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Daily energy expenditure and water turnover in female netball players from the Netball Super League: A doubly labeled water observation study

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Abstract

To establish the criterion-assessed energy and fluid requirements of female netball players, 13 adult players from a senior Netball Super League squad were assessed over 14 days in a cross-sectional design, representing a two- and one-match microcycle, respectively. Total energy expenditure (TEE) and water turnover (WT) were measured by doubly labeled water. Resting and activity energy expenditure were measured by indirect calorimetry and Actiheart, respectively. Mean 14-day TEE was 13.46 ± 1.20 MJ day^{-1} (95% CI, 12.63–14.39 MJ day^{-1}). Resting energy expenditure was 6.53 ± 0.60 MJ day^{-1} (95% CI, 6.17–6.89 MJ day^{-1}). Physical activity level was 2.07 ± 0.19 arbitrary units (AU) (95% CI, 1.95–2.18 AU). Mean WT was 4.1 ± 0.9 L day^{-1} (95% CI, 3.6–4.7 L day^{-1}). Match days led to significantly greater TEE than training (+2.85 ± 0.70 MJ day^{-1}; 95% CI, +1.00– +4.70 MJ day^{-1}; $p = 0.002$) and rest (+4.85 ± 0.70 MJ day^{-1}; 95% CI, +3.13–+6.56 MJ day^{-1}; $p < 0.001$) days. Matches led to significantly greater energy expenditure (+1.85 ± 1.27 MJ; 95% CI, +0.95–+2.76 MJ day^{-1}; $p = 0.001$) than court-based training sessions. There was no significant difference in TEE (+0.03 ± 0.35 MJ day^{-1}; 95% CI, −0.74–+0.80 MJ day^{-1}; $p = 0.936$) across weeks. Calibrated Actiheart 5 monitors underestimated TEE (−1.92 ± 1.21 MJ day^{-1}). Energy and fluid turnover were greatest on match days, followed by training and rest days, with no difference across weeks. This study provides criterion-assessed energy and fluid requirements to inform dietary guidance for female netball players.

KEYWORDS
nutrition, physiology, team sport

Highlights

- The energy and fluid requirements of female netball players were greatest on match days, followed by training and rest days, with no difference across a one- or two-match weekly microcycle. Therefore, players are encouraged to periodise their intake on a daily basis, aligning with the demands of their training and match schedule.
- Female netball players have in-season energy requirements representative of a vigorously active lifestyle (physical activity level: >2.0 arbitrary units). Water turnover varied widely amongst participants (range: 62 mL fat-free mass [FFM] day^{-1}), while total energy requirements were more homogenous (range: 0.05 MJ FFM day^{-1}).
- Calibrated Actiheart 5 monitors underestimated female netball player total energy expenditure in comparison to the doubly labelled water criterion (range: −0.38–3.84 MJ day^{-1}). Further research is now required to investigate the validity of Actiheart for measuring team sport athlete energy expenditure.

1 | INTRODUCTION

Optimal health and performance in female netball players is contingent upon adequate energy and nutrient intake, alongside proper hydration (Thomas et al., 2016). Netball, a sport with a global participation of 20 million across 80 countries (Delextrat et al., 2010), is characterised by intermittent periods of high and low intensity activity. During a match, players predominantly walk (32%–52% of the time), interspersed with brief instances of jogging, shuffling, running and sprinting, often lasting less than 6 s (Fox et al., 2013). These high intensity actions elevate players' heart rates to 75%–85% of their maximum during matches, compared to a training intensity which often does not exceed 75% (Steele, 1990). Center court players, in particular, engage in frequent multidirectional movements, with a change in activity approximately every 2.8 s and a work-to-rest ratio of 1:2 (Davidson et al., 2016). Within the English Netball Super League, center court players undertake an average of 8.6–10.9 directional changes per minute, while goal shooters perform approximately 0.9 jumps per minute, reflecting their role-specific physical requirements (Mackay et al., 2024). Such positional requirements delineate players into four main categories: goalkeepers and goal shooters; centers; wing attack and wing defense; and goal attack and goal defense, highlighting the varied intensity and movement types across positions in netball (Young et al., 2016).

Despite their importance, definitive guidelines regarding the energy and fluid requirements of female netball players remain to be established, presenting a critical knowledge gap (Whitehead et al., 2021). This absence of guidance could lead to suboptimal nutrition and hydration strategies across rest, training and match days, potentially resulting in negative health outcomes and performance effects (Thomas et al., 2016). Recent evidence from the ANZ Premiership in New Zealand indicates that 53% of recruited female netball players were "at risk" of low energy availability, with a significantly greater associated risk of injury, gastrointestinal and menstrual disfunction (Davie et al., 2021). A parallel issue was identified in the English Netball Super League, where a pervasive lack of understanding regarding the energy requirements of netball exists among players, coaches and, to a lesser extent, medical professionals (O'Donnell et al., 2023). This is often compounded by player concerns over body image and the practical challenges associated with fueling (O'Donnell et al., 2023). Clearly, there is a requirement to accurately establish the energy and fluid requirements of female netball players, paramount to the development of effective dietary guidance required to support this demographic.

Therefore, this study utilised the doubly labeled water (DLW) technique to assess the total energy expenditure (TEE) and water turnover (WT) of female netball players across a 14-day in-season period, spilt into a one-match and two-match 7-day microcycle. Actiheart monitors were used to measure daily changes in energy expenditure across rest, training and match days. It was hypothesised that energy and fluid requirements would be greatest on match days and during the two-match microcycle, attributed to increased match-play. A secondary aim was to validate TEE measured by Actiheart against the DLW criterion for the first time in a cohort of senior female team sport athletes (Brage et al., 2005; Rousset et al., 2015; Santos et al., 2014; Silva et al., 2015).

2 | MATERIALS AND METHODS

2.1 | Participants

Thirteen adult female netball players from the senior squad of a Netball Super League franchise were purposefully recruited (all registered squad players alongside one injured player). Eligibility criteria included squad registration and >18 years. Participant characteristics (age: 26 ± 5 years) are presented in Table 1. Participant one sustained a grade I medial collateral ligament sprain on day four, while participant 10 was 11 weeks into rehabilitation from a plantar fasciitis injury at the start of the study. Injured participants completed all testing procedures and prescribed rehabilitation. Participants free from injury completed 76 ± 20% (range: 53%–99%) and 72 ± 28% (range: 33%–100%) of total training and match duration, respectively. Six participants reported using contraceptives: two were on oral combined contraceptives (Rigevidon), two had contraceptive implants, one used an intrauterine system and one had an intrauterine device.

2.2 | Equity, diversity and inclusion statement

This study aimed to address the underrepresentation of females in sport science research by recruiting female athletes from netball (an underserved sport in research). The research team included seven females and eight males at different stages of their careers.

2.3 | Study design

In a cross-sectional design, TEE, WT and training load were measured over 14 days (2021/2022 season). The average temperature and humidity over the study period was 11°C and 72%, respectively. Total energy expenditure and WT were measured by DLW. Resting energy expenditure (REE) was measured by indirect calorimetry. Activity energy expenditure (AEE) was measured by Actiheart and calculated by DLW. Training load was measured by Actiheart, sessional ratings of self-perceived exertion (sRPE) and microtechnology units. Body composition was measured by deuterium isotope dilution. Menstrual cycle phase and contraceptive use were self-reported through a specifically designed questionnaire. Due to concerns about the accuracy of self-reported menstrual cycle phase data (Gloe et al., 2023), this information has not been presented. The schedule is presented in Figure 1.

2.4 | Familiarisation

Familiarisation included a 2-day trial of Actiheart and a ten-minute indirect calorimetry assessment at Leeds Beckett University. Participants reported skin irritation from electrode use (Ambu White-Sensor WS), so a second electrode was purchased (Ambu BlueSensor VLC). To further alleviate skin irritation, electrodes were used

TABLE 1 Participant baseline characteristics.

Participant (position)	Stature (cm)	Body mass (kg)	Total body water (L)	Fat-free mass (kg)	Fat mass (kg)	Percent body fat (%)	Internationally capped
1 (GK)	180.5	77.7	42.9	58.8	18.7	24.1	No
2 (GK)	181.0	90.5	48.3	66.2	24.2	26.7	No
3 (GD)	179.0	79.4	48.1	65.9	14.1	17.6	Yes
4 (WD)	178.0	81.4	44.6	61.1	21.0	25.6	Yes
5 (WD)	179.5	93.0	44.6	61.1	33.1	35.1	No
6 (C)	174.0	74.1	42.4	58.2	13.5	18.9	Yes
7 (C)	173.0	69.9	34.8	47.8	22.7	32.2	No
8 (WA)	169.5	70.1	40.1	55.0	14.7	21.2	No
9 (GA)	175.0	76.0	38.8	53.3	23.1	30.4	No
10 (GA)	180.0	82.4	47.5	65.1	18.4	22.0	No
11 (GS)	187.0	91.5	47.4	65.1	27.3	29.6	Yes
12 (GS)	187.5	80.7	45.5	62.4	20.1	24.4	No
13 (GS)	185.0	85.4	43.0	58.9	25.9	30.5	No
Squad (*n* = 13)	179.0 ± 5.5	80.9 ± 7.6	43.7 ± 4.0	59.9 ± 5.5	21.3 ± 5.6	26.0 ± 5.3	70% = No 30% = Yes

Abbreviations: C, center; GA, goal attack; GD, goal defense; GK, goalkeeper; GS, goal shooter; MD, match day; WA, wing attack; WD, wing defense.

Week	Day 0	Week 1							Week 2						
Day	(Wednesday)	MD-1 (Thursday)	MD (Friday)	MD-1 (Saturday)	MD (Sunday)	MD+1 (Monday)	MD+2 (Tuesday)	MD+3 (Wednesday)	MD-4 (Thursday)	MD-3 (Friday)	MD-2 (Saturday)	MD-1 (Sunday)	MD (Monday)	MD+1 (Tuesday)	MD+2 (Wednesday)
Team Schedule	**Data Collection** (06:30) - Anthropometric - Resting energy expenditure - Doubly labelled water - Actiheart calibration	**Court Session** (09:00) - Warm-up (10 min) - Hand-Eye (15 min) - Walk throughs (35 min) - Individual extras (15 min)	**Match** (19:00) - Warm-up (25 min) - Match (67 min)	**Rest**	**Match** (16:00) - Warm-up (23 min) - Match (65 min)	**Rest**	**Court Session** (09:00) - Warm-up (10 min) - Ball work (5 min) - Technical drills (40 min)	**Gym** (08:30)	**Court Session** (09:00) - Warm-up (15 min) - Ball work (10 min) - CPA (20 min) - Match-play (40 min)	**Gym + Court Session** (08:30) - Warm-up (15 min) - Ball games (35 min) - Individual extras (20 min)	**Rest**	**Court Session** (17:00) - Warm-up (10 min) - Technical skills (10 min) - CPA or CPD (15 min) - Walk throughs (40 min)	**Match** (15:30) - Warm-up (23 min) - Match (65 min) - Post-match con (7 min)	**Rest**	**Gym** (08:30)
Participant Load Modification	1 (GK)*	**Extras**			**INJ**		**Rest**		**Rehab**	**Gym**	**Rehab**	**Rehab**	**Rehab**		**Rest**
	2 (GK)		**<1 Quarter**												
	3 (GD)	**Modified**								**Modified**					
	4 (WD)	**Rest**						**Rest**		**Rest**	**Remote** (On-feet con)				
	5 (WD)	**Remote** (Club training)	**<1 Quarter**		**<1 Quarter**		**Modified**		**Remote** (Club training)	**Remote** (Gym)	**Remote** (Club match)		**<1 Quarter**		
	6 (C)			**Extras**		**Extras**								**Extras**	
	7 (C)	**Remote** (On-feet con)	**<1 Quarter**		**<1 Quarter**	**Extras**			**Remote** (On-feet con)	**Remote** (Gym)		**Modified**	**<1 Quarter**		**Rest**
	8 (WA)							**Rest**	**Modified & Extras**	**Rest**	**Remote** (Gym)	**Modified**			**Rest**
	9 (GA)	**Modified**					**Rest**	**Rest**	**Extras**						
	10 (GA)*	**Rest**	**Gym**		**Rest**	**Gym**	**Off-feet con**		**Rest**	**Gym**	**Off-feet con**	**Rest**	**Gym**		**Rest**
	11 (GS)								**Rest**						
	12 (GS)						**Rest**					**Rest**	**<1 Quarter**		**Rest**
	13 (GS)	**Extras**	**<1 Quarter**		**<1 Quarter**		**Modified**	**Rest**		**Rest**			**<1 Quarter**		**Rest**

FIGURE 1 Overview of the schedule over the 14-day assessment period. Days are labeled based on their proximity to match day (MD), represented as days before (–) or after (+) MD. '*' denotes injured participants. Participant load modifications are shown in bold. Extras (completed additional activity, e.g. recovery, conditioning or gym). Modified (stated activity was altered). Remote (completed non-team related activity). <1 Quarter (completed less than 1 quarter of the match). injured (the participant sustained an injury). C, center; CPA, centre–pass–attack; CPD, centre–pass–defend; GA, goal attack; GD, goal defense; GK, goalkeeper; GS, goal shooter; MD, match day; Off-feet con, off-feet conditioning; WA, wing attack; WD, wing defense.

interchangeably with the Actiheart elasticated chest belt (CamNtech Limited) throughout the study.

2.5 | Total energy expenditure

Doubly labelled water was used to measure TEE. Individual doses were prepared at the University of Aberdeen based on the body mass (BM) of participants and a dose enrichment of 10 atom percent excess oxygen-18 (^{18}O) and 5 atom percent excess deuterium (SERCON Ltd.), using the calculation:

$$\text{Dose (mL)} = 0.65\ (\text{BM, grams}) \times \text{DIE} / \text{IE} \qquad (1)$$

where 0.65 is the approximate proportion of the body comprised of water, DIE = desired initial enrichment (DIE = 618.923 × BM, $kg^{-0.305}$) and IE = initial enrichment (10%) 100,000 parts per million (Speakman, 1997).

On day zero, participants provided a baseline urine sample (second pass) and then consumed a single dose of DLW (07:30–10:00). A second urine sample was collected after 3.54 ± 0.29 h to determine initial isotope enrichment following total body water equilibrium (Speakman, 1997). The initial post-dose enrichment of ^{18}O and deuterium was 2222.07 ± 15.12 ppm and 256.78 ± 6.72 ppm, respectively (background enrichment ^{18}O: 1987.00 ± 1.81 ppm; deuterium: 151.87 ± 0.77 ppm). Participants engaged in representative activities during the equilibrium period (60-min gym session, ad libitum consumption of food and liquids).

Morning urine samples (07:30–10:00) were collected each day into 25 mL containers (Sarstedt AG & Co. KG) and recorded to the nearest minute until day 15, as previously described (Costello et al., 2018). Isotope background and enrichment of urine were performed blind using a Liquid Isotope Water Analyser (Los Gatos Research) (Berman et al., 2013) at the University of Aberdeen, Scotland, UK. Briefly, the urine was vacuum distilled (Nagy, 1983), and the resulting distillate was used for analysis. Three international and five in-house standards were used to correct for daily machine variation. Daily isotope enrichments were $\log_e$ converted and the elimination constants (k_o and k_d) were calculated by fitting a least squares regression model to the data. The back extrapolated intercept (multi-point method) was used to calculate the isotope dilution spaces (N_o and N_d). A two-pool model, specifically Speakman et al. (2021) with a respiratory quotient of 0.85, was used to calculate rates of CO_2 production.

Total energy expenditure was calculated over 14-days and split into two 7-day microcycles. Total energy expenditure is also reported across days, which has recently been shown to introduce a potentially acceptable error of 9.4 ± 4.5% (Van Hooren et al., 2022), especially when compared to other TEE assessment methods. To further increase accuracy, a physiologically implausible estimate of daily TEE was defined as a physical activity level (PAL; TEE/REE) of <1.35 (Goldberg et al., 1991). Corresponding TEE values were removed from the analysis alongside the subsequent day (which was assumed to be artificially inflated). On average, 2 ± 3 days were removed per participant (range: 0–9 days). Finally, participant TEE was averaged across rest (4 ± 2 days), training

(5 ± 2 days) and match (3 ± 1 days) days to further reduce random errors.

Daily TEE was also calculated by Actiheart 5 monitors. This involved adding measured REE plus the thermic effect of food (assumed to be 10% of TEE) with AEE measured by Actiheart.

2.6 | Resting energy expenditure

Resting energy expenditure was measured on day zero using open-circuit indirect calorimetry (Cortex 3B-R3 MetaLyzer, CORTEX Biophysik GmbH) under standardised conditions (i.e., overnight fast, >8-h abstention from alcohol, nicotine and caffeine) (Compher et al., 2006) and a transparent ventilated hood system (Cortex Canopy System, CORTEX Biophysik GmbH). Data were collected over 20 min, with the second 10 min used to calculate REE (Iraki et al., 2023), as described previously (Costello et al., 2019). Four participants required reassessment on day seven due to a coefficient of variance (CV) >10% for $\dot{V}O_2$ and $\dot{V}CO_2$ (Compher et al., 2006). All participants presented with a CV <10% after the second assessment (final group CV; $\dot{V}O_{2:\ 5.4\%\ \pm\ 1.5\%;}$ $\dot{V}CO_{2:\ 7.0\%\ \pm\ 1.6\%}$).

2.7 | Activity energy expenditure

Activity energy expenditure was measured using Actiheart 5 (firmware: Ah5 21, CamNtech Limited) and calculated by the DLW method. Actiheart was attached as instructed (user manual, version 5.1.31) after a standardised signal test to ensure accurate placement (protocol: 2 min at rest, walking and light jogging). One participant did not generate a detectable signal in this location. Consequently, the Actiheart was positioned at the level of the third intercostal space, which is above the breasts. Importantly, Actiheart placement has been shown to have no effect on measured energy expenditure in these two locations in women (Brage et al., 2005).

Individual heart rate calibration was derived from a submaximal step test (Actiheart software version 5.0.5) on day zero (Heydenreich et al., 2019), excluding participant 10, who was injured. Actiheart was worn at all times, excluding showers, with daily placement checked by a trained female researcher. Participants wore Actiheart for 94 ± 4% of the assessment period (range: 88%–99%) (training: 100 ± 2%; match-play: 99 ± 3%). Actiheart monitors were taped to chest belts or secured beneath sport bras during matches to mitigate the risk of displacement.

Energy expenditure data was measured in 1-min epochs and calculated with the "Group Cal JAP2007/Step HR" branched model. Energy expenditure was measured over 14 days. The assessment period was also spilt into two 7-day microcycles, alongside grouped rest, training and match days. Energy expenditure was measured by the Actiheart during court-based training sessions (n = 4 ± 1) and matches (n = 3 ± 0).

Activity energy expenditure was also calculated by the DLW method. This involved the subtraction of measured REE plus the thermic effect of food from TEE measured by DLW.

2.8 | Physical activity energy expenditure

The PAL was calculated as TEE measured by DLW divided by REE.

2.9 | Body composition and water turnover

Body composition and WT were measured by deuterium isotope dilution. Total body water was calculated from the stable isotope dilution spaces based on the intercept of the deuterium elimination plot (Agency, 2011):

$$N = [(N_o/1.007) + (N_d/1.043]/2 \quad (2)$$

whereby, N_o and N_d are the ^{18}O and deuterium dilution space, respectively (Speakman, 1997).

Fat-free mass (FFM) (kg) was determined using a two-compartmental model of body composition by dividing total body water (kg) by 73.2 (Widdowson et al., 1951). Fat mass (kg) was calculated by subtracting FFM from initial BM (kg).

WT was calculated by multiplying the rate constant of the post-dose decline in deuterium enrichment by the total water pool (Lifson & McClintock, 1966). Fluid requirement (minus the small surface fluxes) was estimated by subtracting metabolic water production from WT. Metabolic water production was calculated as follows:

$$W = 0.123\ K \quad (3)$$

where W and K are total metabolic water (g) and total energy production (kcal) (Morrison, 1953), respectively.

2.10 | Internal and external training load

The internal load was measured using sRPE and heart rate. Participants reported their ratings of percieved exertion 30 min after the completion of each training session or match using a modified Borg scale, in isolation from other participants. Ratings of perceived exertion were then multiplied by session duration to calculate sRPE in arbitrary units (AU). The heart rate was measured by Actiheart, with a dropout rate of 3 ± 4% (range: 0%–12%) and 2 ± 4% (range: 0%–10%) for training and match-play, respectively.

External loads were measured using microtechnological units (Catapult Vector s7, Catapult Innovations, Melbourne, Australia). The same unit was worn by each participant for all observations in a tight-fitted vest between the scapulae. Each unit contained a tri-axial accelerometer, gyroscope and magnetometer, all sampling at 100 Hz. Accelerometer-derived PlayerLoad™ metrics, quantified in AU, along with High PlayerLoad™ instances—defined as the sum of instantaneous PlayerLoad exceeding 1.0 AU—were analysed in line with previous netball-specific research (Brooks et al., 2020). Furthermore, metrics derived from inertial movement units, including the number of accelerations, decelerations and changes of direction were aggregated for analysis. This approach is consistent with the methods utilised by Mackay et al. (2024) and is underpinned by the reliability findings reported by Luteberget et al. (2018), alongside preliminary findings investigating the validity of discrete movements specific to netball.

All load variables were measured over 14-days and split into two 7-day microcycles, alongside grouped rest, training and match days. Load variables were also measured during court-based training sessions and matches.

2.11 | Data analysis

Statistics were performed in R (version 4.2.0). Descriptive and difference data are reported as mean ± standard deviation or standard error, respectively. Participants 1 and 10 were excluded from all statistical analyses due to injury, while participant 5 was excluded from load analyses due to incomplete data. There is no missing data, except for instances specifically mentioned.

Generalised linear mixed models with a Gaussian distribution were used to compare differences between microcycles and days using the *lme4* package (Bates et al., 2015). The participant was included as a random effect. Model assumptions were assessed visually using the *performance* package (Lüdecke et al., 2021). Differences between groups were compared using pairwise comparisons with the *emmeans* package (Lenth et al., 2023). The statistical significance was set at $p < 0.05$, with effect sizes (ES) and 95% confidence intervals, interpreted using established thresholds (Hopkins et al., 2009).

Multiple regression was used to identify the best predictors of TEE and WT (inclusion: FFM, fat mass and all training load variables). The best model was auto-selected using the *olsrr* package (Hebbali, 2022), with a limit of 2 predictor variables due to the number of observations. The resultant coefficients were used to develop regression equations.

Bland–Altman plots were used to compare variables by different methods and prediction equations. To avoid mathematical bias from composite variables (i.e., TEE data relative to FFM) (Ravussin & Bogardus, 1989), only absolute measures of TEE and FFM are presented for comparison across cohorts in a regression bivariate plot.

3 | RESULTS

3.1 | Training and match load

Total training duration was significantly greater across the one-match (+124 ± 34 min; ES = 1.65, 0.53–2.77; $p = 0.005$; Supplementary Materials, Figure S1A) than the two-match microcycle. Total match duration was significantly greater across the two-match (+60 ± 11 min; ES = 1.66, 0.73–2.58; $p < 0.001$; Supplementary Materials, Figure S1A) than one-match microcycle. Match days had a significantly greater PlayerLoad™ (+207 ± 67 AU; ES = 1.17, 0.26–2.09; $p = 0.013$; Supplementary Materials, Figure S1I), High PlayerLoad™ (+132 ± 47 AU; ES = 1.00, 0.16–1.84; $p = 0.020$; Supplementary Materials, Figure S1J) and combined accelerations, decelerations and change of directions (+324 ± 85 *n*; ES = 1.43, 0.48–2.38; $p = 0.004$; Supplementary Materials, Figure S1K) than training days. All other differences were non-significant across microcycles ($p > 0.110$; Supplementary Materials, Figure S1B–G) and days ($p > 0.053$; Supplementary Materials, Figure S1H,L–N).

3.2 | Energy expenditure measured by doubly labelled water

The 14-day TEE of non-injured participants was 13.51 ± 1.31 MJ day^{-1} (0.23 ± 0.02 MJ kg^{-1} FFM). Baseline REE was 6.53 ± 0.60 MJ day^{-1} (0.11 ± 0.01 MJ kg^{-1} FFM). Therefore, AEE and PAL were 5.63 ± 0.99 MJ day^{-1} (0.09 ± 0.02 MJ kg^{-1} FFM) and 2.08 ± 0.19 AU (range: 1.77–2.44 AU), respectively.

The 14-day TEE of injured participants was 13.19 ± 0.01 MJ day^{-1} (0.21 ± 0.02 MJ kg^{-1} FFM). Baseline REE was 6.56 ± 0.65 MJ day^{-1} (0.11 ± 0.02 MJ kg^{-1} FFM). Therefore, AEE and PAL were 5.31 ± 0.64 MJ day^{-1} (0.09 ± 0.00 MJ kg^{-1} FFM) and 2.02 ± 0.20 AU (range: 1.88–2.16 AU), respectively.

There was no significant difference in TEE (+0.03 ± 0.35 MJ day^{-1}; ES = 0.04, −0.79–0.86; $p = 0.936$; Figure 2A), AEE (+0.06 ± 0.36 MJ day^{-1}; ES = 0.07, −0.83–0.97; $p = 0.866$; Figure 2B) or PAL (−0.03 ± 0.05 AU, ES = 0.19; −0.63–1.02; $p = 0.624$; Figure 2C) across the two- or one-match microcycle.

Match days had significantly greater TEE (+2.85 ± 0.70 MJ day^{-1}; ES = 1.05, 0.44–1.65; $p = 0.002$; Figure 2E), AEE (+2.56 ± 0.64 MJ day^{-1}; ES = 1.07, 0.45–1.70; $p = 0.002$; Figure 2F) and PAL (+0.42 ± 0.10 AU; ES = 1.11, 0.49–1.72; $p = 0.001$; Figure 2G) than training days. Match days had significantly greater TEE (+4.85 ± 0.70 MJ day^{-1}; ES = 1.78, 1.06–2.50; $p < 0.001$; Figure 2E), AEE (+4.42 ± 0.64 MJ day^{-1}; ES = 1.85, 1.11–2.60; $p < 0.001$; Figure 2F) and PAL (+0.73 ± 0.10 AU; ES = 1.91, 1.16–2.66; $p < 0.001$; Figure 2G) than rest days. Training days had significantly greater TEE (+2.00 ± 0.70 MJ day^{-1}; ES = 0.73, 0.17–1.30; $p = 0.026$; Figure 2E), AEE (+1.86 ± 0.64 MJ day^{-1}; ES = 0.78, 0.19–1.37; $p = 0.023$; Figure 2F) and PAL (+0.31 ± 0.10 AU; ES = 0.80, 0.22–1.38; $p = 0.015$; Figure 2G) than rest days.

3.3 | Energy expenditure measured by Actiheart

There was no significant difference in TEE (−0.19 ± 0.26 MJ day^{-1}; ES = −0.30, −1.18–0.58; $p = 0.478$), AEE (−0.08 ± 0.24 MJ day^{-1}; ES = −0.15, −1.07–0.78; $p = 0.741$) or PAL (−0.02 ± 0.04 AU; ES = −0.27, −1.14–0.60; $p = 0.519$) across the two- or one-match microcycle.

Match days had significantly greater TEE (+3.24 ± 0.40 MJ day^{-1}; ES = 1.20, 0.73–1.67; $p < 0.001$), AEE (+2.98 ± 0.37 MJ day^{-1}; ES = 1.22, 0.75–1.70; $p < 0.001$) and PAL (+0.49 ± 0.06 AU; ES = 1.64,

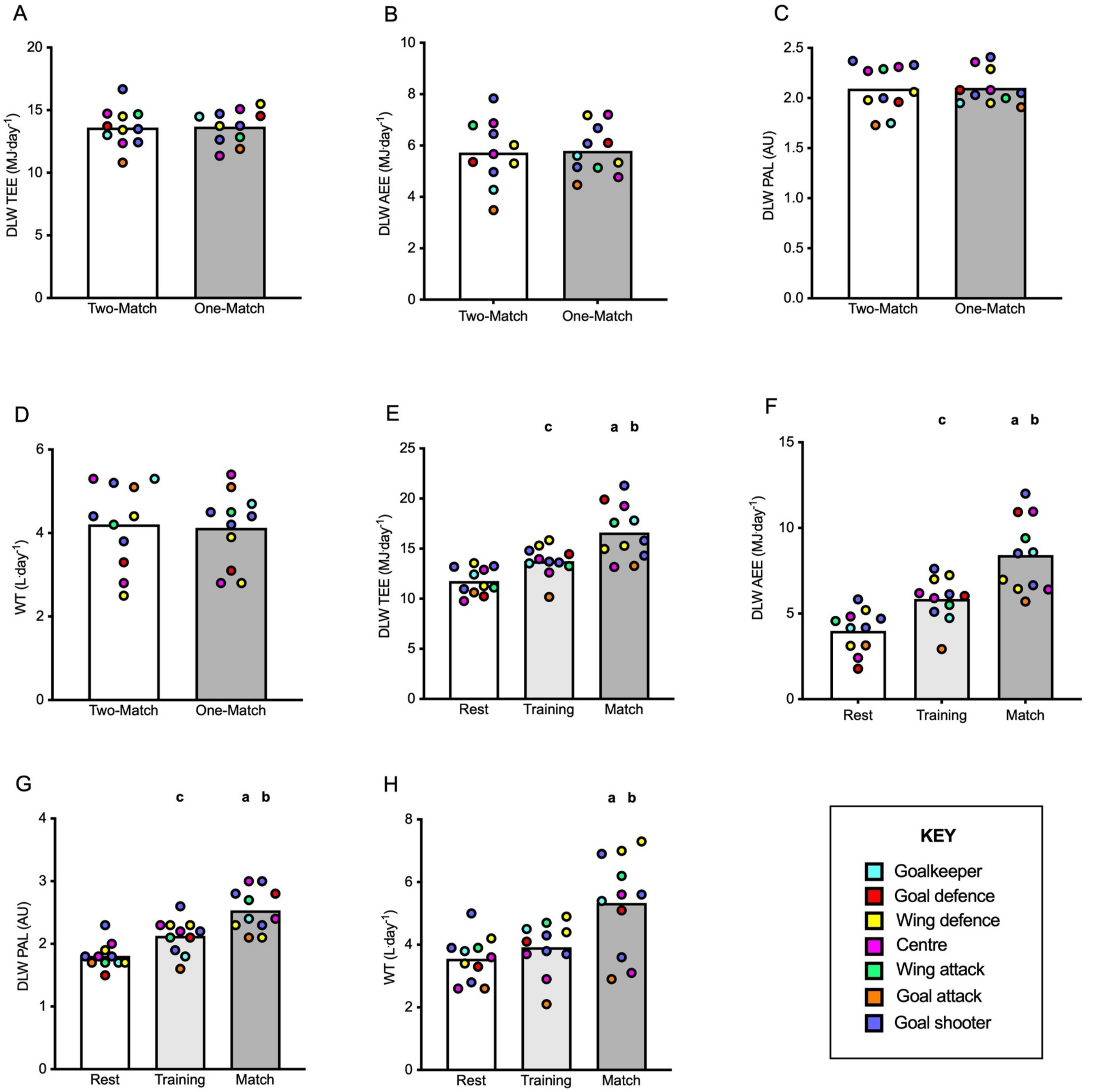

FIGURE 2 Energy expenditure and water turnover (WT) measured by doubly labeled water over the assessment period. (A) Total energy expenditure (TEE), (B) activity energy expenditure (AEE), (C) physical activity level (PAL), and (D) WT per day over the two- and one-match microcycle. (E) TEE, (F) AEE, (G) PAL and (H) WT per day over grouped rest (TEE: 11.76 ± 1.34 MJ day^{-1}; AEE: 4.00 ± 1.24 MJ day^{-1}; PAL: 1.8 ± 0.2 AU; 3.6 ± 0.7 L day^{-1}), training (TEE: 13.76 ± 1.51 MJ day^{-1}; AEE: 5.85 ± 1.30 MJ day^{-1}; PAL: 2.1 ± 0.3 AU; 3.9 ± 0.8 L day^{-1}) and match days (TEE: 16.60 ± 2.75 MJ day^{-1}; AEE: 8.42 ± 2.17 MJ day^{-1}; PAL: 2.5 ± 0.3 AU; 5.3 ± 1.5 L day^{-1}). White bars represent the two-match microcycle or rest days. Light gray bars represent training days. Dark gray bars represent the one-match microcycle or match days. [a]A significant difference from rest days, $p < 0.05$. [b]A significant difference from training days, $p < 0.05$. [c]A significant difference from rest days, $p < 0.05$. All data are representative of $n = 11$, in accordance with participants who were free from injury (participants 1 and 10). Participants are color coded by the positional group. AU, arbitrary units.

1.02–2.25; $p < 0.001$) than training days. Match days had significantly greater TEE (+4.79 ± 0.40 MJ day^{-1}; ES = 1.78, 1.17–2.38; $p < 0.001$), AEE (+4.31 ± 0.37 MJ day^{-1}; ES = 1.77, 1.17–2.37; $p < 0.001$) and PAL (+0.73 ± 0.06 AU; ES = 2.43, 1.64–3.23; $p < 0.001$) than rest days. Training days had significantly greater TEE (+1.55 ± 0.40 MJ day^{-1}; ES = 0.57, 0.21–0.94; $p = 0.003$), AEE (+1.33 ± 0.37 MJ day^{-1}; ES = 0.55, 0.19–0.91; $p = 0.005$) and PAL (+0.24 ± 0.06 AU; ES = 0.80, 0.33–1.26; $p = 0.002$) than rest days.

Matches had significantly greater energy expenditure (+1.85 ± 1.27 MJ; ES = 1.92, 0.81–3.04; $p = 0.001$) than court-based training sessions.

3.4 | Water turnover

The 14-day WT of non-injured and injured participants was 4.2 ± 0.9 L day^{-1} (70 ± 13 mL kg^{-1} FFM) and 4.0 ± 0.4 L day^{-1} (64 ± 2 mL kg^{-1} FFM), respectively.

There was no significant difference in WT (−0.1 ± 0.1 L day^{-1}; ES = −0.48, −1.35–0.37; $p = 0.237$; Figure 2D) across the two- or one-match microcycle.

Match days had significantly greater WT than training (+1.4 ± 0.3 L day^{-1}; ES = 0.93, 0.47–1.39; $p < 0.001$; Figure 2H) and rest (+1.8 ± 0.3 L day^{-1}; ES = 0.16, 0.66–1.66; $p < 0.001$; Figure 2H) days. There was no significant difference in WT across training (+0.4 ± 0.3 L day^{-1}; ES = 0.23, −0.15–0.61; $p = 0.418$; Figure 2H) and rest days.

3.5 | Factors affecting total energy expenditure and water turnover

Two variables typically accessible to practitioners, FFM and sRPE, were identified to predict TEE measured by DLW ($R^2 = 0.65$).

$$\text{TEE}\left(\text{MJ day}^{-1}\right) = 5.8299 + 0.0992 \times \text{FFM (kg)} + 0.0006 \times \text{sRPE (AU)} \quad (4)$$

Two variables, High PlayerLoad™ and combined acceleration, deceleration, and change of direction, were identified to predict WT measured by deuterium ($R^2 = 0.67$).

$$\text{WT}\left(\text{L day}^{-1}\right) = 2.4124 - 0.0007 \times \text{High PlayerLoad}^{\text{TM}}\ (\text{AU}) + 0.0008 \times \text{combined acceleration, deceleration and change of direction}\ (n) \quad (5)$$

All load variables refer to summed values across the 14-day assessment period.

3.6 | Validity of energy expenditure and water turnover measures

Actiheart underestimated TEE in comparison to the 14-day DLW criterion (−1.92 ± 1.21 MJ day^{-1}; Supplementary Materials, Figure S2A). Prediction equations established from the International Atomic Energy Agency DLW database (Pontzer et al., 2021; Yamada et al., 2022) displayed a mean bias for female netball player TEE (−0.78 ± 1.92 MJ day^{-1}; Supplementary Materials, Figure S2B) and WT (+0.96 ± 1.40 L day^{-1}; Supplementary Materials, Figure S2D) measured by DLW. Equations four and five displayed a mean bias for female netball player TEE (0.00 ± 1.55 MJ day^{-1}; Supplementary Materials, Figure S2C) and WT (0.00 ± 0.99 L day^{-1}; Supplementary Materials, Figure S2E).

4 | DISCUSSION

Practitioners working with female netball players require a high-quality evidence base to support player health and performance. Therefore, this study utilised criterion methods to determine the TEE and WT of female netball players. Energy and fluid requirements were greatest on match days, followed by training and rest days, with no difference across a one- or two-match microcycle. Actiheart underestimated athlete TEE. These findings are critical to inform the dietary guidance provided to female netball players.

Female netball players have energy requirements representative of a vigorously active lifestyle (PAL: >2.0 AU) (Westerterp, 2013). Mean TEE for female netball players is very similar to values reported for female international soccer players (Morehen et al., 2022), alongside female university cross-country runners (Edwards et al., 1993) (Supplementary Materials, Figure S3). Interestingly, a female tennis player competing at a Grand Slam expended more energy per kg of FFM (Ellis et al., 2021); although, female open water swimmers (Sagayama, Mimura, et al., 2019), cross-country skiers (Sjödin et al., 1994) and marine recruits (Castellani et al., 2006) expended considerably more. When optimising female netball player energy intakes, practitioners should consider individual variability in energy requirements, which ranged by 0.05 MJ FFM day^{-1} across participants (potential for up to 3 MJ day^{-1} variation for a ~80 kg player with 60 kg FFM).

Female netball players have greater WT than values estimated for active females (3.5 L day^{-1}) (Sawka et al., 2005). Isotope-tracking studies on female athletes are limited (Yamada et al., 2022). A recent analysis of 5604 DLW samples (3729 female) revealed that athletes have a greater WT of ~1 L day^{-1} compared to non-athletes, with 13 females achieving a turnover of >7 L day^{-1} (5.4 L day^{-1} upper limit in this study) (Yamada et al., 2022). Female netball players have a similar WT to female dinghy sailors (Sagayama, Toguchi, et al., 2019) but substantially lower than female soft tennis players (Horiuchi et al., 2008). Daily WT can triple in very hot versus temperate conditions (e.g., from 20 to 40°C) (Sawka et al., 2005). Consequently, the WTs reported in this study may lack generalisability to arid or tropical climates where netball is popular (e.g., Australia, South Africa and Jamaica). Finally, when optimising female netball player fluid intakes, practitioners should consider individual variability in WT, which ranged widely by 62 mL FFM day^{-1} across participants (potential for up to 3.7 L day^{-1} variation for a ~80 kg player with 60 kg FFM).

Female netball players have increased energy and fluid requirements on match days, followed by training and rest days. Contrary to our hypothesis, the two-match microcycle did not result in increased TEE or WT compared to the one-match microcycle. This could potentially be attributed to an increased requirement for recovery, which necessitated a reduced training frequency, duration and intensity during the two-match versus one-match microcycle. Therefore, female netball players are encouraged to periodise their energy and fluid intake on a daily basis, aligning with the demands of their training and match schedule, in accordance with the "fuel for the work required" paradigm (Impey et al., 2018). This recommendation is further supported by evidence of significantly greater energy expenditure during netball matches compared to court-based training in this study and strengthened by the two distinct methods of energy expenditure assessment that independently demonstrated significant differences in daily energy requirements, namely the DLW technique and Actiheart.

Contrary to our expectations, following injury, participant one experienced no meaningful reduction in energy expenditure (+0.85 MJ day^{-1}; PAL: +0.12 AU) or WT (−0.2 L day^{-1}) across the second microcycle despite a large reduction in load (session duration: −239 min; sRPE: −430 AU). Conversely, participant 10 had a similar load across microcycles (session duration: −20 min; sRPE: −75 AU), although expenditure (−1.17 MJ day^{-1}; PAL: −0.19 AU) and WT were lower (−0.7 L day^{-1}). Notably, the average TEE between injured and non-injured female netball players appears similar in this study (−0.32 MJ day^{-1}). Likewise, TEE for an injured male soccer (Anderson et al., 2019) and female tennis player is similar per kg of FFM to those presented in this study (Ellis et al., 2023). However, relative TEE appears lower for a female soccer player during rehabilitation (Parker et al., 2022). Given the small sample sizes and requirement for replication, it is advised that female netball players avoid substantial reductions in energy intake during recovery from injury until further data is available.

4.1 | Practical applications

Using the TEE data obtained through the DLW method in this study, and adhering to established sport nutrition guidelines (protein: 1.2–2.0 g kg BM^{-1}; fat: 20%–35% of total energy intake) (Thomas et al., 2016), an average 80 kg female netball player with 60 kg FFM would require a carbohydrate intake ranging from 6.28 to 9.44 MJ day^{-1} to achieve daily energy balance (EB), equivalent to 3.6–7.0 g kg BM^{-1}. These requirements largely align with existing carbohydrate recommendations relevant to female netball players, with moderate intakes for skill-based activities (3–5 g kg BM^{-1}) through to higher amounts for carbohydrate loading (7–12 g kg BM^{-1}) (Thomas et al., 2016).

Given the variability in energy demands over rest, training and match days measured in this study, dietary intakes should be periodised accordingly. Thus, to facilitate the practical application of the research outcomes, specific energy, macronutrient and fluid targets are proposed for female netball players across rest, training and match days in Table 2, with an example of daily macronutrient distribution also presented (Supplementary Materials, Table 1). While these guidelines may predict a slight daily negative EB, this is offset by a substantial energy surplus on the days before (MD-1) and after a match (MD+1). This strategy ensures an overall EB throughout the week (Supplementary Materials, Table 2), accommodating for increased carbohydrate intake and reduced training intensity on MD-1/+1, which are both fundamental sport science strategies employed to enhance match preparation and recovery. Published literature and practical experience suggest that achieving carbohydrate intakes of 7–8 g kg BM^{-1} is challenging for players without professional guidance, highlighting MD-1 and MD+1 as key timepoints for practitioner focus within the weekly microcycle (Davie et al., 2021; O'Donnell et al., 2023; Morehen et al., 2022). Finally, as these nutritional recommendations are based on group average DLW measurements, individual adjustments are required when providing nutrition advice to female netball players in practice.

4.2 | Study limitations

This study utilised the DLW technique to measure day-to-day variations in TEE, which is not always possible (e.g., sufficient divergence in isotopes is required) and can introduce a measurement error (i.e., 9 vs. 5% in comparison to the DLW technique over a 5-day period) (Van Hooren et al., 2022). The DLW technique can also introduce errors at an individual level (0.4 ± 7.7%) (Speakman et al., 2021); therefore, individual TEEs could range above or below reported values by ~1.04 MJ day^{-1}. The participant menstrual cycle phase was not accurately recorded and has been shown to influence REE during sleep by 6.1 ± 2.7% (Bisdee et al., 1989). Study findings are drawn from a small sample, comprised of 13 players from one club, which may limit generalisability. However, the research benefits from the application of gold standard methods across an entire Netball Super League squad. This encompassed all seven positional groups, starting and non-starting players, alongside two injured players, thus providing a robust evidence base within a previously under-represented cohort (Whitehead et al., 2021). Further research should investigate the underestimation of TEE by Actiheart (range: −0.38–3.84 MJ day^{-1}) in team sport athletes, alongside female netball player energy requirements during periods of reduced load (e.g., injury and substitution) and across positional groups.

4.3 | Conclusion

Female netball players require sufficient dietary energy and fluid intakes to support health and performance. This study provides the first criterion-assessed energy expenditure and WT data for female netball players. Energy and fluid requirements are greatest on match days, followed by training and rest days, with no difference across a one- or two-match week. Actiheart underestimated athlete TEE. These findings are critical to inform the dietary energy, macronutrient and fluid support provided to female netball players.

TABLE 2 Proposed dietary energy, macronutrient and fluid targets for female netball players based on energy expenditure and fluid requirements measured in this study.

Player FFM (kg)		45			50			55			60			65			70	
Associated BM (kg)		61			68			74			81			88			95	
Microcycle day	Rest	Train	Match (-1/+1)	Rest	Train	Match (-1/+1)	Rest	Train	Match (-1/+1)	Rest	Train	Match (-1/+1)	Rest	Train	Match (-1/+1)	Rest	Train	Match (-1/+1)
CHO periodisation	LOW	MOD	HIGH	LOW	MOD	HIGH	LOW	MOD	HIGH	LOW	MOD	HIGH	LOW	MOD	HIGH	LOW	MOD	HIGH
TER (MJ day^{-1})	9.00	10.35	12.60	10.00	11.50	14.00	11.00	12.65	15.40	12.00	13.80	16.80	13.00	14.95	18.20	14.00	16.10	19.60
CHO (g day^{-1})	182 to 243	304 to 365	426 to 486	203 to 270	338 to 405	473 to 541	223 to 297	372 to 446	520 to 595	243 to 324	405 to 486	568 to 649	264 to 351	439 to 527	615 to 703	284 to 378	473 to 568	662 to 757
PRO (g day^{-1})		97			108			119			130			141			151	
Fat (g day^{-1})		67			74			82			89			97			104	
Fat (% of TEI)	31	25	20	31	25	20	31	25	20	31	25	20	31	25	20	31	25	20
Fluid (L day^{-1})	2.2	2.4	3.3*	2.5	2.7	3.7*	2.7	3.0	4.1*	2.9	3.2	4.4*	3.2	3.5	4.8*	3.4	3.8	5.2*
TEI (MJ day^{-1})	7.20 to 8.22	9.24 to 10.25	11.27 to 12.29	8.00 to 9.13	10.26 to 11.39	12.52 to 13.65	8.80 to 10.04	11.29 to 12.53	13.78 to 15.02	9.60 to 10.96	12.31 to 13.67	15.03 to 16.39	10.40 to 11.87	13.34 to 14.81	16.28 to 17.75	11.20 to 12.78	14.37 to 15.95	17.53 to 19.12
Daily EB (MJ day^{-1})	−1.80 to −0.78	−1.11 to −0.10	−1.33* to −0.31*	−2.00 to −0.87	−1.24 to −0.11	−1.48* to −0.35*	−2.20 to −0.96	−1.36 to −0.12	−1.62* to −0.38*	−2.40 to −1.04	−1.49 to −0.13	−1.77* to −0.41*	−2.60 to −1.13	−1.61 to −0.14	−1.92* to −0.45*	−2.80 to −1.22	−1.73 to −0.15	−2.07* to −0.48*
One-match microcycle EB (MJ day^{-1})		−0.47 to 0.55			−0.52 to 0.61			−0.57 to 0.67			−0.63 to 0.73			−0.68 to 0.79			−0.73 to 0.86	
Two-match microcycle EB (MJ day^{-1})		−0.02 to 1.00			−0.02 to 1.11			−0.02 to 1.22			−0.02 to 1.34			−0.02 to 1.45			−0.02 to 1.56	

Note: Low, moderate and high carbohydrate periodisation refer to rest, training and match days (−1 and +1), respectively. Energy targets are 0.20, 0.23 and 0.28 MJ FFM day^{-1} as measured by doubly labeled water in this study for low, moderate and high carbohydrate days, respectively. Carbohydrate targets are 3–4, 5–6 and 7–8 g kg^{-1} of body mass for low, moderate and high carbohydrate days, respectively. Protein and fat targets are standardised at 1.6 and 1.1 g kg^{-1} of body mass, respectively. Fluid targets represent 49, 54 and 74 mL kg^{-1} of fat-free mass as measured by doubly labeled water in this study for low, moderate and high carbohydrate days, respectively. *Denotes fluid requirements and energy balance on match days rather than all high carbohydrate days (e.g., match day −1 and +1). Energy balance across the one-match microcycle includes one match, four training, and two rest days. Energy balance across the two-match microcycle includes two matches, two training, and three rest days. Energy values of 16.73, 16.73 and 37.65 kJ have been used for carbohydrate, protein, and fat, respectively. Associated body mass is estimated with the mean fat-free mass percentage from this cohort measured by deuterium isotope dilution (74%). The color denotes the traffic light system.

Abbreviations: BM, body mass; CHO, carbohydrate; EB, energy balance; FFM, fat-free mass; MOD, moderate; PRO, protein; TEI, total energy intake; TER, total energy requirement.

AUTHOR CONTRIBUTIONS

Nessan Costello, Ben Jones, and Sarah Whitehead: Conceptualization; methodology; funding acquisition; data curation and visualization; writing—original draft; writing—review and editing. Nessan Costello, Stephanie Roe, Cameron Blake, Anthony Clark, Sarah Chantler, Cameron Owen, Lara Wilson, Oliver Wilson, Antonis Stavropoulos-Kalinoglou, Catherine Hambly, John R. Speakman, and Sarah Whitehead: Investigation and formal analysis. Susan Backhouse: Funding acquisition; writing—review and editing. Dina C. Janse van Rensburg: Writing—review and editing. All authors approved the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

SW, AC, and SC provide sport science support to the senior squad of the Netball Super League franchise that participants were recruited from. The authors have no other competing interests to declare.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article. Any further information is available upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.