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ENERGY EXPENDITURE OF INTERNATIONAL FEMALE RUGBY UNION PLAYERS DURING A MAJOR INTERNATIONAL TOURNAMENT: A DOUBLY LABELLED WATER STUDY

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ABSTRACT

The purpose of this study was to quantify the total energy expenditure (TEE) of international female rugby union players. Fifteen players were assessed over 14-days throughout an international multi-game tournament, which represented two consecutive one-match microcycles. Resting metabolic rate (RMR) and TEE were assessed by indirect calorimetry and doubly labelled water, respectively. Physical activity level (PAL) was estimated (TEE:RMR). Mean RMR, TEE, and PAL were 6.60 ± 0.93 $MJ\cdot day^{-1}$ (1578 ± 223 $kcal\cdot day^{-1}$), 13.51 ± 2.28 $MJ\cdot day^{-1}$ (3229 ± 545 $kcal\cdot day^{-1}$), and 2.0 ± 0.3 AU, respectively. There was no difference in TEE (13.74 ± 2.31 [3284 ± 554 $kcal\cdot day^{-1}$] *vs*. 13.92 ± 2.10 $MJ\cdot day^{-1}$ [3327 ± 502 $kcal\cdot day^{-1}$]; p = 0.754), or PAL (2.06 ± 0.26 AU *vs.* 2.09 ± 0.23 AU; p = 0.735) across microcycles, despite substantial decreases in training load (total distance: -8088 m, collisions: -20 n, training duration: -252 min). After correcting for body composition, there was no difference in TEE (13.80 ± 1.74 [3298 ± 416 *adj.* $kcal\cdot day^{-1}$] *vs.* 13.16 ± 1.97 [3145 ± 471 *adj.* $kcal\cdot day^{-1}$] *adj.* $MJ\cdot day^{-1}$, p = 0.190), RMR (6.49 ± 0.81 [1551 ± 194 *adj.* $kcal\cdot day^{-1}$] *vs.* 6.73 ± 0.83 [1609 ± 198 *adj.* $kcal\cdot day^{-1}$] *adj.* $MJ\cdot day^{-1}$, p = 0.633) or PAL (2.15 ± 0.14 vs 1.87 ± 0.26 AU, p = 0.090) between forwards and backs. For an injured participant (n = 1), TEE reduced by 1.7 $MJ\cdot day^{-1}$ (-401 $kcal\cdot day^{-1}$) from pre-injury. For participants with illness (n = 3), TEE was similar to pre-illness (+0.49 $MJ\cdot day^{-1}$ [+117 $kcal\cdot day^{-1}$]). The energy requirements of international female rugby players were consistent across one-match microcycles. Forwards and backs had similar *adjusted* energy requirements. These findings are critical to inform the dietary guidance provided to female rugby players.

KEYWORDS

Energy expenditure, female athletes, team sport, sports nutrition, injury, illness

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INTRODUCTION

To enhance the health and performance outcomes of female rugby union players, it is critical to accurately determine their energy needs. Rugby union is an intermittent team sport, characterised by periods of high intensity running and collision events, such as tackles, scrums, rucks, and mauls (Nolan et al., 2023; Suarez-Arrones et al., 2014; Woodhouse et al., 2021; Hughes et al., 2017). Players are categorised primarily by two playing positions, forwards, and backs. Forwards typically have greater collision involvement during match-play (Woodhouse et al., 2021; Nolan et al., 2023), and are generally taller (+8.6 cm), heavier (+20.5 kg) and possess more fat-free mass (+10.6 kg) (Posthumus et al., 2020). Whereas the backs predominantly perform more running and sprinting efforts (Suarez-Arrones et al., 2014; Woodhouse et al., 2021; Nolan et al., 2023). Collision-based activities during training and match-play are associated with muscle damage (Naughton et al., 2018), muscle soreness (Fletcher et al., 2016), and high energy costs (Costello et al., 2018; Hudson et al., 2019; Naughton et al., 2018). To develop optimal nutritional strategies which promote fuelling and recovery from such demands, it is essential to accurately establish the total energy expenditures (TEE) of female rugby union players. Considering the distinct anthropometric and sport profiles of forwards and backs, investigating whether there are differential energy requirements between these positional groups is also necessary.

Despite the availability of high-quality research on the energy needs of male rugby players, there remains a critical knowledge gap concerning female rugby players in the literature. Recent studies have quantified TEE among female university rugby players (9.56 ± 0.7 MJ.day-1 [2286 ± 168 kcal.day-1]) (Traversa et al., 2022) and international seven's players

(14.6 ± 1.6 MJ.day-1 [3490 ± 382 kcal.day-1]) (Curtis et al., 2023). However, these studies are limited by the use of indirect assessment methods, which could not be worn during competition, and may not account for non-training activities and the energy cost of muscle recovery (Costello et al., 2018; Hudson et al., 2019; Costello et al., 2022). In contrast, in-season energy expenditures measured using the gold standard doubly labelled water (DLW) method, have been reported for senior male rugby league players (22.5 ± 2.7 MJ.day-1 [5378 ± 645 kcal.day-1]) (Morehen et al., 2016), as well as for young male rugby league (18.28 ± 4.1 MJ.day-1 [4369 ± 979 kcal.day-1]) and union (18.26 ± 4.69 MJ.day-1 [4365 ± 1122 kcal.day-1]) players (Smith et al., 2018). Additionally, pre-season TEE data is available for young male rugby league players (18.36 ± 3.05 MJ.day-1 [4388 ± 729 kcal.day-1]) (Costello et al., 2019). However, the application of these findings is limited by the anthropometric and physiological differences between the sexes (e.g., with regard to reproductive endocrinology) (Brazier et al., 2020; Yao et al., 2021; Hackney et al., 2019; Wohlgemuth et al., 2021), along with differences in match demands (Woodhouse et al., 2021) and training schedules (Hackney et al., 2019; Wohlgemuth et al., 2021). Thus, specific research is required to accurately determine the energy requirements of female rugby players, including during match-play.

The expansion of female rugby participation and the rise in professionalism (World Rugby, 2022) underscores the importance of quantifying TEE to establish a robust evidence-base for informing dietary recommendations (Holtzman and Ackerman, 2021). This is of particular interest given recent reports documenting a high prevalence (47%) of female rugby players are at risk of low energy availability (LEA; <30 Kcal·kg^{-1} fat free mass (FFM) per day) (O'Neill et al., 2022). High incidence (23-88%) of LEA among other male and female team sport athletes is also well documented (Dobrowolski and Wlodarek, 2020; Magee et al., 2020; Moss et al., 2021; Morehen et al., 2021; Tokuyama et al., 2021). A common explanation for LEA is the unintentional mismatch of energy intakes to expenditure, which may highlight a lack of knowledge regarding individual energy requirements (Mountjoy et al., 2018). Energy deficits of −47% and −50% have been observed throughout training and competition periods in international female rugby seven players, with accompanying decreases in body mass (Curtis et al., 2023). Unchecked energy deficits can lead to problematic LEA, adversely affecting training and performance, and may result in health-related consequences associated with relative energy deficiency in sport (REDs), including menstrual dysfunction, decreased bone density, endocrine and metabolic disturbances, and increased illness and injury prevalence (Mountjoy et al., 2018; Areta et al., 2021; Mountjoy et al., 2023). These findings reaffirm the importance of accurately quantifying energy requirements in female players.

Accordingly, the aim of this study was to establish the TEE of international female rugby union players by DLW, during an in-season period inclusive of competitive match-play. A secondary aim was to establish players resting metabolic rate (RMR) and physical activity levels (PAL), while investigating any differences between forwards and backs.

MATERIALS AND METHODS

Study design and participants

Fifteen international female RU players, from the same team, were purposefully recruited from each playing position, to participate in a 14-day cross-sectional study during the Women's Six Nations Championship, 2022. Eligibility criteria included internationally capped, free from illness and injury and > 18 years. The assessment period was split into two 7-day one-match microcycles, and included eight training days, three rest days, one travel day, and two match days (Table 1). All participants were selected to play in international matches on days 3 (home game) and 10 (away game). Participants completed coach prescribed training. On day three of the assessment period, one participant sustained an anterior cruciate ligament (ACL) injury. On day four, three participants tested positive for Covid-19. Participants with injury and illness completed all research testing procedures and prescribed protocols. Specifically, the injured participant completed off-feet conditioning and upper body gym-based training. Participants with Covid-19, isolated at home, and did not return to camp until returning a negative polymerase chain reaction (PCR) test on days 9 and 12. Whilst isolating, these participants completed home-based loads inclusive of walking, gentle jogging, and circuit training. Table 1 provides an overview of the training and match schedule and details home-based loads completed away from the training environment by each participant.

Total energy expenditure was measured by DLW. Resting metabolic rate was measured by indirect calorimetry. Body composition and water turnover was determined by the deuterium isotope dilution approach. Internal training load, including home-based loads, was assessed by sessional ratings of perceived exertion (sRPE). External load was assessed by global position system (GPS) and notational analysis. Training loads were quantified for all pitch-based training sessions and matches. All testing took place within the team's accommodation and training facilities. Ethics approval was provided by Leeds Beckett University (100577). Participants provided informed consent before participating in the study and consented to the sharing of individual data. Participants baseline characteristics are presented in Table 2.

INSERT TABLE 1 NEAR HERE

INSERT TABLE 2 NEAR HERE

Body mass & stature

Body mass (BM) and stature (SECA, Birmingham, United Kingdom) were measured on the morning of day 0, following an ≥8 hour overnight fast and the removal of heavy clothing (nearest 0.1 cm and 0.1 kg) by an ISAK (the International Society for the Advancement of Kinanthropometry) Level-1 accredited practitioner (Marfell-Jones et al., 2006). Thereafter, BM was collected on days 1, 2, 3, 6, 7, 8, 9, 10 and 14, under the same conditions, between 07:00 – 09:00 (Table 1).

Resting metabolic rate

Resting metabolic rate was measured between 08:00 – 10:00 on day 0 by indirect calorimetry (Cortex 3B-R3 MetaLyzer, CORTEX Biophysik GmbH, Leipzig, Germany) under a ventilated hood system. Participants were assessed under standardised conditions (i.e., >8-hour overnight fast, >12-hour abstention from alcohol, nicotine, and caffeine) (Compher et al., 2006). Up to four assessments simultaneously took place in a quiet, dimly lit, thermoneutral (20°C – 25°C) room within the teams accommodation (Compher et al., 2006). Prior to each assessment, the calorimeter was calibrated to within 0.02% of two known gas concentrations (15% O_2 and 5% CO_2, and ambient air (20.93% and 0.04%)). Participants laid in a comfortable supine position and were instructed to stay awake (Compher et al., 2006).

Data were collected over a 20-minutue period. The first 10-minutes of data were discarded and the second 10 minutes was used to calculate RMR (Iraki et al., 2021). Ventilatory oxygen (VO_2) and carbon dioxide consumption (VCO_2) were measured continuously by an online gas analyser (Metalyzer 3BR3, Cortex, Leipzig, Germany), and averaged every 30 seconds to remove artefacts (e.g., changes in breathing patterns). All participants had a coefficient of variation of ≤ 10% for VO_2 and VCO_2 (7.0% ± 2.0% and 7.3% ± 1.6%), respectively, during the 10-minute assessment period (*Supplementary material, resource 1*). Data were exported into Microsoft Excel (2019, Seattle, USA) for substrate oxidation rate calculations (Frayn, 1983). Subsequently, energy expenditure was estimated using the Frayn equation (Southgate and Durnin, 1970).

Doubly labelled water

Total energy expenditure

Total energy expenditure was measured using the DLW technique (Speakman, 1997). A single bolus dose consisting of deuterium (^2H) and oxygen (^{18}O) stable isotopes was prepared for each participant and weighed to four decimal places. Doses were calculated relative to the participants BM (Schoeller et al., 1980), which were recorded two weeks prior to the assessment period. Doses were approximately 5% deuterium and 10% oxygen^{18} and were characterised to calculate the exact enrichment of the dose provided.

Dose administrations occurred on day 0. A baseline urine sample was provided before oral DLW consumption (07:30 – 09:30). Time of dosing was recorded to the nearest minute. A second urine sample was collected after 6.75 ± 1.1 hours, allowing for total body water equilibrium of the isotopes (Schoeller et al., 1980). During the equilibrium period, participants were rested and consumed food and fluids *ad libitum*. Thereafter, participants provided daily morning urine samples (second pass of the day) for the duration of the study to determine elimination rates of both isotopes via the multipoint method. Samples were collected in 35 mL sample tubes (Sarstedt AG & Co. KG, Nümbrecht, Germany) and placed in time, date, and participant ID labelled zip-lock bags. On days 4, 5, 11, 12 and 13, urine samples were collected remotely and stored in the home-fridges of participants, until returning to camp with their samples. Urine samples were filtered in compliance with the Human Tissue Act 2004, at Leeds Beckett University, England, UK. Once filtered, samples were stored at -80 ^{O}C in 2 mL micro tubes (Sarstedt AG & Co. KG, Nümbrecht, Germany) until later analysis.

Analysis was performed using a Liquid Isotope Water Analyser (Los Gatos Research, USA)(Berman et al., 2013), at the University of Aberdeen, Scotland, UK. Urine was encapsulated in capillaries, then vacuum distilled (Nagy, 1983), and water from the resulting distillate was used. Samples were run alongside five laboratory standards and three international standards for each isotope to adjust for day-to-day variation and correction from delta values to ppm. Carbon dioxide production was calculated from the isotope elimination rates (k_d and k_o) and the isotope dilution spaces (N_o and N_d) using the Speakman et al. (2021) two-pool equation (Speakman et al., 2021), and converted to energy expenditure using the Weir equation and an estimated respiratory quotient of 0.85 (RQ) (Speakman et al., 2021), given all participants consumed a mixed diet (Ainslie et al., 2003; Westerterp, 1999).

Total energy expenditure ($MJ \cdot day^{-1}$ [$kcal \cdot day^{-1}$]) is reported as a 14-day and two 7-day averages. Physical activity level (PAL) was calculated by dividing TEE by measured RMR ($MJ \cdot day^{-1}$ [$kcal \cdot day^{-1}$]).

Body composition and water turnover

Body composition and water turnover were measured by deuterium isotope dilution. Total body water was calculated from the stable isotope dilution spaces based on the intercept of the elimination plot of deuterium (Speakman et al., 2021).

$$N = [(N_o/1.007) + (N_d/1.043]/2 \quad \text{[eq. 1]}$$

Whereby, N_o is the oxygen dilution space and N_d is the deuterium dilution space (Speakman et al., 2021).

Body composition was determined using a two-compartmental model of fat-mass (FM) and fat-free mass (FFM) (Krumbiegel, 2010; *Introduction to body composition assessment using the deuterium dilution technique with analysis of urine samples by isotope ratio mass spectrometry*, 2011; Westerterp, 2018). Fat-free mass (kg) was determined by dividing total body water (kg) by 0.732. Fat mass (kg) was calculated by subtracting FFM (kg) from BM (kg) (Fomon et al., 1982). Body fat percentage (%) was calculated by diving FM (kg) by BM (kg) and multiplying by 100 (Withers et al., 1998).

Water turnover was calculated by multiplying the rate constant of the post-dose decline in deuterium enrichment by the total water pool (Lifson and McClintock, 1966), and is reported as a 14-day average.

Quantification of training, match, and home-based loads

External loads were quantified by GPS, triaxial accelerometers, and notional analysis. Participants were assigned their own GPS units (Vector S7, Catapult Innovations, Melbourne Australia) which were placed in their shirts on the upper back between both scapulae. Variables selected for analysis were training and match duration (min), total distance (m), average speed (m.min-1), high speed running (m; >5m/s), and player load (AU) (Bridgeman and Gill, 2021; Roe et al., 2016). Notational analysis was used to quantify collision-based events. Expert analysts filmed (7 years' experience; Sony CX625 Hancam) and coded (5 years' experience; Hudl Sportscode) the sum of collision events (i.e., rucks, mauls, scrums, tackles, and ball carries). Internal loads were assessed by sRPE. Participants reported their RPE, in isolation, 30 minutes after each training session and match using a modified Borg scale (Foster et al., 2001), which was multiplied by session duration to calculate the load in arbitrary units (AU) (Foster et al., 2001). Participants also reported their RPE and the duration of any non-prescribed activities and home-based loads, such as walking and swimming, using an online form.

Statistical analysis

Statistics were conducted in SPSS (version 29; SPSS, Chicago, USA). Data are reported as mean ± standard deviation (SD). Statistical significance was set at $p < 0.05$. Participants 3, 8, 12 and 14 were excluded from statistical analysis due to injury and illness, respectively. Data for RMR is presented as n = 15 as this was collected pre-injury and illness.

General linear models were used to evaluate the effect of positional group and microcycle on TEE. To control for the effects of body composition, adjusted TEE (*adj.* MJ·day^{-1} [kcal·day^{-}1]) and RMR (*adj.* MJ·day^{-1} [kcal·day^{-}1]) was calculated by including FFM and FM as covariates (Ravussin and Bogardus, 1989). Participants were included as a random effect and playing position (i.e., forwards and backs) was included as a fixed effect. Separate models were specified with microcycle as a fixed effect, with no covariates included. The normality of residuals was checked through visual inspection of Q-Q plots. Tukey pairwise comparisons were performed to identify significant differences ($p < 0.05$). A paired t-test was used to assess changes in BM across microcycles, where BM was an average of days 0-2 and 14-15, respectively. Relationships between energy expenditure, anthropometric, and load variables were assessed using Pearson's correlation.

To avoid mathematical bias from composite variables (i.e., TEE relative to FFM), only absolute values of TEE and FFM have been compared to the literature (Ravussin and Bogardus, 1989).

RESULTS

Training and match load

Training and match load variables for participants who were free from injury or illness (n=11) are presented by microcycle and position in Figure 1A-H. Training duration (Figure 1A; forwards: -222 min, P = 0.028; backs: -289 min, P = 0.043), total distance (Figure 1C; forwards: -7132 m, P = 0.001; backs: -9235 m, P = 0.001), player load (Figure 1F; forwards: -602 AU, P = 0.001; backs: -791 AU, P = 0.001), and sRPE (Figure 1H; forwards: -961 AU, P = 0.001; backs: -980 AU, P = 0.001) were significantly lower in microcycle 2 compared to microcycle 1. Average speed was significantly higher in microcycle 2 compared to microcycle 1, for backs (Figure1D; +9 m/min, P = 0.022). All other differences across weekly microcycles were non-significant (P > 0.061).

Training duration (Figure 1A; microcycle 1: +78 min, P = 0.017), total distance (Figure 1C; microcycle 1: +5665 m, P = 0.017), average speed (Figure1D; microcycle 1: 10 m/min, P = 0.001; microcycle 2: 14 m/min, P = 0.005), high-speed running (Figure1E; microcycle 1: 1082 m, P = 0.001; microcycle 2: 593.9, P = 0.044), player load (Figure 1F; microcycle 1; 467 AU, P = 0.010), was significantly greater in backs than forwards. Contact count (Figure 1G; microcycle 1: 33 n, P = 0.021, microcycle 2; 53 n, P = 0.019) was significantly greater in forwards than backs. All other differences between forwards and backs were non-significant (P > 0.087).

The training load for the injured participant (n=1) was lower in all variables in microcycle 2 compared to microcycle 1 (training duration: -278 min, match duration: -10 min, total distance: -6975 m, average speed: - 145 m/min, high-speed running: - 205 m, player load: -675 AU, collisions: -30 n, and sRPE: -259 AU).

The training load for participants experiencing illness (n=3) was lower in microcycle 2 compared to microcycle 1 (training duration: -365 ± 100 min, match duration: -78 ± 3 min, total distance: -9586 ± 1939 m, high-speed running: -367 ± 299 m, player load: -909 ± 149 AU, collisions: -63 ± 16 n, and sRPE: -657 ± 373 AU). Average speed was higher in microcycle 2 (30 ± 7 m/min).

INSERT FIGURE 1 NEAR HERE

Resting and total energy expenditure

Participants free from injury and illness

Mean 14-day TEE, RMR and PAL for participants who were free from injury or illness (n=11) was 13.51 ± 2.28 MJ·day^{-1} (range, 9.10 – 16.12 MJ·day^{-1} [3229 ± 545 kcal·day^{-1}]), 6.60 ± 0.93 MJ·day^{-1} (range, 5.27-7.72 MJ·day^{-1} [1578 ± 223 kcal·day^{-1}]), and 2.0 ± 0.2 AU (range, 1.6 – 2.3). Mean 14-day water turnover (n=11) was 4.1 ± 0.8 L·day^{-1} (range; 2.7 – 5.2 L·day^{-1}).

There was no significant difference in TEE (13.74 ± 2.32 MJ·day^{-1} [3284 ± 554 kcal·day^{-1}] *vs.* 13.92 ± 2.10 MJ·day^{-1} [3327 ± 502 kcal·day^{-1}]; p = 0.754), or PAL (2.06 ± 0.26 AU *vs.* 2.09 ± 0.23 AU; p = 0.735) across weekly microcycles. There was no significant change in BM across the 14-days (0.4 ± 0.7 kg; p = 0.101).

Forwards had a significantly greater 14-day TEE than backs (14.89 ± 1.45 MJ·day^{-1} [3560 ± 346 kcal·day^{-1}] *vs.* 11.85 ± 2.02 MJ·day^{-1} [2832 ± 483 kcal·day^{-1}]; p = 0.025). There was no significant difference in RMR (6.90 ± 0.56 MJ·day^{-1} [1660 ± 155 kcal·day^{-1}] *vs.* 6.26 ± 1.20 MJ·day^{-1} [1496 ± 287 kcal·day^{-1}]; p = 0.233) or PAL (2.15 ± 0.14 AU vs 1.87 ± 0.26 AU; p = 0.090) between forwards and backs. When adjusted for body composition (FFM and FM), there was no significant difference in TEE (13.80 ± 1.74 *adj.* MJ·day^{-1} [3298 ± 416 *adj.* kcal·day^{-}

^{1}] *vs.* 13.16 ± 1.97 *adj.* MJ·day^{-1} [3145 ± 471 *adj.* kcal·day^{-1}]; *p* = 0.628) or RMR (6.49 ± 0.81 *adj.* MJ·day^{-1} [1551 ± 194 *adj.* kcal·day^{-1}] *vs*. 6.73 ± 0.83 *adj.* MJ·day^{-1} [1609 ± 198 *adj.* kcal·day^{-1}]; *p* = 0.633) between forwards and backs. Figure 2A-B shows TEE by positional group for each microcycle.

******INSERT FIGURE 2 NEAR HERE******

Participants who had injury and illness

The 14-day TEE of the injured participant was 13.61 MJ·day^{-1} (3253 kcal·day^{-1}). Total energy expenditure was 14.55 MJ·day^{-1} (3478 kcal·day^{-1}) and 12.85 MJ·day^{-1} (3071 kcal·day^{-1}) during microcycle 1 (when the participant sustained the injury) *vs.* microcycle 2 (when they were injured). The corresponding PAL was 2.14 and 1.89 AU. Mean 14-day water turnover was 4.3 L·day^{-1}.

The 14-day TEE of participants with COVID-19 was 13.0 ± 2.74 MJ·day^{-1} (3107 ± 655 kcal·day^{-1}). Total energy expenditure was 13.17 ± 2.28 MJ·day^{-1} (3148 ± 545 kcal·day^{-1}) and 13.66 ± 3.13 MJ·day^{-1} (3265 ± 748 kcal·day^{-1}) during microcycle 1 (when participants tested positive for COVID-19) *vs.* microcycle 2 (when participants were isolating), respectively. The corresponding PAL was 2.15 ± 0.22 and 2.21 ± 0.09 AU. Mean 14-day water turnover was 3.6 ± 1.1 L·day^{-1} (range; 2.7 – 4.9 L·day^{-1}).

Factors affecting energy expenditure

A correlation matrix has been provided in *supplementary material, resource 2.* Individual data are reported in Figure 3.

******INSERT FIGURE 3 NEAR HERE******

DISCUSSION

Practitioners working with female rugby union players require a high-quality evidence-base to support athlete health and performance. Therefore, this study utilised gold-standard methods to measure the resting and total energy expenditures of international female rugby union players across an in-season period inclusive of competitive match-play. Female rugby union players have energy requirements representative of a vigorously active lifestyle. For participants who were free from injury and illness, there was no difference in TEE across the two one-match microcycles, despite a substantial decrease in load across the second microcycle. Despite insignificant differences in RMR and PAL between forwards and backs, forwards had significantly greater TEEs. However, when adjusted for differences in FM and FFM, TEEs were non-significant between positional groups. For participants who had an injury or illness, there was a decrease and no change in TEE across microcycles, respectively. These findings are critical to ensuring the provision of evidence-based dietary guidance to female rugby players.

In this study, female rugby union players exhibited energy needs indicative of high activity levels (>2.0 AU) (Westerterp, 2013), with a RMR similar to that of sub-elite and elite counterparts (6.91 ± 0.7 $MJ \cdot day^{-1}$ [1651 ± 167 $kcal \cdot day^{-1}$]) (O'Neill et al., 2022), but less than adolescent males (Smith et al., 2018; Costello et al., 2019), likely due to males' greater BM and FFM. We report higher reported TEEs than that of university female players (+3.9 $MJ \cdot day^{-1}$ [932 $kcal \cdot day^{-1}$]) (Traversa et al., 2022), but lower than female rugby seven's players (-1.0 - 2.0 $MJ \cdot day^{-1}$ [237 - 476 $kcal \cdot day^{-1}$]) (Curtis et al., 2023), potentially reflecting differences in training intensity and frequency. However, the indirect assessment methods used by Traversa et al. (Traversa et al., 2022) and Curtis et al. (Curtis et al., 2023) may have resulted in underestimated TEEs. When compared to male adolescents (pre-season; - 4.9 $MJ \cdot day^{-1}$ [-1171 $kcal \cdot day^{-1}$])(Costello et al., 2019), (in-season; - 4.8 $MJ \cdot day^{-1}$ [-1147 $kcal \cdot day^{-1}$])(Smith et al., 2018), and male senior (in-season; - 9 $MJ \cdot day^{-1}$ [-2151 $kcal \cdot day^{-1}$])(Morehen et al., 2016) rugby players, female players have lower TEEs but similar physical activity levels (1.4 – 2.0

AU). These findings suggest that the higher energy expenditures in males could be attributed to their greater FFM and RMR.

Compared to other female team-sport athletes, we report higher (~2.2 $MJ \cdot day^{-1}$ [526 $kcal \cdot day^{-1}$]) TEEs than in-season values for international female soccer players measured by DLW (Morehen et al., 2021). Despite comparable PALs (1.4–2.2), differences in absolute TEEs may be explained by the greater levels of FFM possessed by female rugby players (+15.7 kg), alongside the recovery costs of a collision-based sport. On the contrary, reported TEEs are lower (~1.12 $MJ \cdot day^{-1}$ [268 $kcal \cdot day^{-1}$]) than those observed in elite junior female basketball players (Silva et al., 2013). Although female rugby players have a greater BM, FFM, and RMR (+12.2 kg, 8 kg and 286 $kcal \cdot day^{-1}$, respectively), female basketball players had a more condensed training schedule, reflected by a high PAL (2.6 AU), which may account for their greater overall TEEs.

Mean TEEs were similar across the two one-match microcycles, suggesting that player energy requirements may not differ, despite differences in training load (Figure 1). The collision-induced muscle damage sustained on MD (microcycle 1), could have accounted for the similar TEEs observed in microcycle two (+0.18 $MJ \cdot day^{-1}$ [+43 $kcal \cdot day^{-1}$]) (Costello et al., 2018; Hudson et al., 2019), despite participants completing less overall load (total distance: -8088 m, collisions: -20 n, training duration: -252 min, and sRPE: -969 AU). Muscle damage has been shown to disrupt homeostasis by initiating biochemical, endocrine (McLellan et al., 2011), and neuromuscular responses (McLellan and Lovell, 2012), which can remain elevated for 2-5 days following collision activity (Smart et al., 2008; Cunniffe et al., 2010). Such responses may have large energy costs due to the associated requirements of recovery (i.e., increased protein turnover) (Peake et al., 2017). Match-day collisions have been associated with increases in RMR (0.97 $MJ \cdot day^{-1}$ [231 $kcal \cdot day^{-1}$])(Hudson et al., 2019). As such, when players train less to recover from collision-based damage (as evidenced by the removal of a training session in microcycle two by the coaching team (Table 1)), it appears that their TEEs may remain elevated due to the energy cost of recovery from such damage. This is supported by comparable PALs observed across microcycles (2.06 ± 0.26 *vs.* 2.09 ± 0.23 AU), which may indicate increases in the players RMR, although this was not re-assessed. Accordingly, female rugby players (and other collision-based athletes) should consider fuelling for the “muscle damage caused” alongside the kinematic “work required” (Costello et al., 2018; Hudson et al., 2019).

Forwards had a greater TEE than backs, potentially due to their greater FFM and collision involvement. On average, forwards expended 3.04 $MJ \cdot day^{-1}$ (727 $kcal \cdot day^{-}$1) more than backs, however, this was non-significant when adjusting for differences in body composition (FM and FFM). Individuals with greater levels of FFM have been shown to have an increased capacity for energy expenditure due to an increase in metabolically active tissue (Pontzer et al., 2021; Gallagher et al., 1996). Moreover, training-based collisions have been shown to increase TEE by 4.96 ± 0.97 MJ (1186 ± 232 $kcal \cdot day^{-1}$) over a five-day period (Costello et al., 2018), whilst collisions during match-play are followed by increased RMR (Hudson et al., 2019). Despite this, forwards have reduced running demands than backs. Therefore, the increased energy cost of collisions in forwards, is potentially off set by the reduced locomotor demands associated with their tactical role. Consequently, practitioners should consider individualising player fuelling requirements by differences in body composition (FM and FFM) rather than position.

This study provides DLW assessed TEE for a female rugby player during injury. Participant 3 sustained a non-collision related anterior cruciate ligament (ACL) injury on day 3 (MD) of the assessment period. The participant was not immobilised, but was non-weight bearing on her injured limb, resulting in reduced training loads (total distance: -6975 m, collisions: -30, training duration: -278 min, and sRPE: -259 AU). Reduced load corresponded with a decrease of -1.69 $MJ \cdot day^{-1}$ (407 $kcal \cdot day^{-1}$; -11.6%) in TEE from microcycle one. Similar absolute energy requirements have also been observed in a female Super League netball player during week 1 of a medial collateral ligament injury (13.82 $MJ\cdot day^{-1}$ [3303 $kcal\cdot day^{-1}$]). However, there was no accompanying decrease in TEE from pre-injury (+0.85 $MJ\cdot day^{-1}$ [203 $kcal\cdot day^{-1}$]) (Costello et al., *unpublished observations*). Until further data is available, injured players should be supported in line with their specific level of immobilization and rehabilitation, with a focus on lean mass maintenance (Rollo et al., 2021). Further research is required to support practitioners working with female athletes through injury.

Total energy expenditure is also presented for three players during a period of illness. Participants 8, 12 and 14 tested positive for Covid-19 on day 4 (MD+1) and were required to isolate until returning a negative PCR test on days 13, 10, and 13, respectively. Despite reduced loads, mean TEE was similar across microcycles for these participants. These findings may reflect increased metabolic demands associated with illness (Cicchella et al., 2021). For example, prolonged and progressive increases in RMR have been observed via indirect calorimetry in patients with Covid-19 (+0.03 $MJ\cdot kg\cdot BM\cdot day^{-1}$ [7.2 $kcal\cdot kg\cdot BM\cdot day^{-1}$]) (Niederer et al., 2021). However, these data were collected on critically ill patients in the intensive care unit. An alternative hypothesis is that the comparable TEEs observed across microcycles are a consequence of the elevated energy cost of recovery from damage accrued during MD, as all participants played the full 80 minutes. Consequently, players should maintain energy intakes during bouts of illness, especially when recovering from previously high training and match loads.

Study limitations

This study is limited by the inability of the DLW technique to report day-to-day variations in TEE. Therefore, recommendations for daily energy intake could not be presented. In addition, data are collected from a relatively small sample of players from one international team, reducing the generalisability to the wider population, although this sample is similar to other studies. Case examples are presented for specific episodes of illness and injury, however metabolic responses may be different depending on each presentation of injury and illness. This study is strengthened by employing high-quality methods in an under-represented sample of female athletes taking part in international competition. Future research should investigate how energy requirements change day-to-day, alongside periods of reduced load (e.g., substitution, injury, and illness).

CONCLUSION

This study provides the first gold standard assessed TEE data for female rugby union players. Energy requirements were repeatable across one match microcycles, despite large reductions in training load. Forwards have significantly greater energy requirements compared to backs, however, when adjusted for differences in FFM and FM, TEEs were comparable. These findings suggest that fuelling strategies should be consistent across one-match microcycles and individualised by player body composition as opposed to positional groups. Practitioners should consider the increased energy demands associated with recovery from the collision nature of the sport. Injury resulted in a decrease in energy expenditure, in line with reduced training loads. There was no change in energy requirements in players will illness. These data now provide a much-needed foundation to develop strategies which serve to protect female rugby players health and optimise their performance.

Practical Implications

- Mean TEE was similar across two one-match microcycles, despite a substantial reduction in training load across the second microcycle. Accordingly, female rugby players should consider fuelling for the “muscle damage caused” alongside the kinematic “work required”. Meanwhile, practitioners can plan for a consistent nutrition service delivery and coaching of player fuelling and recovery behaviours, across one-match microcycles.

- Forwards and backs had comparable TEEs when adjusted for differences in body composition (FM and FFM). Consequently, practitioners should consider individualising player fuelling requirements by differences in body composition (e.g., how much FFM and FM individuals have), rather than by position.
- These findings provide a foundation from which practitioners can develop evidence based nutritional strategies to support female rugby players with training and match demands.

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Author Contributions

LW, BJ, SB, AB and NC conceptualised the study. Data were collected and analysed by LW, CH, FM, BS, JRS and SR. Data interpretation and manuscript preparation was undertaken by LW, BJ and NC. All authors approved the final version of the manuscript.

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Competing Interests

LW is responsible for nutrition service delivery to the National Women's Team at the Scottish Rugby Union (SRU). AB is head of athletic development at the SRU. CR and FM provide sports science support to the SRU.

Patient Consent for Publication

Not applicable.

Patient and Public Involvement

Patients and/or the public were not involved in the design, conduct, reporting, of dissemination of this research.

Ethics Approval

This study involved human participants and was approved by the Local Ethics Committee, Leeds Beckett University (100577).

Provenance and Peer Review

Not commissioned, externally peer reviewed.

Equity, Diversity, and Inclusion Statement

To address the underrepresentation of females in sport science research, this study deliberately recruited female rugby players, some of whom are members of the LGBTQIA2S+ community. The research team included four females and seven males, who are early career (four), mid-career (three) and senior researchers (four). The effects of race/ethnicity or socioeconomic status was not considered. We discuss the effect of sex on our findings.

Data Availability Statement

All data relevant to the study are included in the manuscript or uploaded as supplementary material.

Supplementary Material

This content has been supplied by the author(s).

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Table 1. An overview of the assessment, training, and match schedule for the fourteen-day observational period.

			MICROCYCLE 1							**MICROCYCLE 2**						
		WEDNESDAY DAY 0	**THURSDAY DAY 1**	**FRIDAY DAY 2**	**SATURDAY DAY 3**	**SUNDAY DAY 4**	**MONDAY DAY 5**	**TUESDAY DAY 6**	**WEDNESDAY DAY 7**	**THURSDAY DAY 8**	**FRIDAY DAY 9**	**SATURDAY DAY 10**	**SUNDAY DAY 11**	**MONDAY DAY 12**	**TUESDAY DAY 13**	**WEDNESDAY DAY 14**
Team Schedule	Testing Procedures	**07:00-10:00** BM, US, DLW Administration, RMR **14:00-15:30** US	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** US sRPE	**07:00-09:00** US sRPE	**07:00-09:00** US GPS & Video sRPE	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** BM, US sRPE	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** BM, US GPS & Video sRPE	**07:00-09:00** US sRPE	**07:00-09:00** US sRPE	**07:00-09:00** US sRPE	**07:00-09:00** BM, US GPS & Video sRPE
	Training & Match	Rest	**11:00 Pitch S** (Speed) **15:00 Gym**	**11:00 CR** (Clarity)	**12:00 Match**	**Rest**	**Gym - Remote**	**15:00 PS** (Clarity)	**11:00 PS** (Physical) **14:30 PS** (Units)	**12:45 Travel (Air)**	**11:00 Walk** **14:00 CR** (Clarity)	**16:45 Match**	**Rest**	**Gym - Remote**	**Rest** ***PS- Removed**	**11:00 PS** (Physical) **14:30 PS** (Units)
Individual Player Schedules	P1 (FR)	Rest	Rest			**11:00** Walk (20)	**07:30** Gym (40)			**17:20** Mobility (15)			Rest	**07:30** Gym (40)	Rest	
	P2 (FR)	**16:00** Swim (30)	**14:45** Mobility (45)			**12:00** Walk (120)	**12:00** Walk (60) **15:00** Gym (45)			**15:30** Walk (45)			**17:30** Walk (60)	**12:00** Walk (100) **17:00** Gym (60)	Rest	
	*P3 (FR)	**16:00** Swim (30)			**INJ**	Rest	**16:30** Gym (60)	Rest	Rest	**16:00** Upper Gym (60) **19:00** Arms Assault Bike (25)	Rest	Rest	Rest	**15:30** Upper Gym (60) **17:45** Seated Ski Erg (25)	**07:45** Seated Ski Erg (45) **19:00** Upper Body Gym (45)	Rest
	P4 (SR)	**16:30** Walk (30)				**11:30** Walk (15)	**16:15** Gym (60)			**16:00** Walk (20)			**12:00** Walk (30)	**12:00** Gym (60)	**12:00** Walk (20)	
	P5 (SR)	Rest				**12:00** Walk (30)	**07:00** Gym (60)			**17:00** Walk (40)			Rest	**07:00** Gym (50) **12:00** Walk (30)	Rest	
	P6 (BR)	Rest				**11:30** Walk (30)	**10:00** Walk (60) **17:00** Gym (60)			**17:00** Walk (30)			Rest	**12:00** Gym (60)	Rest	
	P7 (BR)	**16:30** Walk (25)				**12:00** Walk (30)	**10:15** Gym (45)			**16:00** Walk (40)			**11:45** Walk (100)	**13:30** Walk (30) **14:15** Gym (50)		
	**P8 (BR)	**16:00** Swim (20)				**Positive PCR**	Rest	Rest	Rest	**15:00** Run (20)	**14:00** Circuit Training (30)	**18:00** Run (30)	**17:00** Walk (20)	**16:00** Gym (60) **Negative PCR**	**09:00** Watt Bike & Core (30) **10:00** Walk (30)	
	P9 (SH)	**16:00** Walk (30)				**12:00** Walk (60)	**12:00** Walk (30) **17:15** Gym (60)			**16:30** Walk (30)			**11:00** Walk (45)	**14:00** Gym (80) **17:00** Walk (30)	Rest	
	P10 (IB)	**14:30** Walk (30)				**14:00** Walk (60)	**10:00** Gym (70)			**16:30** Walk (30)			**12:00** Walk (30)	**09:00** Gym (60) **11:00** Walk (30)	Rest	
	P11 (IB)	**14:30** Walk (30)				**12:00** Walk (60)	**10:00** Gym (75) **12:30** Walk (45)			**16:30** Walk (30)			Rest	**12:00** Gym (60)	Rest	
	**P12 (IB)	**15:00** Walk (30)				**Positive PCR**	Rest	Rest	Rest	**13:00** Run (20)	**10:00** Run (20) **Negative PCR** **Travel**		**10:30** Run (30)	**07:15** Run (40)	**07:30** Run (30) **11:30** Gym (60)	Rest
	P13 (OB)	Rest	**14:45** Bike & Mobility (45)			Rest	**10:00** Gym (90)			**16:00** Walk (30)			Rest	**09:00** Gym (60) **12:00** Walk (100)	Rest	
	**P14 (OB)	Rest				**Positive PCR**	Rest	Rest	Rest	**12:40** Walk (45)	**14:00** Circuit Training (20)	**11:35** Walk (40)	**17:25** Walk (68)	**12:20** Walk (70) **Negative PCR**	**17:00** Gym (60)	
	P15 (OB)	**15:45** Swim (15)				Rest	**10:00** Gym (70)			Rest			Rest	**09:00** Gym (60)	Rest	

Table highlights research testing and prescribed training and match schedules. Modified or home-based loads completed away from the training environment are detailed for each participant. Number in parentheses represents duration in minutes. Four participants (P3, P8, P12 and P14) had altered schedules due to injury or illness. '*' denotes injured participant. '**' denotes participants with Covid-19. Participant positions are shown as; FR, Front Row; SR, Second Row; BR, Back Row; SH, Scrum Half; IC, Inside Centre and OC, Outside Centre. INJ (the participant sustained an injury). PS (pitch session). CR (captains run). RMR (resting metabolic rate). DLW (doubly labelled water). US (urine sample). GPS (global positioning system). sRPE (sessional ratings of perceived exertion). PCR (polymerase chain reaction test).

Table 2. Baseline characteristics of international female rugby union players

	Forwards (*n* = 8)	**Backs** (*n* = 7)	**Mean** (*n* = 15)
Age (Years)	27.5 ± 2.5	26.4 ± 2.8	27.0 ± 2.6
Stature (cm)	170.2 ± 6.2	168.9 ± 5.5	169.6 ± 5.7
Body mass (kg)	81.9 ± 7.2	69.7 ± 9.9	76.2 ±10.4
Total body water (L) *^{2}H*	45.2 ± 2	40.5 ± 4.0	43.0 ± 4.0
Fat-free mass (kg) *^{2}H*	62.0 ± 3.7	55.5 ± 5.5	58.9 ± 5.5
Fat mass (kg) *^{2}H*	19.9 ± 4.6	14.2 ± 6.4	17.2 ± 6.1
Percent body fat (%) *^{2}H*	24.1 ±3.9	19.7 ± 6.3	22.1 ± 5.5

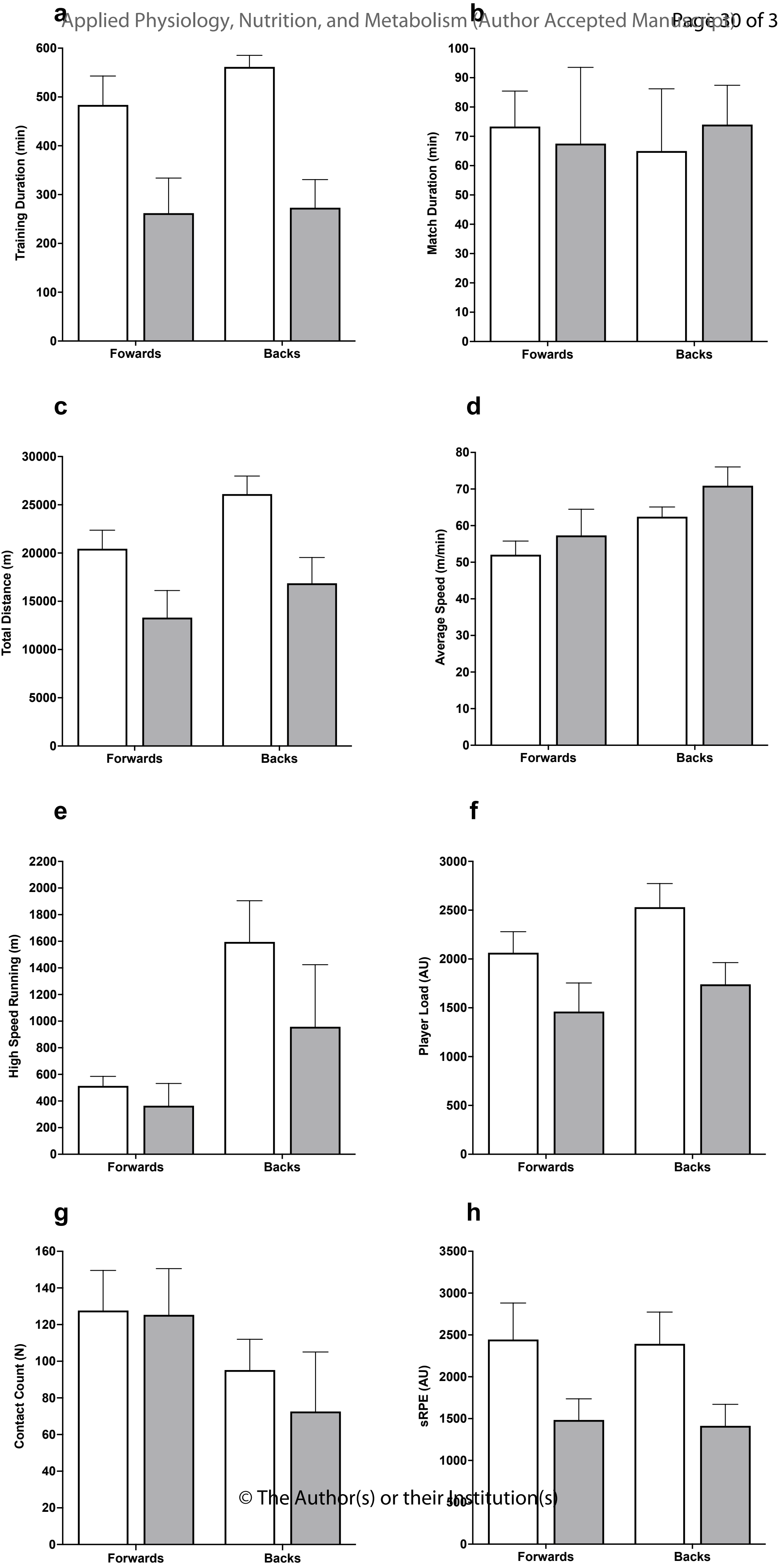
Body composition assessment technique is labelled in *italics* (deuterium (^{2}H)).

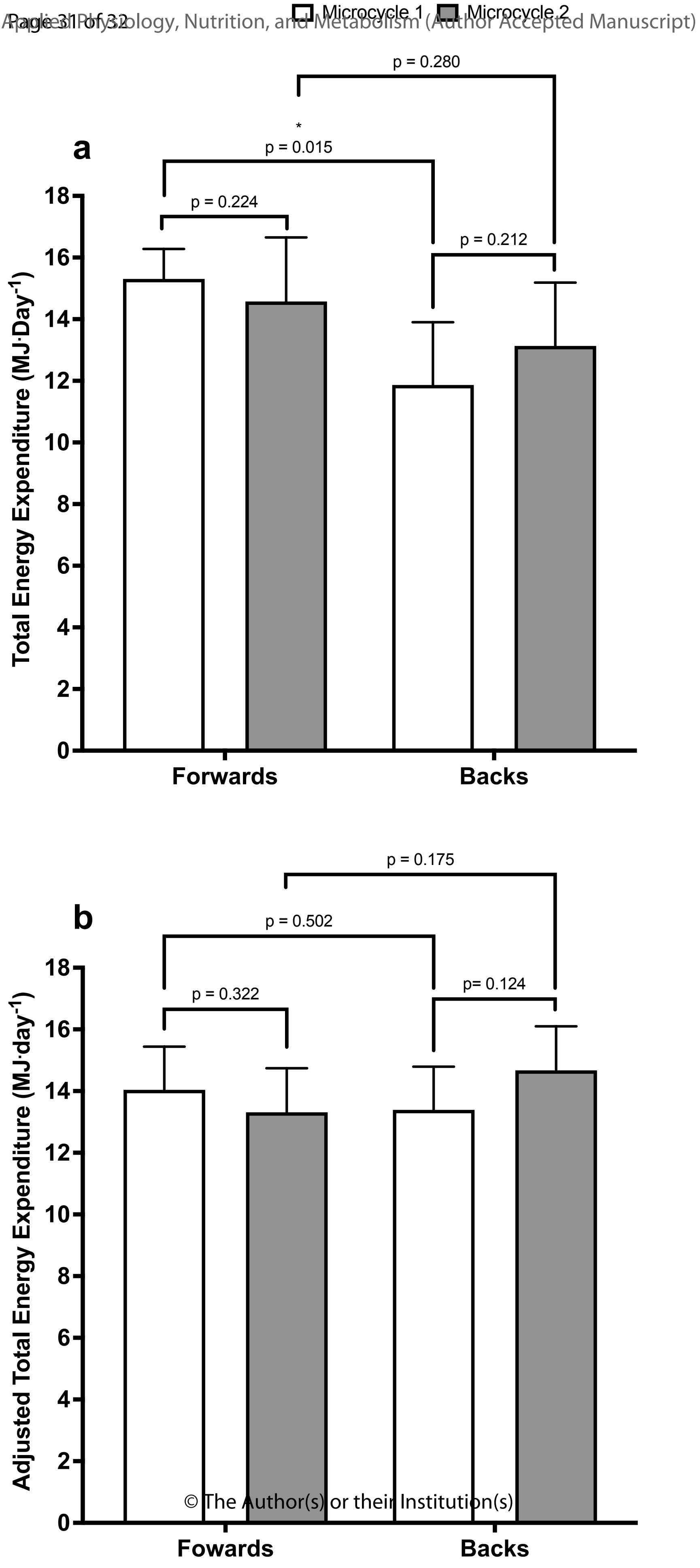
Figure Legends

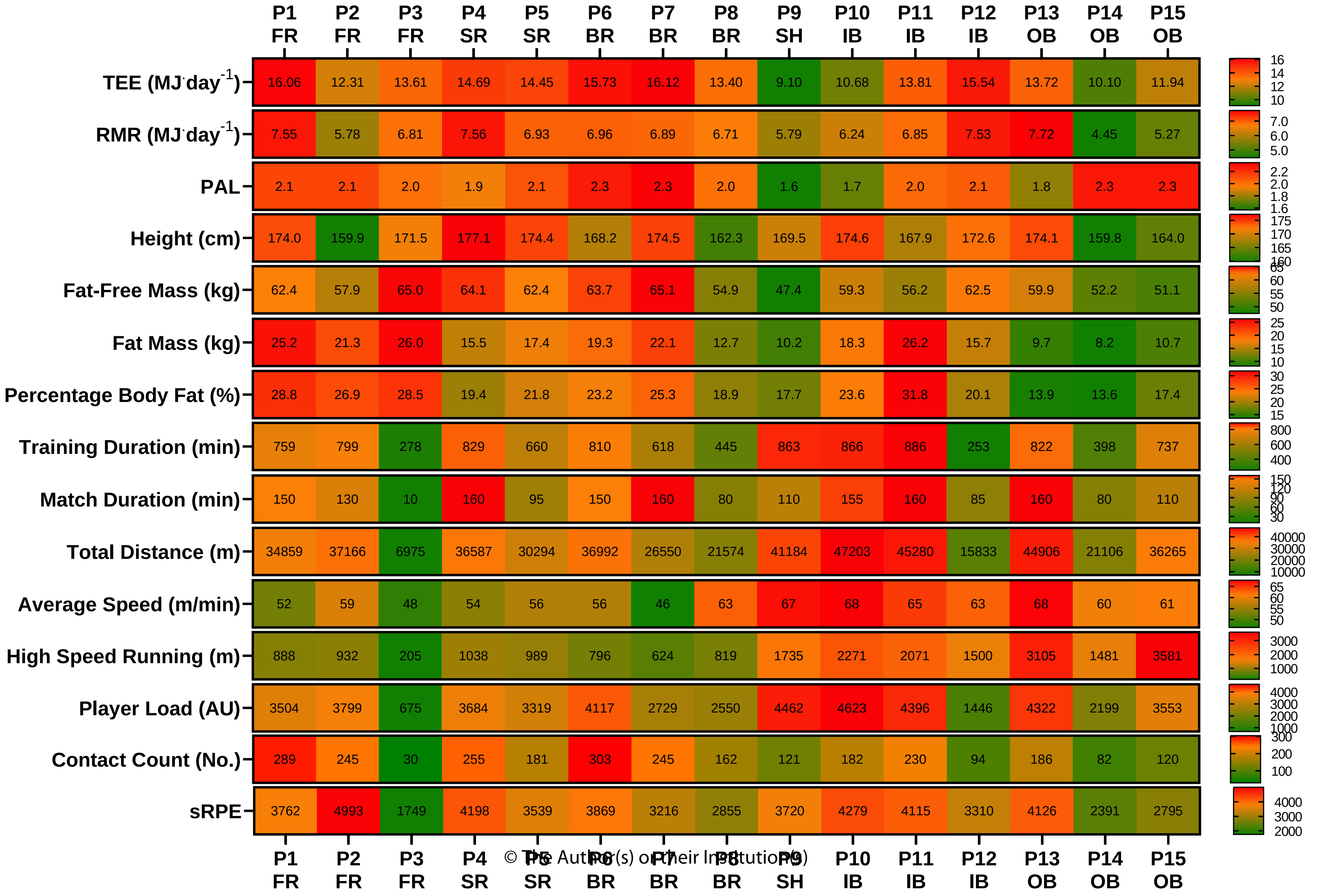
Figure 1: (A) Training duration (B) match duration, (C) total distance, (D) average speed, (E) high speed running (> 5 m/s), (F) player load, (G) contact count and (H) sRPE for forwards and backs, microcycle 1 (white bars) and microcycle 2 (grey bars). Load data is the summed values for the 14-day period. Bars represent mean ± SD (n=11) in accordance with the players who attended all training and games. * $p < 0.05$. ** $p < 0.01$.

Figure 2: (A) Total energy expenditure (MJ.day^{-1}) and (B) *adjusted* total energy expenditure (*adj.* MJ.day^{-1}), for forwards and backs, microcycle 1 (white bars) and microcycle 2 (grey bars). Adjusted TEE represents TEE controlled for differences in body composition (FFM and FM). Bars represent mean ± SD (n=11) in accordance with the players who attended all training and games. * $P < 0.05$.

Figure 3: A heat map depicting individual participant data for anthropometric, energy expenditure and training load variables over the 14-day observational period. Columns represent each participant and rows represent variables. All load variables refer to 14-day summed values. Participant positions are shown as; FR, Front Row; SR, Second Row; BR, Back Row; SH, Scrum Half; IC, Inside Centre and OC, Outside Centre.


a
Training Duration (min)
0
100
200
300
400
500
600
Fowards
Backs
b
Match Duration (min)
0
10
20
30
40
50
60
70
80
90
100
Fowards
Backs
c
Total Distance (m)
0
5000
10000
15000
20000
25000
30000
Forwards
Backs
d
Average Speed (m/min)
0
10
20
30
40
50
60
70
80
Forwards
Backs
e
High Speed Running (m)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Forwards
Backs
f
Player Load (AU)
0
500
1000
1500
2000
2500
3000
Forwards
Backs
g
Contact Count (N)
0
20
40
60
80
100
120
140
160
Forwards
Backs
h
sRPE (AU)
0
500
1000
1500
2000
2500
3000
3500
Forwards
Backs


Microcycle 1
Microcycle 2
a
p = 0.280
*
p = 0.015
p = 0.224
p = 0.212
Total Energy Expenditure (MJ·Day^{-1})
0
2
4
6
8
10
12
14
16
18
Forwards
Backs
b
p = 0.175
p = 0.502
p = 0.322
p= 0.124
Adjusted Total Energy Expenditure (MJ·day^{-1})
0
2
4
6
8
10
12
14
16
18
Fowards
Backs



	P1 FR	P2 FR	P3 FR	P4 SR	P5 SR	P6 BR	P7 BR	P8 BR	P9 SH	P10 IB	P11 IB	P12 IB	P13 OB	P14 OB	P15 OB
TEE (MJ$\cdot$day^{-1})	16.06	12.31	13.61	14.69	14.45	15.73	16.12	13.40	9.10	10.68	13.81	15.54	13.72	10.10	11.94
RMR (MJ$\cdot$day^{-1})	7.55	5.78	6.81	7.56	6.93	6.96	6.89	6.71	5.79	6.24	6.85	7.53	7.72	4.45	5.27
PAL	2.1	2.1	2.0	1.9	2.1	2.3	2.3	2.0	1.6	1.7	2.0	2.1	1.8	2.3	2.3
Height (cm)	174.0	159.9	171.5	177.1	174.4	168.2	174.5	162.3	169.5	174.6	167.9	172.6	174.1	159.8	164.0
Fat-Free Mass (kg)	62.4	57.9	65.0	64.1	62.4	63.7	65.1	54.9	47.4	59.3	56.2	62.5	59.9	52.2	51.1
Fat Mass (kg)	25.2	21.3	26.0	15.5	17.4	19.3	22.1	12.7	10.2	18.3	26.2	15.7	9.7	8.2	10.7
Percentage Body Fat (%)	28.8	26.9	28.5	19.4	21.8	23.2	25.3	18.9	17.7	23.6	31.8	20.1	13.9	13.6	17.4
Training Duration (min)	759	799	278	829	660	810	618	445	863	866	886	253	822	398	737
Match Duration (min)	150	130	10	160	95	150	160	80	110	155	160	85	160	80	110
Total Distance (m)	34859	37166	6975	36587	30294	36992	26550	21574	41184	47203	45280	15833	44906	21106	36265
Average Speed (m/min)	52	59	48	54	56	56	46	63	67	68	65	63	68	60	61
High Speed Running (m)	888	932	205	1038	989	796	624	819	1735	2271	2071	1500	3105	1481	3581
Player Load (AU)	3504	3799	675	3684	3319	4117	2729	2550	4462	4623	4396	1446	4322	2199	3553
Contact Count (No.)	289	245	30	255	181	303	245	162	121	182	230	94	186	82	120
sRPE	3762	4993	1749	4198	3539	3869	3216	2855	3720	4279	4115	3310	4126	2391	2795