09:30-11:00 Training	Sunday 10:30 – 12:00 Match	Monday OFF	Tuesday 17:30 – 19:30 Training	Wednesday 15:00-19:00 Training	Thursday 17:30 – 19:30 Training	Friday OFF
Total Distance (km)	5.4 ± 0.6	7.3 ± 0.9 [acde#*]		6.1 ± 0.6	6.1 ± 0.8	5.8 ± 0.9	
Average Speed ($m.min^{-1}$)	61.9 ± 7.3	87.1 ± 7.6 [acde#*]		62.5 ± 6.5	70.7 ± 5.4	73.7 ± 12.6[*]	
High Speed Running (m)	160±57	324 ± 104 [acde#*]		70 ± 38	103 ± 29	109 ± 80	
Accelerations (n)	28 ± 8[#*]	32 ± 10 [#*]		39 ± 7[#*]	32 ± 6[#*]	33 ± 10[#*]	
Decelerations (n)	32 ± 7[#*]	40 ± 11[#*d]		34 ± 7[#*]	27 ± 7[#]	30 ± 10[#*]	
Non-academy	Friday OFF	Saturday 10:30 – 12:00 Match	Sunday OFF	Monday OFF	Tuesday OFF	Wednesday OFF	Thursday 18:00 – 20:00 Training
Total Distance (km)		4.4 ± 2.0					6.3 ± 0.5
Average Speed ($m.min^{-1}$)		51.6 ± 23.7					60.8 ± 5.6
High Speed Running (m)		38 ± 7					57 ± 60
Accelerations (n)		9 ± 6					8 ± 5
Decelerations (n)		12 ± 9					11 ± 6

5.4.3 Physical activity

Comparisons in physical activity data between groups are presented in Table 13. Academy players displayed significantly greater mean ENMO (Euclidean Norm Minus One) ($p < 0.01$) with non-academy players displaying more negative intensity gradient ($p < 0.01$) over the 14-day period. In relation to time spent in specific physical activity threshold zones, academy players spent more time in the 150-300 (milli-gravity) mg ($p = 0.02$) and >600 mg zones ($p < 0.01$), resulting in greater moderate to vigorous physical activity (MVPA; $p < 0.01$) compared with non-academy players.

Table 13. Average daily ENMO (mg), intensity gradient (mg) and time spent within different physical activity zones (minutes) between academy and non-academy groups across the 14-day assessment period. * denotes significant difference between groups. [b] highlights significant difference from 150 – 300 mg (milli-gravity), [c] denotes significant difference from 300 – 450 mg, [d] denotes significant difference from 450 – 600 mg, [e] denotes significant difference from > 600 mg. Data is displayed as mean ± SD with range in paratheses.

Physical Activity	ACAD	NON-ACAD	95% CI
14-day ENMO	62 ± 8* mg (42 – 80)	45 ± 7 mg (28 – 76)	8.7 to 26.7
14-day IG	- 2.0 ± 0.1* mg (-2.2 – -1.9)	- 2.7 ± 0.1 mg (-2.9 – -2.3)	0.6 to 0.8
14-day PA 0-150 mg	1312 ± 27 min [bcde] (1273 – 1365)	1341 ± 25 min [bcde] (1303 – 1369)	- 58.5 to 2.0
14-day PA 150-300 mg	80 ± 16 min *[cde] (47 – 109)	62 ± 14 min [cde] (50 – 82)	1.1 to 35.1
14-day PA 300-450 mg	20 ± 5 min (11 – 30)	16 ± 6 min (10 – 25)	- 1.9 to 10.5
14-day PA 450-600 mg	9 ± 3 min (5 – 13)	11 ± 4 min (6 – 18)	- 5.9 to 1.9
14-day PA >600 mg	13 ± 4 min* (7 – 20)	7 ± 3 min (3 – 10)	2.3 to 9.9
MVPA > 200 mg	124 ± 17 min* (69 – 158)	79 ± 18 min (42 – 149)	24.6 to 65.1

5.4.4 Self- reported energy and macronutrient intake

Mean absolute and relative energy and macronutrient intake is presented in Figure 13. Absolute energy (ACAD: 2178 ± 319 kcal.d^{-1}, NON-ACAD: 1768 ± 362 kcal.d^{-1}; 95% CI, 13 to 807, $p < 0.05$) and carbohydrate (ACAD: 279 ± 42 g.d^{-1}, NON-ACAD: 217 ± 24 g.d^{-1}; 95% CI, 20 to 104, $p < 0.05$) intake was greater in the academy group. There was no difference between absolute protein (ACAD: 86 ± 18 g.d^{-1}, NON-ACAD: 71 ± 19 g.d^{-1}; $p = 0.13$) and fat (ACAD: 79 ± 18 g, NON-ACAD: 69 ± 25 g; $p = 0.37$) intake. There was no difference between relative energy (ACAD: 44 ± 12 kcal.kg.d^{-1}, NON-ACAD: 35 ± 9 kcal.kg.d^{-1}; $p = 0.13$), carbohydrate (ACAD: 5.6 ± 0.2 g.kg.d^{-1}, NON-ACAD: 4.3 ± 0.6 g.kg.d^{-1}; $p = 0.09$), protein (ACAD: 1.7 ± 0.6 g.kg.d^{-1}, NON-ACAD: 1.4 ± 0.3 g.kg.d^{-1}; $p = 0.19$) and fat (ACAD: 1.6 ± 0.6 g.kg.d^{-1}, NON-ACAD: 1.4 ± 0.5 g.kg.d^{-1}, $p = 0.39$) intake between groups.

Self-reported energy and macronutrient intake within both squads and a breakdown of energy intake provided by the host club across the weekly microcycle is presented in Figure 14. Within the academy group there was no difference across the training week for absolute energy ($p = 0.47$), carbohydrate ($p = 0.12$) and protein ($p = 0.59$) intake. Similarly, there was no difference between days for energy ($p = 0.28$), carbohydrate ($p = 0.29$) and protein ($p = 0.20$) in the non-academy group.

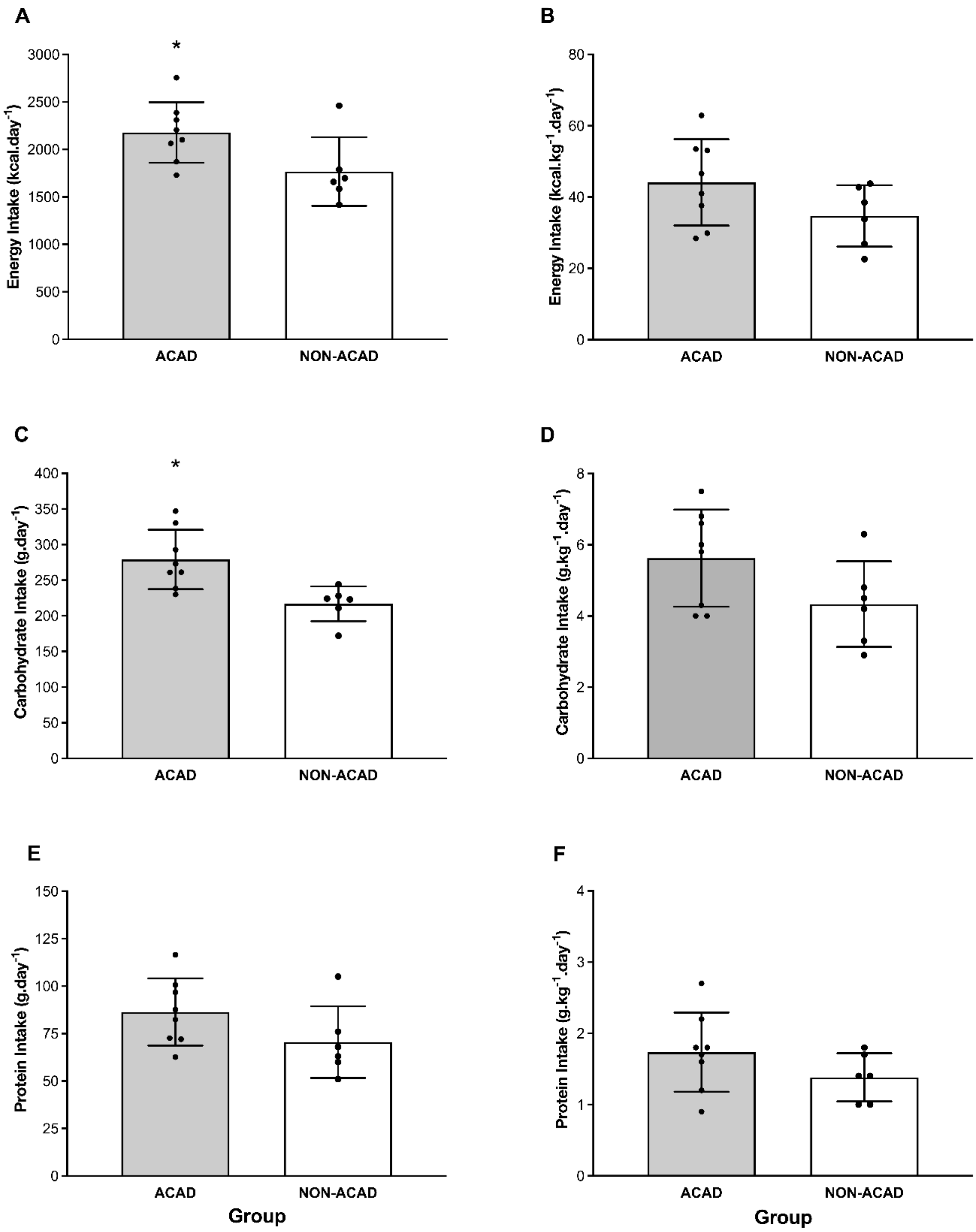

Figure 13. Overview of the mean daily absolute energy (A), carbohydrate (C), and protein (E) intake, and relative energy (B), carbohydrate (D) and protein intake (F) across week one between groups. Grey bars represent energy and macronutrient intake in the academy group, white bars represent the non-academy group. Black dots represent individual data points. * denotes significant difference between groups, $p < 0.05$.

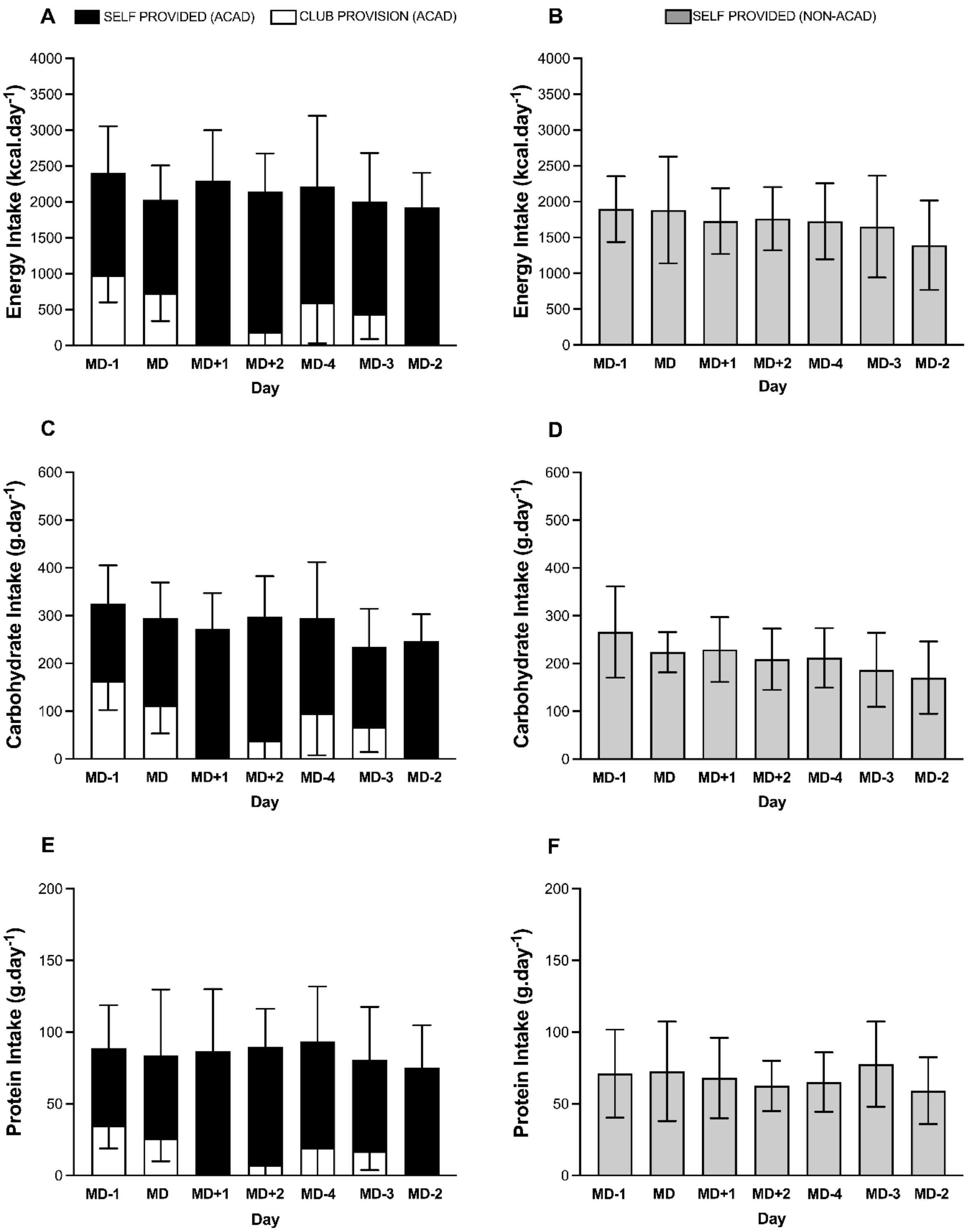

Figure 14. Overview of mean daily absolute energy and macronutrient intake throughout the week one training microcycle. Absolute energy (A), carbohydrate (C) and protein intake (E) of the academy group presented in black and white bars, with white bars representing food and drink provision from the host club. Absolute energy (B), carbohydrate (D) and protein intake (F) of the non-academy groups is presented in light grey bars.

5.4.5 Energy expenditure, estimated activity energy expenditure and estimated energy availability

Energy expenditure of both groups is presented in Figure 15. Absolute energy expenditure in week one (ACAD: 3323 ± 500 kcal.d^{-1}, NON-ACAD: 2670 ± 215 kcal.d^{-1}; 95% CI, 175 to 1131, $p < 0.05$), week two (ACAD: 3512 ± 843 kcal.d^{-1}, NON-ACAD: 2522 ± 453 kcal.d^{-1}; 95% CI, 158 to 1822, $p < 0.05$) and over the total 14-day assessment period (ACAD: 3380 ± 517 kcal.d^{-1}, NON-ACAD: 2641 ± 308 kcal.d^{-1}; 95% CI, 218 to 1258, $p < 0.05$) was greater in academy players compared with non-academy players (see Figure 15). Similarly, relative energy expenditure in week one (ACAD: 65 ± 6 kcal.kg.d^{-1}, NON-ACAD: 53 ± 10 kcal.kg.d^{-1}; 95% CI, 3 to 22, $p < 0.05$), week two (ACAD: 69 ± 12 kcal.kg.d^{-1}, NON-ACAD: 45 ± 8 kcal.kg.d^{-1}; 95% CI, 8 to 32, $p < 0.05$) and over the 14-day period (ACAD: 66 ± 6 kcal.kg.d^{-1}, NON-ACAD: 52 ± 9 kcal.kg.d^{-1}; 95% CI, 5 to 24, $p < 0.05$) was greater in the academy group.

Estimated AEE was greater in week one (ACAD: 1281 ± 449 kcal.d^{-1} NON-ACAD: 801 ± 182 kcal.day^{-1}; 95% CI, 54 to 906, $p < 0.05$), week two (ACAD: 1470 ± 806 kcal.d^{-1}, NON-ACAD: 653 ± 414 kcal.d^{-1}; 95% CI, 28 to 1606, $p < 0.05$) and over the 14 day period (ACAD: 1337 ± 468 kcal.d^{-1}, NON-ACAD: 772 ± 265 kcal.d^{-1}; 95% CI, 98 to 1032, $p < 0.01$) in academy players versus non-academy players.

When assessed over week one, no differences were apparent in estimated energy availability between playing groups (ACAD: 22 ± 19 kcal.kg^{-1} FFM, NON-ACAD: 25 ± 9 kcal.kg^{-1} FFM; $p = 0.38$). Given that estimations of energy and macronutrient intake were not determined for week two, estimations of energy availability were not determined.

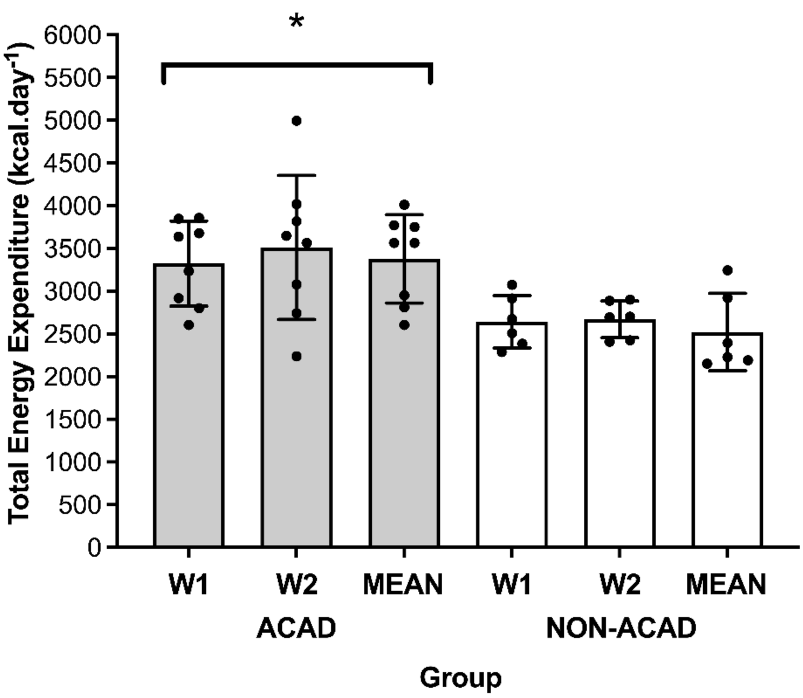

Figure 15. Mean daily energy expenditure for week one, week two and over the 14-day period, Grey bars represent mean academy data, white bars represent mean non-academy data. Black dots represent individual data points. *denotes significant difference from the non-academy group, $p < 0.05$.

5.4.6 Factors affecting total daily energy expenditure.

As shown in Figure 16, there was a significant correlation between TDEE and stature ($r^2 = 0.62$; $p < 0.05$), fat-free mass ($r^2 = 0.88$; $p < 0.05$), RMR ($r^2 = 0.87$; $p < 0.01$), and AEE ($r^2 = 0.99$; $p < 0.01$). There was also a positive relationship between TDEE and training and match duration ($r^2 = 0.65$; $p < 0.05$) and total distance covered ($r^2 = 0.73$; $p < 0.05$). There was also a positive correlation between mean daily ENMO ($r^2 = 0.64$; p < 0.05) and TDEE. There was no correlation between TDEE and body mass, physical activity intensity gradient nor average speed.

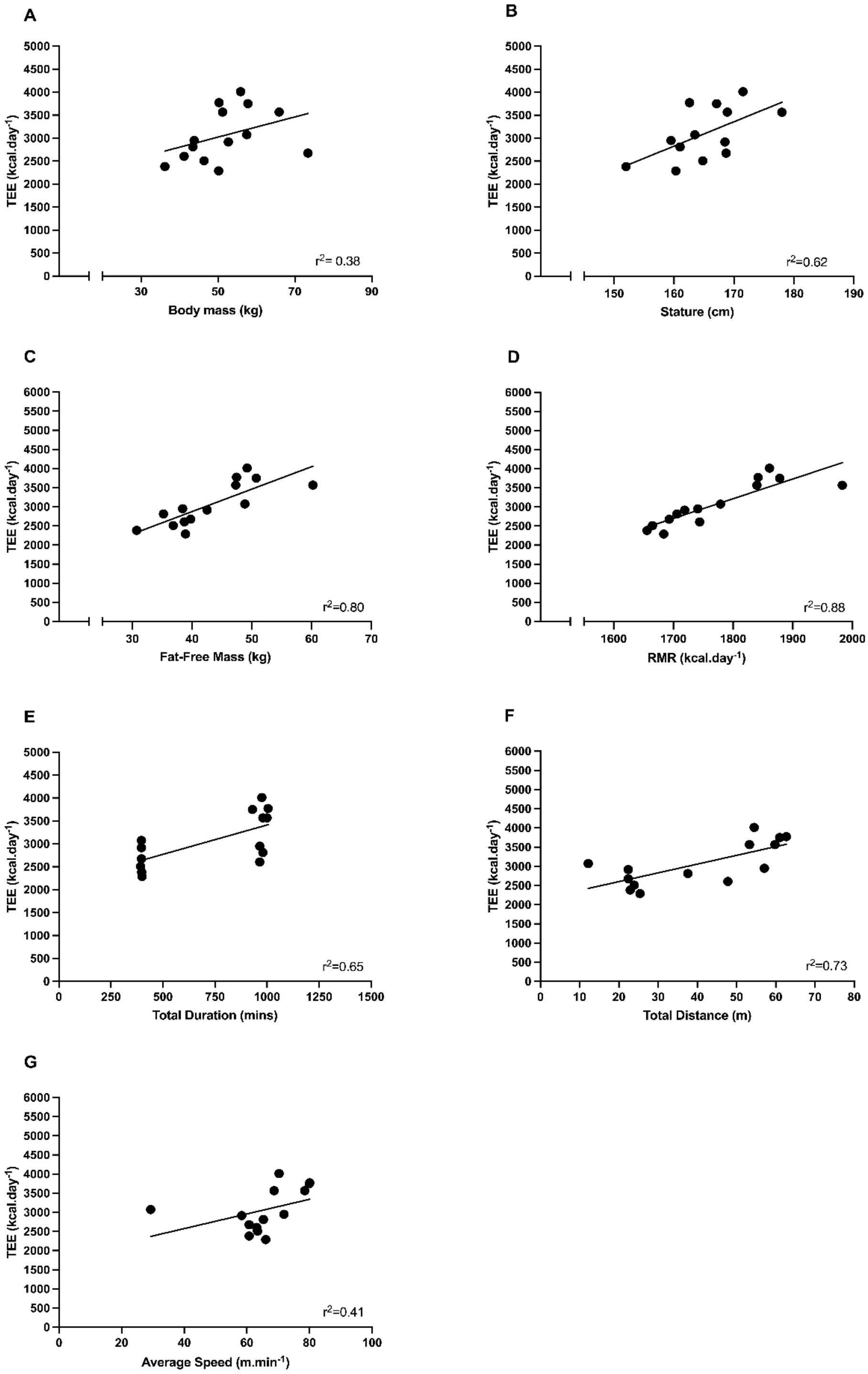

Figure 16 —The relationship between mean daily TEE and body mass (A; $p = 0.38$), stature(B; $p = 0.02$), FFM (C; $p < 0.01$) and RMR (D; $p < 0.01$). In addition, the relationship between mean daily TEE and training and match-play duration (E; $p = 0.01$), total distance (F; $p < 0.01$) and average speed (G; $p = 0.03$).

5.5 Discussion

In using the doubly labelled water method, the present data confirm the hypothesis that the total daily energy expenditure of academy soccer players is significantly greater than age-matched non-academy soccer players. This increased energy expenditure is likely due to the significantly greater training and competition demands that are placed upon academy players, as stipulated by the mandate from the EPPP for academy players to engage in a specific duration of formalised coaching. From a practical perspective, our data highlight the requirement for academy soccer players to consume sufficient daily energy intake to meet the energy cost of growth, maturation and the apparent enhanced energy requirements of the training and game schedule associated with formalised academy soccer programmes.

To address our aims, we recruited players from a Category One academy from the English Premier League whilst also studying a cohort of age-matched non-academy soccer players who were playing at a "grassroots" standard of competition. When considered across the 14-day period, we observed greater energy expenditure in academy players (3380 ± 517 $kcal.d^{-1}$; range, 2811 – 4013) compared with the non-academy players (2641 ± 308 $kcal.d^{-1}$; range, 2288 - 3075). Importantly, the present data extend our previous observations from another Category One academy (Hannon et al., 2021b) where we also reported similar absolute daily energy expenditures in U12/13 (2859 ± 265 $kcal.d^{-1}$; range 2275 - 3903), U15 (3029 ± 262 $kcal.d^{-1}$; range 2738 – 3726) and U18 players (3586 ± 487 $kcal.d^{-1}$; range 2542 - 5172). Furthermore, evaluation of both mean and individual data in both the U13 players studied here and previously (Hannon et al., 2021b) also demonstrate comparable absolute energy expenditures to our previous assessments from adult players (3566 ± 585 $kcal.d^{-1}$) from the EPL (Anderson et al., 2017).

Given that we observed no differences in body mass, stature or fat-free mass (see Table 11) between the academy and non-academy players, our data suggest that the reported differences in total daily energy expenditure between groups is most likely related to the greater energy cost associated with formalised coaching. Indeed, as stipulated by the EPPP, players within the Youth Development Phase of Category One soccer academies are required to receive for a minimum of eight hours coaching exposure per week (Premier League, 2011). Accordingly, we observed distinct differences in physical loading patterns between groups where the academy players were exposed to a greater exercise duration (975 ± 23 min) and completed a greater distance (54.1 ± 8.5 km) over the 14-day period compared with non-academy players (397 ± 2 min and 21.6 ± 4.7 km, respectively). In this regard, it is noteworthy that the estimated mean daily activity energy expenditure of the academy players over the two-week period (1337 ± 468 kcal.d^{-1}; range 640 - 1942) was approximately 600 kcal.d^{-1} greater than the non-academy players (772 ± 265 kcal.d^{-1}; range 436 - 1118). Furthermore, when considering the whole sample, positive correlations were evident between total energy expenditure and both training and match duration and total distance covered (i.e. training volume; see Figure 16). In relation to external load metrics, the average weekly total distance completed by the U13 players reported here (27 ± 4 km) was greater than that previously reported in U12/U13 academy players (20 ± 2 km) but comparable to both U18 (26 ± 3 km) (Hannon et al, 2021a) and adult EPL players (27 ± 2 km) (Anderson et al., 2017). When taken together, these data clearly demonstrate that the training and match schedules of academy soccer programmes (even within the U13 age-group) induces exercise volumes and daily energy expenditures that are comparable to adult professional players, albeit at a time when such individuals are not yet fully mature and may not have access to appropriate nutrition support (Carney et al., 2022).

In addition to a greater exercise volume, the present data also demonstrate that academy players are exposed to significantly greater intensity of physical loading compared with non-academy players, as evidenced by both GPS metrics and evaluation of accelerometery data. Indeed, the intensity of training and matches was greater in academy players versus non-academy players, as indicated by a higher average speed (see Figure 12 C), high-speed running distance (see Figure 12 D) and frequency of accelerations and deceleration (see Figure 12 E and Figure 12 F, respectively). In relation to daily physical activity levels, evaluation of triaxial accelerometery data also demonstrate that academy players spend more time engaged in moderate-to-vigorous activity compared with non-academy players (see Table 13). It is noteworthy, however, that both academy and non-academy players also displayed greater time engaged in MVPA compared to children and adolescents in the general population (Fairclough et al., 2023). Although we did not specifically evaluate the timing and type of physical activity completed by both groups in relation to soccer versus non-soccer activity (e.g. additional sports, school playground activity, physical education etc.), it is reasonable to suggest that it was soccer training that accounted for the majority of this additional moderate-to-vigorous activity in the academy players. Although it is acknowledged that moderate-to-vigorous physical activity (Tobias et al., 2007) and increased training volume (Varley et al., 2017b) is facilitative of bone formation and skeletal development in adolescents, it is noteworthy that sub-optimal carbohydrate intake before, during and/or after acute exercise (Hammond et al., 2019a, Sale et al., 2015) can also impair acute bone turnover. Such data are of relevance to the present population when considering that academy players habitually "under fuel" as reported in Chapter Four in preparation and in recovery from academy training sessions (Stables et al., 2022). Furthermore, we also reported that the most prevalent injury occurring in academy players from England, Europe and South America was growth related injuries in the anatomical location of the knee, lower back, sacrum and pelvis, the prevalence of which was most evident during periods of peak height velocity (Hall et al., 2020). Collectively, these data further demonstrate the requirement for specific education and behaviour change strategies that ensure sufficient CHO availability and intake is promoted in what is clearly an “at risk” population.

In relation to self-reported energy intake, we also observed a significantly greater energy intake in academy players versus non-academy players (see Figure 13). Notwithstanding the error associated with dietary assessment (Stables et al., 2021) and difficulties when comparing methodologies between studies, the academy players studied here reported less absolute energy intake (2178 ± 319 kcal.d^{-1}) than our previous assessments of U12/13 players (2659 ± 187 kcal·d^{-1}) from another Category One academy cohort (Hannon et al., 2021b). When considering sub-optimal fuelling and recovery practices observed in Chapter Four, it is unsurprising that players failed consume sufficient energy throughout the training day. Whilst we accept the principal investigator being on-site for the academy group will have strengthened the quality of energy and macronutrient intake data versus the non-academy group, possibly leading to greater reporting, only three players reported a daily CHO intake >6 g.kg^{-1} per day, an intake that is recommended to support the typical volume of exercise that is completed by these players (Collins et al., 2021). Interestingly, approximately 125 g of CHO intake that was self-reported by academy players was attributable to food and drink provision that was provided by the host club as opposed to sources that were purchased by the player or related stakeholders (e.g. parents and guardians). However as observed in Chapter Four, provision of food and drink alone does not correlate to players achieving energy and carbohydrate intake targets. Indeed, in accordance with a designated “Category One” status, the host club studied here provided on-site food provision and players and staff were also exposed to a full-time nutritionist to ensure both education and service provision. In contrast, however, our recent audit of nutrition provision across soccer academies in England demonstrated that the extent of nutrition service provision differs considerably between clubs in relation to whether they are deemed as Category One, Two or Three status (Carney et al., 2022). Lower ranked academies provide breakfast, lunch and snacks with lesser frequency than Category One academies. As such, it is possible that players enrolled at a “lower category academy” may present with an increased risk and prevalence of under-fuelling despite the fact that they are likely completing significantly greater training volumes than non-academy players. Energy and carbohydrate provision to players at breakfast and lunch with specific pre-, during and post-training fuelling strategies should be employed to mitigate such risk.

In summary, we report for the first time that the daily energy expenditure of male academy soccer players is significantly greater than age matched soccer players who are not enrolled on a formalised academy coaching programme. Additionally, our data demonstrate that the typical weekly training volumes (e.g. total distance covered) and daily energy expenditure of adolescent academy players are comparable to adult professional players, albeit at a time when they are not yet physically mature. Given the injury risk associated with high training loads completed during periods of growth and maturation, our data clearly demonstrate the requirement for academy players to consume sufficient energy (and CHO) intake, with specific reference to the timing of pitch-based training to support the enhanced energy cost associated with formalised academy coaching programmes.

Chapter 6

Training with reduced carbohydrate availability affects markers of bone resorption and formation in male academy soccer players from the English Premier League.

The aims of the chapter were to evaluate the effects of an acute soccer training session upon markers of bone (re)modelling and calcium metabolism in a cohort of male academy soccer players. We also aimed to quantify the effects of training with reduced CHO availability in modulating markers associated with bone (re)modelling calcium metabolism.

Liam Anderson, Rachel Dunn, William Fraser and Jon Tang assisted with the data analysis for this study.

Stables R, Anderson L, Sale C, Hannon MP, Dunn R, Tang JCY, Fraser WD, Costello NB, Close GL, Morton JP. Training with reduced carbohydrate availability affects markers of bone resorption and formation in male academy soccer players from the English Premier League. Eur J Appl Physiol. 2024 Dec;124(12):3767-3780.

6.1 Abstract

Chapters 4 and 5 of this thesis highlights that despite high daily energy expenditures attributable to pitch-based training, academy players fail to consume optimal energy and carbohydrate pre-, during and post-training. This study aimed to test the hypothesis that training with reduced carbohydrate (CHO) availability increases bone resorption in adolescent soccer players. In a randomised crossover design, ten male players (age: 17.4 ± 0.8 years) from an English Premier League academy completed an acute 90-minute field-based training session (occurring between 10:30 - 12:00) in conditions of high (TRAIN HIGH; 1.5 $g.kg^{-1}$, 60 g, 1.5 $g.kg^{-1}$ and 1.5 $g.kg^{-1}$ consumed at 08:00, during training, 12:30 and 13:30, respectively) or low CHO availability (TRAIN LOW; 0 $g.kg^{-1}$). Participants also completed a non-exercise trial (REST) under identical dietary conditions to TRAIN LOW. Venous blood samples were obtained at 08:30, 10:30, 12:30 and 14:30 for assessment of bone resorption (βCTX), bone formation (PINP) and calcium metabolism (PTH and ACa). External training load did not differ (all $P > 0.05$) between TRAIN HIGH and TRAIN LOW, as evident for total distance (5.6 ± 0.8; 5.5 ± 0.1 km), average speed (81 ± 9; 85 ± 12 $m.min^{-1}$) and high-speed running (350 ± 239; 270 ± 89 m). Area under the curve for both βCTX and PINP was significantly greater ($p < 0.01$ and $p = 0.03$) in TRAIN LOW versus TRAIN HIGH, whilst no differences in PTH or ACa ($p = 0.11$ and $p = 0.89$) were observed between all three trials. To this end CHO restriction before, during and after an acute soccer training session increased bone (re)modelling markers in academy players. Despite acute anabolic effects of bone formation, the long-term consequence of bone resorption may impair skeletal development and increase injury risk during growth and maturation

6.2 Introduction

The purpose of soccer academies is to develop the technical, tactical, physical, and psychosocial capabilities of young players (Wrigley et al., 2012). Within the English academy system, players are exposed to a formalised and structured coaching programme whereby they transition through distinct development phases, that is, the Foundation Phase (FP: under 9-11 years old), Youth Development Phase (YDP: under 12-16 years old) and Professional Development Phase (PDP: under 17-21 years old). In relation to physical development, the typical weekly training volume (e.g. total weekly duration of activity and distance covered) that players are exposed to increases as they progress through each development phase (Hannon et al., 2021a). In addition, academy players experience similar absolute training volumes (Brownlee et al., 2018, Hannon et al., 2021a, Stables et al., 2023) as their adult counterparts from the English Premier League (EPL) (Anderson et al., 2016a), albeit it a time when they are not yet fully mature. When taken together with previous research, data in Chapter Five highlights how individual players across the academy pathway (*i.e.,* from U12 to U18) may present with an absolute total daily energy expenditure (*i.e.,* 3000 – 5000 $kcal.day^{-1}$) that is comparable to, or exceeds (Hannon et al., 2021b, Stables et al., 2023), observations from adult players of the EPL (Anderson et al., 2017).

Despite such high training volumes and energetic demands reported in Chapters Four and Five, data in Chapter Four highlights that academy players "under-fuel" (*i.e.,* fail to consume sufficient energy and carbohydrate intake), in the acute period before, during and after training sessions, as reported previously through the training microcycle (Hannon et al., 2021b, Naughton et al., 2016, Stables et al., 2022). Although the negative outcomes associated with sub-optimal fuelling and recovery are often considered from a performance perspective, a more concerning outcome for adolescent athletes is the potential impact upon risk of injury to skeletal structures (Goulding, 2007), especially when considering that adolescence is a critical time for bone development (Zhang et al., 2023). In this regard, failing to increase daily energy intake (as seen in Chapter Five) in consideration of the increased resting metabolic rate that accompanies growth and maturation alongside the enhanced energetic cost that is inherent to academy coaching programmes (Hannon et al., 2020), may increase the risk of players with presenting chronically low energy availability (LEA) (Mountjoy et al., 2023). In this way, players may subsequently present with negative symptoms associated with LEA, where such symptoms could include reductions in bone accrual (Mountjoy et al., 2018) While such conditions may not directly lead to stress fractures alone, under a state of imbalance between microdamage to skeletal tissue formation and breakdown, bone stress injuries may occur. The continual substantial loading to microcracks in the bone under stress therefore presents an increase in stress fracture risk (Hoenig et al., 2023). This is of critical importance for academy soccer players given the prevalence of growth-related injuries to the knee, lower back, sacrum and pelvis, as reported in academy players from England, Europe and South America (Hall et al., 2020).

A growing of body of literature now demonstrates the complex interplay between exercise, nutrient availability, and bone (re)modelling (Dolan et al., 2020). Previously we (Hammond et al., 2019b) and others (Sale et al., 2015, de Sousa et al., 2014) observed that the mechanical and/or metabolic stress associated with running exercise is sufficient to increase bone resorption in male adults (as evidenced by acute changes in β-carboxyterminal telopeptide, βCTX – a marker of the degradation of mature type 1 collagen). Although the greater rates of bone resorption (especially at bony sites) within the adolescent compared to adult population are considered essential to facilitate skeletal development (Zhang et al. 2023), it is noteworthy that the exercise-induced increases in βCTX in adults is significantly reduced if carbohydrate

(CHO) has been consumed before, during and/or after exercise (Townsend et al., 2017, Sale et al., 2015, Hammond et al., 2019b, de Sousa et al., 2014). Furthermore, when a cohort of male adult racewalkers (Fensham et al., 2022) adhered to a short-term six-day dietary intervention comprising reduced daily CHO intake (*i.e.,* 0.5 $g.kg^{-1}$ CHO, energy availability of 41 kcal·kg $FFM^{-1}·d^{-1}$), concentrations of procollagen-1 N-terminal peptide (PINP; a marker of bone formation) were significantly reduced when compared to a control diet matched for energy availability but higher daily CHO intake (*i.e.,* 41 kcal·kg $FFM^{-1}·d^{-1}$ and 9.8 $g.kg^{-1}$ CHO) or a diet representative of LEA and moderate daily CHO intake (*i.e.,* 15 kcal·kg $FFM^{-1}·d^{-1}$ and 5 $g.kg^{-1}$ CHO per day). When taken together, such data suggest that reductions in both acute (*i.e.,* CHO consumed within several hours of training) and chronic daily CHO intake, such as nutritional practices observed in both Chapter Four and Chapter Five, increases bone resorption the result of which, if persistent over time, might contribute to compromised skeletal development. However, despite the observation that soccer training is considered anabolic to bone (Varley et al., 2023), the acute effects of the habitual soccer training sessions completed by academy players, and the context of such effects within the wider process of acute bone resorption and formation has not yet been evaluated, let alone any potential modulatory role of CHO availability.

With this in mind, the aims of this present study were two-fold. First, we sought to evaluate the effects of an acute soccer training session on markers of bone resorption, bone formation and calcium metabolism in a cohort of male academy soccer players. Given the results of Chapter Four whereby players repeatedly failed to achieve optimal fuelling and recovery targets, we also aimed to evaluate the effects of training with reduced CHO availability in modulating markers associated with bone resorption, formation and calcium metabolism. We hypothesised that training with reduced CHO availability (*i.e.,* under-fuelling) would increase markers of bone resorption and reduce markers of bone formation (effects occurring independent of alterations to calcium metabolism).

6.3 Methods

6.3.1 Participants. Twelve male outfield soccer players from an English Premier League academy volunteered to participate in this study. However, two participants had to withdraw from the study due to pitch-based injuries (not occurring during the training sessions completed as part of this study), leaving ten players who completed all experimental trials. Participant characteristics are detailed in Table 6, section 3.2. On the basis of previous assessments from our laboratory (albeit on adult males) using acute high-intensity intermittent running as an exercise stimulus and a CHO feeding intervention (Hammond et al., 2019b), sample size was estimated according to our primary outcome variable of βCTX assuming an effect of CHO availability of 0.3 ng·mL^{-1} and a group standard deviation of 0.2 ng·mL^{-1}. These data would provide an effect size of dz = 1.5 where a sample size of 8 would provide an alpha value of 0.05 and statistical power of 0.95 (G* Power, version 3.1). All procedures conformed to the standards of the Declaration of Helsinki, written informed parental / guardian consent and player assent was obtained, and ethical approval was granted by Liverpool John Moores University.

6.3.2 Study Design.

In a repeated measures (and crossover) design, participants completed three experimental trials that occurred over a 3 week in-season period in April 2023. With trials separated by one week to minimise any washout effect. Trial 1 was a non-exercise trial (REST) that occurred on the Wednesday of week 1 and represented a non-training day for the participants. Trial 2 was a training day that occurred on the Tuesday of week 2 and took place 4 days before the players' next game (referred to as match day minus 4, MD - 4). In trial 2, players were randomised such that half of the sample (n = 5) completed the training session in conditions of high CHO availability (TRAIN HIGH) whilst the remaining participants (n = 5) completed the session in conditions of low CHO availability (TRAIN LOW). Trial 3 occurred on the Tuesday of week 3 (*i.e.,* MD - 4) and on this occasion, participants crossed over in trials such that those players who completed trial 2 with high CHO availability now adhered to the low CHO availability trial and *vice versa*. Players were blinded to CHO availability throughout all trials and completed an overnight fast prior to each trial. To examine the effects of CHO availability upon markers of bone resorption and formation, both REST and TRAIN LOW trials were CHO restricted. An unintended consequence of this is, of course, that these trials were also energy restricted in comparison to TRAIN HIGH given the caloric loss by removing CHO. To alleviate this, an option would have been to manipulate the fat and/or protein contents of the dietary intake, but both of these are also known to have independent effects on bone, specifically the action of IGF-1 (Walsh and Henriksen, 2010). The club coaching staff were instructed to replicate the session duration and content (*i.e.,* training drill content, duration and sequence) during both trial 2 and trial 3 to match the exercise stimulus as closely as possible, similarly all participants completed the same exercise stimulus the day before the TRAIN HIGH and TRAIN LOW trials, although this was not directly controlled within the study. An overview of the experimental design which details dietary intake of each trial is presented in Figure 17. Further details of the dietary trials and experimental protocols are provided in Table 14.

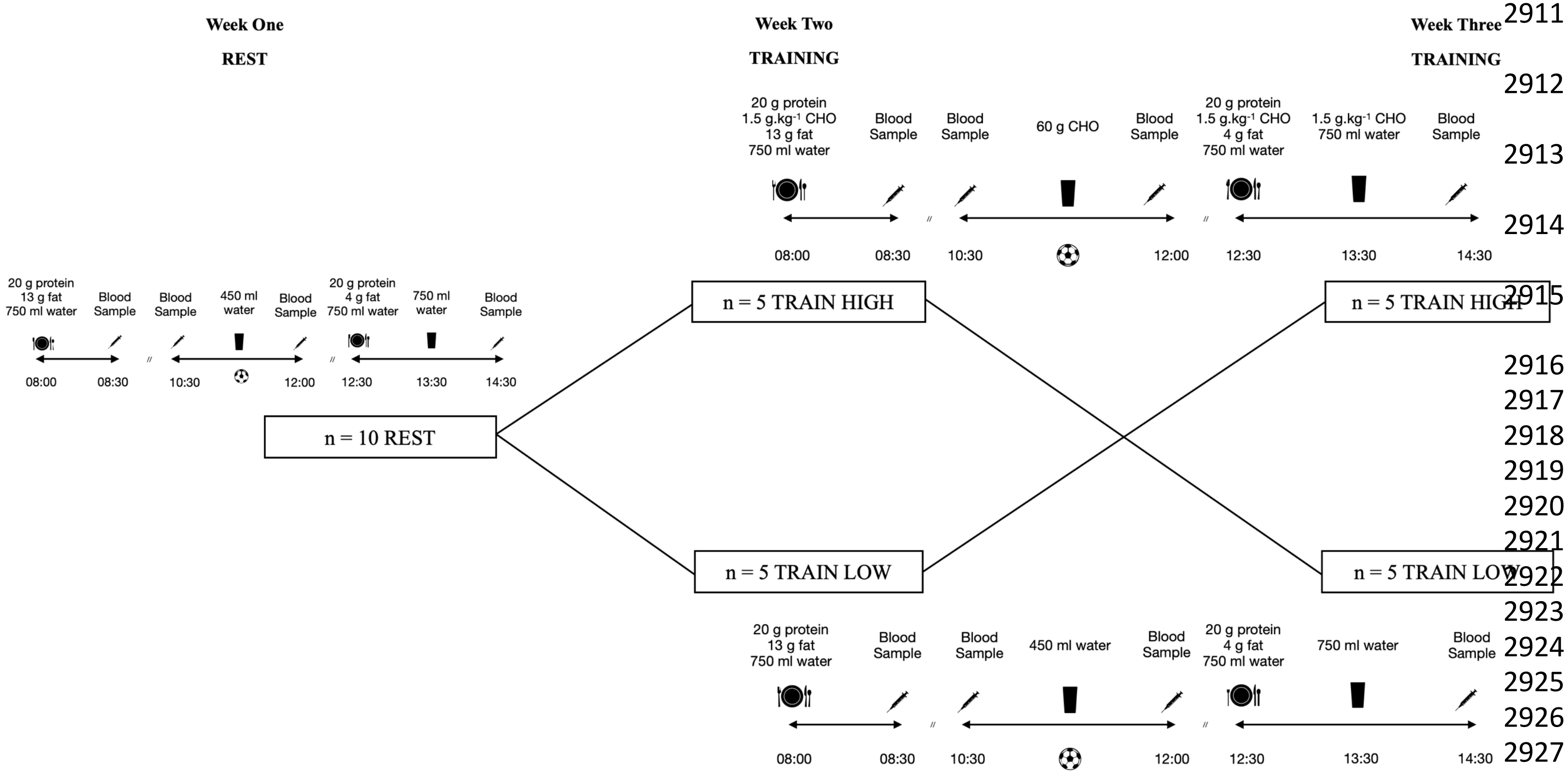

Figure 17. Schematic overview of the experimental design. Participants completed one rest day followed by two experimental trials separated by one week respectively.

Table 14. Dietary protocol adhered to by participants during the TRAIN HIGH, TRAIN LOW and REST trials. Mean energy (kcal) and carbohydrate (g) is reported alongside the standardised protein (g), fat (g), fluid (L) and calcium intake (mg). In relative terms, CHO intake corresponded to 5.3 ± 0.1 $g.kg^{-1}$ body mass.

	TRAIN HIGH	TRAIN LOW	REST
Energy (kcal)	1733 ± 163	380	380
Carbohydrate (g)	396 ± 41	0	0
Protein (g)	40	40	40
Fat (g)	17	17	17
Fluid (L)	2.7	2.7	2.7
Calcium (mg)	75	75	75

6.3.3 Experimental Protocols.

For all trials, participants reported to the training ground of the host club at 08:00 in a fasted state. Participants underwent assessment of body mass as outlined in section 3.3. Participants subsequently consumed breakfast (details for each trial provided below) and an initial venous blood sample was then obtained at 08:30. Due to limitations of the number of samples that could be taken and a lack prior access to participants, no fasted blood sample could be obtained. Further venous blood samples were collected at subsequent 2-hour intervals, corresponding to 10:30, 12:30 and 14:30 to monitor acute changes in remodelling markers as well as the short-term effects of pitch-based training.

REST trial: During the REST trial, participants remained at the host training ground and took part in light activities only (e.g. performance analysis education sessions, watching television, playing video games and/or playing pool). Participants consumed a 750 ml placebo beverage at breakfast (150 ml of sugar free orange cordial (Robinsons, UK) diluted in 600 ml of water) and a portion of scrambled egg equivalent to approximately 20 g of protein and <15 g fat. Participants also consumed 3 x 150 ml boluses of the placebo beverage (125 ml boluses of water mixed with 25 ml of sugar free cordial) at 10:30, 10:50 and 11:10, to replicate the pattern of fluid ingestion that would occur during the training sessions to be completed in both the TRAIN LOW and TRAIN HIGH trials. At 12:30, participants then consumed another 750 ml bolus of the placebo solution, a chicken breast (equivalent to approximately 20 g of protein) and small mixed leaf salad (30 g portion with negligible energy). A final 750 ml bolus of the placebo beverage was consumed at 13:30.

TRAIN LOW trial: During the TRAIN LOW trial, participants adhered to the same dietary trial as that administered in the REST trial and participants took part in a 90-minute field-based training session occurring between 10:30 and 12:00.

***TRAIN HIGH* trial:** During the TRAIN HIGH trial, participants adhered to the same order and timing of dietary intake and fluid ingestion (including the consumption of scrambled eggs and chicken / salad at breakfast and post-training), though a high CHO availability trial now occurred. Carbohydrate was consumed at 08:00 (1.5 $g.kg^{-1}$ of maltodextrin added to 600 ml of water and 150 ml of sugar free cordial during training) followed by 60 g during training (equivalent to 3 x 20 g intakes of maltodextrin consumed at 10:30, 10:50 and 11:10, delivered as 3 x 125 ml boluses of water mixed with 25 ml of sugar free cordial). Carbohydrate was also consumed immediately post-training at 12:30 and again at 13:30 (both timepoints consisted of 1.5 $g.kg^{-1}$ maltodextrin added to 600 ml of water and 150 ml of sugar free cordial). In this way, the timing and total dietary intake of protein (40 g), fat (16 g) and fluid ingestion (2.7 L) was matched between all 3 experimental trials though participants consumed a total of approximately 5-6 $g.kg^{-1}$ CHO when completing the TRAIN HIGH trial (administered as maltodextrin, supplied by Science in Sport, UK; sugar free cordial was manufactured by Robinsons, UK).

6.3.4 Quantification of training load.

Pitch based training load was assessed using global positioning system (GPS) technology (Vector, Catapult, Melbourne, Australia) as detailed in section 3.5. Participants also reported their pre- and post-training assessment of ratings of perceived exertion (RPE 6 – 20) (Borg, 1982), within minutes of the commencement and completion of the training sessions.

6.3.5 Blood collection and analysis.

Five millilitres of venous blood was drawn into one ethylenediaminetetraacetic acid (EDTA) tube (BD Vacutainer) and kept on ice until centrifugation at 1200 g for 10 min at 4°C. A second five millilitre blood sample was collected into a serum tube and allowed to clot at room temperature for sixty minutes, before being centrifuged for 10 minutes at 1200 g at 4°C. Following centrifugation, aliquots of plasma and serum were stored in eppendorfs at −80°C for subsequent analysis of plasma C-terminal telopeptide of type 1 collagen (βCTX), procollagen type I N Propeptide (PINP) and parathyroid hormone (PTH), and serum calcium (Ca), albumin and albumin adjusted calcium (ACa). These markers of bone resorption and formation can be released during bone (re)modelling and are, therefore, thought to reflect bone (re)modelling activity, with some suggestions that their measurement in blood can be useful in assessing bone turnover, and downstream prediction of bone loss (Vasikaran, 2018). Fluctuations in protein concentrations, especially albumin, can cause total Ca concentrations to change independently of the ionized calcium concentration, as such Ca concentrations were adjusted against albumin concentrations to give an albumin-adjusted calcium (ACa) value using the following equation: $\text{ACa} = [\text{total calcium}] + 0.02 \times (40-[\text{albumin}])$. Analysis of βCTX, PINP, PTH, Ca and ACa were performed at the Bioanalytical Facility, University of East Anglia by on a fully automated COBAS e601 system (Roche Diagnostics, Mannheim, Germany). βCTX, PINP and PTH were measured using electro-chemiluminescence immunoassay (ECLIA); kit# 09005773190, 03141071190 and 11972103122, respectively. Quality controls (QC) were tested with each batch of samples; the inter-assay coefficient of variation (CV) for βCTX ($n = 8$) was ≤3% between 0.2-1.5 μg/L with the sensitivity of 0.01 μg/L; Inter-assay CV for PINP ($n = 8$) was < 3% between 20-600 μg/L with a sensitivity of 8 μg/L. the inter-assay CV for PTH ($n = 8$) was ≤3.8% across the analytical range of 0.127-530 pmoL. Total calcium and albumin concentrations were measured COBAS c501 system (Roche) by spectrophotometric methods; kit# 05061482190 and 03183688, respectively. The inter-assay CV (n=8) for Ca was ≤1.6%, and albumin was ≤1.1%. βCTX, PINP, PTH, Ca and ACa were selected for use as they are the preferred markers to assess the calcium homeostasis and bone turnover status in clinical studies (Vasikaran et al., 2011).

6.3.6 Statistical analysis.

All data were initially assessed for normality of distribution using the Shapiro-Wilk test. Comparisons between trials in training load metrics between TRAIN HIGH and TRAIN LOW trials were assessed using students t-tests for paired samples, where ninety-five percent confidence intervals (95% CI) for the differences are also presented. Comparisons of bone turnover markers and calcium metabolism between trials were assessed using a within subjects repeated measures general linear model where the within factors were time (*i.e.,* blood samples collected at 08:30, 10:30, 12:30 and 14:30) and trial (*i.e.,* REST, TRAIN LOW and TRAIN HIGH). Where significant main effects were present, Bonferroni *post hoc* analysis was conducted to locate specific differences and 95% CI for the differences are also presented where appropriate. All data in text, tables and figures are expressed as means and SD with $p < 0.05$ indicating statistical significance. Statistical tests were performed using SPSS for Windows (version 29, SPSS Inc, Chicago, IL).

6.4 Results

6.4.1 Training with reduced CHO availability does not affect training volume and intensity.

The external and internal training load metrics of participants while training in TRAIN HIGH and TRAIN LOW conditions are presented in Table 15. No significant differences were apparent for total distance ($p = 0.88$), average speed ($p = 0.56$), high speed running distance ($p = 0.72$), number of accelerations ($p = 0.65$) and decelerations ($p = 0.72$). There was also no significant difference for average heart rate ($p = 0.62$) or post-session RPE ($p = 0.96$). When taken together, such data demonstrate that CHO availability did not affect the intensity and volume of training, therefore confirming that the acute training stimulus was comparable when players completed training in both TRAIN HIGH and TRAIN LOW conditions.

Table 15. An overview of external and internal training metrics for the TRAIN HIGH and TRAIN LOW trials. Data are presented as means with ± SD with range displayed in parentheses.

	TRAIN HIGH	**TRAIN LOW**	**95% CI**
Total Distance (km)	5.6 ± 0.8 (4.2 – 6.8)	5.5 ± 1.1 (2.7 – 6.8)	-1012 to 1067
Average Speed (m.min^{-1})	81 ± 9 (70 - 95)	85 ± 12 (59 - 99)	-15 to 9
High Speed Running (m)	350 ± 239 (33 - 533)	270 ± 89 (127 - 407)	-148 to 202
Accelerations (n)	40 ± 12 (18 - 58)	44 ± 13 (15 - 62)	-18 to 12
Decelerations (n)	38 ± 14 (7 - 55)	40 ± 12 (12 - 60)	-15 to 12
Heart Rate (bpm)	139 ± 10 (127 - 158)	142 ± 10 (127 - 158)	-15 to 9
Post-session RPE	13 ± 3 (8 - 16)	14 ± 2 (10 - 16)	-3 to 0

6.4.2 Completing an acute soccer-specific training with reduced CHO availability increases markers of bone resorption and formation.

βCTX

As a marker of bone resorption, βCTX displayed significant main effects for time ($p = 0.02$), condition ($p < 0.01$) and interaction ($p = 0.03$) (see Figure 18A). In relation to effects of time, pairwise comparisons demonstrate βCTX was significantly lower at 10:30 ($p = 0.01$) and 14:30 ($p = 0.02$) compared with 08:30. Such data suggest that nutrient ingestion in all three trials may have a role in reducing circulating βCTX. Furthermore, βCTX was significantly greater at 12:30 compared with both 10:30 ($p = 0.018$) and 14:30 ($p < 0.01$), thus suggesting that the acute training session significantly increased βCTX.

When considering pairwise comparisons for main effects of condition, βCTX was significantly lower in TRAIN HIGH compared with both TRAIN LOW ($p < 0.01$; 95% CI: -0.32 to -0.11 $ng.mL^{-1}$) and REST ($p = 0.04$; 95% CI: -0.31 to -0.01 $ng.mL^{-1}$), though no difference was apparent between TRAIN LOW and REST ($p = 0.53$; 95% CI: -0.06 to 0.17 $ng.mL^{-1}$). Accordingly, the AUC for βCTX (see Figure 18B) was significantly greater in TRAIN LOW compared with TRAIN HIGH ($p < 0.01$) while differences between TRAIN HIGH and REST were not significantly different ($p = 0.07$).

PINP

As a marker of bone formation, PINP displayed significant main effects for time ($p < 0.01$), condition (< 0.01) and interaction ($p < 0.01$) (see Figure 18C). In relation to effects of time, pairwise comparisons demonstrate PINP was significantly greater at 12:30 compared with both 10:30 ($p = 0.01$) and 14:30 ($p < 0.01$).

When considering pairwise comparisons for main effects of condition, TRAIN LOW was significantly greater than REST (p = 0.02; 95% CI: 2.8 to 30.3 ng.mL^{-1}) yet there was no significant difference to TRAIN HIGH (p = 0.08; 95% CI: -1.3 to 22.2 ng.mL^{-1}) and no difference was apparent between REST and TRAIN HIGH (p = 0.87; 95% CI: -21.9 to 9.8 ng.mL^{-1}). In relation to AUC data (see Figure 18D), TRAIN LOW was significantly greater than both TRAIN HIGH (p = 0.03) and REST (p = 0.01), though no difference was apparent between REST and TRAIN HIGH (p = 0.810).

6.4.3 Completing an acute soccer-specific training with reduced CHO availability does not affect calcium metabolism.

PTH

Changes in plasma PTH are presented in Figure 18E. There was a significant main effect for time ($p < 0.01$), but no effect of condition (p = 0.14) or interaction effect (p = 0.32). In relation to pairwise comparisons for main effect of time, PTH was significantly greater at 10:30 (p = 0.02) and 12:30 ($p < 0.01$) compared with 08:30. Differences between 12:30 and 10:30 were not significantly different (p = 0.09). In accordance with no main effects for condition, the AUC also did not differ (p = 0.11) between trials (see Figure 18F). These data suggest that the metabolic effects of acute feeding at breakfast and/or acute soccer-specific training is sufficient to increase PTH.

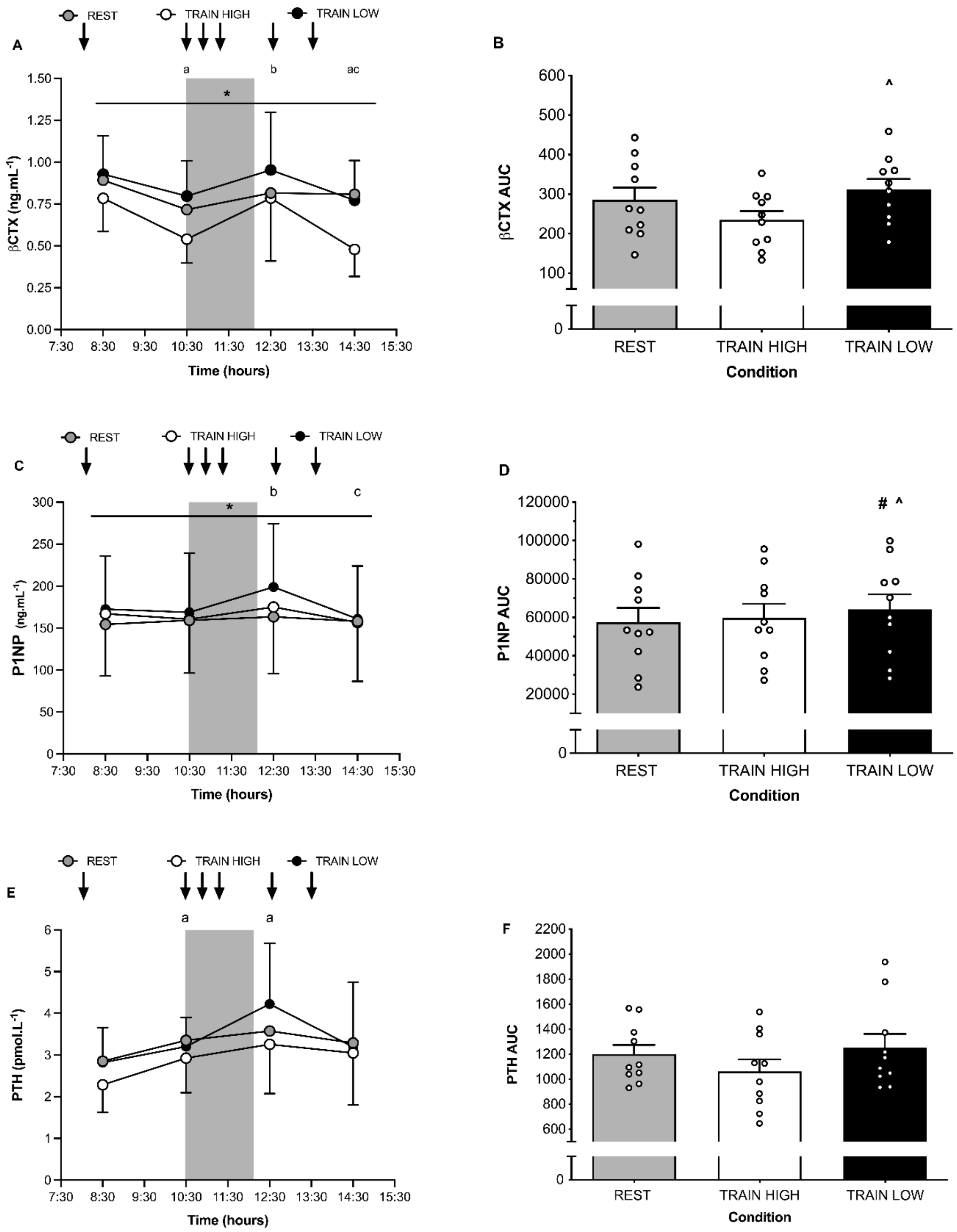

Figure 18. Plasma βCTX (A), PINP (C), PTH (E) concentrations before, during and after training. Shaded grey area denotes pitch-based training, downward arrows denote timing of feeding. Total area under the curve (AUC) for βCTX (B), PINP (D) and PTH (F) is also shown. [*] Denotes significant main effect for difference between conditions, [a] denotes significant pairwise comparison difference from 08:30, [b] denotes significant difference from 10:30 and [c] denotes significant difference from 12:30, all $p < 0.05$; ^ denotes significant difference in AUC between TRAIN LOW and TRAIN HIGH, # denotes significant difference in AUC between TRAIN LOW and REST, all $p < 0.05$. Grey, white and black bars represent mean data, individual data points are shown by white circles.

Calcium

Changes in serum calcium are presented in Figure 19A. There were no main effects of time (p = 0.91), condition (p = 0.20), or interaction (p = 0.07). In accordance, the AUC (see Figure 19B) was also not significantly different between conditions (p = 0.30).

Albumin

Changes in serum albumin are presented in Figure 19C. There was a significant main effect for time ($p < 0.01$), condition (p = 0.02) and an interaction effect ($p < 0.01$). In relation to pairwise comparisons for main effect of time, serum albumin was significantly different at 12:30 and 14:30 compared with 08:30 (both $p < 0.01$). In considering effects of condition, REST was significantly lower compared with TRAIN LOW (p = 0.03; 95% CI: -2.1 to – 0.1 $g.L^{-1}$), though no differences were apparent between REST and TRAIN HIGH (p = 1.0; 95% CI: -1.2 to 0.9 $g.L^{-1}$) or between TRAIN LOW and TRAIN HIGH (p = 0.21; 95% CI: -0.4 to 2.3 $g.L^{-1}$). In relation to AUC data (see Figure 19D), differences between conditions did not achieve statistical significance (p = 0.05).

Albumin adjusted calcium.

Changes in albumin adjusted calcium are presented in Figure 19E. There were no main effects for time (p = 0.59), condition (p = 0.67) or interaction (p = 0.23). In relation to AUC data (see Figure 19F), there was no significant difference between conditions (p = 0.89) representing not change in albumin adjusted calcium as a response to feeding and exercise.

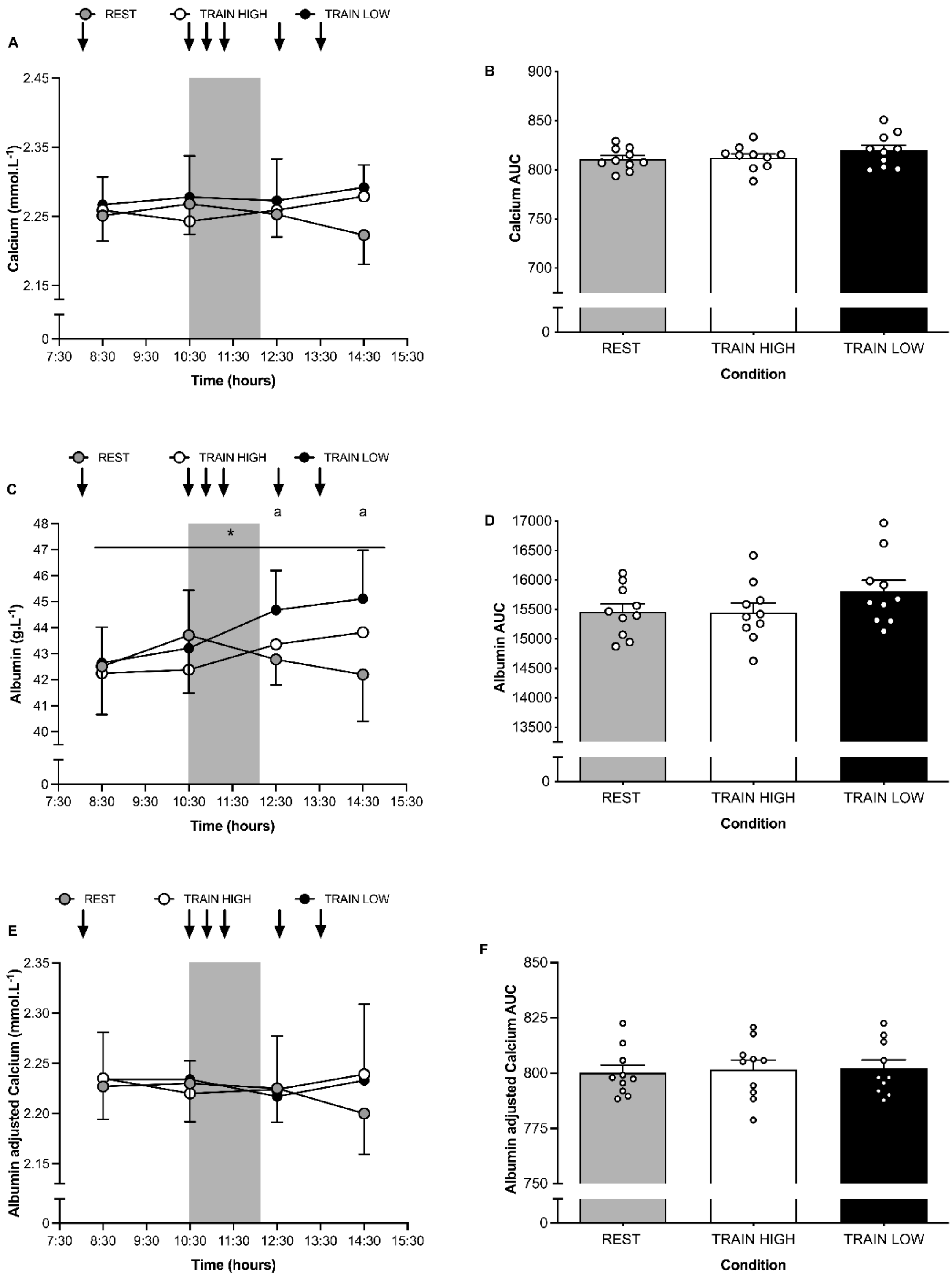

Figure 19. Serum calcium (A), albumin (C) and albumin adjusted calcium (E) concentrations before, during and after training. Shaded grey area denotes pitch-based training, downward arrows denote timing of feeding. Total area under the curve (AUC) for calcium (B), albumin (D) and albumin adjusted calcium (F) is also shown.* Denotes significant main effect for difference between conditions, [a] denotes significant pairwise comparison difference from 08:30, all $p < 0.05$. Grey, white and black bars represent mean data, individual data points are shown by white circles.

6.5 Discussion

In confirming our hypothesis, the present data demonstrate that completing an acute soccer-specific training session with reduced CHO availability increases bone resorption in academy soccer players. However, in contrast with our hypothesis, we also report that training with reduced CHO availability increases bone formation markers. Such alterations to markers of bone (re)modelling also occurred independent to changes in markers of calcium metabolism. Although the chronic implications of such acute fluctuations in bone (re)modelling markers could not be determined, it is possible that the combination of sub-optimal CHO intakes and high daily training volumes may in part, contribute to an increased risk of bone stress related injury and compromise bone development during growth and maturation. This assertion is especially relevant to the present population given the high daily energy demands associated with formalised training programmes, a culture of under-fuelling, and the prevalence of growth-related injuries.

Both longitudinal (Varley et al., 2023) and cross-sectional (Hagman et al., 2018) studies using bone imaging through employment of radioactive tracers (i.e., DEXA) demonstrate that the loading stimulus associated with soccer training is anabolic to bone. It has also been reported that the loading stimulus induced by 12 weeks of soccer-specific training in academy players (with similar chronological age as the present cohort) was sufficient to induce increased tibial bone mass and density (Varley et al., 2023), whereas the training stimulus completed by a control group of recreational soccer players (*i.e.,* not enrolled on a formalised academy coaching programme) did not induce any detectable changes in bone characteristics (Varley et al., 2023). The present study extends our understanding of bone responses to soccer training by representing the first attempt to evaluate the acute bone response of markers of bone resorption and formation and calcium metabolism responses induced by an acute soccer training session in male players. Indeed, the ecological validity of our experimental model is strengthened by utilising a "real world" training session involving a field-based training session, as opposed to laboratory-based exercise. We also evaluated the role of CHO availability in modulating bone resorption and formation markers by utilising a repeated measures crossover design whereby players completed the session in conditions considered as best practice nutrition (Collins et al., 2021) or those indicative of the sub-optimal fuelling practices (*i.e.,* CHO restriction before, during and after training) previously reported by our group (Stables et al., 2022). Importantly, no significant differences were apparent in external and internal training load metrics between trials (see Table 15), thus suggesting that the training stimulus (*i.e.,* mechanical load) was likely similar between TRAIN HIGH and TRAIN LOW trials.

As an accepted marker of bone resorption, it is now well documented that βCTX is sensitive to the acute effects of both feeding and exercise (Walsh and Henriksen, 2010). Notwithstanding the circadian variation of this marker, the data presented here is in agreement with previous literature (Clowes et al., 2002) in considering that we observed that consumption of "breakfast" in all three trials significantly reduced βCTX concentrations in the two-hour postprandial period (see Figure 19A), where the magnitude of reduction was more pronounced when CHO had been consumed in the TRAIN HIGH trial. In accordance with the effects of acute exercise (Dolan et al., 2022), completion of the acute soccer training session subsequently increased βCTX, although the effects of CHO feeding before and during the TRAIN HIGH trial ensured that absolute βCTX concentrations remained suppressed when compared with the TRAIN LOW trial. Similar to the effects of feeding at breakfast, post-training nutrient intake (*i.e.,* lunch) also caused a reduction in βCTX where again, the consumption of CHO in the TRAIN HIGH trial caused a greater magnitude of reduction. When taken together, such data clearly demonstrate that CHO feeding reduces βCTX concentrations (even in the presence of a high-intensity training stimulus) compared to training without CHO intake pre-, during and post training, which are nutritional practices presented in Chapter Four. We acknowledge, however, that future studies with greater access to elite participants and the potential for a greater sampling frequency should also obtain a fasted true baseline blood sample with additional sampling in the hours post-training to better understand changes in bone (re)modelling markers in the hours after pitch-based training. The relatively small number of samples which were obtained due to the nature of participants in this study may be considered a limitation to this study.

As a marker of bone formation, exercise-induced changes in PINP are less responsive than changes in βCTX, owing to the temporal processes underpinning bone resorption and formation whereby the basic multicellular unit is activated by an initial increase in bone resorption such that changes in bone formation would lag that of bone resorption (Dolan et al., 2020). Given the greater degree of uncoupled and site-specific bone remodelling that occurs in adolescence (in addition to (re)modelling during skeletal growth in adolescence), it should also be noted that bone formation markers will be higher within this population as players develop peak bone mass (Seeman and Delmas, 2006). The compounding impact upon these acute changes however would likely be negated given that the average age of participants in this study (17.4 ± 0.8 years) would be at the time whereby academy soccer players typically approach full skeletal maturity (Johnson et al., 2017) and a number of years post-PHV when growth rate would be highest during adolescence (Philippaerts et al., 2006). Previous research showed significant increases in PINP in adult males immediately after 60 minutes of treadmill running at 65% VO_{2max} (Scott et al., 2012), the magnitude of which was not affected if the exercise was performed fasted or fed (as achieved by a standardised breakfast of approximately

80 g CHO, 20 g fat, 10 g protein and 116 mg calcium). In contrast, Sale et al. (2015) later reported that the exercise-induced increases in PINP (also in adult males) immediately after 120 minutes of running at 70% VO_{2max} was significantly reduced when CHO was ingested during exercise at a rate of 0.7 $g.kg^{-1}$ per hour (equivalent to approximately 50 $g.h^{-1}$). Such data appear to agree with the present study given that we also observed significant increases in PINP at 12:30 (*i.e.,* post-training) when compared with the baseline sample at 08:30 (see Figure 19C) and also when considering the fact that the AUC for PINP was significantly greater in TRAIN LOW versus both TRAIN HIGH and REST (see Figure 19D). Although there is debate within the literature (Dolan et al., 2022) as to the physiological significance of such small and transient increases in PINP (*i.e.,* such short-term timescales may not be representative of true exercise-induced increase in collagen deposition), it is noteworthy that the model of acute CHO restriction used here increased both bone (re)modelling markers βCTX and PINP. In this way, evaluation of the temporal responses of PINP across the sampling period are suggestive of the possibility that such elevated PINP responses in TRAIN LOW may occur as a compensatory response to the earlier challenge of CHO (and energy) restriction at breakfast and during exercise that has already presented as acute increases in bone resorption markers, which would otherwise be attenuated in the TRAIN HIGH trial due to greater CHO and energy availability. As such, the early and later responses of βCTX and PINP, may indeed represent an acute physiological adjustment to rates of bone (re)modelling markers to try and maintain the dynamic balance between bone resorption and formation in the face of the physiological challenge of both CHO restriction and high-intensity exercise. Such data suggest that under conditions of low CHO availability, acute soccer-specific training significantly increases PINP, yet it was not possible to determine the physiological relevance of such an acute change to bone tissue. To that end, it should be noted that βCTX and PINP are not specific to bone tissue

and the increase observed here could also reflect leakage from connective tissue or collagen metabolism from other tissues, specifically tendons and ligaments (Vasikaran et al., 2011).

The mechanisms by which manipulation of CHO availability before, during and after exercise affects exercise-induced alterations in markers of bone resorption and formation are not yet well understood. However, in agreement with previous researchers (Scott et al., 2012, Sale et al., 2015), we also observed that CHO restriction did not affect albumin adjusted calcium (see Figure 19 A, B, E and F) or exercise-induced increases in PTH (see Figure 18 E and F) suggesting that calcium metabolism is not regulated by CHO availability. Although we acknowledge that our frequency of sampling did not allow for evaluation of calcium metabolism during exercise (nor the ability to measure free calcium due to the limitations of testing in the elite athlete environment, particularly as this pertains to the required timeframe of sampling), our data are in support of the hypothesis that CHO likely regulates exercise-induced bone resorption and formation through pathways not related to calcium metabolism. Rather, it is possible that the provision of nutrient intake before exercise causes an initial reduction in bone resorption that is mediated, in part, through the gut derived incretin hormones of glucose-dependent insulinotropic polypeptide (GIP) and glucagon-like peptide 1 (GLP-1) (Bergmann et al., 2019). The combination of CHO restriction before and during high-intensity exercise may also facilitate cross-talk between muscle, adipocytes and bone (Kirk et al., 2020), as facilitated through the action of key myokine and adipokines such as interleukin 6 and leptin. While outside the scope of this work, evidence in support for a modulatory role of interleukin-6 (IL-6) in regulation of acute markers of bone metabolism is provided from several studies. For example, when exercising in conditions of CHO restriction (Heikura et al., 2019) or with low muscle glycogen (Keller et al., 2001b, Steensberg et al., 2001, Keller et al., 2001a), release of muscle derived IL-6 (Febbraio and Pedersen, 2002) and circulating IL-6 concentrations (Starkie et al., 2001) are augmented compared to when CHO has been ingested before and/or during exercise. In such situations, IL-6 is thought to act in an endocrine like action upon the liver to maintain glucose homeostasis (Pedersen and Febbraio, 2008). However, its effect on bone may be less favourable and indeed, evidence from *in vitro* and animal models collectively demonstrate that IL-6, in the presence of soluble IL-6 receptors, can stimulate osteoclastogenesis and a net resorptive effect (Kirk et al., 2020). Interestingly, Sale et al. (2015) previously observed a significant correlation between exercise-induced changes in IL-6 and βCTX, thus providing further evidence in support of a mechanistic link between muscle and bone under the physiological stress of CHO restriction and exercise. In addition, we previously observed in a similar model of CHO (and energy) restriction to that studied here (*i.e.,* restriction of CHO intake before, during and after 1 hour of high-intensity intermittent running) that exercise completed with reduced CHO availability significantly augmented both IL-6 and leptin concentrations immediately post- and at 3 hours post-exercise compared with exercise completed in conditions where CHO had been fed before (3 $g.kg^{-1}$), during (60 g) and after (4 $g.kg^{-1}$) exercise (Hammond et al., 2019b). Nonetheless, we acknowledge the limitation that our sampling volume and frequency did not allow us to assess a broader range of bone markers alongside myokine, osteokine and adipokine related signalling, including both blood glucose and insulin. Notably glucose and insulin have been shown to acutely attenuate bone resorption (Sherk et al., 2020), which may provide further context for the results of this study. Indeed while the bone resorption and formation markers employed within this study are reference bone markers and biochemical by-products of osteoblast activity (Vasikaran et al., 2011), there remains no bone marker that reflects the bone (re)modelling process with perfect specificity and sensitivity (Vasikaran, 2008). Further studies are now required to provide a more rigorous assessment of the mechanisms by which CHO restriction and exercise may regulate bone resorption.

It is thought that an initial transient period of bone catabolism is necessary to stimulate the bone (re)modelling cycle (Robling et al., 2006, Dolan et al., 2020) and hence, an initial increase in exercise-induced bone resorption provides the stimulus to subsequently increase bone formation. In this regard, our data could be interpreted to support the anabolic potential of soccer training for bone, given that the training session completed here was sufficient to initiate the acute bone (re)modelling process. However, if the process of resorption is left unchecked and the sub-optimal fuelling and recovery practices observed in Chapter Four are repeated (as stimulated by high daily training volumes and sub-optimal CHO and energy intake *i.e.,* TRAIN LOW conditions), this may favour bone resorption. Such a model has been suggested to play a contributory role in mediating the low bone mineral density in road cyclists (Hilkens et al., 2023) and of note, most prevalent injury that occurs in academy players during the times of peak height velocity has been reported as growth related injuries to the lower back, sacrum, pelvis, and knee (Hall et al., 2020). Although there is a potential theoretical benefits (e.g. cell signalling regulating oxidative adaptions) for consuming reduced CHO intake in relation to aerobic type training (Bartlett et al., 2015, Impey et al., 2016), our data further demonstrate that athletes who wish to regularly train in a state of reduced CHO availability should be aware of potential negative effects upon bone. This is of specific relevance to both male and female adolescent athletes and the present data provide further justification that CHO restriction should not be practiced in athletic populations who are not yet physically mature.

In summary, the present study provides the first report to characterise the effects of an acute soccer-specific training session on markers of bone resorption, bone formation and calcium metabolism in male academy soccer players. Importantly, our data demonstrate that soccer training increases bone (re)modelling makers and that training with reduced CHO availability (such as reported in academy players in Chapter Four) augments bone resorption and formation markers. While an increase in bone formation markers may be seen as anabolic to bone, it is suggested that the commonly reported sub-optimal fuelling practices of academy players (as replicated in the present experimental design) and apparent increase in bone resorption markers may impair skeletal development during growth and maturation as players transition through the academy development pathway. Further studies are now required to ascertain the mechanisms by which training with CHO availability regulates bone resorption. Given the growing body of literature demonstrating that CHO availability affects exercise-induced bone (re)modelling markers, our data also suggest that the benefits of CHO should be communicated to players and stakeholders over and above that of physical and technical performance.

Chapter 7

A qualitative investigation of the reasons underpinning sub-optimal fuelling and recovery practices in a Category One Academy from The English Premier League.

Having assessed the acute fuelling and recovery practices of academy soccer players in the acute period in the hours before, during and after training, the aim of this chapter was to explore the barriers and enablers to optimal nutritional intake at this time. Through utilisation of the COM-B model this chapter interviewed players, parents and staff members providing a qualitative estimation of the reasons players fail to achieve optimal energy and carbohydrate intake pre-, during and post-training.

7.1 Abstract

This study aimed to understand the barriers and enablers to players achieving optimal energy macronutrient intake in the acute period in the pre-, during and post-training. Semi-structured interviews (36 ± 12 min; range 20 - 61 min) were conducted with 31 participants from an English Category One academy, including players (n = 8), parents/guardians (n = 10), soccer coaches (n = 3), senior management (n = 2) sport scientists (n = 3), physiotherapists (n = 2), player care (n = 1), psychology (n=1) and catering staff (n = 1). In using the COM-B model data demonstrate a lack of understanding of nutritional requirements (i.e., capability) with reference to the four hours pre-, during and four hours post-training as a main barrier to food and drink intake. Parents and players cited a lack of opportunity, namely a lack of food and drink provision and a lack of time as a key barrier to optimal energy and carbohydrate intake, especially in the hours before training where external factors such as travel and education commitments present a further barrier. Staff highlighted that player motivation was a barrier, yet increased food provision, providing time for players to consume energy and carbohydrate both before and during sessions would act as an enabler to facilitate positive fuelling practices. Data highlights the needs for targeted stakeholder education with reference to pre-, during and post-training, with host clubs having a responsibility of to either food and drink provision or to schedule time to improve energy and macronutrient intake at this vital time.

7.2 Introduction

As players progress through the distinct development phases of English soccer academies, that is the Foundation Phase (FP: under 9-11 years old), Youth Development Phase (YDP: under 12-16 years old) and Professional Development Phase (PDP: under 17-21 years old) they are exposed to increasing pitch-based loading (Hannon et al., 2021a). Despite the need for sufficient totality of energy and macronutrient intake within appropriate timing of training, external factors such as full-time education, travel to and from training and non-football specific activity (i.e., gym-based strength training) have implications for a player's ability to achieve optimal nutritional intake (Carney et al., 2024). Data presented in Chapters Four and Five respectively highlights how players fail to achieve optimal both acute carbohydrate intake pre- and post-training (with players on occasion failing to consume any food or drink) (Stables et al., 2022) and chronic carbohydrate intake through the training week (Stables et al., 2023). For example, although experiencing rapid growth and maturation (Hannon et al., 2020), data presented in Chapter Four details how U13 aged players consumed less than 1 $g.kg^{-1}$ in the four hours before and the four hours after training (Stables et al., 2022).

The additional training and match load experienced by academy players reported in Chapter Five coupled with rapid growth and maturation results in daily energy expenditures which are ~ 750 $kcal.day^{-1}$ greater than their age matched counterparts (Stables et al., 2023). The comparable pitch-based loading to their adult counterparts (Anderson et al., 2017) at this time results in academy soccer players exhibiting total daily energy expenditures (*i.e.,* 3000 – 5000 $kcal.day^{-1}$) which are comparable to (or exceed) adult players from the Premier League (Anderson et al., 2016a, Hannon et al., 2021b). To this end there is a clear need to consume optimal energy and carbohydrate intake in the hours before and after training to support technical and physical performance (Goedecke et al., 2013). Data within this thesis (Chapter

Six) has shown that failure to consume sufficient carbohydrate in the hours before, during and after training increases acute bone (re)modelling, which if repeated over time may have implications for injury risk and bone health. Indeed such data provides rationale as to why injury frequency to skeletal structures, specifically the hip, pelvis and sacrum is greatest during adolescence (Hall et al., 2020). In contrast optimal carbohydrate consumption in the two hours before, during and two hours after soccer training was reported in Chapter Six to suppress βCTX activity (a marker of bone resorption) to below that of βCTX activity at rest (Stables et al., 2024). When considering the complex interplay between nutrient (specifically carbohydrate) availability and bone (re)modelling in academy soccer players, it is essential that academy players seek to increase energy and carbohydrate consumption in the acute phase before, during and after training.

In attempts to better understand the reasons underpinning nutritional choices in athletes, the COM-B model provides an approach which has been utilised in both adult male (Carter et al., 2022) and academy soccer players (Carney et al., 2024). The COM-B model explores an individual's physical capability (*i.e.,* knowledge of acute fuelling requirements), the social and physical opportunity (*i.e.,* appropriate pre- and post-training food provision) and the motivation to complete such a behaviour (*i.e.,* for a performance outcome) in the face of conflicting alternatives (Michie et al., 2018). Without the physical and psychological capability, the physical and social opportunity or the reflective and automatic motivation to display a behaviour (*i.e.,* increase energy and macronutrient intake in the hours before and after training) it is unlikely that a behaviour change outcome would be achieved (Michie, 2014). Indeed, while previous observations highlight nutritional knowledge (*i.e.,* capability), time and food provision (*i.e.,* opportunity) as well as role modelling (*i.e.,* motivation) as factors which act as both barriers and enablers to optimal nutritional practice in academy soccer (Carter et al., 2022), no data exists with reference to the acute period in the hours before, during and after training.

In using the COM-B framework, our aim was to qualitatively explore the behaviours that underpin nutritional intake of academy soccer players in the acute period before and after training. We aimed to determine if a lack of capability, opportunity or motivation was the reason for sub-optimal fuelling and recovery practices seen within this population. To address our aim we interviewed a cohort of players (n = 8), parents and / or guardians (n = 10) and members of staff in varying roles (excluding sport nutritionists) (n = 13) from a Category One academy from the EPL. It is hoped that the present data will inform player and stakeholder education, and behaviour change interventions seeking to increase energy and macronutrient intake during the hours before and after pitch-based training.

7.3 Methods

A relativist ontology and post-positivist epistemology, which assumes that reality is relative according to how each individual experiences it (Sparkes and Smith, 2014), comprised the philosophical underpinnings to this study. To address our aims, we undertook a qualitative investigation to understand the experiences and perceptions of individuals (*i.e.,* players, parents and staff members) within complex social environments (*i.e.,* soccer academies) (Sparkes and Smith, 2014) using a COM-B approach (Michie et al., 2011). The sampling, data collection, and data analysis procedures outlined below sought to establish a player's capability, opportunity and motivation to achieve optimal nutritional intake pre-, during and post-training. This approach considers the role of the first author as the performance nutritionist working at the club, acknowledging that their identity within the social context (and how this is viewed by participants) may influence what they observe and therefore create biases which impact upon conclusions drawn from data provided by the participants.

7.3.1 Sample

To gain detailed insights into the multiple perspectives of nutrition in academy soccer players, parents, and staff from a variety of roles from an English Premier League academy of Category One status were invited to take part in this study. This approach is comparable to previous qualitative explorations of nutrition practices in professional sport (Logue et al., 2021, Carney et al., 2024, Carter et al., 2022, McHaffie et al., 2022) and allowed for a broad understanding of the soccer context in question. Participants invited to take part in this study were contacted through a gatekeeper at the club via an email including details of the study and participant information details. Data drawn from this single club allowed for specific insights and actions to be formed upon the data provided both to the host club (Lobo et al., 2017) and extrapolation across the English Premier and Football League. All players (n = 8) recruited in this study were all enrolled on a full-time programme at the host club. Parents or guardians of players from the Youth Development Phase (YDP; aged 11 - 16) (n = 10) also took part. Staff members all worked full-time at the club in varying roles at the time of data collection. These roles included soccer coaches (n = 3), senior management (n = 2), sport scientists (n = 3), physiotherapists (n = 2), player care (n = 1), psychology (n=1) and catering staff (n = 1). This sample allowed for an in depth understanding of nutrition in academy soccer. Ethical approval was granted by Liverpool John Moores University Ethics Committee (22/SPS/081) 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. Consistent with qualitative research (Sparkes and Smith, 2014), the sample size was not decided a priori, but determined by the analysis, with recruitment stopping within participant groups once saturation occurred. This involved the lead researcher ceasing to recruit participants when no new insights were derived from further interviews.

7.3.2 Data Collection

Semi-structured, 'open-ended' (Gall et al., 1996) interviews were undertaken with all participants. Questions were presented in a conversational and informal manner, to allow for maximal voluntary contribution and detail (Lincoln, 1985), aiming to understand the lived experiences, thoughts and perceptions of all stakeholders within the ecosystem of academy soccer (Sparkes and Smith 2014). The data sampling, collection and analysis outlined below provide aimed to provide a succinct and thorough assessment of the barriers and enablers to players achieving optimum energy and macronutrient intake in the four hours before and the four hours after soccer training. Open ended questions were followed by 'probing' (Jones and Gratton, 2014) via naturally occurring follow-up questions allowing for further depth in responses (Turner III, 2010). This format of data collection allowed participants to express their experiences and opinions with minimal constraints and to self-navigate towards areas they felt significant (Clarke and Braun, 2013) whilst aiming to reduce bias towards an answer on the side of the interviewer. The interview was centred on exploring the participants' perceptions on the role of acute fuelling and recovery practices before and after academy soccer training, whilst aiming to establish the barriers to optimal practice. A sample of questions (parent / guardian questions) outlined in table 16 were devised with the study aims and findings of previous literature in mind (Hannon et al., 2021b; Carney et al., 2022; Carter et al. 2022) based upon founding literature of the COM-B model of behaviour change. The questions were devised by the lead research based upon existing literature with support of the wider research team who acted as "critical friends" given their experience in qualitative and quantitative data collection within academy soccer.

All participants were invited to take part in the interview at the club's training facility. If they were unable to attend the training facilities at the club, participants were offered the option of taking part in the interview via online software (Microsoft Teams) with cameras on. All interviews were recorded and subsequently transcribed verbatim. The interviewer was acquainted with the academy soccer subculture having worked as a performance nutritionist in the industry for the previous three years. Whilst this may be viewed negatively due to the potential for them to lead the interview based on their own personal biases and experiences, this was deemed advantageous due to their relationship with participants allowing for free discussion in addition to fluency in the interviewer's jargon and informal terminology enhanced by the open nature of the discussion (Cook et al., 2014).

Table 16 A sample of parents / guardian questions with prompts assessing the barriers and enablers to optimal nutritional intake in the hours before and after training.

DOMAIN 1: CAPABILITY

Does the participant have the relevant psychological (e.g. knowledge) and physical (e.g. practical skills) capability to nutritionally prepare and recover from training?

Q1: How would you describe the role of nutrition in supporting the development of an academy player?

PROMPTS AND THOUGHT STIMULUS: Probe for understanding of meeting fuel and energy demands (e.g. supporting daily training intensity), supporting growth and maturation (e.g. muscle and skeletal growth), reducing injury and illness risk etc

Q2: Can you describe the function of carbohydrate, protein and fat within the diet of an academy footballer? Do you know what foods are rich in carbohydrate, fat and protein?

PROMPTS AND THOUGHT STIMULUS: Probe for basic understanding of macronutrients and sources etc

Q3: Do you know what types of foods an academy player should be eating before and after training? Do you know what times an academy player should be consuming foods before and after training? What does your child currently eat before and after training and when do they normally eat it?

PROMPTS AND THOUGHT STIMULUS: Probe understanding of timings in relation to training as well as what foods participants think their child should be eating etc

Q4: Do you understand what portion sizes of certain foods players should be consuming before and after training?

PROMPTS AND THOUGHT STIMULUS: Probe participants understanding of participants ability to actively plan pre-training and post-training meals etc

Q5: Relating to questions 2, 3 and 4, what level of understanding do you believe that your child has to the role of macronutrients, the types and the portions of foods they should be having before and after training.

Q6: How confident are you that you have the relevant cooking or food preparation skills to actively plan a pre-training and post-training meal?

PROMPTS AND THOUGHT STIMULUS: Probe participant's ability to purchase the correct foods and also plan, cook and prepare a relevant pre-training and post-training meal etc

Q6: What are the key gaps in your knowledge or practical skills related to food preparation that currently prevent your child from fuelling and recovering from training?

PROMPTS AND THOUGHT STIMULUS: Probe participant's perception of barriers to optimal fuelling and recovery etc

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DOMAIN 2: OPPORTUNITY

Does the participant have the relevant physical (e.g. time, location, finance resources) and social opportunity (e.g. access to support network and culture of school, home life and academy) to nutritionally prepare and recover from training?

Q1: Do you feel that you have sufficient time available to prepare foods and drinks which allow your child to fuel for training and recover from training?

PROMPTS AND THOUGHT STIMULUS: Probe for barriers related to timing of school, time taken to travel to and from training etc

Q2: Do you feel that you have sufficient food available (at home / on route to training etc) to allow your child to nutritionally prepare and recover from academy training?

PROMPTS AND THOUGHT STIMULUS: Probe for food availability at home and to purchase on route, probe for what their physical journey looks like in terms of location and timing between school and training and training and home etc

Q3: Do you feel that you have the sufficient financial resources allowing your child to nutritionally prepare and recover from academy training?

PROMPTS AND THOUGHT STIMULUS: Probe for the role of finance as a limiting factor to optimal nutrition practices etc

Q4: Do you feel that the people in your support network and environment (e.g. school, academy) supports you and your child to nutritionally prepare and recover from academy training?

PROMPTS AND THOUGHT STIMULUS: Probe for role of stakeholders such as schoolteachers, parents, siblings, grandparents, academy coaches etc in helping you to nutritionally prepare and recover

Q5: Within your present environment (e.g. home / school life, academy environment, time available, financial resource etc), what do you perceive as the biggest barrier that could prevent your child from optimally preparing and recovering from training?

PROMPTS AND THOUGHT STIMULUS: Probe for perceptions on barriers related to physical and social opportunity to nutritionally prepare and recover from training etc

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DOMAIN 3: MOTIVATION

Does the participant have the relevant reflective (e.g. beliefs) and automatic motivation (e.g. impulses, drives, habits) to nutritionally prepare and recover from training?

Q1: What are your perceived benefits from optimal nutrition before and after training? What would the impact be during and after each training session and how would it impact your son if you performed this routine long term? Have you any prior experiences where nutrition has positively affected the training sessions your son has partaken in?

PROMPTS AND THOUGHT STIMULUS: Probe for participants beliefs on how nutrition might positively affect development, performance, health and wellbeing?

Q2: What are the perceived negative consequences from not fuelling correctly before and after training? What would the impact be during and after each training session and how would it impact your son if you performed this routine long term? Have you any prior experiences where nutrition has negatively affected training sessions your son has partaken in?

PROMPTS AND THOUGHT STIMULUS: Probe for participants beliefs on how under-fuelling might negatively affect development, performance, health and wellbeing?

Q3: Have you got a current nutrition plan that you follow before and after training that is intended to help your son nutritionally prepare and recover from training? If so, what has influenced your beliefs around nutrition? Is the plan suited for your son's preferred food preferences and tastes?

PROMPTS AND THOUGHT STIMULUS: Probe for participant's motivation to follow a plan and who has influenced beliefs

Q4: Does your child show any good habits or routines that help them to nutritionally prepare and recover from training? Does your child have any bad habits that can prevent them from nutritionally preparing and recovering from training?

PROMPTS AND THOUGHT STIMULUS: Probe for positive and negative habit formation and input from any associated stakeholders such as parent that can facilitate good or bad habit formations etc

Q5: What factors would help you and your child to stay on track when following a nutrition plan that is designed to help them nutritionally prepare and recovery from training?

PROMPTS AND THOUGHT STIMULUS: Probe for participants understanding of routines, nudges and role of stakeholders such as parents and coaches in influencing motivation and behaviour etc

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7.3.3 Data Analysis

All interviews were recorded and transcribed verbatim into a word document. A six-stage process of thematic analysis was employed (Braun and Clarke, 2006) as previously cited by Carter et al., (2022) and Carney et al., (2024): (1) familiarisation and immersion of the data was achieved by repeated reading and listening of the data during the transcription process; (2) a systematic process of initial coding (NVivo) allowed for any relevant content to be identified; (3) initial codes were re-examined to identify patterns in the data and generate initial themes; (4) identified themes were reviewed for their appropriateness by the research team by comparing them to the raw data; (5) following agreement of the themes, they were refined, defined and named; and finally, (6) data extracts from each theme were used to provide a concise, coherent, logical, nonrepetitive, and interesting account of the story the data tell, both within and across themes (Braun and Clarke, 2006).

6.3.4 Rigour

Several procedures were undertaken to ensure scientific rigour. This included the recruitment of a varied sample and by piloting the interview questions. Members of the research group and those with experience in both the research and applied aspect of academy soccer independent of the primary author also acted as a critical friend to provide critique of the questions used in the data sampling prior to data collection. In doing so, the team sought to provide credible and transparent perceptions of the role of nutrition in the development and performance of academy soccer players. The findings and discussion section that follows presents four themes and relevant quotations from the data, allowing readers to interpret the data in their own way and consider the transferability of findings to their own context (Smith, 2018).

7.4 Findings and Discussion

Via a reflexive thematic analysis of the interviews (mean: 36 ± 12 min; range 20 - 61 min), themes were established under an individual's capability, opportunity or motivation, that present a narrative of the key issues underpinning acute sub-optimal nutritional practices of academy soccer players. It was evident there were several common themes across players, support staff and parents / guardians within the COM-B framework. Such themes consisted of capability (i.e., generic nutritional knowledge and a lack of understanding of optimal fuelling and recovery practices), opportunity (i.e., food provision pre- and post-training and a lack of time pre- and post-training) and motivation (i.e., acute performance implications and long-term consequences of repeated behaviours). These themes are presented below, and player and stakeholder quotes are presented verbatim to support the narrative.

7.4.1 Theme 1 Capability : A variation in nutritional knowledge across the academy soccer ecosystem.

Academy soccer players, support staff and parents / guardians have previously cited good nutritional knowledge as an enabler to adherence of optimal nutritional intake, despite conceding that their knowledge could be improved (Carter et al., 2022). It is well established that the nutritional knowledge of soccer players is poor (Andrews and Itsiopoulos, 2016, Devlin et al., 2017) which was evident within this data set with many stakeholders unable to articulate the role of acute fuelling pre- and post-training. In part it is fair to attribute a lack of nutritional understanding to the limited access to a full-time nutritionist (Carney et al., 2022) with reliance upon other staff members or external sources for education support (Carney et al., 2024). Indeed it is often strength and conditioning coaches or the internet which disseminate nutritional advice which can be incorrect or harmful (Cockburn et al., 2014). Such a sentiment was highlighted by one member of sport science staff: "*I think that's why it's important that you can believe in that person or not just you, the nutritionist leans on that person so that everyone is singing from the same hymn sheet… but the flip side of that is coaches will often pass on information that is maybe not always the right information or not exactly how you want it"*. The consequence is a lack of understanding of the nutritional requirements before and after training, as conceded by one parent *"It's difficult cos I come from a, with much, like, very, very little knowledge".* Although parents and guardians are often responsible for food provision to younger players at this time, they often lack adequate theoretical and practical knowledge to facilitate optimal pre- or post-training fuelling, as highlighted here by sport scientist 1

Sport Scientist 1: *"Knowing, depending on when they get home, you're gonna eat whatever's in the cupboard, you're not gonna go out and get something else if you're 13 so it's like what do the parents have and then where do they get that education from to make that decision and then the shop to buy that and then to cook it when they're at home."*

A theory which was echoed by a parent of a YDP player:

Parent 1: *"I think I just panic, like you said, to try and make sure I'm refuelling him enough just over three meals. So I'd probably say on his training days he's probably having four cos he'll have his lunch at school, a snack before he comes training and his food after. So those probably days I am but it's just what can I do different other than pasta and chicken?"*

Throughout the data it became clear there is a great disparity of understanding by academy players themselves of their nutritional needs. As highlighted firstly by academy coach who highlighted that players are not necessarily aware of the additional demands caused by the academy programme:

Coach 1:*"The other one that you've probably mentioned there is the lads, some of the lads are fed, if you're an Under 14, like, maybe the education is 'well you're not actually just an Under 14, you're also on the academy programme"*.

With a member of senior management suggesting that player's knowledge would correlate with their age group, with variations in knowledge through the academy system:

Senior Management 1:*"I have some decent connections with our 13s, some of them would be able to tell you, some of them wouldn't. Some of them, they would be able to prescribe what they should probably be eating before, during, well, before and after stuff. Erm, most 18s I would say should be able to describe what they should be eating, er, and then on a sliding scale downwards"*.

The suggestion that a player's nutritional knowledge improved with age was reinforced by PDP player 1: "*I think, well, I think obviously coming in as, like, a scholar I weren't, I weren't really aware… I'd say my knowledge on, like, the importance of it especially, like, before has got a lot better"*. It is perhaps unsurprising that a player feels their knowledge improves as they join the professional development phase due to the skewed nature of provision and education towards players at this age (Carney et al., 2022). This was then reinforced by the view of academy parent two, in suggesting how their son's understanding will improve as they progress through the academy system.

Parent 2: *"I think as (player name) matures and gets older and more independent and, you know, ultimately spends less time with us as parents, erm, I think it's huge that he understands what he has to eat and why he has to eat it and when he has to eat it. I don't think he's there yet with it."*

A view which was shared by two academy staff members, who believed that players tend to "fuel" or "recover" as part of their daily routine, rather than with conscious thought to the health and performance benefit. A view which had previously been cited in academy soccer with reference to the role of nutrition in player development (Carney et al., 2024).

Sport Scientist 1*: "For a 12 year old they don't necessarily think about that, they might just be 'oh I normally have a snack before I train and then my mum or dad makes me dinner', erm, so the principles remain similar, obviously they'll be hydrating in the session as well so that's maybe their intra fuel if you like but the, erm, the principles remain the same but it's probably just the depth of understanding, the depth of, erm, knowledge around it."*

Player Care Staff 1: *"So getting up and having cereal or porridge or something is one thing or toast and having that before training, getting up and looking at the grams compared to body mass, body weight and what goals I'm after is, yeah, I don't think they've got to that sort of point, erm, in terms of what they actually need to be applying and eating for them specifically as an athlete"*

This was reinforced by sport scientist two when describing what he thought was appropriate for a younger player to consume pre-training, compared to their older counterparts "*if an under 12 was to have a cereal bar in the car on the way to training you'd probably be happy with that as their pre-training fuel, if an under 18 was just to wake up and have or a 19 year old,* *like we said, wake up and have a cereal bar for breakfast and then train we probably wouldn't be happy with that as pre-training fuel"*. Many staff members who act as surrogates for passing nutritional information on to players conceded a lack of understanding with regards to the carbohydrate needs of players in the hours before and after training. This notion was exemplified by a firstly a physiotherapist and then sport scientist, both working within the PDP:

Physiotherapist 1:"*Not, not really, no I wouldn't say that I would know definitely what he should definitely be eating before and what after. I know kind of carbohydrates are kind of quite important, but I wouldn't know what it should be."*

Sport Scientist 2: *"carbohydrates I know that… that definitely goes off, erm, per kilogram of body weight and I don't know off the top of my head. I wouldn't be comfortable, yeah, with prescribing that"*

This sentiment was the same with reference to protein requirements pre- and post-session, with staff and players alike able only to articulate basic recommendations:

Sport Scientist 2: *"So as long as from my perspective if I was giving someone 20-25 grams after a heavy bout of exercise, I'd be quite happy with that."*

Physiotherapist 2: *"Without knowing the specifics in terms of, like, I have no idea in terms of protein, in terms of, like, a daily target, in terms of 2g per kg, er, but in terms of, like, pre-session I wouldn't have a huge idea."*

Player 1: "*protein wise get one, one big source of protein, so that be one chicken breast or one piece of salmon, erm, yeah…I know what it should roughly look like on the plate, yeah*"

Inability of support staff to provide nutritional information or relay incorrect information (*i.e.,* sub-optimal carbohydrate prescription) to players and key stakeholders presents a risk to health and performance through players habitually "underfuelling". Data presented in Chapter Six highlighted how failure to consume sufficient energy and macronutrient intake in the hours pre- and post-training, as observed throughout academy age groups in Chapter Four, will have negative implications for acute performance and bone (re) modelling (Stables et al., 2024). If players repeatedly fail to consume optimal energy and carbohydrate intake at this time, there is a risk of chronic implications for growth and development, low energy availability and RED-S (Stellingwerff et al., 2021). In addition to theoretical knowledge, practical nutritional knowledge and cooking skills was highlighted by both staff and players as a barrier to optimal nutrition intake, as described here by one player:

Player 2: "*I would be pushed, if something would happen and I would be pushed to my limit, let's say that, erm, to my limit and I would have to cook for myself, erm, then I would do it and I would learn but probably now my, my confidence in my skills is not the highest but if I would have to then probably I would, er, make sure I, I can cook meals with a good nutrition in it.*"

This experience was reported by a physiotherapist working across the Youth and Professional Development Phases.

Physiotherapist 3: "*I wouldn't think that there's many of them have got the requisite cooking skills or probably with some of them the confidence to be able to go on and do it and try it.*

Previous research within this population has shown the influence of parents and host families on food provision, eluded to here by sport scientist three.

Sport Scientist 3: *I think it's down to their, is it a life skill of being able to cook and prepare food for themselves? Erm, a lot of them have lived at home the majority of their lives and if they don't, they live in digs and food is prepared for them at training, food is prepared for them at home, they're never required to prepare their own food, erm, so as easy as it might be to boil some pasta, they probably aren't comfortable with doing that"*

Despite a clear lack of understanding across all stakeholders, participants could clearly articulate the consequences of underfuelling as outlined by academy coach 1 *"You can definitely tell the periods in which, erm, a player might be fuelled appropriately to when it's, to when they're not. So if you think about players that might have just come out of school release and they might not have eaten since then, they might be, erm, their performance might be lower or, you know, their physical outputs might be slightly lower in the session whereas if they are coming after lunch in their own session then they might be a little bit more engaged, might be a little bit, erm, decision making might be quicker"*. Such data highlights a disconnect between theory and practice, with a knowledge gap which practitioners and policy makers must seek to bridge. As highlighted by sport scientist one, while players are failing to achieve optimal energy and macronutrient intake in the acute period before and after training and the consequences are visible, failure to understand the reasons for under-fuelling is neglected by support staff:

Sport Scientist 1 *"okay they're skipping an exercise in the gym then there's a reason for that, so they either don't understand why they're doing it, they don't like doing it and but maybe then no-one has ever delved into that. If they're skipping (pre-training fuelling) that's not because (nutritionist) hasn't educated them or they haven't been in a workshop, that might just be that they can't eat and that there's nothing in their digs, for example".*

The lack of educational support across the academy ecosystem is well established (Carney et al., 2022) yet there remains no obligation for nutritional education to the ~ 14,300 soccer players enrolled at English Premier League and English Football League academies (Premier League, 2022). Overall theme one demonstrates that players, stakeholders and staff members have poor understanding of the nutritional requirements in the hours pre- and post-training. With this in mind policy makers (*i.e.,* The Premier League) and performance nutritionists must develop targeted educational curriculums to increase knowledge of the acute fuelling and recovery requirements of academy soccer players.

7.4.2 Theme 2 Physical opportunity: academy players and parents are too busy to eat.

A recurring theme within this body of work is the lack of physical opportunity in which academy soccer players have to consume food and drink in the acute period in the hours before and after training. Academy players can be away from home for more than twelve hours per day when factoring in time for full-time education, external physical activity and travel (Carney et al., 2024, Hannon et al., 2020, Johnson et al., 2022). Despite completing comparable training loads to their adult counterparts when not being physically mature (Hannon et al., 2021a), young academy players have a lesser ability to store exogenous carbohydrate to fuel pitch-based training (Timmons et al., 2003). As such importance of optimal energy and carbohydrate intake pre-training cannot be understated. Yet as observed in Chapter Four players fail to consume sufficient energy and carbohydrate at this time, with academy parents highlighting a lack of time in the hours before pitch-based training proving to be a rationale.

Parent 2: *"Yeah. It is a challenge cos I think he's; his lunch time is about 1 o'clock. So he could potentially be going from 12 o'clock to 4 when he gets home and literally a bowl of cereal and then coming out.*

With parents suggesting that schooling has an impact on their son's ability to consume food and drink in the hours before training:

Parent 3: *"He's literally coming in from school, erm, and then we're near enough running out the door. So I try to have something ready for him, erm, sort of in the slow cooker. So he eats a lot of, like, pasta, spaghetti bolognese, scrambled eggs on toast, anything where he can get something quickly into him and off to training."*

The result being that players often have to eat in the car or en-route to training as there is simply not enough time:

Parent 1: *"he finishes at 4 and literally we leave at 4.15. So timing is, it's, it's really, really tight. So it's usually something in the car. So he has to have something in the car, like, today it's been some dry cereal…that's all he's got is a bowl of kind of dry cereal because there's literally no time to do anything else really"*

Parent 4: *"he has to eat a lot of it in the car on the way so straight from school to the Academy and, you know, that's not ideal".*

Within academy staff there was an appreciation that younger academy players, typically those who train in the evening after school experience time as a barrier to a greater extent than their older counterparts, highlighted by the academy psychologist: "*FP and YDP players will have been at school the entire day and then come to us and then they're with us all evening they literally have maybe 20 minutes to eat it sometimes on a really busy school release day".*

Sport Scientist 1: *"I think it's about with the boys who train in the evening it's about getting something into them, the timing obviously isn't gonna be ideal cos if you look at their day, they might start training at 5.30, some of them aren't finishing school until 3.30, 4.00 so they're not gonna be able to get that snack in at that ideal 3-hour window"*

With academy staff members conceding that the busy schedules of academy players make it almost impossible to consume any food or drink between school and training:

Physiotherapist 3: "*I think one of the challenges within the schoolboy programme would be that gap between school and training where it's perhaps a bit too early to have a proper dinner before training but then if they're having nothing from school until after training there's a massive gap and they're gonna be going in under fuelled to training."*

The result of which is players often have to revert away from traditional mealtimes and follow 'ad-hoc' on the go eating practices as a result of their hectic schedules.

Sport Scientist 3*: "like we said, about 3 hours before and then as you're getting closer to the time within, like, 90 minutes, an hour of training having those quicker release energies in those snacks. So that ideal situation but in (an academy player's) life there's so many stuff that goes on that you can't always stick to that."*

This data highlights how a lack of time pre-training is often outside of the control of an academy player and external factors such as schooling compound the barrier of time as concluded here by academy coach 1:*"Can you imagine going into school and going 'oh I've got training in 2 hours, do you mind if I have my whatsit?', 'you're not eating in class' sort of thing ... especially when it's that and they've got journeys to travel. So in our phase you can travel up to an hour and a half."* When taken together it is clear that key stakeholders must facilitate time within schedules to allow players to consume food and drink prior to training. Moreover clubs must seek to facilitate increased food provision to Youth Development phase to correct the correct skewed nature of provision towards the PDP (Carney et al., 2022). The consequence of which is many players may not eat from lunch time at school, or even breakfast both of which will fail to provide the optimal energy and macronutrient requirements inherent with academy programmes (Hannon et al., 2021b). Sub-optimal nutritional practices pre-training will lead to both acute and chronic implications to academy players such as that described by one parent:

Parent 1*: "it's highly competitive and (player's name) come off cos he was dizzy and felt sick and that's when I kind of used that and talked to him and went 'it's because you didn't eat' and he's like 'but we didn't get chance to, we couldn't stop to eat"*

Such a sentiment was reiterated by this coach working within the youth development phase:

Coach 1: *"I don't think they do (have enough time), I don't because they're coming home from school at whatever time they're gonna get in from school, then they've gotta have something in the car… so they come 'I'm light headed, I feel sick, I've got no energy', it's all those bits and you go 'oh are you feeling unwell?' and then you get to the bottom of it and it's 'what have you had to eat?' and 'oh I've not eaten since I had a sausage roll at 10 o'clock this morning at playtime', 'oh okay' and they're like 'oh I've not had chance to eat".*

In addition to a lack of time in the hours before training, there was a similar pattern of a lack of time post-training to consume sufficient energy and carbohydrate.

Parent 1 *"we get home on a good night at 8 o'clock, (player's name) is not one for eating heavy when he comes in from training, he doesn't like it, he'll have cereal. 9 times out of 10. It is difficult, anyone who says this is normal, it's not.*

Parent 5: *We don't get home until about 9, 9.10 so it is a case of, like, he's, erm, getting home, kind of, like, having a quick shower and then having some food and then, er, then, like, obviously sleep as well, sleep's important so it is, like, everything's, like, 100mph just to cram everything in."*

When commenting on a lack of time and nutritional understanding as barriers to achieving sufficient energy and macronutrient intake, players, staff members and parents regularly cited food provision as a key enabler to improving nutritional habits of academy players. Despite being cited to enhance nutritional intake of academy soccer players (Carter et al., 2022) food and drink provision is limited within academy soccer, with older academy players prioritised over players from the Youth Development and Foundation Phases (Carney et al., 2022) despite comparable training loads and daily energy expenditures (Hannon et al., 2021a, Hannon et al., 2021b, Stables et al., 2023). Failure to provide food and drink to players will further stimulate poor nutritional choices (Carter et al., 2022) as highlighted by academy sport scientist two: *"take that problem out of everybody's hands if we can provide the food then can be fuelled correctly for the session. At the moment nobody wins, they don't fuel, they go into training under fuelled and they don't eat until afterwards, after the session's already finished so they're increasing their risk of injury. I think that we need to support them better."*

Academy Psychologist: *"I know that we do provide, erm, post-training food especially at the older age groups but then you still get, you know, the wraps and the milkshakes and things like that for younger age groups. That's potentially not enough and if we think about some players, that might then be the only thing that they have after training."*

While limited to a relatively small number of academy players, provision pre- and post-training may contribute to reaching recommended intake guidelines, achieving total daily energy balance, improve health and performance while acting as an enabler to nutritional intake:

Academy Physiotherapist 3: *"Do you put on a provision before a session? delay sessions? so it's in the window and then refuel lads within the 4 hours after sessions? I think that's probably the easiest thing because that gets rid of the, erm, uncertainty, no, inconsistency."*

Sport Scientist 2: *"I think as myself as, like, a YDP parent if I had to collect my child, have their kit in a bag and take them straight to (host club) and I knew (host club) were fuelling them and feeding them that would be another less worry for me. I'd probably be able to get the child* *there earlier, quicker, erm, and yeah, I think both people could win in that situation if the fuel or the food was already at the training ground."*

This was reinforced by one player reflecting on the difference in his journey from YDP to PDP and the consequences of greater provision in the PDP:

Player 3: "*I'm comparing that to last year (when in the YDP) when I'm obviously not doing as much but I think obviously last year when we had to train and we had to go home and me and my brother would go home and my mum would be, like, would make us food and then it'd be there ready for when we go in. So I'd say, like, obviously now we finish training we have food straight away so, like, we fuel up again straight away."*

Focusing specifically upon the PDP players at the host club, players had no provision of breakfast before training, as such would likely commence training with low carbohydrate availability given that macronutrient intake within this population is typically skewed towards the afternoon and evening (Naughton et al., 2016). When discussing the possibility of food and drink provision to players at this time, many suggested that food provision would be an enabler to increasing energy and carbohydrate intake:

Player 4: *I mean, having, well, if it was an option with food here it'd probably be better even if it meant coming in 15 minutes earlier cos that also would take a bit of pressure off me rather than rushing to make something. So I'd feel a little bit more relaxed."*

Exemplified through this player who discussed not eating breakfast before training in the morning (i.e., typically 10:30), a barrier which could be removed by increasing food provision.

Player 5: *We don't have breakfast… (I am) waking up at 7 o'clock, setting off at 8, not having any food and then coming in being hungry until 12.30."*

Theme two highlights the busy daily schedules of academy soccer players and the role which external factors such as schooling and travel have upon creating a lack of time for players to consume optimal food and drink in the hours before and after training. Players, staff members and parents illuded to the role which increasing food provision pre-, during and post-training may facilitate positive nutritional habits and act as an enabler for players seeking to increase carbohydrate intake as seen in Chapter Five whereby provision form the host club accounted for ~ $125 g.d^{-1}$ carbohydrate intake. Our research group have previously reported that food provision for players in the Youth Development Phase before training in a 'pit-stop' style can increase energy and carbohydrate intake (Hannon et al., 2021b), yet most clubs throughout the EPL and EFL do not provide any form of snacks in the hours before and after training to their players outside of the PDP (Carney et al., 2022). To remove this barrier to optimal nutritional intake host clubs must seek to allow time in busy schedules for players to consume food and drink pre-, during and post-training, while facilitating provision of food and drink where possible to players, especially between the end of school and commencement of pitch-based training.

7.4.3 Theme three : Motivation for players to achieve optimal energy and macronutrient intake

In the absence of food and drink provision responsibility for achieving optimal nutritional intake in the hours before and after training falls upon players and parents / guardians. The complex interaction between an individual's perception of the role of nutrition and their motivation to achieve optimal nutritional intake then acts as either a barrier or enabler to the individual. When discussing their motivations for achieving optimal energy and macronutrient intake in the hours pre-, during and post-training many players cited performance as the main driver behind their nutritional choices.

Academy Player 4: ***"****I feel like if I don't eat correctly before, before a training session or a game I feel like it does impact my performance and it might be that I'm, say, less tired or have less energy, that one extra sprint that my legs might go a little bit, feel a little bit wobbly so I feel like eating the right foods before, like, it has quite a big impact on me".*

It is commonplace for practitioners to use performance metrics when educating athletes upon nutritional strategies (Bentley et al., 2021, Birkenhead and Slater, 2015, Foo et al., 2021). As such players were able to articulate the feeling of optimal nutrition pre-training in relation to their performance outcomes:

Player 6: *"I think definitely before training you'll probably feel lethargic and you'll, like, your overall quality and performance will probably take a hit from that. I think subconsciously you probably feel better (when you eat well), you feel more awake and you feel more alert and I think it helps you with your concentration as well and also it's probably a mindset as well, you kind of think 'oh I've done alright, I've prepared well' so I think, I think that kind of can play on your mind."*

Despite being able to articulate the role of nutrition and the consequences of sub-optimal fuelling this did not translate directly to the nutritional practices of players. Data from Chapter

Four quantified that players regardless of age group fail to consume optimal energy and carbohydrate intake either side of training (Stables et al., 2022). With players commenting that a lack of motivation to prepare food and drink pre- and post-training or make time to consume food and drink in the hours before and after training as key barriers:

Player 4: *"I could give myself more time to let's say make myself that egg or cut myself that avocado in the morning but it's, like, I don't wake, I wake up at 8 which is not that early especially compared to others, but I can't be bothered to wake up even, like, 10-15 minutes earlier."*

Player 5: *"I think it's just the effort of having to get all the stuff and then thinking 'oh what am I gonna eat, what am I gonna make?' and then I think I could, like, I think I could do it it's just I, mentally I'd just go 'oh I can't be *****."*

Poor player motivation was further highlighted by staff members at the host club, with players regularly simply not eating in the hours before training:

Physiotherapist 1: *"seeing people not eating enough before training. Erm, you know, you see players that will come in and moan that they've not had breakfast and that they haven't eaten enough before training but we, despite, you know, despite all the information that we've given them, and you'll see they haven't planned ahead to eat"*

Senior Management 1: "*I think that's tough to get a kid, educate themselves to get out of bed to eat 7.30 latest. Erm, there's still that laziness wanna stay in bed or whatever it is, tiredness,* *cos it's tough. Erm, I think they can if they're, how much are they prepared to push themselves. Erm, I think there's probably still a real laziness around not eating."*

With one coach suggesting that the scheduling associated with academy football is a factor in poor player motivation.

Coach 2: *"I'd say it probably is a football thing, but you also look at the schedule that a footballer goes on, it's a 9, 10-month schedule and I think having that level of intensity towards nutrition will have huge positives but there will also be psychological factors within that. I think if you look at a cycling team and say they're on the go for a month, it's a bit like being at a World Cup, I think you can commit your life to a month's World Cup, very different to committing, you know, for 10 months of the year."*

Overall theme three highlighted how players lack motivation to have autonomy over their nutritional habits pre- and post-training. Indeed in the face of conflicting behaviours (*i.e.,* extra time asleep) fuelling pre-session and recovery post-session was not prioritised. However it would be fair to say that the interaction between other themes presented here (*i.e.,* a lack of time, food provision and nutritional understanding) contributes to poor motivation for players to achieve their nutritional guidelines. It is the interaction between player understanding and motivation which practitioners, policy makers and support staff must seek to bridge to illicit positive habits in the hours before and after training, as illuded to here by sport scientist one: *"it's having that importance of knowing 'I've got …' say you're playing in the Champions League final straight after you've finished school you'd try and make sure everything was ready so you can perform your best and win the trophy."* Indeed staff members also illuded to the idea that nutrition is seen as inferior to other disciplines within the academy ecosystem, as highlighted here:

Physio 2: *"you're expecting elite performances, from players and elite adaptations to physical programmes…I think for me that's the, one of the only sides of the provision, er, from an Academy point of view that is seen as a, er, a luxury rather than a requirement."*

Which therefore will likely impact the opinions of academy players in their motivation to display positive behaviours in the acute period pre- and post-training. Moving forwards key stakeholders must seek ways to increase player motivation to consume optimal energy and carbohydrate intake either side of training, such interventions will likely be a combination of enhancing player, staff and parent knowledge alongside facilitating schedule changes alongside provision of food and drink to players at this time.

7.5 Summary of findings and future research directions

A qualitative assessment of the acute fuelling and recovery practices of academy soccer players in the hours before and after training highlighted several key themes which have considerable implications for practice. With reference to the four hours before and four hours after pitch-based training it was evident that players, staff members and parents / guardians were unaware of the nutritional requirements at this time. It was clear that despite often acting as surrogates for nutrition information, support staff lacked the knowledge of energy and macronutrient requirements for players pre- and post-training, a theme which was consistent in academy parents who are often responsible for food and drink provided to players at this time. To reduce this barrier to optimal fuelling practices there is a clear need for player and stakeholder education upon the fuelling and recovery requirements of academy players. While it was clear that key stakeholders simply did not have the necessary level of nutritional knowledge, education alone is unlikely to facilitate positive behaviour change (Alaunyte et al., 2015, Spronk et al., 2015). Indeed a second theme within this research was the apparent lack of time which academy players have to consume sufficient food and drink, both before and after training. To alleviate the time pressures of schooling, travel and external physical activity, it is essential that coaches and policy makers facilitate changes in academy schedules before and during sessions to allow players to consume sufficient energy and carbohydrate. Many players, staff members and parents / guardians cited the role of food provision at this time to enable positive fuelling and recovery practices when players may simply be 'too busy to eat'. Currently many clubs within the English Premier and English Football do not provide food and drink to players in the hours before and after training (Carney et al., 2022), yet data presented in Chapter Five has shown that provision of breakfast and post-training snacks can increase energy intake of academy players by ~ 700kcal.d^{-1} (Stables et al., 2023). Facilitating changes in academy schedules with appropriate education to allow players to consume food and drink provided by the host club would act as an enabler to achieving energy and macronutrient targets at this time, allowing players to meet the additional energy requirements inherent with weekly academy training and match load as detailed in Chapter Five (Stables et al., 2023). Taken together such factors would alleviate the barrier of poor player motivation to consume sufficient food and drink in the hours before and after training. Indeed many of the issues which arise with reference to poor fuelling and recovery at this time is the result of players and parents /guardians having to provide food and drink to players with little understanding of acute nutritional requirements while competing with conflicting behaviour of additional rest or travel time. Given that this dataset was drawn from one club and the failure of this body of work to include players for the Youth Development and Foundation Phases, interventions moving forwards must seek to capture players, parents and staff members from a number of academies of different classification as such varying levels of support. Solutions presented here require additional consideration due to the uneven landscape of nutrition provision and financial capabilities of academies across English Football.

7.6 Conclusions

The present study used a qualitative case study methodology to explore player and stakeholder perspectives of the enablers and barriers to optimal fuelling and recovery practices in the acute period in hours before and after training in academy soccer players. Data suggests that players, parents / guardians and staff members have little understanding of the nutritional fuelling and recovery targets pre- and post-training. As such despite parents being responsible for food and drink at this time, they often lacked the understanding of what to provide. Moreover while participants could articulate the consequences of optimal fuelling and recovery practices (*i.e.,* how they would feel), they were unable to articulate consequences of sub-optimal fuelling and recovery (*i.e.,* increased bone (re)modelling). Taken together with a lack of theoretical knowledge it became clear there was a significant deficit of practical knowledge with parents and staff members reporting little confidence in practical skills of players (*i.e.,* knowledge of what to cook). The absence of an understanding of nutritional requirements was compounded by a lack of time to eat in the busy daily lives of academy soccer players. With travel time, schooling and scheduling of the academy programme presenting a barrier to players consuming food and drink, which when taken in the context of little or no dedicated staffing or food and drink provision creates the perfect storm of academy soccer players repeatedly underfuelling at such a vital time of growth and maturation and presents rationale for the data presented in Chapter Four. When considering all the data presented therein, there is now a clear responsibility to target enhancing stakeholder knowledge, enhancing food and drink provision while facilitating time within academy's schedules to allow players to consume food and drink before, during and after pitch-based training. Given many academy players and parents do not have access to a full-time nutritionist within their respective clubs and the additional financial cost of providing food and drink to players, a one size fits all approach would be inappropriate. Instead future work must focus upon policy makers facilitating increased nutrition staffing provision with the development of a nutrition education curriculum to all players, parents / guardians and staff members, considering a centralised approach to education support given the current inequality in nutrition provision.

Chapter 8

Synthesis of findings

The aim of this Chapter is to provide a summary of the findings from this thesis in relation to the original aims and objectives outlined in Chapter 1. A general discussion is then presented, which focuses on how the data derived from this thesis has furthered our understanding of the energy requirements of academy soccer players. Finally, the practical implications, limitations and recommendations for future research will be outlined.

8.1 Achievement of thesis aims and objectives

The aim of this thesis was to test the hypotheses that academy soccer players from the English Premier League exhibit sub-optimal fuelling practices in the hours before and after training and to investigate the effects of mechanical (i.e., training load) and metabolic (i.e., nutritional intake) upon markers of bone (re)modelling. It was hoped that data derived from the studies listed within this thesis would enhance the nutritional practice and provision to academy soccer players acutely before and after training as well as throughout the training microcycle. This aim was achieved through a series of studies conducted in chapters 4, 5, 6 and 7 using a total of 103 participants with participant data provided in table 6. An overview of each objective is provided below.

Objective 1: To quantify the acute fuelling and refuelling practices of academy soccer players in the four hours pre- and post-training. This objective was achieved through the completion of study 1 (Chapter 4).

Using a cross-sectional design this study assessed the acute energy and macronutrient intake of academy soccer players in the four hours before and the four hours after training using the RFPM. This study recruited forty-eight players from U12, U13, U14, U15/16, U18 and U21 age groups (all n = 8). These data demonstrated that academy players regardless of age group fail to consume optimal energy and carbohydrate intake pre- and post-training. Failure to achieve optimal energy and macronutrient intake will acutely impact performance and may have chronic implications for skeletal development during such a vital phase of growth and development. Data also showed how variation in physical activity and travel times before and after training may also create barriers to a player achieving optimal energy and macronutrient intake.

Objective 2: To quantify the additional daily demands of academy soccer programmes compared to those enrolled on a grassroots soccer programme. This objective was achieved through the completion of study 2 (Chapter 5).

Data presented in this study demonstrated the additional daily energy expenditure as a result of being enrolled on a full-time academy programme. Data showed that energy expenditure of U13 academy soccer players was comparable to (or exceeded) their adult counterparts and exceeded their non-elite grassroots counterparts by ~ 750 $kcal.day^{-1}$. Despite such high energy expenditures and food and drink provision by the host club players regularly failed to consume sufficient daily energy and macronutrient intake throughout the training week. When taken together with data with from Chapter Four, which highlighted players regularly display low carbohydrate availability in the hours pre- and post-training, data suggests that players may regularly be at risk of an energy deficit and the associated consequences of low energy availability and RED-S. In addition to total daily energy expenditure facilitated in part by greater pitch-based loading during training and match play, academy players were also more physically active. Showing a greater level of moderate to vigorous activity that their non-elite counterparts. Repeatedly displaying sub-optimal nutritional practices in line with high daily physical activity presents negative health, performance and growth and maturation implications with specific reference to skeletal development.

Objective 3: To quantify the acute effects of carbohydrate availability upon markers of bone (re)modelling in academy soccer players. This objective was completed through the completion of study 3 (Chapter 6).

Considering the findings from Chapter Four in that players fail to consume sufficient carbohydrate intake before and after training, Chapter Six aimed to assess the effects of high and low carbohydrate availability upon markers of bone (re)modelling following pitch-based training, compared to rest in conditions of low carbohydrate availability. Findings from this study show that low carbohydrate availability pre-, during and post-training increased markers of bone (re)modelling compared to training with high carbohydrate availability. Failure to consume carbohydrate at this time increased βCTX indicating increased bone resorption. Indeed training with high carbohydrate availability suppressed βCTX to below that of levels in the rest condition at rest. Data suggests that training with optimal carbohydrate intake in the hours before, during and after pitch-based training reduces circulating markers of bone (re)modelling. Repeatedly failing to consume sufficient carbohydrate intake pre- during and post-training as seen in Chapter Four presents an increase in bone resorption markers which if left unchecked over a period of weeks and moths may pose a risk to skeletal health and increase the risk of skeletal injury. To this end further research is required to determine the medium to long term morphological changes to bone which may risk skeletal injury.

Objective 4: To determine the barriers and enablers to achieving optimal energy and macronutrient intake in the acute period pre- and post-training in academy soccer players using qualitative research methods. This objective was achieved through the completion of study 4 (Chapter 7).

When synthesising the quantitative data from this thesis is clear that despite high daily energy requirements, greater than both their adult and non-elite counterparts as observed in Chapter Five, male academy soccer players fail to consume sufficient energy and macronutrient intake in the hours before, during and after-training detailed in Chapter Four. In using a qualitative approach, participants highlighted that a lack of physical opportunity create a barrier to players being able to consume food and drink at this time. A lack of time in the hours between schooling and the start of training compounded by extensive travel, a lack of available food at both the host club and at home provide context for the findings of study one (Chapter Four), particularly those in the YDP who typically train in the evening (18:00 – 20:00). As evidenced by some players failing to consume and food or drink at this time, a lack of understanding of a player's nutritional requirements at this time presented a second barrier to optimal nutritional intake. Staff members, players and parents displayed poor knowledge of the energy and carbohydrate requirements in the hours before and after training. It is worth noting that the participants in this study had access to a full-time nutritionist suggesting it would be fair to say that nutritional knowledge of stakeholders across all 89 EPL and EFL academies would be poor, given that many do not have access to a dedicated nutritionist (Carney et al., 2022). Increasing stakeholder education and providing physical opportunity for players to eat, either through food and drink provision by host clubs or by scheduling time before, during and after sessions for players to eat would facilitate good nutritional practice in the acute period before and after training. Policy makers such as The Premier League must empower clubs to increase dedicated nutrition staffing resources who can deliver targeted education programmes with the goal of increasing energy and macronutrient intake. Where possible and financially viable there is also a responsibility of clubs to provide food and drink to players given the greater energy demands which players experience as a result of enrolment upon academy programmes as data highlights in Chapter Five and the consequences of increased bone (re)modelling under conditions of low carbohydrate availability.

8.2 General discussion of findings

8.2.1 Daily energy expenditure of academy soccer players

It is known that as players transition through the academy pathway, they undergo processes of growth and maturation. Indeed, such changes, namely an increase in fat free mass stimulate increases in resting metabolic rate (Hannon et al., 2020). It would be fair to assume therefore that in line with increasing resting metabolic rate, total daily energy expenditure also increases. In using the doubly labelled water method prior to the completion of works within this thesis there was only one study which has provided data on the daily energy expenditure of elite academy soccer players (Hannon et al., 2021b). Data presented by Hannon et al., (2021b) detailed that U18 players presented with a TEE (3586 ± 487 kcal.d^{-1}; range: 2542-5172 kcal.d^{-1}) that was approximately 600 and 700 kcal.d^{-1} higher than both the U15 (3029 ± 262 kcal.d^{-1}; range: 2738-3726 kcal.d^{-1}) and U12/13 players (2859 ± 265 kcal.d^{-1}; range: 2275-3903 kcal.d^{-1}) respectively. Data shows large variation within squads and indeed individuals within U12/13 squads had comparable daily energy expenditure to their older academy counterparts. Perhaps more interesting however is the conclusion that academy age players display TDEE which is comparable to (or exceeds) their first team counterparts (Anderson et al., 2017). Such data underlines the importance for seeking solutions to increase energy and macronutrient intake, despite sub-optimal practices observed within this thesis (Chapters Four and Five) and previous work (Hannon et al., 2021b).

Despite such data allowing for the development of nutritional guidelines for academy soccer players, data was drawn from only one club with no data detailing the additional energetic demands of academy programmes compared to grassroots players not enrolled on an academy programme. To this end we report in Chapter Five how daily energy requirements of academy soccer players from an U13 age group (3380 ± 517 kcal.d^{-1}; range, 2811 – 4013) are approximately ~ 750 kcal.d^{-1} greater than those not enrolled on a formal programme and although small differences in calculations between studies should be noted, data was greater than previously reported by Hannon et al., (2021b). With differences between elite and recreational players being as great as ~1,700 kcal.d^{-1}. To this end there is a clear need for an increase in food and drink provision, staffing and education provided to soccer academies, despite being a currently under-resourced discipline (Carney et al., 2022). Indeed despite an average ~700 kcal.d^{-1} intake in the academy group which was provision from the host club, players on occasion still failed to meet the additional energy expenditure as a result of their academy programme. Given there was no difference between the anthropometric profile between the elite and non-elite players it is fair to suggest that pitch and match loading was the contributing factor to greater daily energy expenditure.

8.2.2 Sub-optimal fuelling and recovery practices of academy players

The importance of optimal nutrition to support acute soccer performance, achieve daily energy and macronutrient intake targets and specifically attenuate bone resorption have been explored within this thesis. Despite clear ergogenic effects of optimal energy and carbohydrate intake in the hours before and after training academy soccer players often display poor nutritional practices at this time. Indeed within this body of work players failed to consume optimal energy and macronutrient intake pre- and post-training (Chapter Four) as well as through the training week (Chapter Five). Previous data has also shown how despite great daily energy expenditure values, players on occasion fail to achieve optimal energy and macronutrient intake. Data presented by Hannon et al. (2021b) is the only dataset from academy soccer to date apart from work within this thesis to assess energy and macronutrient intake using the RFPM alongside energy expenditure using doubly labelled water. Absolute energy intake of U12/13 (2859 ± 265 kcal.d^{-1}), U15 (3029 ± 262 kcal.d^{-1}), U18 (3586 ± 487 kcal.d^{-1}) intake was greater than we observed in U13 academy soccer players, although caution should be exercised when comparing age groups of different anthropometric profiles, different clubs and therefore different schedules.

When quantifying the energy and macronutrient intake of U13 academy soccer players (Chapter Five) we observed average daily absolute energy (2178 ± 319 kcal.d^{-1}), carbohydrate (279 ± 42 g), protein (86 ± 18 g) and fat intake (79 ± 18g) and relative energy (44 ±12 kcal.kg.d^{-1}), carbohydrate (5.6 ± 0.2 g.kg.d^{-1}), protein (1.7 ± 0.6 g.kg.d^{-1}), and fat (1.6 ± 0.6 g.kg.d^{-1}) intake across a seven-day microcycle. Energy intake observed here was less than previously observed within academy soccer players (Hannon et al., 2021b) of the same age (2659 ± 187 kcal.day^{-1}), despite having contact to a full-time nutritionist and food and drink provision from the host club. With reference to relative intake there was no difference in energy, carbohydrate, protein and fat intake between academy and non-elite players. Only three players from the academy group managed to achieve the recommended 6 g.kg.day^{-1} despite provision of approximately 125 g of carbohydrate (2.4 g.kg^{-1}) per day provided by the host club in the form of breakfast, a pre-training snack or a post-training snack dependent upon training times. Notably there was no difference in energy or macronutrient intake between training days which illudes to a lack of periodisation within this age group in line with previous observations from a Category One academy (Hannon et al., 2021b)

8.2.3 Training and match load of academy soccer players

There is extensive research examining the training and match load of adult elite male soccer players (Anderson et al., 2016a, Anderson et al., 2016b, Baptista et al., 2020, Kelly et al., 2020, Malone et al., 2015, Morgans et al., 2023) yet data within academy soccer remains less studied. While GPS is seen as the gold standard measure of soccer training load quantification, historically a variety of metrics such as heart rate (Wrigley et al., 2012) have been used to provide estimations of training and match load in academy soccer. Such variations in reporting in the literature made comparisons between training and match loading inaccurate. Recent quantification of training and match load and whole season microcycle variation (Hannon et al., 2021a) provided an assessment of GPS characteristics of training and match play within academy soccer, however data was limited to that of one club. While data showed that academy players could complete comparative weekly training and match volume to their adult counterparts despite not being fully mature, it remained unclear if this was an accurate representation of the academy soccer landscape. It also remained unknown the additional pitch-based training and match loading which players were completing compared to their non-elite counterparts.

Data in Chapter Four highlighted physical loading of two (U12 – U14) and three (U15/16 - U21) training sessions across a single game microcycle were quantified using GPS technology. Despite failing to depict the entire microcycle, quantification of session duration can allow for recommendations of intra-session fuelling, with comparisons of total distance, average speed, accelerations and decelerations being drawn between individual days (i.e., MD - 4) of existing data (Hannon et al., 2021a). Despite all pitch-based sessions lasting longer than 60 minutes no energy or carbohydrate intake was consumed during training, which is especially concerning given the sub-optimal fuelling and recovery practices observed across all age groups in Chapter Four when considering the effect of consuming no carbohydrate during training upon markers of bone (re)modelling reported in Chapter Six. Training load data presented here encourages players to consume carbohydrate during training (i.e., sports drinks) and should allow coaches to facilitate breaks for players to do so. When comparing total distance, U18 and U21 players completed less accumulative distances across three sessions than U15/16 players, despite completing full time programmes and training in the morning without schooling commitments in the day compared to their younger counterparts. U21 players also completed less total distance than U12 players. Rationale for such a finding may be due to an increase in training periodisation within the older age groups, with a focus upon performance rather than development. Given players in the Youth Development Phase are completing absolute training loads which are greater than their older academy (often professional) counterparts at a time when they are not skeletally mature, there is a clear rationale for increased nutrition provision.

Markers of absolute training intensity (i.e., high speed running, accelerations and decelerations) were greater in older academy players compared to younger academy players; however this is likely due to younger players being less physically developed and not having physical capabilities to complete such high intensities. Indeed high-speed running meters of U15/16, U18 and U21 players were all greater than U12, U13 and U14 players. Yet when comparing relative markers of training intensity, average speed (m.min^{-1}) was similar in U13 players (those most likely to be experiencing PHV) to U14, U18 and U21 players.

Weekly training and match load observed in Chapter Five presents only the second assessment of U13 elite soccer players from a Category One academy. Indeed mean weekly training load (27 ± 4 km) was greater than previously reported by U12/13 aged players (20 ± 2 km) but comparable to U18 (26 ± 3 km) academy (Hannon et al., 2021a) and men's first team players (27 ± 2 km) (Anderson et al., 2017). When comparing accumulative training and match load compared to their non elite counterparts, academy players completed an additional four training sessions (975 ± 23 min) and completed a greater distance (54.1 ± 8.5 km) over the 14-day period compared to non-academy players (397 ± 2 min and 21.6 ± 4.7 km, respectively). Indeed total distance was greater in week one, week two and as a 14-day mean compared to their non elite counterparts. When comparing measures of exercise intensity average speed and accumulative high-speed running meters were greater in week one, week two and as a 14-day mean in the academy group. Considering there was no difference in participant characteristics between groups in Chapter Five and that positive correlations exist between energy expenditure and training and match load it is fair to suggest that the greater mean daily energy expenditure of ~ 750 kcal.d^{-1} between groups was a result of greater pitch-based loading. Indeed to our knowledge this was the first paper to calculate pitch-based loading of non-elite soccer players in comparison to their elite counterparts whilst directly using measures of energy expenditure. It should be noted therefore that as a result of greater training and match loads stipulated by the EPPP academy players are completing pitch-based loading during growth and maturation which far exceed their non-elite counterparts and are comparable to or exceed older academy and first team players, despite sub-optimal nutritional practices (as seen in Chapters Four and Five) and receiving less nutrition provision (Carney et al., 2022).

8.2.4 The interaction between nutrition, load and bone health

It is well established that through childhood and adolescence, children undergo processes of growth and maturation. The most rapid phase of growth in stature occurs during PHV where adolescents can grow ~10 cm per year (Hannon et al., 2020). Throughout a young footballer's journey through academy football they undergo sustained skeletal development, not reaching full skeletal maturity until seventeen (Malina et al., 2010). While the training load associated with academy soccer programmes is comparable to and in some cases exceeds that of their elite male counterparts, under optimal nutrition conditions load may provide an anabolic stimulus to bone (Varley et al., 2023). To this end it is known that metabolic changes (i.e., nutritional intake) provide a greater stimulus to bone (re)modelling than mechanical load (i.e., pitch-based training) (Dolan et al., 2020). However the sub-optimal nutritional habits of academy soccer players observed in Chapter Four and Five respectively, may present a challenge to the skeletal systems of academy players which is yet to be fully understood. Despite such high training and match loads and daily energy expenditure, we have observed in the completion of this thesis, through work presented in Chapter Four, that academy players fail to achieve optimal energy and carbohydrate intake values both acute pre- and post-training but also throughout the training week. Repeatedly underfuelling in this manor may present an increased risk of low energy availability, which may present as reduced bone mineral accrual and dispose players to an increased risk of stress fractures (Papageorgiou et al., 2017). Indeed such rationale likely provides reasoning for the increased incidence of bone stress injuries to the knee, lower back, sacrum and pelvis to academy soccer players globally (Hall et al., 2020).

In adult runners, mechanical stress of physical exercise has been shown to increase bone resorption through increases in βCTX, whereby the degree of (re)modelling is attenuated in the presence of acute carbohydrate intake (Sale et al., 2015; de Sousa et al., 2014; Hammond et al., 2019). When carbohydrate intake is restricted chronically over a period of six-days bone formation markers were significantly reduced (Fensham et al., 2022). When taken together such data suggests that both acute (Chapter Four) and chronic (Chapter Five) failure to achieve carbohydrate intake targets may increase bone (re)modelling in academy soccer players in response to pitch-based training. In adolescent athletes protein feeding has shown to reduce βCTX concentrations twenty four hours after a swimming protocol (Theocharidis et al., 2020), yet there is no data quantifying bone (re)modelling with reference to carbohydrate intake in response to soccer specific exercise. While present data is only available in adult populations often due to the invasive nature (i.e., repeated blood sampling) or cost (i.e., DXA) of methodologies it is fair to assume that such an effect would be seen in adolescent athletes. Indeed the response maybe be more pronounced given the already increased turnover and formation owing to skeletal development at that age (Seeman and Delmas, 2006).

To this end Chapter Six aimed to quantify markers of bone (re)modelling in response to soccer specific training under conditions of high and low carbohydrate availability compared to at rest. Indeed while bone imaging studies have used longitudinal (Varley et al., 2023) and cross-sectional (Hagman et al., 2018) data to investigate the changes in bone response to soccer training, the acute interaction of nutritional intake with training load remained unknown. Similar to previous observations of low carbohydrate availability (Scott et al., 2012; Sale et al., 2015) we reported an increase in PINP following the onset of exercise, yet the physiological significance of such findings remains to be debated within the literature, as increased PINP may be from other tissues such as collagen and is not bone specific (Vasikaran et al., 2011). It should be noted that that when training under conditions of high carbohydrate availability pre-, during and post-training βCTX was suppressed to lower levels than at rest. While training with no carbohydrate intake pre-, during and post-training increased βCTX concentrations. Whilst it is not possible to link such responses directly to an increased injury risk, data clearly shows that training with reduced carbohydrate availability increases bone (re)modelling, which at a vital time of skeletal development may increase the stress response to bone leading to fractures and osteoporosis long term if repeated over a chronic period of weeks and months. This remains the only estimation of the activity of bone (re)modelling markers in academy soccer players however similar responses have been linked to reduced bone mineral density in road cyclists (Hilkens et al., 2023), albeit with significantly less mechanical loading than those experienced by academy soccer players.

8.2.5 A lack of stakeholder understanding and physical opportunities are barriers to optimal nutritional intake

Both quantitative and qualitative nutrition research within academy soccer remains in its infancy. To date only a small number of quantitative studies exist within this population and the number of participants involved in qualitative research relative to the number of players and key stakeholders within the academy soccer ecosystem is minute. Qualitative research has aimed to determine the perceived role of nutrition within academy soccer with a focus on providing context to the dietary behaviours of players. Yet work within this thesis sought to be the first to understand the barriers and enablers to food and drink intake in the hours before, during and after training at a time when players fail to achieve optimal nutritional intake, with some players failing to consume any food or drink either side of pitch-based training.

Despite data being drawn from one academy with very specific scheduling and nuances compared to other environments it was clear a lack of capability and physical opportunity to display optimal nutritional behaviours were key issues for players, parents and staff members. While all stakeholders communicated an understanding for the need to consume optimal energy and carbohydrate intake both pre- and post-training, with many players citing performance benefits of consuming energy and carbohydrate at this time, participants were unable to articulate the specific nutritional requirements of an acute soccer player in the hours before and after training. Indeed many parents who are often responsible for the food and drink intake of younger academy players (Foundation Phase / Youth Development Phase) and support staff who often act as surrogates to nutritional information showed little to no understanding of how much players should eat pre-, during and post-training. Alongside capability, physical opportunity to consume food and drink in the four hours before and after training was highlighted by parents, players and staff as a barrier. Parents of players in the Youth Development Phase cited a lack of time between school and training and again between the end of training and players going to bed as a key factor in players failing to achieve optimal nutritional intake, which was compounded by extensive travel time with players simply being too busy to eat, something which is not unique to this single academy (Carney et al., 2024). Access to food and drink provided by the host club has previously been cited as an enabler to good nutritional practice (Carter et al., 2022) and while data presented in both Chapters Four and Five highlights how players on occasion fail to achieve optimal carbohydrate intake despite provision of food and drink by the host club, parents, players and staff members suggested that provision of food and drink either side of training would increase energy and macronutrient intake. When taken together academies must also seek to provide time within training schedules to allow players to eat pre- and post-training with many participants in this study highlighting how players were often having to eat on the way to training (i.e., in the car) due to a lack of time. Alongside a lack of understanding and opportunity to consume food and drink, a lack of motivation to consume food and drink, especially pre-training was highlighted by players and staff members. Provision of food and drink to academy players is varied across the academy landscape, with younger players and those from lower ranked academies receiving less provision than their older counterparts (Carney et al., 2022). To this end players and staff cited a lack of motivation as a key barrier to players achieving their carbohydrate intake targets when they are tasked with taking responsibility for their own nutrition at this time. A lack of confidence in their practical nutrition skills or conflicts with other activities (i.e., sleep or socialising) were highlighted as reasons players failed to eat or drink before training, especially in the Professional Development Phase.

Compounding effects of a lack of understanding, busy schedules, a lack of time and food availability both at home and the respective training ground all act as barriers to players achieving optimal nutritional intake in the hours before and after training. Given the busy schedules of academy players it is important for coaches and support staff to schedule breaks during sessions to allow players to consume carbohydrate. Food and drink provision by host clubs and targeted education programmes would facilitate energy and macronutrient intake by players and provide parents with the knowledge to support players and remove the barriers to optimal energy and carbohydrate intake cited within this thesis.

8.3 Summary

A complex interplay of growth and maturation, daily physical activity and training and match load result in the total daily energy expenditures of academy soccer players which are comparable to (or exceed) their first team counterparts (Anderson et al., 2017) and exceed their aged match peers by ~ 750 kcal.d^{-1}. Indeed high levels of physical activity and pitch-based loading provides sound rationale for daily nutritional recommendations previously suggested by Hannon et al., (2021b) of relative intakes for carbohydrate, fat and protein corresponding to 6-8 g.kg^{-1}, 1.5-2.5 g.kg^{-1} and 2 g.kg^{-1} body mass. Building upon this early work it is essential that in the four hours before and after training academy players aim for 2g.kg.h^{-1} carbohydrate and 0.3g.kg.h^{-1} protein to enhance training adaptation and reduce bone (re)modelling during such a vital phase of skeletal development and increased injury risk. Adherence to such recommendations will enhance on pitch performance and reduce activity of bone turnover markers to below that at rest. Despite the development of practical recommendations it is clear that players fail to achieve both acute and weekly nutritional recommendations often due to a lack of time, understanding, capability and opportunity. As such targeted education programmes, increased food and drink provision and changes in scheduling of pitch-based training to allow players time to consume energy and carbohydrate before, during and after training would all enable players to achieve their nutritional intake targets in the hours before and after training.

Figure 20. Proposed Daily Nutrition Plan for an U15 Youth Development Phase aged player with a body mass of 55kg, enrolled on an English academy soccer programme, providing optimal fuelling and refuelling intakes of 2 g.kg carbohydrate in the acute period pre-, during and post-training.

	Absolute Intake				**Relative Intake**			
	Energy (kcal)	**CHO (g)**	**PRO (g)**	**FAT (g)**	**Energy ($kcal.kg^{-1}$)**	**CHO (g)**	**PRO (g)**	**FAT (g)**
Breakfast – before school (07:00)								
Wholemeal toast with two scrambled eggs and beans, 150ml orange juice	390	40	26.2	13.7	7.1	0.7	0.5	0.2
Morning Snack (10:00)								
Granola pot with yoghurt	319	46	8.6	11.3	5.8	0.8	0.2	0.2
Lunch (12:30)								
Toasted chicken and green pesto panini with a handful of mixed fruit and nuts	558	49	26.9	28.4	10.1	0.9	0.5	0.5
Afternoon Snack (14:30)								
250ml mixed fruit smoothie	174	33	5.3	2.3	3.1	0.6	0.1	0.1
Dinner (16:30)								
One medium bowl of vegetable pasta bake with 2 slices of garlic bread, followed by four Jaffa cakes	698	110	16	24	12.7	2	0.3	0.4
- 4 hours pre - training	872	143	21.3	4.7	15.8	2.6	0.4	0.5
During – training (18:00 – 19:30)								
Sports drink consumed at regular intervals providing 60 $g.hr^{-1}$ CHO	364	90	0	0	6.6	1.6	0	0
Immediately Post – training								
One banana and a small handful of jelly sweets	180	42	3	0.2	3.2	0.8	0.1	0
Post - training								

One salmon fillet, sticky white rice, teriyaki sauce and stir fry vegetables	473	45	28.7	20	8.6	0.8	0.5	0.4
Pre - bed								
One large bowl of cereal with whole milk	170	25	6.2	5	3.1	0.5	0.1	0.1
+ 4 hours Post – training	823	112	37.9	25.2	14.9	2.1	0.7	0.5

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8.4 Limitations

Each of the studies conducted within thesis have produced data which has enhanced knowledge, understanding and practice for nutritional service provision in academy soccer. These studies are not without limitation, however. Despite the governance of EPL soccer academies by the Premier League, the logistics of pitch-based loading (i.e., session timing, frequency and duration) are at the discretion of the host club form which this data was collected. Indeed data was collected solely from one academy which may not be representative of the pitch based training and daily schedules (i.e., education or gym-based training) of other academies. Indeed as such the limitations of such studies are that sampling remains from one host club (Morgans et al., 2023). In completion of this thesis the author was also a full-time nutritionist within the host club which may have influenced nutrition provision of both food and drink as well as education to participants within all studies of this thesis. Only fourteen Category One academies employ a full-time nutritionist (Carney et al., 2022) and given that a lack of staffing provision is seen as a barrier to optimal nutritional practice, similar studies carried out within clubs without dedicated nutritional staff may have yielded different results. A number of limitations also exist which are specific to each study which are outlined below.

Study 1

When attempting to assess the typical acute fuelling and recovery habits of pitch-based training, three sessions through the week was deemed an appropriate sample to provide valid data whilst limiting participant burden, especially given the age range of participants recruited within this study. To provide a more comprehensive assessment of dietary intake and training load, further research may wish to extend the monitoring period which may be seen as a limitation of this work. As aforementioned another limitation of this study, and of much applied research is that data collection is limited to one club or environment. Indeed the rural geographical location of the host club's training ground demands extensive travel by car with little access to external food shops which may not be seen in other environments. The schedule associated with this study is unique to the host club and as such in other academies where training may be at different times (i.e., day release sessions) which may display different habitual eating times. Moreover given the evening schedule associated with players in the YDP sleep schedules would likely provide a barrier to optimal energy and macronutrient intake with reference to both the time available to players yet also the types of foods and drinks habitually consumed at this time compared to earlier in the day.

Study 1 and 2

Both studies utilised the RFPM to provide assessments of energy and macronutrient intake of academy soccer players. Although commonly used within used within elite adult male (Costello et al., 2019), female (Morehen et al., 2021; McHaffie et al., 2024) and youth soccer (Hannon et al., 2021b) players, the RFPM presents a small degree of error in energy and macronutrient analysis (Stables et al., 2022). While efforts were made to reduce this error by using additional SENr nutritionists to validate data, dietary analysis remains one of the most difficult practices within sports nutrition (Burke et al., 2018b). Indeed for study two (Chapter Five), three SENr practitioners to assess dietary intake data, with no differences in estimated energy or macronutrient intake for either group between all three coders, it is hoped this improved the data accuracy.

Study 2

The use of the doubly labelled water method is considered as the gold standard method for assessing free-living energy expenditure. Despite providing assessments for mean total daily energy expenditure as seen previously (Hannon et al., 2021b) it is not possible to provide assessments for a specific day, or for a more specific time period such as a soccer training session. While this study allowed for the comparison of energy expenditure between academy and grassroots players, allowing for suggestions that pitch-based loading was the determining factor in greater TDEE, it was not possible to quantify each session. Similarly although academy players completed greater moderate-to-vigorous activity than their peers, we were unable to quantify time spent completing specific activities are provide qualitative context behind the physical activity (i.e., swimming training). Limited by its invasive nature, DLW requires daily urine samples from participants. For ethical and moral reasons the principal investigator could not be present at the passing of the urine, as a result there was error in reporting by two participants from the control group which resulted in their data being removed from the dataset, reducing the strength of such conclusions. Lastly, while the use of triaxial accelerometery added an additional insight into the physical activity of soccer players, it was not possible to ascertain the type, time or duration of such activity, as such further qualitative research should seek to build a more accurate and detailed report of the daily life of an academy soccer player.

Study 3

Despite providing the first assessment of bone (re)modelling markers in academy soccer players, the invasive nature of the methods used within this study in tandem with the control required over participants and the training programme allowed data to only be collected two training sessions (and one rest day). As such data only provides acute changes and therefore possible long-term implications of such results require further research. Indeed given that academy players are often required to train more than five times per week (Hannon et al., 2021a) and often complete double sessions, the transient nature of such (re)modelling markers requires further investigation greater than the two hours post training used within this study. A limitation of this study is the failure to quantify the effects of multiple sessions of low carbohydrate availability. It is important to note that the metabolites measured in this study were not exhaustive and given the mechanistic link associated with IL-6 and carbohydrate availability, it was a limitation of this study not to measure the response of carbohydrate availability and exercise training upon IL-6 activity. While blood metabolites measured in this study provide the best assessment of bone (re)modelling, neither βCTX or PINP are truly bone specific. In the absence of bone biopsy data which would be inappropriate within such a population due to its invasive nature, assessment of bone (re)modelling relies upon markers of bone turnover which may be seen as a limitation of this work, given the criticism of their application to meaningful change in skeletal tissue (Dolan et al., 2022).

Study 4

While the qualitative nature of this study provided context behind data observed in study one and described the potential rationale for players failing to achieve their energy and carbohydrate intake guidelines in the hours before and after training, data remains from a small sample size. This dataset also failed to determine the views of Youth and Foundation Phase players despite younger players experiencing the challenges of busy schedules, schooling and travel times pre- and post-evening training compared to their older PDP counterparts. Failing to assess the barriers and enablers to this population specifically is a limitation of this study. Data collected in this study is from a relatively small sample size from one club. With respect to the method of data collection it is important to concede the weakness of relying upon video conferencing software for some interviews. While not practically possible to complete all interviews in person, video conferencing can conflict with the perceived strengths of in person interviews, namely the loss of intimacy compared to a face-to-face interview, which may affect quality of questioning, answering and further probing (Irani, 2019). In addition to technical issues which such as poor internet connection, loss of sound or video which would affect data quality or participant compliance (Khan and MacEachen, 2022). To strengthen the quality of this data future research should seek to collect qualitative data with reference to the acute period pre-, during and post-training from a number of difference academies. Different academies will present with variations in factors such as scheduling, geographical location, dedicated staffing provision and food and drink provision to players. As such by understanding the barriers and enablers within different environments policy makers and nutritionists will be better placed to develop initiatives to facilitate players to consume greater energy and carbohydrate pre-, during and post-training.

8.4.1 Recommendations for further research

In addition to founding work within the last five years this thesis increases our understanding of how to support youth soccer players within the English academy system. Despite the advancements in nutrition within this neophyte field many questions remain unanswered which require additional research:

- Utilisation of a nutritional educational assessment tool to determine the nutritional understanding of key stakeholders across Category One, Two, Three and Four academies with reference to certain areas (i.e., pre- and post-training fuelling) at targeted time points (i.e., pre-season).
- Development of a specific educational programme targeted to enhance nutritional education of players, parents, host-families and academy staff.
- The assessment of key barriers and enablers to nutritional intake, specifically in the hours pre, during and post-training across all 89 academies with specific focus on perceptions of academy players and academies of lower classifications.

- Quantification of training load and daily physical activity within the 'full-time model' (U15/U16) age group which shows large variation in scheduling, education and living arrangements across EPL and EFL academies.
- Assessment of within day energy expenditure within academy soccer programmes of different methodologies and schedules. With a specific focus upon double training sessions, day release programmes and non-pitch-based loading (i.e., gym-based work).
- Extend the methods of Chapter Six to understand the response of bone (re)modelling markers following pitch-based training under conditions of low and high carbohydrate availability over a) a longer assessment period, b) more testing days, c) utilising a greater number of blood markers.
- Quantification of the bone turnover markers in response to acute exercise and different degrees of carbohydrate availability within soccer players pre-, circa and post PHV.
- Quantification of the possible ergogenic effect of acute calcium supplementation upon bone turnover makers in line with high carbohydrate availability.

It is also important to note that while this data provides greater understanding of the daily energy expenditures, acute nutritional practices, reasons underpinning such behaviours and the consequential implications to bone (re)modelling, data is exclusive to male academy soccer players. Indeed there is a clear lack of research within their female counterparts. To date a small number of studies have investigated the nutritional practices and requirements of international female players (Morehen et al., 2022; McHaffie et al., 2024) yet there is little understanding of elite academy female players. To this end25 there is a clear need for greater research within this population.

8.5 Thesis Summary

For the first time we report the acute fuelling and recovery practices of academy soccer players in the acute period in the hours before and after training. As hypothesised players regardless of age-group displayed sub-optimal energy and carbohydrate intake, with some players failing to eat either side of pitch-based training. In quantifying bone remodelling markers for the first time within this population we report that, under conditions of high carbohydrate availability in the hours before and after training, pitch-based training is anabolic to bone as such practitioners must seek ways to increase carbohydrate intake pre-, during and post-training. A number of barriers which can be linked to an individual's capability (i.e., understanding of nutritional requirements), opportunity (i.e., access to food or drink) and motivation (i.e, desire to prepare food) all provide rationale for sub-optimal nutritional intake. Players, parents and staff members alike, cited increased food and drink provision, education and dedicated nutrition staff as key enablers to facilitate energy and macronutrient intake within this population. Given that academy soccer players expend approximately 750 $kcal.d^{-1}$ more than their non-elite counterparts and comparable TDEE to their adult counterparts as shown in Chapter Five, promotion of energy and carbohydrate intake through the training day cannot be understated. Chronic failure to meet daily energy and macronutrient intake targets provide an increased risk of the symptoms associated with low energy availability including comprised bone health. When taken together this thesis highlights a need for academy soccer players to increase energy and carbohydrate intake in the hours pre-, during and post-training to facilitate increases in health and performance and reduce the risk of skeletal injury at a vital time of skeletal development. Such high daily energy expenditure and physical activity as a result of enrolment on a full-time academy programme reinforces the need for policy change to facilitate greater levels of nutrition education, food and drink provision and staffing provision throughout youth soccer, not only Category One academies.

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“You miss 100% off shots you do not take.”

Wayne Gretzky

Chapter 9

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