The assessment of total energy expenditure during a 14-day 'in-season' period of professional rugby league players using the Doubly Labelled Water method

James Cameron Morehen[1], Warren Jeremy Bradley[1] Jon Clarke[2], Craig Twist [3], Catherine Hambly[4], John Roger Speakman[4], James Peter Morton[1] & Graeme Leonard Close[1].

[1]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University Liverpool, UK,

[2]Widnes Vikings Rugby League, Cheshire, UK

[3]Department of Sport and Exercise Sciences, University of Chester, Chester, UK

[4]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK

Corresponding author:

Graeme L. Close,
Research Institute of Sport and Exercise Sciences,
Tom Reilly Building,
Byrom St Campus,
Liverpool John Moores University,
Liverpool,
L3 3AF,
UK

Telephone: 0151 904 6266
E-mail: g.l.close@ljmu.ac.uk

Running title: Energy Expenditure in Rugby League Players

Abstract

Rugby League is a high-intensity collision sport competed over 80-minutes. Training loads are monitored to maximise recovery and assist in the design of nutritional strategies although no data are available on the Total Energy Expenditure (TEE) of players. We therefore assessed Resting Metabolic Rate (RMR) and TEE in six Super-League players over two consecutive weeks in-season including one-game per week. Fasted RMR was assessed followed by a baseline urine sample before oral administration of a bolus dose of hydrogen (deuterium ^2H) and oxygen (^{18}O) stable isotopes in the form of water ($^2H_2{}^{18}O$). Every 24 hours thereafter, players provided urine for analysis of TEE via DLW method. Individual training-load was quantified using session rating of perceived exertion (sRPE) and data were analysed using magnitude-based inferences. There were *unclear* differences in RMR between forwards and backs (7.7 ± 0.5 *cf*. 8.0 ± 0.3 MJ, respectively). Indirect calorimetry produced RMR values *most likely* lower than predictive equations (7.9 ± 0.4 *cf*. 9.2 ± 0.4 MJ, respectively). A *most likely* increase in TEE from week-1 to -2 was observed (17.9 ± 2.1 *cf*. 24.2 ± 3.4 MJ) explained by a *most likely* increase in weekly sRPE (432 ± 19 *cf*. 555 ± 22 AU), respectively. The difference in TEE between forwards and backs was *unclear* (21.6 ± 4.2 *cf*. 20.5 ± 4.9 MJ, respectively). We report greater TEE than previously reported in rugby that could be explained by the ability of DLW to account for all match and training-related activities that contributes to TEE.

Keywords: nutrition, physical performance, energy, metabolism

Introduction

Rugby League (RL) is a team sport that places increased physical and metabolic stresses on players during training and competition. In-season, players will typically train 3-5 days a week and, if selected, play in one 80-minute competitive match. RL is unique to many team sports whereby repeated bouts of high intensity and low intensity activity are interspersed with physically demanding high-speed collisions and wrestling bouts (Austin et al., 2011; Gabbett et al., 2012; King et al., 2009; Sirotic et al., 2011; Sykes et al., 2011; Waldron et al., 2011). Given the physical demands of the sport, players strive to maximise lean body mass whilst also maintaining low body fat, with typical percentage body fat for professional players being 15 and 12 % for forwards and backs, respectively (Morehen et al., 2015; Till et al., 2013). To allow optimal nutritional strategies to be devised that help achieve these goals, it is essential to understand the total energy expenditure (TEE) of the athletes. However, these data are not currently available for a typical training week of a professional RL player. To improve nutritional strategies for RL players TEE must also be reported alongside total energy intakes (TEI), which to date has only been reported in isolation (Lundy et al., 2006).

The internal training loads imposed on RL players are typically monitored using heart rate (HR) and session-RPE (sRPE) (Lovell et al., 2013; Waldron et al., 2011; Weaving et al., 2014). Additionally, the growing use of micro technology incorporating GPS and accelerometers has attempted to quantify external training loads in the form of running (Evans et al., 2015; Gabbett et al., 2012; Twist et al., 2014), collisions (Oxendale et al., 2015) and, more recently, metabolic power

(Kempton et al., 2015). Data on TEE are however limited despite such data having clear potential to inform appropriate training loads to maximise performance (Fowles, 2006), body composition (Morehen et al., 2015) and potentially improve recovery from the weekly muscle soreness (Fletcher et al., 2015) by ensuring adequate post-game nutrition is prescribed. Although some studies have attempted to quantify TEE in elite Rugby Union (RU) players (Bradley et al., 2015a; Bradley et al., 2015b) and elite RL players (Coutts et al., 2003) these studies are somewhat limited by the methods employed. For example, Bradley et al. (2015a) utilised Sensewear armbands that cannot be worn during games or physical collisions and therefore these data fail to account for the demands of match day competition and collision-focused training sessions that could contribute a significant amount to the TEE. (Kempton et al., 2015))have also used microtechnology to quantify energy expenditure based on the cost of accelerated running (di Prampero et al., 2005), reporting values of 23-43 $kJ \cdot kg^{-1}$ during match play. However, Buchheit et al. (2015) has questioned the validity of this microtechnology-derived metric, suggesting that it underestimates energy expenditure because of an inability to detect non-ambulatory related activities. One technique that could assess all aspects of TEE in elite rugby players during training and matches, is the doubly labelled water (DLW) method (Schoeller et al., 1986). Despite the high validity associated with such measures, studies employing this approach are generally scarce in elite sporting populations due to financial implications.

Resting metabolic rate (RMR) is a major component of TEE in humans (Speakman et al., 2003) that is often estimated using prediction equations

(Cunningham, 1980), some of which have been validated in athletic populations (Cunningham, 1991; ten Haaf et al., 2014; Thompson et al., 1996). It is noteworthy, however, that the mean lean body mass of athletes in the original validation studies was ~46-63 kg (Cunningham, 1991) and therefore the appropriateness of the Cunningham equation for athletes with a larger body mass could be questioned. To date, no study has reported the typical RMR of elite rugby players measured using indirect calorimetry and consequently, estimates of RMR using standard prediction equations that are commonly used in elite rugby practice might be flawed.

To help estimate an athletes total energy expenditure (TEE) it is common to report the Physical Activity Level (PAL) of the sport, defined as any bodily movement produced by skeletal muscle that results in energy expenditure (Westerterp, 2013). The PAL score is expressed as a magnitude of the RMR and is a useful tool for comparing between sports as well as estimating an athlete's TEE. Whilst the PAL value of a vigorous lifestyle is known (approximately 2.4; (Westerterp, 2013), there has yet been no attempt to quantify the PAL of elite RL players. As a consequence of this lack of basic metabolic data in RL, it is extremely difficult to prescribe science-informed rugby specific nutrition plans to help players achieve ideal body compositions and promote adaptations to training. Therefore, the aims of this study were to (1) assess TEE and TEI of professional RL players during two competitive in-season weeks using the DLW method, food diaries, and calculate the PAL of the sport; (2) measure and compare the RMR of these players to current prediction equations.

Methods

Overall Study Design

The study was conducted during the first two weeks of the 2015 competitive European Super League season. The specific period of the season was chosen since week-1 and week-2 of the study mirrored each other with both beginning on a Monday and matches scheduled for a 3 pm kick off on each respective Sunday. Players continued with their in-season training throughout the two weeks (Table 1), as prescribed by the club coaches. TEE via the DLW method, RMR, body composition and TEI were recorded in all players. During training, sRPE was used to quantify training load. All players completed two six-day food diaries (Monday to Saturday) to assess TEI.

Participants

Six professional RL players from the same club volunteered for the study. Based on playing position, three forwards and three backs were selected to represent typical RL positions (prop, hooker, wide-running forward, and stand-off, halfback, winger). A summary of the participant characteristics can be seen in Table 2. The local ethics committee of Liverpool John Moores University granted approval for the study and participants provided written consent before starting.

Measurement of TEE using Doubly Labelled Water

On Monday morning of week-1, players were weighed to the nearest 0.1 kg (SECA, Birmingham, UK) wearing shorts only. A single baseline urine sample was then provided, after which players were administered orally with a single bolus dose of hydrogen (deuterium ^{2}H) and oxygen (^{18}O) stable isotopes in the form of water ($^2H_2{}^{18}O$). Isotopes were purchased from Cortecnet (Voisins-Le-Bretonneux – France). The desired dose was 10 % ^{18}O and 5 % Deuterium and was calculated according to each participant's body mass measured to the nearest decimal place at the start of the study, using the calculation:

$$^{18}O\ dose = [0.65\ (body\ mass,\ g) \times DIE]/IE$$

Where DIE is the desired initial enrichment (DIE = 618.923 x body mass (kg)$^{-0.305}$) and IE is the initial enrichment (10%) 100,000 parts per million.

To ensure the whole dose was administered, the glass vials were washed with additional water and players were asked to consume the added water. Approximately every 24-hour (between 0900-1000) each player provided body mass and the second urine pass of the day, with the first acting as a void pass. Urine samples were stored and frozen at -80°C in airtight 1.8 ml cryotube vials for later analysis.

For DLW analysis, urine was encapsulated into capillaries, which were then vacuum distilled (Nagy, 1983), and water from the resulting distillate was used. This water was analysed using a liquid water analyser (Los Gatos Research; (Berman et al., 2012). Samples were run alongside three laboratory standards for each isotope and three International standards (Standard Light Artic Precipitate, Standard Mean Ocean Water and Greenland Ice Sheet Precipitation; (Craig, 1961; Speakman, 1997) to correct delta values to parts per million. Isotope enrichments were converted to daily energy expenditure using a two-pool model equation

(Schoeller et al., 1986) as modified by (Schoeller, 1988) and assuming food quotient of 0.85.

Body Composition and Resting Metabolic Rate (RMR)

All players underwent a whole body fan beam DXA measurement scan (Hologic QDR Series, Discovery A, Bedford, MA, USA) as previously described (Morehen et al., 2015) to quantify players lean body mass which is required to predict RMR using prediction equations (Cunningham, 1991). Thereafter, each player's RMR was assessed using the Moxus Modular Metabolic System (AEI Technologies, IL, USA), which had been previously calibrated according to manufacturer's guidelines (Beltrami et al., 2014). Before assessment players were laid supine and asked to relax in a dark room for 15-minutes. The Moxus ventilation hood was then placed over the head and shoulders to measure players RMR (Roffey et al., 2006) for a 15-minute period and data collected were converted using the MAX II Metabolic System software (version 1.2.14, Physio-Dyne Instrument Corp, Quoque) using the Harris and Benedict equation (Harris et al., 1918).

Total Energy intake

Macro-nutrient intakes were analysed from two individual six-day food diaries for all players and reported in megajoules (MJ). The period of six-days is considered to provide reasonably accurate and precise estimations of habitual energy and nutrient consumptions whilst reducing variability in coding error (Braakhuis et al., 2003). This method has also been used previously to assess TEI in professional in RU players (Bradley et al., 2015a). Food diaries were explained to players by the club's sport nutritionist, who is a graduate Sport and Exercise Nutrition Register (SENr) accredited practitioner. Players and the nutritionist also performed 24-hour recalls and a diet history each morning for the previous day's intake (Thompson et al., 2001). The club nutritionist provided daily sport specific supplements and on three occasions in both weeks (Game Day -5, -4 and -2), lunch was provided for all players. To obtain energy and macro nutrient composition the Nutritics professional diet analysis software (Nutritics Ltd, Ireland) was used.

Quantification of weekly training load

Quantification of gym and pitch training loads were assessed using sRPE (Foster et al., 2001), which has previously been used in professional RU (Bradley et al., 2015a) and RL (Lovell et al., 2013; Weaving et al., 2014). Gym and field based training were rated as individual RPE using a modified 10-point Borg Scale (Borg et al., 1987) from which the sRPE (AU) was calculated by multiplying RPE by total training time or total number of repetitions for field and gym sessions, respectively. Daily values were then summed for each individual to provide a weekly total for training load. No measure of load was collected for matches due to the difficulties of interfering with players' match preparation; however, all players completed 80 minutes in both matches.

Statistical analysis

Magnitude-based inferential statistics were employed to provide information on the size of the differences allowing a more practical and meaningful explanation of the data. Fortnightly RMR and body composition along with differences between week-1 and week-2 for TEE, TEI and sRPE were analysed as well as differences between forwards and backs using Cohen's effect size (ES) statistic ± 90% confidence limits (CL), % change and magnitude-based inferences, as suggested by Batterham and Hopkins (2006). Thresholds for the magnitude of the observed change for each variable was determined as the between-participant standard deviation (SD) in that variable x 0.2, 0.6 and 1.2 for a small, moderate and large effect, respectively (Cohen, 1988; Hopkins et al., 2009). Threshold probabilities for a meaningful effect based on the 90% confidence limits (CL) were: <0.5% most unlikely, 0.5–5% very unlikely, 5–25% unlikely, 25–75% possibly, 75–95% likely, 95–99.5% very likely, >99.5% most likely. Effects with confidence limits across a likely small positive or negative change were classified as unclear (Hopkins et al., 2009). All calculations were completed using a predesigned spreadsheet (Hopkins, 2006).

Results

Energy Intake and Expenditure

TEE and TEI data are presented in **Figure 1**. DLW revealed that there was a combined fortnightly TEE of 22.5 ± 2.7 MJ and TEI of 14.0 ± 0.7 MJ. There was a *most likely* increase in mean TEE from week-1 to week-2 (35.3%; ES 1.8 ± 0.71). Over the same period, there was also a *likely* increase in mean TEI (5.6%; ES 0.74 ± 0.78). Differences in TEE between forwards and backs were *unclear* in both week-1 (12.4%; ES 0.44 ± 1.07) and week-2 (1.4%; ES 0.05 ± 1.03). Differences in TEI between forwards and backs were *unclear* in week-1 (5.3%; ES 0.85 ± 2.23) but *very likely* higher for forwards in week-2 (9.1%; ES 3.2 ± 2.19). Forwards TEE was *very likely* and *most likely* higher than TEI in week-1 (21.4%; ES 1.43 ± 0.73) and week-2 (38.7%; ES 2.87 ± 0.72), respectively whilst backs TEE was *unclear* and *very likely* higher than TEI in week-1 (18.3%; ES 1.4 ± 1.58) and week-2 (42%; ES 2.1 ± 1.07).

Resting Metabolic Rate and sRPE

RMR data are presented in **Figure 2**. Mean RMR was *most likely* lower (16.5%; ES 2.5 ± 0.87) when assessed using direct calorimetry (7.9 ± 0.4 MJ) compared with predicted RMR using the Cunningham equation (9.2 ± 0.4 MJ). A difference in RMR between forwards and backs was *unclear* (2.9%; ES 0.25 ± 0.9) when measured using direct calorimetry.

Mean sRPE **(Figure 3)** was *most likely* higher in week-2 compared to week-1 (29%; ES 4.61 ± 0.24). Differences in weekly sRPE between forwards and backs were *unclear* in both week-1 (4.4%; ES 0.86 ± 1.57) and week-2 (4.9%; ES 1.26 ± 1.62).

Discussion

The aims of the present study were to: (1) determine the TEE and TEI of professional RL players during a competitive fortnight (including competitive matches) using the DLW technique and food diaries and (2) measure and compare the RMR of these players to a current predictive equation. We report for the first time that average TEE of all players using the gold standard DLW method was 22.5 MJ per day with clear differences between weeks and of note the TEE was significantly greater than the mean daily TEI of 14 MJ. We also report that RMR was 16.5% lower than values derived from commonly used predictive equations.

Despite within group variations, there were no differences between forwards and backs in RMR. These data have immediate translational potential by informing applied practitioners working with professional RL players about the high TEE from the training and match demands of in-season RL. We also report caution when using a predictive equation to estimate RL players' RMR.

For the first time we have employed the DLW technique to quantify the TEE associated with RL training and match play, which incorporated running, physical collisions and recovery periods. Interestingly, the high TEE in both forwards (19.1 and 24.0 MJ) and backs (16.6 and 24.3 MJ) reported for week-1 and week-2, respectively, are higher than those values reported in-season using accelerometery for RU forwards (15.9 ± 0.5 MJ) and backs (14.0 ± 0.4 MJ) (Bradley et al., 2015a). Differences in TEE between rugby codes could be because of differences in training and playing demands. However, weekly training loads (sRPE) were similar between studies, meaning the higher TEE reported in this study probably reflects: (1) the inability of previous studies to quantify physical contact and/or (2) that anaerobic contributions to training are difficult to quantify using wearable technology (Buchheit et al., 2015). A limitation of the present study was that DLW was only performed on six players and future studies might wish to confirm these data using more players.

There were no differences in the TEE between the forwards and backs. Backs typically have longer playing times and perform more running whereas forwards are involved in more physical collisions (Twist et al., 2014; Waldron et al., 2011). In the present study, all players completed 80 minutes in both games and therefore we propose that the greater internal load caused by collisions in forwards (Mullen et al., 2015) matches the greater running volumes in backs (Gabbett et al., 2012), the outcome of which is the similar TEE observed between positional groups. Unfortunately with DLW technique the TEE of individual training sessions cannot be quantified and further work is required to understand the energy demands of rugby collisions.

There was no significant difference in RMR between forwards and backs, although there were inter individual variations. Despite the widespread use of prediction equations to estimate RMR (Cunningham, 1980), we report a difference of ~16.5% (~310 kcal) between this equation and indirect calorimetry. While RMR is a less important component of TEE in highly active rugby players compared to sedentary individuals (Speakman et al., 2003) it remains a fundamental measure to accurately prescribe nutritional advice. The Cunningham equation was originally validated on runners (~46-63 kg), so is likely to over estimate RMR in our study because of the higher lean body mass observed in elite rugby players (Morehen et al., 2015). Interestingly, lean body mass did not predict RMR in the six players tested in this study, with the highest RMR reported in the players with the lowest lean mass. Estimations of RMR in rugby players using existing predictive equations should be avoided, with future studies seeking to develop predictive RMR equations for athletes with higher lean body mass.

There was a large variation (as much as 7.5 MJ or 1800 Kcal) in the TEE between players that could not be explained by the RMR or the sRPE of the monitored training sessions. This variation in TEE suggests that non-exercise activity thermogenesis (NEAT) is a major contributor to the TEE in rugby players, despite the present study being unable to quantify these activities. Given that every aspect of a player's training day is carefully monitored (Weaving et al., 2014) and this information is then used to prescribe training loads (Weaving et al., 2014), it is essential that support staff understand and attempt to quantify the significant contribution of NEAT to TEE which might include players using wearable technology away from clubs. Similar observations have been reported in the Australian Football League, where a significant amount or TEE was from NEAT and suggests the habitual lifestyle of players outside of training is meaningful (Walker et al., 2015). The present study also attempted to define the Physical Activity Levels (PAL) of professional rugby players. The players in this study had an average PAL value of 2.9, which is considerably higher than the 2.4 value suggested for people with vigorously active lifestyles but lower than 4.0 expressed by professional endurance athletes (Westerterp, 2013). Knowing an approximate PAL might provide a starting point for the prescription of nutritional plans as well as being a useful tool to compare between sports.

The reported TEI was lower than the TEE in both the forwards and backs. Although some of the meals consumed by the players were provided and therefore monitored, the large discrepancy between TEE and TEI probably reflects inaccuracies in self-reporting dietary intake (Bingham, 1987; Deakin, 2000). This is further supported by the players' body mass remaining unchanged during the study (94.7-94.8 kg). Previous research has suggested that the self-reported TEI bias can be as high as 34% (Ebine et al., 2000; Fudge et al., 2006; Hill et al., 2002), which appears likely in the present study. These data confirm that caution should be taken when interpreting food diaries from athletes, even when considerable care has been taken by the athlete and the practitioner to complete them accurately.

To conclude, we report average weekly TEE values of ~22.5 MJ in professional RL players that are higher than reported previously in RU players (Bradley et al., 2015a; Bradley et al., 2015b). We speculate that this high TEE reflects the ability of DLW to assess all aspects of rugby activity, including the physical collisions that have previously not been examined. The high NEAT reported in the present study also suggests that support staff should try to quantify (and perhaps control) activities that players are performing away from the rugby club. The large discrepancy between TEE and TEI again raises serious questions over the assessment of TEI and suggests practitioners should interpret TEI data with caution. Finally, we report a discrepancy between the assessment of RMR using a prediction equation and indirect calorimetry, and suggest that future studies might wish to develop prediction equations more suitable for athletes with high muscle mass. We believe that the data presented have immediate translational potential to help support staff within rugby clubs to evaluate the energy cost of their training as well as aiding in the design of rugby specific diet plans.

Acknowledgments

The study was designed by JCM, JC, and GLC; data were collected and analysed by JCM and University of Aberdeen DLW Resource Centre; data interpretation and

manuscript preparation were undertaken by JCM, WJB, JC, CT JPM and GLC. All authors approved the final version of the paper.

References

Austin, D. J., Gabbett, T. J., & Jenkins, D. J. (2011). Repeated high-intensity exercise in a professional rugby league. *J Strength Cond Res, 25*, 1898-1904.

Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform, 1*, 50-57.

Beltrami, F. G., Froyd, C., Mamen, A., & Noakes, T. D. (2014). The validity of the Moxus Modular metabolic system during incremental exercise tests: impacts on detection of small changes in oxygen consumption. *Eur J Appl Physiol, 114*, 941-950.

Berman, E. S., Fortson, S. L., Snaith, S. P., Gupta, M., Baer, D. S., Chery, I., Blanc, S., Melanson, E. L., Thomson, P. J., & Speakman, J. R. (2012). Direct analysis of delta2H and delta18O in natural and enriched human urine using laser-based, off-axis integrated cavity output spectroscopy. *Anal Chem, 84*, 9768-9773.

Bingham, S. (1987). The dietary assessment of individuals; methods, accuracy, newtechniques and recommendations. *Nutr Abstr Rev Ser Hum Exp, 57*, 705-742.

Borg, G., Hassmen, P., & Lagerstrom, M. (1987). Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *Eur J Appl Physiol Occup Physiol, 56*, 679-685.

Braakhuis, A. J., Meredith, K., Cox, G. R., Hopkins, W. G., & Burke, L. M. (2003). Variability in estimation of self-reported dietary intake data from elite athletes resulting from coding by different sports dietitians. *Int J Sport Nutr Exerc Metab, 13*, 152-165.

Bradley, W. J., Cavanagh, B., Douglas, W., Donovan, T. F., Twist, C., Morton, J. P., & Close, G. L. (2015a). Energy intake and expenditure assessed 'in-season' in an elite European rugby union squad. *Eur J Sport Sci*1-11.

Bradley, W. J., Cavanagh, B. P., Douglas, W., Donovan, T. F., Morton, J. P., & Close, G. L. (2015b). Quantification of training load, energy intake, and physiological adaptations during a rugby preseason: a case study from an elite European rugby union squad. *J Strength Cond Res, 29*, 534-544.

Buchheit, M., Manouvrier, C., Cassirame, J., & Morin, J. B. (2015). Monitoring locomotor load in soccer: is metabolic power, powerful? *International Journal of Sports Medicine. In Press, In Press*.

Coutts, A., Reaburn, P., & Abt, G. (2003). Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: a case study. *J Sports Sci, 21*, 97-103.

Craig, H. (1961). Standard for Reporting Concentrations of Deuterium and Oxygen-18 in Natural Waters. *Science, 133*, 1833-1834.

Cunningham, J. J. (1980). A reanalysis of the factors influencing basal metabolic rate in normal adults. *Am J Clin Nutr, 33*, 2372-2374.

Cunningham, J. J. (1991). Body composition as a determinant of energy expenditure: a synthetic review and a proposed general prediction equation. *Am J Clin Nutr, 54*, 963-969.

Deakin, V. (2000). *Measuring nutritional status of athletes: Clinical and research perspectives.* . Sydney: McGraw-Hill Book Company.

di Prampero, P. E., Fusi, S., Sepulcri, L., Morin, J. B., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *J Exp Biol, 208*, 2809-2816.

Ebine, N., Feng, J. Y., Homma, M., Saitoh, S., & Jones, P. J. (2000). Total energy expenditure of elite synchronized swimmers measured by the doubly labeled water method. *Eur J Appl Physiol, 83*, 1-6.

Evans, S. D., Brewer, C., Haigh, J. D., Lake, M., Morton, J. P., & Close, G. L. (2015). The physical demands of Super League rugby: Experiences of a newly promoted franchise. *Eur J Sport Sci, epub ahead of print*.

Fletcher, B. D., Twist, C., Haigh, J. D., Brewer, C., Morton, J. P., & Close, G. L. (2015). Season-long increases in perceived muscle soreness in professional rugby league players: role of player position, match characteristics and playing surface. *J Sports Sci*1-6.

Fowles, J. R. (2006). Technical issues in quantifying low-frequency fatigue in athletes. *Int J Sports Physiol Perform, 1*, 169-171.

Fudge, B. W., Westerterp, K. R., Kiplamai, F. K., Onywera, V. O., Boit, M. K., Kayser, B., & Pitsiladis, Y. P. (2006). Evidence of negative energy balance using doubly labelled water in elite Kenyan endurance runners prior to competition. *Br J Nutr, 95*, 59-66.

Gabbett, T. J., Jenkins, D., & Abernethy, B. (2012). Physical demands of professional rugby league training and competition using microtechnology. *Journal of Science and Medicine in Sport, 15*, 80-86.

Harris, J. A., & Benedict, F. G. (1918). A Biometric Study of Human Basal Metabolism. *Proc Natl Acad Sci U S A, 4*, 370-373.

Hill, R. J., & Davies, P. S. (2002). Energy intake and energy expenditure in elite lightweight female rowers. *Med Sci Sports Exerc, 34*, 1823-1829.

Hopkins, W. G. (2006). Spreadsheets for analysis of controlled trials, with adjustment for a subject characteristic. *Sport Science, 10*, 46-50.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc, 41*, 3-13.

Kempton, T., Sirotic, A. C., Rampinini, E., & Coutts, A. J. (2015). Metabolic power demands of rugby league match play. *Int J Sports Physiol Perform, 10*, 23-28.

King, T., Jenkins, D., & Gabbett, T. (2009). A time-motion analysis of professional rugby league match-play. *J Sports Sci, 27*, 213-219.

Lovell, T. W., Sirotic, A. C., Impellizzeri, F. M., & Coutts, A. J. (2013). Factors affecting perception of effort (session rating of perceived exertion) during rugby league training. *Int J Sports Physiol Perform, 8*, 62-69.

Lundy, B., O'Connor, H., Pelly, F., & Caterson, I. (2006). Anthropometric characteristics and competition dietary intakes of professional rugby league players. *Int J Sport Nutr Exerc Metab, 16*, 199-213.

Morehen, J. C., Routledge, H. E., Twist, C., Morton, J. P., & Close, G. L. (2015). Position specific differences in the anthropometric characteristics of elite European Super League rugby players. *Eur J Sport Sci, epub ahead of print.*

Mullen, T., Highton, J., & Twist, C. (2015). The Internal and External Responses to a Forward-Specific Rugby League Simulation Protocol Performed With and Without Physical Contact. *Int J Sports Physiol Perform, 10*, 746-753.

Nagy, K. (1983). *The Doubly Labelled Water (3HH18O) Method: a Guide to its Use.* . Los Angeles, CA: : UCLA Publication 12-1417.

Oxendale, C. L., Twist, C., Daniels, M., & Highton, J. (2015). The Relationship Between Match-Play Characteristics of Elite Rugby League and Indirect Markers of Muscle Damage. *Int J Sports Physiol Perform*.

Roffey, D. M., Byrne, N. M., & Hills, A. P. (2006). Day-to-day variance in measurement of resting metabolic rate using ventilated-hood and mouthpiece & nose-clip indirect calorimetry systems. *JPEN J Parenter Enteral Nutr, 30*, 426-432.

Schoeller, D. A. (1988). Measurement of energy expenditure in free-living humans by using doubly labeled water. *Journal of Nutrition, 118*, 1278-1289.

Schoeller, D. A., Ravussin, E., Schutz, Y., Acheson, K. J., Baertschi, P., & Jequier, E. (1986). Energy expenditure by doubly labeled water: validation in humans and proposed calculation. *Am J Physiol, 250*, R823-830.

Sirotic, A. C., Knowles, H., Catterick, C., & Coutts, A. J. (2011). Positional match demands of professional rugby league competition. *J Strength Cond Res, 25*, 3076-3087.

Speakman, J. R. (1997). *Doubly Labelled Water; Theory and Practice.* . London: Chapman & Hall.

Speakman, J. R., & Selman, C. (2003). Physical activity and resting metabolic rate. *Proc Nutr Soc, 62*, 621-634.

Sykes, D., Twist, C., Nicholas, C., & Lamb, K. (2011). Changes in locomotive rates during senior elite rugby league matches. *J Sports Sci, 29*, 1263-1271.

ten Haaf, T., & Weijs, P. J. (2014). Resting energy expenditure prediction in recreational athletes of 18-35 years: confirmation of Cunningham equation and an improved weight-based alternative. *PLoS One, 9*, e108460.

Thompson, F. E., & Subar, A. F. (2001). Dietary Assessment Methodology. In A. M. Coulston, C. L. Rock & E. R. Monsen (Eds.), *Nutrition in the Prevention and Treatment of Disease*. San Diego, CA: Academic Press.

Thompson, J., & Manore, M. M. (1996). Predicted and measured resting metabolic rate of male and female endurance athletes. *J Am Diet Assoc, 96*, 30-34.

Till, K., Cobley, S., J, O. H., Cooke, C., & Chapman, C. (2013). Considering maturation status and relative age in the longitudinal evaluation of junior rugby league players. *Scand J Med Sci Sports*.

Twist, C., Highton, J., Waldron, M., Edwards, E., Austin, D., & Gabbett, T. J. (2014). Movement demands of elite rugby league players during Australian National Rugby League and European Super League matches. *Int J Sports Physiol Perform, 9*, 925-930.

Waldron, M., Twist, C., Highton, J., Worsfold, P., & Daniels, M. (2011). Movement and physiological match demands of elite rugby league using portable global positioning systems. *J Sports Sci, 29*, 1223-1230.

Walker, E. J., McAinch, A. J., Sweeting, A., & Aughey, R. J. (2015). Inertial sensors to estimate the energy expenditure of team-sport athletes. *J Sci Med Sport*.

Weaving, D., Marshall, P., Earle, K., Nevill, A., & Abt, G. (2014). Combining internal- and external-training-load measures in professional rugby league. *Int J Sports Physiol Perform, 9*, 905-912.

Westerterp, K. R. (2013). Physical activity and physical activity induced energy expenditure in humans: measurement, determinants, and effects. *Front Physiol, 4*, 90.

Table 1. A typical in-season training week is shown in Table 1. This was mirrored for both week-1 and -2 of the study. Training days are shown in relation to game day rather than days of the week. Number in parentheses indicates the duration in minutes of the particular activity measured using sRPE. Swimming was performed off site whilst all other activities were performed on site at the rugby club.

	Game Day-5	Game Day-4	Game Day-3	Game Day-2	Game Day-1	Game Day	Game Day +1
AM	Swim (30) Weights (40)	Weights (40)	Rest	Mobility (15)	Captains Run (30)	Game	Recovery
Mid-AM	Skills (40)	Skills (30)	Rest	Power Weights (30)	Rest	Game	Recovery
PM	Rest	Rugby (45)	Rest	Rugby (45)	Rest	Game	Recovery

Table 2. Body composition and metabolic characteristics for all 6 players.

Player	Height (cm)	Body Mass (kg)	Lean Mass (kg)	Fat Mass (kg)	Body Fat (%)	RMR (MJ)
1	180.6	91.3	75	10	11.3	8.11
2	183	95.5	79.2	10.3	11.1	7.17
3	185.5	100.2	80.5	12.9	13.4	7.97
4	182.4	85	69	10	12.2	8.27
5	179	92.3	74.7	10.5	12	8.00
6	186	103.9	82	14.2	14.3	7.64
Mean	182.8	94.7	76.7	11.3	12.4	7.86
(SD)	(2.7)	(6.7)	(4.8)	(1.8)	(1.2)	(0.40)