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Isolated & combined wearable technology underestimate the total energy expenditure of professional young rugby league players; a doubly labelled water validation study.

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Abstract

Accurately determining total energy expenditure enables the precise manipulation of energy balance within professional collision-based sports. Therefore, this study investigated the ability of isolated or combined wearable technology to determine the total energy expenditure of professional young rugby league players across a typical pre-season and in-season period. Total energy expenditure was measured via doubly labelled water, the criterion method, across a fourteen-day pre-season (n=6) and seven-day in-season (n=7) period. Practical measures of total energy expenditure included SenseWear Pro3 Armbands in isolation and combined with metabolic power derived from microtechnology units. SenseWear Pro3 Armbands significantly under-reported pre-season (5.00 (2.52) MJ·day^{-1}; $p = 0.002$) and in-season (2.86 (1.15) MJ·day^{-1}; $p < 0.001$) total energy expenditure, demonstrating a *large* and *extremely large* standardised mean bias, and a *very large* and *large* typical error, respectively. Combining metabolic power with SenseWear Pro3 Armbands *almost certainly* improved pre-season (0.95 (0.15) MJ·day^{-1}; ES = 0.32 ±0.04; $p < 0.001$) and in-season (1.01 (0.15) MJ·day^{-1}; ES = 0.88 ±1.05; $p < 0.001$) assessment. However, SenseWear Pro3 Armbands combined with metabolic power continued to significantly under-report pre-season (4.04 (2.38) MJ·day^{-1}; $p = 0.004$) and in-season (2.18 (0.96) MJ·day^{-1}; $p = 0.002$) expenditure, demonstrating a *large* and *very large* standardised mean bias, and a *very large* and *large* typical error, respectively. These findings demonstrate the limitations of utilising isolated or combined wearable technology to accurately determine the total energy expenditure of professional collision-based sport athletes across different stages of the season.

Key words: Energy Expenditure, Validity, Wearable Technology, Rugby

INTRODUCTION

Accurately determining the total energy expenditure (TEE) of professional collision-sport athletes is imperative in supporting desired manipulation of energy balance and recovery from training load across the season. In particular, professional young (10, 34) and senior (34) rugby players have large energetic demands, most likely influenced by the energetic cost of collisions following training (11) and match play (9). Such energetic demands have been shown to vary across the season, therefore necessitating more specific nutritional periodisation and intervention (12). However, prescribing precise, individualised dietary advice requires accurate knowledge of daily energetic demands, which are likely to vary considerably across stages of the season (i.e. pre-season vs. in-season), age groups (i.e. scholarship vs. academy vs. senior), playing positions (i.e. forwards vs. backs) and individuals (i.e. body mass)(34). Consequently, practitioners require valid, reliable and practically accessible TEE assessment tools to maximise the health, development and subsequent performance of professional collision-sport athletes across the season.

Accurate TEE assessment methods are currently expensive, impractical or ecological invalid within sporting environments; and as such new, practically accessible approaches are required. Total energy expenditure can be accurately determined via direct (i.e. measurement of heat loss) or indirect calorimetry (i.e. measurement of oxygen consumption, carbon dioxide production and urine-nitrogen loss) (24). Direct calorimetry is performed within a metabolic chamber under controlled laboratory conditions andlacks applicability within professional sport (24). Accordingly, indirect calorimetry is more commonly utilised; although, is likewise methodologically confounded by equipment requirements (i.e. breath by breath analysers) that reduce ecological validity within professional team sports (19).

Conversely, the doubly labelled water (DLW) approach (a distinct version of indirect calorimetry) has been increasingly utilised to determine the energetic demands of professional collision-sport athletes (10-12, 34), providing valid and reliable assessment of free-living TEE (39). Nevertheless, DLW assessment duration is limited to one to three times the biological half-life of the ingested isotopes, preventing accurate day-by-day or session-by-session energetic assessment (39). Therefore, despite being the gold standard assessment method within free-living environments, the DLW approach is a financially and methodologically inappropriate tool via which to regularly assess the TEE or exercise expenditure of professional collision-sport athletes.

Combined wearable technology represents a potentially viable approach via which to measure the TEE of athletes within everyday applied practice (19), however, validation is required. Wearable technology (i.e. heartrate monitors, motion sensors and combined approaches) are convenient, relatively inexpensive, non-invasive and versatile (Ndahimana and Kim, 2017). Furthermore, utilising a combination of these technologies has been shown to improve outcomes by reducing the influence of any limitations from individual sensors or devices (19). One such wearable technology is the SenseWear Pro3 Armband (SWA), which incorporates a triaxial accelerometer with additional biological variables (i.e. heat flux, galvanic skin response) and machine learning algorithms (2) to report enhanced accuracy over contemporary methods (5). Despite this, SWA report poor measurement accuracy at high, sport specific exercise intensities (40), which might compromise the validity of athletic TEE assessment. Alternatively, metabolic power (derived from microtechnology units) has been specifically designed to determine the metabolic cost of high intensity activity (i.e. accelerations, decelerations) during team sports (13) and could provide both an accurate and

practically accessible assessment of TEE within applied practise (38) when combined with SWA.

Therefore, this study included two novel research aims: (i) investigate the validity of SWA in isolation as is commonly performed within collision-sport literature (4, 38), or (ii) combined with microtechnology derived metabolic power, to determine the TEE of professional young rugby league players for the first time across a pre-season and in-season period, against a literature gold standard DLW assessed criterion.

METHODS

Subjects

A total of eight healthy, professional young male rugby league players were recruited for this study from one European Super League academy. This included six participants for the pre-season period and seven participants for the in-season period. Five of the same participants were recruited across both periods. The same participants could not be included across both assessment periods due to injury. Participant characteristics were (mean (SD) age; 17 (1) years, height; 179.5 (8.7) cm, body mass (BM); 90.5 (11.4) kg). Participants were chosen from a representative range of playing positions including Loose Forward, Prop Forward, Half Back, Hooker, Full Back, Back Row and Wing, highlighting any potential positional differences between participants. Prior to volunteering, all participants signed a written statement of consent. Ethics approval was granted by the Research Ethics Committee (Leeds Beckett University, UK).

Design

The investigations contained in this study occurred over two distinct time points, including a typical fourteen-day pre-season and seven-day in-season assessment period. Participants undertook normal coach prescribed training, match preparation and match-play across both assessment periods. Specifically, the pre-season assessment period included ten resistance-training sessions, ten field sessions and four rest days as has previously been described (10). Alternatively, the shorter in-season assessment period included three resistance-training sessions, three field sessions, two rest days, one captains run and one competitive match. The criterion measure of free-living TEE across both assessment periods was DLW, the literature gold standard (39). SenseWear Pro3 Armbands were worn at all times excluding field-training, periods submerged in water (i.e. showers & baths) and match-play, whereas micro-technology units were worn during all field-training sessions and match-play.

Total Energy Expenditure – SenseWear Pro3 Armbands

The TEE of participants was either entirely or partly (i.e. combined with metabolic power) determined by SWA. Participants wore SWA at all times excluding field-training, periods submerged in water (i.e. showers & baths) and match-play. This protocol protected players and SWA equipment from injury or damage (i.e. collisions or water), respectively, and is commonly reported within professional team sports (4, 38); evidencing ecological validity. Across both assessment periods, SWA values were considered incomplete if worn for less than 95 % of the assessment duration, not inclusive of training or match-play. This

did not occur across either the pre-season (98 ± 2.1 %) or in-season (97.1 ± 1.3 %) assessment period.

The SWA (BodyMedia) is a multi-sensor device that estimates TEE via a triaxial accelerometer, heat flux, galvanic skin response, skin temperature and near-body ambient temperature. SenseWear Pro3 Armbands were placed on the back of the left medial triceps brachii of participants via a Velcro band, as per manufacturer instructions (2). Energy expenditure was calculated in one minute epochs via a proprietary algorithm operating at a default sampling rate of 30 Hz, alongside manually entered individual participant characteristics (sex, age, mass, height, handedness, smoking status), which determined participant resting metabolic rate (2). Total energy expenditure was calculated via the latest internal proprietary algorithm (v5.2), on SenseWear Innerview Research Software (v8.0, Pittsburgh, USA).

Total Energy Expenditure – Microtechnology Units

Across both assessment periods, the TEE of participants was also determined by SWA outputs combined with microtechnology unit derived metabolic power. Microtechnology units were securely positioned between the scapulae of participants using a custom-made vest and worn during all field sessions and competitive match-play, as commonly performed within professional team sports (4, 17); again evidencing ecological validity. Participants utilised the same microtechnology unit across both pre-season and in-season data collection periods to eliminate inter-device variability. Units housed a global positioning system (GPS) and triaxial accelerometer sampling at 10 and 100 Hz, respectively, alongside a gyroscope and magnetometer (Optimeye S5, Catapult Innovations, Melbourne,

Australia). Ten Hz microtechnology units have been shown to provide accurate assessment of total distance and high-intensity (i.e. high speed & high power) activity for team sport athletes (28).

All units were turned on prior to field session or match warm-ups and turned off immediately after each session or match completion. Data was then downloaded, trimmed and analysed to provide metabolic energy ($kcal \cdot kg^{-1}$), based on metabolic power equations (13), using Catapult Sprint software [Catapult Innovations, Melbourne, Australia; pre-season number of satellites, version 5.1.7, 15 (3); pre-season horizontal dilution of precision 0.8 (0.6); in-season number of satellites, version 5.1.7, 11.9 (2.3); in-season horizontal dilution of precision 0.8 (0.1)]. Metabolic power estimates the metabolic 'internal' cost of activities from players' 'external' movements. It is assumed that accelerated or decelerated running on a flat surface is energetically equivalent to incline running at a constant velocity, where the angle of the incline is equal to the extent of forward acceleration, which then provides an instantaneous energetic cost for high intensity intermittent activities during team sports (13).

Total Energy Expenditure - Doubly Labelled Water

Stable Isotope Doses

The DLW method was used as the criterion measure of TEE across pre-season and in-season assessment periods. Doubly labelled water bolus doses consisting of deuterium (^2H) and oxygen (^{18}O) stable isotopes were prepared for each participant in three stages, as has previously been described (11). Doses were calculated relative to the largest BM of any participant included in the study (33). This included ^2H_2O (99 atom %) and $H_2^{18}O$ (10 atom %) based on 0.14 $g \cdot kg^{-1}$ and 0.90 $g \cdot kg^{-1}$ of BM, respectively.

DLW Administration, Urine Collections and IRMS Analyses of Urine Samples

Each dose was provided one day prior to the start of the assessment period, as has previously been described (10). A baseline urine sample was provided before oral consumption of a single bolus of DLW ($^2H_2^{18}O$), made under close supervision. To ensure consumption of the whole bolus, the dose bottles were washed twice with additional water that participants also consumed. Baseline enrichment was determined from a later urine sample provided by participants at 22:00, allowing for total body water (TBW) equilibrium (Schoeller 1988).

Participants provided daily urine samples at 22:00 across both data collection periods, as has previously been described (10, 11). Samples were collected directly into two date, time and participant ID registered 5 mL cryovials and filtered in compliance with the Human Tissue Act. Analysis of urine samples for ^2H and ^{18}O abundance was performed following gas exchange using a HYDRA 20-22 IRMS (SerCon, Crewe UK), as has previously been described (11). All data were imported into a Microsoft Excel template where the calculation of total body water (TBW), TEE and quality control parameters could be performed.

Total Body Water and Total Energy Expenditure Calculations

Total body water was calculated from stable isotope dilution spaces, based on the intercept of the elimination plot of deuterium (1). The tracer elimination rates and subsequent isotope enrichments were calculated from baseline tracer abundance for the fourteen-day pre-season period and seven-day in-season assessment period, specifically. Total energy expenditure was then calculated from the stable isotope elimination rate constants and "pool

space" (1). Throughout the study, tracer enrichment in body water remained above the

minimum recommendation (1). The Pearson product moment correlation of the tracer

elimination plots was greater than 0.99 in all cases. A respiratory quotient of 0.85 was

assumed (32).

Statistical Analyses

Raw data are presented as mean (SD). Agreement between practical (SWA; SWA &

metabolic power) and criterion (DLW) measures were determined with 90% confidence

limits, using an excel spreadsheet (2016, Seattle, USA) to calculate mean bias, typical error

of the estimate and Pearson correlation coefficient (Hopkins, 2015). Method comparisons

were assessed via magnitude-based inferences and paired t-tests, which were run in R Studio

(v 1.414). All data were first log-transformed to reduce bias arising from non-uniformity

error.

The standardised mean bias was assessed as *trivial* (<0.20)*, small* (0.2 to 0.6)*,*

moderate (0.6 to 1.2), *large* (1.2 to 2.0), *very large* (2.0 to 4.0) or *extremely large* (>4.0). The

standardised typical error as assessed as *trivial* (<0.1)*, small* (0.1 to 0.3)*, moderate* (0.3 to

0.6), *large* (0.6 to 1.0), *very large* (1.0 to 2.0) or *extremely large* (>2.0) (Hopkins, 2015). The

magnitude of correlation was assessed as *trivial* (<0.1)*, small* (0.1 to 0.29)*, moderate* (0.3 to

0.49), *large* (0.5 to 0.69), *very large* (0.7 to 0.89), *nearly perfect* (0.9 to 0.99) or *perfect*

(>0.99) (Hopkins, 2015). For null-hypothesis significance testing, statistical significance was

assumed at 5% ($P < 0.05$).

RESULTS

Individual participant TEE measured via DLW, isolated or combined wearable technology across the pre-season and in-season period are reported in Table 1.

INSERT TABLE 1 HERE

SenseWear Pro3 Armband

SenseWear Pro3 Armbands significantly under-reported pre-season and in-season DLW assessed TEE by 5.00 (2.52) MJ·day^{-1} and 2.86 (1.15) MJ·day^{-1}, respectively (Table 2). This represents a *large* and *extremely large* standardised mean bias and *very large* and *large* typical error of the estimate, respectively.

INSERT TABLE 2 HERE

SenseWear Pro3 Armband and metabolic power

Combined SWA and metabolic power significantly under-reported pre-season and in-season DLW assessed TEE by 4.04 (2.38) MJ·day^{-1} and 2.18 (0.96) MJ·day^{-1}, respectively (Table 2). This represents a *large* and *very large* standardised mean bias and *very large* and *large* typical error of the estimate, respectively.

INSERT TABLE 3 HERE

Method Comparison

Across the pre-season period, there was an *almost certainly* small improvement (0.95 (0.15) MJ·day^{-1}; ES = 0.32 ±0.04; p < 0.001) in the daily TEE error reported by the combined SWA and metabolic power (5.00 (2.52) MJ·day^{-1}) compared with the SWA alone (4.04 (2.38) MJ·day^{-1}). Across the in-season period, there was an *almost certainly* moderate improvement (1.01 (0.15) MJ·day^{-1}; ES = 0.88 ±0.10; p < 0.001) in the daily TEE error reported by the combined SWA and metabolic power (2.18 (0.96) MJ·day^{-1}) compared with the SWA alone (3.19 (0.97) MJ·day^{-1}).

DISCUSSION

This study represents the first investigation of isolated or combined wearable technology to accurately determine the TEE of professional young rugby league players across either a pre-season or in-season period, against a literature gold standard DLW assessed criterion. The results demonstrate the low measurement validity of both the SWA in isolation or combined with microtechnology derived metabolic power across the season. Ultimately, these results highlight the limitations of using either SWA, or SWA combined with metabolic power, to accurately determine the TEE of professional young collision sport athletes across different stages of the season.

SenseWear Pro3 Armbands displayed *large* and *very large* systematic bias, as well as *very large and large* typical error of the estimate across assessment periods, evidencing poor measurement accuracy within a professional collision-sport cohort. Despite reporting strong

correlations with DLW assessed TEE across pre-season (r = 0.61) and in-season periods (r = 0.77), the SWA substantially underestimated TEE by 1195 kcal·day^{-1} and 762 kcal·day^{-1}, respectively, while also reporting unacceptable random variation. These results contradict validations of SWA within the general population, when performing light to moderate physical activity (5, 8, 31). This is perhaps unsurprising, as the SWA has been repeatedly validated during submaximal activities of up to 10 METs (i.e. resting, sitting, standing, walking, jogging) (21); and shown to be less accurate during the higher exercise intensities typically performed by athletes (i.e. running, biking, circuits, resistance exercise) (23). More specifically within athletic populations, SWA have reported large systematic underestimations of exercise energy expenditure during a simulated rugby protocol (1.9 %), recovery from a simulated rugby protocol (17 %; (40)), basketball skills session (24 %) and 20 minute shuttle test (10.8 %; (35)). Collectively, these results highlight the methodological limitations of this approach within applied athletic TEE assessment.

Combining microtechnology derived metabolic power with SWA *likely* and *almost certainly* improved measurement accuracy across assessment periods. However, combined technologies still displayed *large* and *very large* systematic bias, as well as *very large and large* typical error of the estimate; evidencing low overall measurement accuracy. The addition of field session and match-play energy expenditures from metabolic power calculations substantially improved TEE estimations by 227 kcal·day^{-1} and 241 kcal·day^{-1} across pre-season and in-season periods, respectively. Such improvement was expected, due to SWA not being worn during field sessions or match-play; a major limitation of published literature (4) and applied practise (17) within professional collision-based sports due to player and equipment safety concerns. Despite this, combined SWA and metabolic power outputs still substantially under-reported DLW assessed pre- and in-season TEE by 965 kcal·day^{-1} and

$520\,kcal{\cdot}day^{-1}$, respectively. These findings are consistent with published literature, whereby metabolic power outputs have been shown to underestimate the true energetic costs of multidirectional running (52 %), linear running (34 %; (27)), soccer specific drills (51 %; (7)), field sport movements (19 %; (6)) and collision-based activity (45 %; (18)). Therefore, despite improvements in TEE assessment, the combination of metabolic power with SWA does not accurately determine the TEE of professional collision-sport athletes across either a pre-season or in-season period.

SenseWear Pro3 Armbands have been shown to reliably detect activity patterns and rest periods (15, 22), which suggests that consistent under-estimation of expenditure during high intensity exercise (15, 16, 23, 25, 29) and intermittent exercise recovery periods (i.e. post exercise oxygen consumption; (40)) is likely a result of non-specific exercise expenditure algorithms (23). This hypothesis is supported by improvements in SWA measurement accuracy when proprietary algorithms have been updated (v2.2 vs. v5.2; (3) and exercise-specific equations developed (20). Additionally, exercise capacity (21), body mass, body composition (5), sweat rate (15) and high external temperatures (36) have all been shown to affect SWA measurement accuracy; all of particular concern for practitioners working with athletes.

Under-estimation of exercise energy expenditure via metabolic power calculation is multifactorial, although most likely attributed to the inability of microtechnology units to detect energy transfer during periods of rest or non-locomotor activities. Professional collision-based sports are dominated by high intensity collisions (26), which are metabolically damaging (30) and energetically expensive (11). Metabolic power is

determined from accelerations and decelerations associated with movement demands (13) and was therefore not designed to assess the energetic cost of rest periods (i.e. common within all team sports (17)), static exertions (i.e. collisions; (17)) or associated recovery costs (9, 11, 26). For example, excess post-exercise oxygen consumption has been shown to almost entirely account for the under-estimation of energy expended during collision activity (18) and soccer specific drills (7); understandably not detected by locomotor-based microtechnology units. Other potential sources of error include the magnitude and duration of accelerations typically achieved within team sports (7), individual athlete variation in running economy (i.e. stride length, movement efficiency, body inclination), concentration of mass (17), changes of direction (27), air resistance (6) and the inability of 10 Hz microtechnology units to accurately measure accelerations or decelerations greater than 4 m/s^2 (37). Evidently, applying steady state models of expenditure to intermittent team sports involving frequent collisions will result in substantial underestimation of true energetic demands.

Future research should focus upon developing and investigating sport-specific algorithms for SWA and metabolic power, improving upon limitations of the current study, while also pioneering innovative technology. Firstly, this study employees a small sample of professional young RL players, with five participants involved across both assessment periods; highlighting a requirement for replication across larger cohorts, age-groups and sports. Moreover, study conclusions would have been strengthened by an equal sample length across investigated pre-season (i.e two-weeks) and in-season (i.e. one-week) periods, although consideration for the extensive cost of the DLW approach is required. Parameters measured by SWA are directly associated with physical exertion and, therefore, could theoretically provide improved assessment of exercise specific energy expenditure with sophisticated statistical modelling (21). However, this prospect seems unlikely due to

required access to proprietary protected algorithms owned by a currently discontinued company (SWA; Body Media). On the contrary, microtechnology use and development within professional team sports is evident and fast paced (17), demonstrated by current revision of the metabolic power equation to differentiate between walking and running episodes and include air resistance (14). Nevertheless, revisions were not intended to improve collision or intermittent rest period energy expenditure assessment and are unlikely to improve measurements of TEE investigated in this study (17); clearly, development and validation of new or novel approaches is required

In conclusion, this study provides novel insights into the accuracy of isolated or combined wearable technology to determine the TEE of professional young rugby league players across different stages of the season. Despite high practicality, the results signal the low measurement validity of SWA in isolation, or combined with metabolic power, across a typical pre-season and in-season period. Utilisation of 10 Hz microtechnology units, the latest SWA algorithms and literature gold standard as the criterion measure, strengthens study conclusions within an ecologically valid research design and population. These results highlight the need for caution and a clear understanding of individual and combined method limitations before application within the applied sphere of practise or research.

PRACTICAL APPLICATION

This study evidences the low measurement validity of SWA in isolation, or combined with metabolic power, to accurately determine the TEE of professional young rugby league players across the season. Despite the attractive practicality of contemporary wearable technology, researchers and practitioners should not utilise SWA or SWA combined with

metabolic power to accurately determine the TEE of professional young collision-sport

athletes within applied practise or research.

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Table 1. Individual participant pre-season and in-season TEE measured via DLW (criterion), isolated (SenseWear Pro3 Armband; SWA) or combined (SWA & metabolic power) wearable technology.

Participant Number	Participant Position	DLW (MJ·day⁻¹)	SWA (MJ·day⁻¹)	SWA & Metabolic Power (MJ·day⁻¹)
		$(MJ^{.}day^{-1})$	$(MJ^{.}day^{-1})$	$(MJ^{.}day^{-1})$
Pre-Season				
1	Half Back	16.28	11.99	12.80
2	Hooker	17.13	14.47	15.31
3	Wing	16.15	13.35	14.23
4	Prop Forward	19.32	13.01	14.15
5	Loose Forward	24.11	14.74	15.91
6	Prop Forward	17.03	12.46	13.38
In-Season				
1	Half Back	16.17	14.84	15.65
2	Hooker	15.56	11.21	12.06
3	Wing	15.87	12.59	13.74
4	Prop Forward	16.96	13.73	14.83
5	Loose Forward	16.15	12.24	13.35
7	Full Back	15.04	11.50	12.36
8	Back Row	17.26	14.58	15.76

Table 2. Pre-season & in-season TEE measured via DLW vs. SenseWear Pro3 Armband (SWA) measured total energy expenditure.

Measure of TEE	DLW (MJ·day⁻¹)	SWA (MJ·day⁻¹)	Standardised Mean Bias	Typical Estimate of Error	Correlation	*P* value
Pre-Season (N = 6)	18.35 ± 3.04	13.35 ± 1.09	-1.74 [-2.24 to -1.05] *Large*	1.31 [0.40 to 4.03] *Very Large*	0.61 [-0.24 to 0.93] *Large*	0.002
In-Season (N = 7)	16.16 ± 0.77	12.96 ± 1.45	-4.23 [-5.51 to -2.95] *Extremely Large*	0.77 [0.31 to 3.95] *Large*	0.79 [0.25 to 0.96] *Very Large*	<0.001

Table 3. Pre-season & in-season TEE measured via DLW vs. SenseWear Pro3 Armband (SWA) combined with metabolic power derived from microtechnology units.

Measure of TEE	DLW (MJ·day^{-1})	SWA & Metabolic Power (MJ·day^{-1})	Standardised Mean Bias	Typical Estimate of Error	Correlation	*P* value
Pre-Season (N = 6)	18.35 ± 3.04	14.31 ± 1.16	-1.40 [-2.05 to -0.75] *Large*	1.07 [0.34 to 8.88] *Very Large*	0.68 [-0.11 to 0.95] *Large*	0.004
In-Season (N = 7)	16.16 ± 0.77	13.97 ± 1.49	-2.91 [-4.08 to -1.74] *Very Large*	0.67 [0.27 to 2.69] *Large*	0.83 [0.35 to 0.96] *Very Large*	0.002