


MYTHS AND METHODOLOGIES

Resting metabolic rate prediction equations and the validity to assess energy deficiency in the athlete population

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Abstract

Resting metabolic rate (RMR) is the amount of energy the body uses at rest. A suppressed RMR has been correlated with low energy availability and therefore used as an indicator of an individual's energy state. Furthermore, confounding identification of low energy availability within an athletic population are the physiological measures required, which can be time consuming and require professional expertise. To negate the demands of laboratory protocols in measuring RMR, predicted RMR (p RMR) equations were developed. Caution should be exercised when applying the p RMR equations for determining low energy availability in athletes owing to the population used to develop the equations and the higher metabolic cost of fat-free mass, thus elevated RMR, associated with athletes. Moreover, a low ratio of measured RMR to p RMR is often used as an alternative marker for energy deficiency. Predictive equations should implement fat-free mass within the algorithm when estimating RMR in athletic populations. The purpose of this paper is to describe p RMR equation development and the issues associated with use of p RMR equations for athletic populations. As professional sport increases, validation of p RMR equations in the modern athlete population is needed to monitor energy availability for athletic health and performance.

KEYWORDS

athlete, energy availability, methodology, predictive resting metabolic rate, resting metabolic rate, validity

1 | INTRODUCTION

Resting metabolic rate (RMR) is the minimum energy the body requires to perform its basic functions and is principally dependent on lean mass. In an applied setting, RMR can be used as an indicator of energy availability (EA), defined as the energy remaining for metabolic processes once the energy cost of exercise has been subtracted from dietary intake. Sufficient energy is crucial for training consistency, particularly during intensified periods, because prolonged energy restriction can lead to impaired physiological function and increased risk of fatigue, illness and injury, and to maladaptation to the prescribed training (Mountjoy et al., 2014). It is known that energy homeostasis is centrally regulated, and RMR is closely linked to appetite and energy intake (Blundell, Finlayson, Gibbons, Caudwell, & Hopkins, 2015; Keeseey & Powley, 2008). Therefore, when energy intake is insufficient to support an intensified training load, athletes are more likely to suffer suboptimal EA and a lower RMR. Given this association with suppressed RMR and suboptimal EA, RMR has been used to estimate EA in determining individuals with low energy availability (LEA; De

Souza et al., 2008; De Souza, Hontscharuk, Olmsted, Kerr, & Williams, 2007; Gibbs, Williams, Scheid, Toombs, & De Souza, 2011; Melin et al., 2015). Low energy availability is correlated with detrimental physiological, psychological and performance effects (De Souza & Williams, 2004; Logue et al., 2018; Mountjoy et al., 2018; Nattiv et al., 2007; VanHeest, Rodgers, Mahoney, & De Souza, 2014); it is known that there is a negative linear relationship between absolute and relative RMR and training (Woods, Garvican-Lewis, Lundy, Rice, & Thompson, 2017). Therefore, accuracy of RMR measurements becomes paramount in monitoring EA and prevention of LEA.

Accessibility, cost, equipment requirements and the time required to measure RMR (m RMR) is often a barrier. To reduce complexity, predictive RMR (p RMR) equations are widely used. However, the Harris-Benedict (HB) equation (Harris & Benedict, 1919) most commonly used today was first developed in 1919. In contemporary practice, it is common to use the standard p RMR for the athletic population. However, there is significant conflicting evidence on the validity of p RMR in athletic populations (De Lorenzo et al., 1999; Jagim et al., 2018; ten Haaf & Weijs, 2014; Thompson & Manore, 1996). Thus, the

first important question to ask is whether ρ RMR is an appropriate tool to use in athletic populations. Secondly, is ρ RMR an appropriate tool to use to assist with LEA classification, owing to the complex variables included in the algorithms of equations? The purpose of this paper is to describe the origin of the most commonly used ρ RMR equations and discuss the issues of using ρ RMR equations for athletic populations. Future directions for research involving m RMR and ρ RMR equations will be discussed specifically for LEA research.

2 | MEASUREMENT OF METABOLIC RATE

Considering total daily energy expenditure (EE), it is noticeable that RMR is its largest component (50–70%), of which fat-free mass (FFM) is the major contributor. Fat-free mass accounts for ~60–70% of RMR, whereas fat mass accounts for as little as 5–7%, with sex and age being minor components (Johnstone, Murison, Duncan, Rance, & Speakman, 2005).

Indirect calorimetry (IC) is one of the most sensitive, accurate and non-invasive techniques for measurement of EE. The principle behind IC can be explained by the chemical energy that is created from the oxidation of fuels. Indirect calorimetry measures the heat generated indirectly, by measuring the volume of oxygen used and the volume of carbon dioxide produced. The energy expended can then be determined using the Weir formula (Weir, 1949).

One IC method for determining whole-body EE is to use the ingestion of doubly-labelled water, with two traceable isotopes (for a review, see Westerterp, 2017). A sample of blood, saliva or urine is collected twice; an initial sample and a sample after a period of time (1–3 weeks), to determine the elimination rate of each isotope. From this, the EE can be calculated from the carbon dioxide produced between the two samples. The use of doubly-labelled water provides an accurate method to measure daily EE without being in a laboratory setting. However, this method is expensive, and stringent protocols are required for accurate results. Other forms of IC have been used to determine EE at rest; for example, the use of a ventilated hood system to measure RMR (Compher, Frankenfield, Keim, & Roth-Yousey, 2006).

3 | MEASURED RESTING METABOLIC RATE

Measurement of RMR by IC is time consuming and expensive and requires specialized equipment. In addition, there are experimental variables that can influence results when measuring RMR that can fall into four categories: the instruments used (hoods *versus* mouthpiece; gas analysis systems), standardized protocols (timing to refrain from exercise, caffeine and nutrition), biological variation (menstrual status in females) and body composition measurement [dual-energy X-ray absorptiometry (DXA) *versus* other methods] (Compher et al., 2006; Fullmer et al., 2015). Therefore, standardized protocols must be adhered to for reliable and valid results (Compher et al., 2006; Fullmer et al., 2015). For example, because the thermic effect of food increases metabolic rate, as does consumption of caffeine, nicotine and alcohol (Compher et al., 2006), these must be controlled for as follows: (i)

New Findings

- **What is the topic of this review?**

We review the issues with using predicted resting metabolic rate equations in athletic populations.

- **What advances does it highlight?**

The use of dated predicted resting metabolic rate equations is not appropriate for athletic populations until more studies have been conducted among these unique populations.

a minimum rest period of 20 min upon arrival at the laboratory to ensure a metabolic steady state of the participant; and (ii) participants must fast for ≥ 7 h, refraining from caffeine or other stimulants for ≥ 4 h before the assessment (Fullmer et al., 2015). Other best practices include restrictions on physical activity before the assessment, ideal room conditions controlling for temperature, humidity, light, noise, and implementing correct data analysis methods (Compher et al., 2006; Fullmer et al., 2015).

Owing to the constraints of testing conditions to create valid findings, testing athletic populations is difficult. For example, batch testing athletes in one day is unachievable owing to the duration of testing protocols (~45 min per test), and typically will be completed in the morning after an overnight fast, before the morning training session. Also, given that athletes are highly active, it is important to make sure no residual exercise EE (e.g. excess postexercise oxygen consumption) carries over from training the previous day. Therefore, measurements after a rest day would be most appropriate. Furthermore, athletes have busy training, competing and travel schedules, subsequently adding another factor to the challenges of coordinating such testing. Anecdotal evidence suggests that athletes also find it hard to remain fasted (food and caffeine) before the RMR assessment, especially when training commences after the RMR assessment. Careful consideration and nutrition planning are needed after an RMR assessment to make sure an athlete's training is not affected.

To overcome complexities of the aforementioned RMR testing protocols, equipment requirements, time and cost, ρ RMR equations have been developed.

4 | PREDICTED RESTING METABOLIC RATE EQUATIONS

Predicted RMR equations were developed to estimate RMR in male and female populations of varying body mass, height and age (Cunningham, 1980; De Lorenzo et al., 1999; Harris & Benedict, 1919; Mifflin et al., 1990; Owen et al., 1986, 1987). The ρ RMR equations differ in their components, using body mass only (Owen et al., 1986), FFM only (Cunningham, 1980), height and body mass (De Lorenzo et al., 1999), or height, body mass and age (Harris & Benedict, 1919; Mifflin et al., 1990; Table 1).

TABLE 1 Common predictive resting metabolic rate equations developed

Source	Population in which equation was developed (n)	Measures used	RMR equation (kcal·day ⁻¹)
Harris and Benedict (1919)	Men (136), women (103) and newborn infants (94) in good health, typical of the general population. Equations were based on ranges of: A, 21–70 years; BM, 25–124.9 kg; H, 151–200 cm. Sixteen athletes (all male) were included: A, 19–29 years; BM, 56.3–108.9 kg; H, 160–198 cm. Infants were aged between 2.5 h and 7 days old	Indirect calorimetry	Males RMR = 66.47 + (13.75 × BM) + (5 × H) – (6.76 × A) Females RMR = 655.1 + (9.563 × BM) + (1.850 × H) – (4.676 × A)
Cunningham (1980)	Men (120) and women (103). Male trained athletes eliminated (16)	Database from Harris and Benedict (1919) LBM estimated	RMR = 500 + (22 × FFM)
Owen et al. (1986)	Lean and obese females (44); eight were trained athletes: A, 18–65 years; BM, 43–143 kg; and H, 150–180 cm. Not menstruating during data collection	Indirect calorimetry. Body composition by underwater weighing and skinfolds. LBM was estimated	Non-athletes RMR = 795 + (7.18 × BM) Athletes RMR = 50.4 + (21 × BM)
Owen et al. (1987)	Lean and obese males (60): A, 18–82 years; BM, 60–171 kg; and H, 163–188 cm. Trained athletes were eliminated	Indirect calorimetry. Body composition by underwater weighing and skinfolds. LBM was estimated	RMR = 879 + (10.2 × BM) RMR = 290 + (22.3 × FFM)
Mifflin et al. (1990)	Normal, overweight and obese men (251) and women (247): A, 19–78 years; normal BM (80 to <119% IBW); obese BM (≥120% IBW); and H, 146–201 cm	Indirect calorimetry. %BF determined with three different sites for males and females using the Jackson-Pollock method. FFM was subsequently determined by calculation [BM – FM (BM × %BF)]	Males RMR = (9.99 × BM) + (6.25 × H) – (5 × A) Females RMR = (9.99 × BM) + (6.25 × H) – (5 × A) – 161
De Lorenzo et al. (1999)	Male athletes (51; judo, karate, water polo)	Indirect calorimetry. DXA scan	RMR = –857 + (9.0 × BM) + (11.7 × H)

Abbreviations: A, age (in years); BM, body mass (in kilograms); %BF, percentage body fat; DXA, dual-energy X-ray absorptiometry; FFM, fat-free mass (in kilograms); FM, fat mass; H, height (in centimetres); IBW, ideal body weight determined by use of 1959 Metropolitan Height Weight Tables; LBM, lean body mass (in kilograms); and RMR, resting metabolic rate.

Investigating the origin of p RMR raises issues when these equations are used in modern populations. Predicted RMR equations have been established using large cohorts of men and women; the participants were typical of the general population of good health, and range in age from infants to elderly subjects.

Participants involved in the development of the HB equation were healthy, male and female and a wide range of ages, but physical activity or percentages of lean mass were not reported (Harris & Benedict, 1919). To expand the validity of p RMR, the Cunningham (C) equation used the database collected by Harris and Benedict (1919) to create formulas for each sex. Cunningham (1980) determined that lean body mass (LBM) was the main predictor of basal metabolic rate and that sex and/or age did not improve the validity. Therefore, the C equation uses LBM as the main predictor of RMR. However, it must be noted that LBM was not measured, but was predicted by using another previously published prediction LBM equation (Cunningham, 1980). This adds an additional level of error when determining RMR.

Owen and colleagues published two papers on the caloric expenditure in healthy lean and obese females (Owen et al., 1986) and males (Owen et al., 1987) to create p RMR equations, respectively. A small percentage (18%, $n = 8$) of the female participants were classified as being athletes, stating non-specific criteria other than 'athletes competed in strenuous physical events and two were Olympic participants... [and maximal O_2 uptake values] ranged from 52–62 ml.kg⁻¹.min⁻¹' (Owen et al., 1986: p. 4). This created differences in regression lines from non-athletes. Therefore, two

predictive equations were developed based on athletes and non-athletes, but not specific for female versus male athletes (Owen et al., 1986; Table 1). Furthermore, Owen et al. (1987) replicated their previous study (Owen et al., 1986) using lean and obese men to create two additional formulae; one based on body mass, the other based on FFM for both lean and obese, non-athletic males (Table 1).

Given that both the HB and the C equations were found to overestimate resting energy expenditure (REE; by 5 and 14–15%, respectively), Mifflin et al. (1990) aimed to establish a new predictive formula using female and male participants, categorized by 'normal' and 'obese' body mass values. In agreement with observations by Cunningham (1980), FFM was highly correlated with REE. However, the inclusion of body mass, height and age improved the correlation of estimated REE with measured REE.

The latest research on p RMR equations comes from the work by De Lorenzo et al. (1999). In this study, seven published p RMR equations were used to investigate the validity and reliability for estimating RMR in male athletes, with a secondary aim of creating a specific equation for male athletes. To standardize for body composition, De Lorenzo et al. (1999) added lean versus fat mass obtained from DXA scans. Contrary to expectations, it was determined that FFM was not the best predictor of RMR; instead, it was the combination of height and body mass.

It is important to mention that trained male athletes were eliminated from data sets in the development of the C and Owen p RMR equations. Of the six p RMR equations mentioned, only the C and Owen

ρ RMR equations incorporated FFM. Given that these ρ RMR equations were developed explicitly on non-athletes, this raises a concern as to why the ρ RMR equations are currently used for athletic populations.

5 | PREDICTIVE RESTING METABOLIC RATE EQUATIONS USED IN ATHLETIC POPULATIONS

Although ρ RMR equations were developed in the 20th century, the equations are still frequently used today. As far as we are aware, there is no systematic review to date to confirm that the HB ρ RMR equation (Harris & Benedict, 1919) is the most prominent ρ RMR equation used. The HB ρ RMR equation is commonly seen in research that estimates RMR, without regard for the specific population being studied. Moreover, in sport and exercise science research, training status and load, body composition, sex, height and body mass play significant roles in the perturbations of RMR.

Muscle is a very metabolically active tissue and has been shown to be the best determinant of 24 h EE, contributing 20–30% of RMR (Ravussin, Lillioja, Anderson, Christin, & Bogardus, 1986). Given that athletes have greater muscle mass, and therefore an increase in metabolic cost, RMR will be greater than in those with less muscle mass (Cunningham, 1980). However, when using ρ RMR equations that do not account for FFM, as some of the common ρ RMR equations omit, the equations are insensitive for differences in body composition. Therefore, RMR could be underestimated. For instance, an equal ρ RMR value would be calculated for two individuals of the same age, height and body mass, even if one individual has greater FFM and less fat mass, compared with the other individual. Therefore, ρ RMR equations should implement FFM within the calculation when estimating RMR in athletic populations to reflect the anthropometric difference. Fat-free mass would be a better predictor of RMR rather than ρ RMR.

Jagim et al. (2018) demonstrated discrepancies between male and female athletes when using the C equation. In female athletes (track and field, soccer, swimming/diving), the C equation was best at predicting RMR. However, in male athletes (baseball, football, track and field), the C equation overestimated RMR, but the HB equation was the best predictor of RMR. Given that the C equation was re-created using the data set from Harris and Benedict (1919), and estimating FFM, this result is not surprising. The C equation also predicted RMR most accurately in male and female trained athletes (Thompson & Manore, 1996) and recreational athletes (ten Haaf & Weijts, 2014).

6 | USING RESTING METABOLIC RATE AS A MARKER OF ENERGY DEFICIENCY

When an individual is in an LEA state, one response of the body is to suppress RMR. A suppressed RMR can be determined using the ratio of m RMR to ρ RMR. A ratio of <0.9 of m RMR to ρ RMR was first used as a marker for energy deficiency (De Souza et al., 2007). This threshold is not without fault, because the threshold value was

originally determined using exercising females and the HB predictive equation (De Souza et al., 2007). It is known that the prevalence of energy deficiency will be dependent on the method used to calculate ρ RMR, owing to the range of ρ RMR equations that are formulated using different variables (i.e. body mass, height, age versus FFM).

A sequential study by De Souza et al. (2008) used a group of exercising women, classified with energy deficiency, to observe relationships between hormone, energy and bone health status. De Souza et al. (2008) clearly explain their reasoning to implement the HB equation in predicting RMR and therefore use in the ratio equation, as follows: (i) the HB equation has been used frequently in previous research; (ii) the HB equation is typically used in underweight individuals, i.e. for anorexia nervosa patients; (iii) the HB and C equations produced similar groupings of energy status in the women; and (iv) the C equation produced a different value to that of the HB equation, but this did not impact groupings. It is important to note that the women in this sample were not underweight (group averages of body mass index >20 kg m⁻²) and were physically active. However, the level of exercise was minimal (<2 h per week) in comparison to athletic populations.

The issues of applying ρ RMR equations in athletic populations have been demonstrated. That being so, where does this leave the use of ρ RMR in athletic populations?

7 | PREDICTED USE OF RESTING METABOLIC RATE IN ATHLETIC POPULATIONS: ASKING CRITICAL QUESTIONS

It is important to be mindful when using ρ RMR in research involving athletic individuals, given the body compositional differences between athletic and non-exercising populations. Typically, RMR will be underestimated if ρ RMR equations are used that do not account for FFM. It is inappropriate to continue to use dated equations without understanding the origin and reasoning behind those equations. In order to use ρ RMR equations confidently, research is needed to develop current ρ RMR equations that are based on contemporary athletic populations and to incorporate sex differences. Updated ρ RMR equations will allow for appropriate estimation of RMR and therefore, more accurate LEA classification. It has been demonstrated that the use of ρ RMR equations to categorize individuals in an energy-deficient state must be carried out with caution, especially in athletic populations. The implementation of a new measure of energy deficiency, EA, has emerged that would be more suitable for athletic populations.

8 | FUTURE DIRECTIONS OF ENERGY DEFICIENCY AND ENERGY AVAILABILITY CLASSIFICATION

A more appropriate measure of energy deficiency among athletic populations, is to determine EA, i.e. the dietary energy remaining to complete normal physiological functioning after exercise (Logue et al.,

TABLE 2 Energy availability threshold values

Threshold category	Value [kcal·(kg FFM) ⁻¹ ·day ⁻¹]
Adequate	45
Subclinical	30–45
Low energy availability	<30

Abbreviation: FFM, fat-free mass.

2018; Loucks, Kiens, & Wright, 2011). To determine EA (in kilocalories per kilogram FFM per day), three key components are required: dietary energy intake (EI; in kilocalories), exercise energy expenditure (EEE; in kilocalories) and FFM (in kilograms), as follows:

$$EA = \frac{EI - EEE}{FFM} \quad (1)$$

As with determining RMR, measurements of these components alone have their limitations, because there is 'no gold standard assessment of energy availability' (Logue et al., 2018: p. 4), and no clear protocols are in place for the duration of assessment and appropriate techniques used to assess LEA (Burke, Lundy, Fahrenholtz, & Melin, 2018). First, EA is 'snap shot' insight into the energy status of the individual. Second, accurate recording and compliance of dietary intake is required, because it is known that there can be bias of under-reporting (Loucks et al., 2011). Third, a standardized definition of exercise energy expenditure is needed and must be recorded accurately, because some studies subtract the energy cost of sedentary movements during exercise (Logue et al., 2018) and use different methods to determine exercise expenditure with different forms of exercise (Loucks et al., 2011). Finally, specialists are required to measure body composition when implementing appropriate FFM analysis (using DXA scans), and best practices are required for the interpretation of DXA results in athletic populations (Hind et al., 2018).

It is clear that these measurements alone are time consuming and require standardized protocols. Without agreement with individual measures, the value of EA will vary between studies, making interpretation and conclusions about EA in athletic populations troublesome. Determining EA should not be completed in isolation. It should be used to confirm LEA status in those with signs of LEA or at risk of LEA and used in conjunction with other markers of LEA (e.g. biochemical, metabolic and haematological results) and dietary eating behaviours (Burke et al., 2018).

9 | ASSOCIATION OF ENERGY AVAILABILITY WITH RESTING METABOLIC RATE

A series of studies have determined threshold EA values that corresponded to changes in RMR and markers of bone health; changes in sex hormones, anabolic hormones and endocrine hormones (Ihle & Loucks, 2004; Loucks, 2003; Loucks & Thuma, 2003; Williams et al., 2015; Williams, Helmreich, Parfitt, Caston-Balderrama, & Cameron, 2001). These studies have determined threshold EA values of energy availability (Table 2).

Given that the equation of EA (Equation 1) is not only focused on the FFM, but also takes into consideration the EI and EEE, this would therefore be a better indication of health status in athletic populations. Research findings to determine the appropriate threshold values in male athletes are sparse; therefore, is an area that needs further investigation.

10 | SUMMARY

There is equivocal evidence of the use of ρ RMR equations in athletic populations. Discrepancies of findings exist owing to a range of factors. First, the definition of 'athlete' is not consistent, as are the sports in which individuals participate; and second, the range of methods used to determine body composition included densitometry, skinfold calculations, FFM estimated by previous published equations, and the gold standard of DXA scans. Caution must be exercised when implementing ρ RMR equations in research, especially when using athletic populations. Despite the time, specialized equipment and expense needed to administer an RMR, it is currently a superior method to determine an athlete's RMR compared with ρ RMR. As sport participation increases, especially at an elite level, further research investigating the modern athlete population, using gold-standard body composition measures, is needed to increase the validity of the well-used ρ RMR equations. By validating ρ RMR equations for athletes and careful monitoring of energy availability for athletic health and performance, these equations can become more reliable, leading to improved outcomes across all spectra of athletes.

AUTHOR CONTRIBUTIONS

All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed. KS: Conception or design of the work, Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content. HT: Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content. SS: Acquisition, analysis, or interpretation of data for the work, Drafting of the work or revising it critically for important intellectual content.

COMPETING INTERESTS

None declared.

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