Original Research

The Journal of Strength and Conditioning Research™

Validity of Average Power, Total Work, and Exercise Energy Expenditure Quantified by Cycling Mechanics

Tanja Oosthuyse,[1,2] Nazeera Bownes,[1] Lauren A. Wiemers,[1] and Andrew N. Bosch[1]

[1]Health through Physical Activity, Lifestyle and Sport Research Centre, Division of Physiological Sciences, Department of Human Biology, Faculty of Health Sciences, University of Cape Town, Cape Town, South Africa; and [2]Department of Physiology, School of Biomedical Sciences, Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, South Africa

Abstract

Oosthuyse, T, Bownes, N, Wiemers, LA, and Bosch, AN. Validity of average power, total work, and exercise energy expenditure quantified by cycling mechanics. *J Strength Cond Res* 39(11): 1138–1147, 2025—Average power, work, and exercise energy expenditure (EEE) are useful metrics in cycling for gauging training load and targeting energy intake. These metrics are easily obtained from bicycle-mounted power meters but not all cyclists train with power meters. We used the laws of mechanics to estimate average power, total work, and EEE compared with power-meter measurements during $n = 100$ training sessions ($n = 32$ on road bicycles; $n = 68$ on mountain bikes [MTBs]) in competitive cyclists, with $p < 0.05$ as significant. Physics-derived average power and power-meter measures had a good agreement (Watts, mean difference ± *SD* −1.04 ± 10.38; *SEM* 1.038; coefficient of variability 4.2%; intraclass correlation coefficient 0.93), producing estimates of total work (−2 ± 24 kcal) and EEE (−10 ± 120 kcal) with negligible mean differences. Although average power was similar (MTB: 2.21 ± 0.31 $W \cdot kg^{-1}$; road: 2.24 ± 0.34 $W \cdot kg^{-1}$), total force produced (F_{Total}) was greater in MTB than in road training (25.8 ± 4.6 N; 20.7 ± 3.0 N). The components of F_{Total} differed, where forces to overcome gradient (12.9 ± 5.2 N; 8.5 ± 3.1 N) and rolling resistance (8.2 ± 1.6 N; 3.9 ± 1.1 N) were greater in MTB, and frictional air drag (4.7 ± 1.9 N; 8.4 ± 2.3 N) was greater in road training. Using the methodology applied, the laws of cycling mechanics produce fair measures of average power, total work, and EEE for cyclists without bicycle-mounted power meters. In addition, deriving the respective force components could support training prescription and equipment adjustments to optimize performance.

Key Words: cycling physics, cycling forces, power output, mountain biking, road cycling

Introduction

The measurement of cycling power and total work is useful for determining cycling training load to manage training prescription, including strength-based cycling training, and to avoid overtraining (17,46,53). Measuring exercise energy expenditure (EEE) in cycling is useful for considering a target energy intake (EI) (54). Competitive cyclists routinely perform high weekly training volumes with a notable high-intensity component, thereby persistently accruing high weekly total work and EEE (17,46,53). Being aware of training loads and daily or weekly accumulated EEE might help cyclists to better manage their refueling behaviors and recovery needs to avoid various symptoms of poor health and under performance that can result from undernutrition (34), and from overtraining (47). Understandably, such symptoms can also arise from conditions unrelated to undernutrition or overtraining (24). Nevertheless, several studies have reported a prevalence of undernutrition in cyclists (3,10,25,50,55), albeit to be interpreted with the known limitations of potential dietary underreporting (24). However, these reports are supported by allostatic evidence, such as suppressed resting metabolic rate (RMR) (10), suppressed endocrine status (3,10), poor bone health (25,55), or weight loss (50). Therefore, there is a need to quantify cycling power, total work, and EEE in not only elite cyclists but also in avid amateur cyclists who maintain high weekly training volumes (25). Cycling total work and EEE can be easily derived from average power output in cyclists who have bike-mounted power meters (18,50,54), where power is simply the rate of work done ($J \cdot s^{-1}$). However, many cyclists do not train with a power meter. For example, in our laboratory, out of 25 cyclists from middle–upper socioeconomic groups ranging from competitive amateurs to subelites who enrolled in studies measuring EEE, only 32% had a bike-mounted power meter (unpublished observation). The ability of scientists and coaches to assess total work and EEE in cyclists remotely, including those without power meter recordings or laboratory measurements, is important for day-to-day evaluations. Estimation of cycling EEE based on other methods, such as predicted metabolic equivalents (1), is less specific and likely produces values with a broad range of error. In addition, although tracking heart rate variability is important to monitor recovery and detect the onset of overtraining (27), it cannot quantify training load where instead matching EI to EEE can prevent overtraining during functional overreaching (42). We propose that cycling power, total work, and EEE can be remotely quantified by the application of the laws of mechanics.

Address correspondence to Dr. Tanja Oosthuyse, oosthuyse@polka.co.za.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (http://journals.lww.com/nsca-jscr).

Journal of Strength and Conditioning Research 39(11)/1138–1147

Work done in cycling can be calculated by applying the laws of mechanics to quantify the force to overcome gradient, rolling resistance, and frictional drag due to air resistance (6,16,30). The force to overcome gradient can be calculated from the combined mass of cyclist-plus-bicycle and routine training data acquired by global positioning system (GPS) devices with a built-in altimeter that include distance, time, and accumulated gain in vertical ascent. The force to overcome rolling resistance can be calculated based on the cyclist-plus-bicycle mass, the training surface type, namely, dirt or tarmac (48), and the tire frictional coefficient of rolling resistance (Crr) that is specific for each tire model, dimensions, and pressure and is available from an online database (7). The force to overcome drag due to air resistance can be calculated based on the average speed of cycling, air density determined from weather records, projected frontal surface area that can be estimated by a validated photographical method (15), and the coefficient of drag, which is inversely related to body mass (20). Other forces encountered in cycling such as possible internal resistance of the bicycle drive chain are less easy to quantify (16) and are assumed small given a well-serviced bicycle. The sum of the 3 major forces multiplied by the total distance covered will produce work done for a given training ride (6,30).

Work done based on mechanics can then be used in the same way as work done derived from the average power output recorded by a bicycle-mounted power meter to calculate cycling EEE (50,54). Gross efficiency in cycling is reported to approximate 20% in trained cyclists (21), and to be similar across a range of cycling training fitness (33). Therefore, the metabolic cost of work done can be calculated as 5-fold the value of work done (50,54). Exercise energy expenditure excludes the contribution of RMR during the time frame of the exercise period and RMR is preferably quantified by indirect calorimetry or for a remote approximation can be calculated using prediction equations (54) derived from lean, healthy populations (12,40) or athlete-specific populations (14,51).

This study aimed first to test the validity of applying the physics laws of mechanics in cycling to calculate average power, total work, and EEE compared with bicycle-mounted power meter measures as the reference standard. The study aimed to consider applications for cycling on both road bicycles and mountain bike (MTB) bicycles and to provide a freely available useable spreadsheet template. A second aim was to compare the physics-derived forces to overcome gradient, rolling resistance, drag due to air friction, and total produced force between road bicycle and MTB training. Knowledge of these force components and differences could be useful for training prescription, including on-the-bike strength-focused training. In addition, a third aim considered the application of EEE to guide target EI.

Methods

Experimental Approach to the Problem

Competitive road and MTB cyclists having bike-mounted power meters were recruited. Using a concurrent validity design, power meter-measured and physics-derived average power, work done, and EEE were compared during $n = 100$ training sessions.

Subjects

Training sessions ($n = 100$) from 8 healthy competitive cyclists (3 men and 5 women, mean ± SD) aged 44 ± 2.6 (range, 40–48) years, height 1.70 ± 0.05 m, body mass 63.6 ± 9.9 kg, hip circumference 90.2 ± 6.7 cm, cycling history 18 ± 8 years, and cycling training 12.3 ± 3.0 $\text{h}\cdot\text{wk}^{-1}$ were included in the study. The cyclists participated in road cycling ($n = 2$), mountain biking ($n = 3$), or both ($n = 3$). All cyclists provided signed consent to take part in the study after the study details and procedures had been explained. The study protocol was granted ethical clearance by the Human Research Ethics Committee of the University of Cape Town (408/2020).

Procedures

Bicycle Specifications and Tire Frictional Coefficient of Rolling Resistance. Each cyclist's height, hip circumference, and body mass were recorded. A scale accurate to 0.1 kg (Fitbit Aria; Fitbit, Inc., San Francisco, CA) was used to measure body mass first while wearing minimal clothing and again while wearing their full cycling kit that included contents that would normally be carried in the pockets of their cycling jersey during training plus the mass of 1 full water bottle. The mass of each cyclist's bicycle was also recorded. The tire specifications for both front and rear tires were recorded that included the tire brand and model, tire diameter and width, and the tire pressure. The frictional Crr for each tire could then be determined from an online database (7). The online database was established by rolling each listed tire at a specified selection of tire pressures on a 42 kg drum at a speed of 8 $\text{m}\cdot\text{s}^{-1}$, where the frictional drag of the drum surface is assumed to be similar to a tarmac-surfaced road. If the cyclist's tire pressure was different to the options available on the database, then the Crr for the cyclist's tire pressure was determined by interpolation. The Crr for the front and rear tires was averaged to produce an average Crr for each cyclist's bicycle.

Measurement of Projected Frontal Area. The total projected frontal area of each cyclist was determined using a validated photograph-based method (15). A frontal photograph was taken of each cyclist while seated on their bicycle maintaining their typical cycling posture while held in a stationary position by a person supporting the cyclist's bicycle by the rear wheel. Importantly, the photographer was positioned 5 m in front of the cyclist so that the photograph captured the full-frontal length of the cyclist using a direct zero-degree angle and included space above the helmet and beyond the contact of the front wheel with the ground (see Table, Supplemental Digital Content 1, http://links.lww.com/JSCR/A668 for a suitable example photograph). Note that a low- or high-angled photograph will distort the tire and rider proportions, which invalidates the method (15). The photograph was processed by Adobe Photoshop software (Adobe, Inc., San Jose, CA) to crop the cyclist and bicycle from the background. The cropped image was selected, and the pixel area expressed as px^2 was generated. The ruler toolbar was used to measure the height of the front tire and wheel on the photograph as pixel height. The actual tire and wheel height measured in meters was then used to generate a scale ratio of pixel to meters. The measured pixel area of the cropped frontal image was then converted to actual projected frontal area in m^2, as follows:

$$\text{Projected frontal area}(\text{m}^2) = (\text{photo area, px}^2) \Big/ (\text{photo tire height, px/actual tire height, m})^2$$

The reported coefficient of variability of this method is 0.1% and the calculated area matches other indirect measures of cycling projected frontal area (15).

Power Meter Specifications. Each cyclist had a bike-fitted power meter on their bicycle. The different power meters used by the cyclists included XCADEY XPower-S (spider measure ~1.5% accuracy) (XCadey, Guangzhou, China); Power2max NG (spider measure ~1.0% accuracy) (Power2max, North Vancouver, Canada); Quarq DZero (spider measure ~1.5% accuracy) (Quarq/SRAM, Chicago, IL); Stages Gen 3 single-sided (arm crank measure ~1.5% accuracy) (Stages Cycling, Boulder, CO); Rotor IN power REX1 (arm crank measure ~1.0% accuracy) (Rotor, Madrid, Spain); Powertap P2 (pedal measure ~1.5% accuracy) (Quarq/SRAM). The manufacturer-reported accuracies of these power meters have been validated (31). All cyclists performed a zero offset of their power meter before each ride.

Training Log. The cyclists recorded their cycling training for 2–4 weeks providing the following details for each ride: the bicycle type (road or MTB), start time of day, closest city or town, average power output, training distance, training time, accumulated vertical gain, kilometers on tarmac, and kilometers on gravel/dirt when mountain biking. The cyclists used GPS devices with a built-in barometric altimeter, for recording training metrics (Garmin Edge 830 or 530; Garmin, Olathe, KS) and uploaded each training session to the STRAVA App (San Francisco, CA) for verification. To avoid the significant drafting effect when cycling in large pelotons (8) from influencing the road bicycle data, only road training rides completed solo or in small groups of 2 or 3 cyclists were included in the analysis. In addition, although not specified, cyclists only used circular or out-and-back routes in their cycling training.

Data Analyses. The equations used to calculate total force (6,30), work done, average power output, and EEE (50) for each training ride are detailed below (see Table, Supplemental Digital Content 1, http://links.lww.com/JSCR/A668 for a summary formula sheet).

The force (N) to overcome gradient (F_{Grad}) was calculated as

$$F_{\mathrm{Grad}} = \mathrm{m}\cdot\mathrm{a}\cdot\sin(\theta),$$

where m is the mass of the cyclist in kit plus a full water bottle and the mass of the bicycle (kg), and a is the acceleration due to gravity ($9.8\ \mathrm{m\cdot s^{-2}}$) and θ is the angle of inclination calculated as

$$\text{Angle of inclination}(\theta) = \tan^{-1}(\text{vertical gain, m}\ /\text{total distance, m}).$$

The force to overcome rolling resistance (F_{Roll}) was calculated as

$$F_{\mathrm{Roll}} = \text{fraction on tarmac}\cdot(\mathrm{Crr}\cdot\mathrm{m}\cdot\cos\theta) + \text{fraction on dirt}\cdot([0.004 + \mathrm{Crr}]\cdot\mathrm{m}\cdot\mathrm{a}\cdot\cos\theta),$$

where Crr is the frictional Crr for the tires as already described. A factor of 0.004 was added to Crr for the fraction of the distance cycled on a dirt/gravel surface, considering that the frictional drag while cycling on gravel is greater than that on tarmac by a unit of 0.004 (48).

The force to overcome drag due to air resistance (F_{Drag}) was calculated as

$$F_{\mathrm{Drag}} = 0.5\cdot\rho\cdot\mathrm{Cd}\cdot\mathrm{FA}\left(\text{average speed, m}\cdot\mathrm{s}^{-1}\right)^2,$$

where average speed refers to the average speed that the cyclist achieved during the training ride measured in $\mathrm{m\cdot s^{-1}}$; FA is the projected frontal area of the cyclist and bicycle measured by the photographic method already described; ρ is air density ($\mathrm{kg\cdot m^{-3}}$) calculated using an online calculator (13) from the ambient temperature, relative humidity, and barometric pressure during each training ride obtained from an online weather records database (52) based on the start time and location (city/town) of each training ride; and Cd is the frictional coefficient of drag estimated from a relation to body mass previously derived from wind tunnel measures (20) as follows:

$$\mathrm{Cd} = 4.45\cdot(\text{body mass, kg})^{-0.45}.$$

The complexity of wind speed and direction is not included but could be negated by the gain in a tailwind being set off by the loss in a headwind when traveling in opposite directions. In this study, all training rides were circular or out-and-back. Therefore, the effective outcome of the study over the wind speeds experienced tested the justification of this approach. The inclusion of point-to-point cycling in a single direction in strong winds was beyond the scope of this study.

The sum of forces (N) yields the total force (F_{Total}) as follows:

$$F_{\mathrm{Total}} = F_{\mathrm{Grad}} + F_{\mathrm{Roll}} + F_{\mathrm{Drag}}.$$

Work done (J) was calculated as the total force multiplied by the total distance (m):

$$\text{Work done(J)} = F_{\mathrm{Total}}\cdot\text{distance}.$$

Average power output (Watts) was calculated as work done divided by exercise time in seconds.

The metabolic energy expended (kcal) to generate the work done, assuming 20% gross efficiency (21,33), was calculated as

$$\text{Metabolic energy expended(kcal)} = \text{Work done}\cdot 5\ /(4.184\times 1000),$$

where the denominator of 4.184 is applied to convert joules to calories.

Exercise energy expenditure was calculated as metabolic energy expenditure less the RMR component of energy expenditure during the time frame of exercise as follows:

$$\text{EEE(kcal)} = \text{Metabolic energy expenditure} - \left(\text{RMR, kcal}\cdot\text{day}^{-1}\big/24\right)\cdot(\text{exercise time, h}).$$

Resting metabolic rate (RMR as $\mathrm{kcal\cdot d^{-1}}$) was predicted using published equations based on body mass (kg) and height (cm or m), or fat-free mass (FFM, kg) that were derived from a lean, healthy population, and from athlete populations, as follows:

Harris–Benedict revised (40)

$$\text{RMR(women)} = 447.593 + (9.247\cdot\text{kg}) + (3.098\cdot\text{cm}) - (4.330\cdot\text{age}).$$

Harris–Benedict revised (40),

$$\text{RMR(men)} = 88.362 + (13.397\cdot\text{kg}) + (4.799\cdot\text{cm}) - (5.677\cdot\text{age}).$$

Ten Haaf & Weijs (51)

$$\text{RMR} = (11.936\cdot\text{kg}) + (587.728\cdot\text{m}) - (8.129\cdot\text{age}) + (191.027\cdot\text{sex, male} = 1;\ \text{female} = 0) + 29.279.$$

De Lorenzo et al. (14)

$$\text{RMR} = (9\cdot\text{kg}) + (1170\cdot\text{m}) - 857.$$

Cunningham (12)

$$\text{RMR} = (22 \cdot \text{FFM}) + 500.$$

Ten Haaf & Weijs (51),

$$\text{RMR} = (22.771 \cdot \text{FFM}) + 484.264,$$

where FFM was determined from the difference between body mass and fat mass, and fat mass was based on an estimate of percentage body fat using a large population-based regression equation modeled on dual-energy x-ray absorptiometry-measured percentage fat mass (5) as follows:

$$\text{Percentage adiposity}(\%) = \left([\text{hip circumference, cm}] \Big/ [\text{height, m}]^{1.5}\right) - 18.$$

This adiposity equation derived from a large cohort is reported to be within 0.9–1.2% of dual-energy x-ray absorptiometry-measured adiposity when ranging between 10 and 30% body fat (5). Likewise, the same mean difference (1.2%) was found in our laboratory, in 10 competitive female cyclists (unpublished observation).

Accordingly, estimated percentage body fat and FFM for the participants in this study were 22.5 ± 3.2% and 49.2 ± 7.8 kg, respectively. The average predicted RMR from these equations for each cyclist was used as their RMR ($\text{kcal} \cdot \text{d}^{-1}$). In our laboratory, we found the average of these predictive equations produced a mean difference of only 119 $\text{kcal} \cdot \text{d}^{-1}$ (or 6.2% CV) compared with actual measured RMR in 10 competitive female cyclists (unpublished observation).

Application of Exercise Energy Expenditure to Derive Target Energy Intakes.

From EEE a target EI can be calculated. Two target EIs were calculated for each training session as follows:

$$\text{Target EI}\left(\text{kcal} \cdot \text{kg}^{-1}\text{FFM}\right) = (\text{EEE} + \text{RMR})/\text{FFM} \qquad (1)$$

$$\text{Target EI}\left(\text{kcal} \cdot \text{kg}^{-1}\text{FFM}\right) = (\text{EEE} + \text{RMR} + [0.45 \cdot \text{RMR}])/\text{FFM} \qquad (2)$$

where equation 1 produces a target EI to meet only basic energy needs, while equation 2 also accounts for the additional energy costs to support nonexercise daily living according to previous guidelines recommending a factor of between 0.4- and 0.5-fold RMR to support the energy cost of seated work over and above RMR (43). Assuming these calculated targeted EIs, the respective energy availabilities (EAs, $\text{kcal} \cdot \text{kg}^{-1}$ FFM) that would be achieved on each training day were calculated, considering that $\text{EA} = (\text{EI} - \text{EEE}) \cdot \text{FFM}^{-1}$ (34). A low EA is more robustly indicated by a change in various energy-sensing biomarkers that suggest energy inadequacy leading to energy-sparing tactics, while an optimal EA is indicated by biomarkers of energy sufficiency promoting optimal physiologic remodeling (4,34,44). More recently, the use of EA value-based thresholds has been abandoned based on the need for more supporting evidence (34). Therefore, the latter is with the understanding that EA values alone are not a firm indication of EA status (34).

Statistical Analyses

Data were assessed for normality by Kolmogorov–Smirnov test, and subsequent parametric or nonparametric tests were conducted accordingly using GraphPad, Prism, version 10.3 (GraphPad Software, Inc., San Diego, CA). A paired *t* test was used to compare the physics-derived and power meter-recorded average power and log-normalized exercise total work and EEE. Bland–Altman analysis was conducted to describe variability of the physics-derived average power compared with the power meter-recorded power, and intraclass correlation coefficient (ICC) by consecutive pairwise analysis was derived (22). Pearson's linear regression analysis was conducted to further validate goodness of fit. Given the *SD* of the mean difference of physics-derived versus power meter-recorded power output of 10.38 W and the within-participant *SD* of 5.4 W, this study has 80% power of identifying a 5-W difference in average power when including a total of at least 18 training rides. Training metrics were compared between training sessions on road bicycles and MTB bicycles using a Mann–Whitney test. The false discovery rate with 2-stage step-up method of Benjamini, Krieger, and Yekutieli (Q = 1%) was applied to confirm discovery when controlling for multiple test bias. A 1-sided *t* test was used to compare the achieved EA from the derived target EIs with 30 and 45 $\text{kcal} \cdot \text{kg}^{-1}$ FFM as historical thresholds (3,32). $p < 0.05$ was considered significant and data are presented as mean ± *SD* (and range) or mean difference and 95% confidence interval (CI) of the difference, as indicated. Cohen's (*d*) effect size was calculated to describe the magnitude of the difference in the forces between road bicycle and MTB training as trivial 0.0–0.2, small 0.2–0.6, moderate 0.6–1.2, large 1.2–2.0, very large >2.0 (23).

Results

Validation Outcome

A total of 100 cycling training sessions were evaluated that included 32 training sessions on road bicycles and 68 training sessions on MTBs. The cyclists' training metrics for each training session and bicycle characteristics were used to derive the respective applied forces during each training session (Table 1). The resultant physics-derived average power output was not significantly different to power meter-measured average power and had a high ICC, low *SEM* of differences, and low CV between physics and meter measures for all training sessions combined, for road bicycle sessions only, and for MTB bicycle sessions only (Table 2 and Figure 1A–C). Bland–Altman analysis revealed a good agreement with small bias and narrow limits of agreement encompassing all besides 5 data points (Figure 1D–F). Physics-derived power was highly correlated with meter-measured power (Figure 1G–I).

In accordance, total work and EEE calculated from physics-derived power produced close estimates to total work and EEE calculated from power meter-measured power, with no significant or physiologically relevant differences (Table 2). A template spreadsheet is available for use by researchers and coaches, where training, bicycle, and weather metrics can be input and then the derived forces, average power, work, and EEE per training session will be autogenerated (see, Supplemental Digital Content 2, http://links.lww.com/JSCR/A669).

Differences in the Physics-Derived Forces for Road and Mountain Bike Training

A comparison of training metrics between road bicycle and MTB bicycle training revealed no differences in training distance or body mass relative average power output between training modes

Table 1

Training metrics when cycling on road bicycles and MTB bicycles, mean ± *SD* (range).*

	All training	Road bicycle training	MTB bicycle training	Road vs. MTB (*p*)
No. of training sessions (*n*)	100	32	68	
Distance (km)	51 ± 30 (14–150)	54 ± 30 (22–150)	50 ± 27 (14–132)	0.5726
Time (h)	2.53 ± 1.29 (0.83–6.17)	2.07 ± 1.12 (0.83–6.17)	2.74 ± 1.32 (0.98–6.00)	**0.0087**
Vertical gain (m)	792 ± 486 (129–2,500)	608 ± 453 (129–2,500)	878 ± 481 (178–2,002)	**0.0031**
Vertical gain per km ($m \cdot km^{-1}$)	16 ± 8 (3–42)	11 ± 5 (3–24)	19 ± 8 (8–42)	**<0.0001**
Angle of inclination (θ)	0.93 ± 0.45 (0.19–2.42)	0.64 ± 0.27 (0.19–1.39)	1.07 ± 0.45 (0.46–2.42)	**<0.0001**
Power meter derived				
Average power ($W \cdot kg^{-1}$)	2.2 ± 0.3 (1.4–3.0)	2.2 ± 0.3 (1.4–3.0)	2.2 ± 0.3 (1.4–3.0)	0.4164
Mechanical work ($kcal \cdot kg^{-1}$)	4.9 ± 2.6 (1.6–12.1)	4.0 ± 2.3 (1.6–12.1)	5.3 ± 2.7 (1.6–10.8)	0.0208
Bicycle characteristics				
Bicycle mass (kg)		8.0 ± 1.1 (6.7–9.3)	11.4 ± 1.0 (10.7–13.2)	**0.0022**
Cycling kit mass (kg)†		2.7 ± 0.4 (2.3–3.4)	2.8 ± 0.3 (2.6–3.4)	0.5758
Tire Crr		0.00485 ± 0.00126 (0.00273–0.00582)	0.01073 ± 0.00197 (0.00904–0.01418)	**0.0043**
Projected frontal area (m^2)‡		0.383 ± 0.027 (0.354–0.414)	0.415 ± 0.016 (0.398–0.432)	0.1255
Coefficient of drag		0.676 ± 0.052 (0.619–0.753)	0.712 ± 0.031 (0.675–0.753)	0.1991

*MTB = mountain bike; EEE = exercise energy expenditure; Crr = coefficient of rolling resistance.

†Cycling kit mass = includes the mass of all clothing and accessories plus the mass of a full water bottle.

‡Projected frontal area for the riders' preferred posture, which for road bicycles was with the cyclists' hands resting on the handlebar hoods. A *p*-value when in bold indicates a significant discovery by FDR for significance at the $p < 0.05$ level.

(Table 1). Likewise, ambient conditions (temperature: 16.9 ± 5.2 and 14.6 ± 3.2° C; relative humidity: 75 ± 14% and 75 ± 12%; barometric pressure: 1,017 ± 5 and 1,020 ± 5 mbar; wind speed: 13 ± 5 $km \cdot h^{-1}$, range 4–22 and 11 ± 7 $km \cdot h^{-1}$, range 4–32 $km \cdot h^{-1}$) and air density (1.216 ± 0.027 and 1.217 ± 0.032 $kg \cdot m^{-3}$) were similar for road and MTB training sessions, respectively. However, vertical gain and training duration were greater in MTB training owing to a higher angle of inclination (or vertical gain per km), greater tire Crr and bicycle mass (Table 1). During MTB training, 44 ± 35% of total distance was on dirt or gravel surfaces (ranging from 0 to 100% of distance on dirt). Most MTB training rides included cross-country riding over a mixture of surface types including firm gravel/dirt, rocky sections, larger rock or root obstacles, drop-offs, berms, small jumps, short 2–20 m sections of thick sand, or loose gravel. These differences resulted in a higher force to overcome gradient (F_G range, road: 2.6–15.7 N; MTB: 5.9–27.2 N, $d = 1.04$) and rolling resistance (F_R range, road: 1.6–5.0 N; MTB: 5.9–14.1 N, $d = 3.08$) in MTB than in road bicycle training (Figure 2A). While projected frontal area was not different between road and MTB bicycle training, the force to overcome drag due to air resistance (F_D range, road: 3.7–14.1 N; MTB: 2.1–9.3 N, $d = -1.74$) was greater when training on road bicycles than MTB owing to a greater speed during training on a road bicycle (Table 1 and Figure 2A). The sum of forces equating to total force produced (F_T range, road: 15.2–26.9; MTB: 17.2–39.7, $d = 1.30$) was greater in MTB than in road bicycle training (Figure 2A). These force comparisons between road bicycle and MTB training attained significance at the $p < 0.05$ level with all comparisons producing absolute *p*-values <0.0001. This resulted in significant differences in the fractional components of the forces contributing toward total force when training on a road bicycle compared with that on MTB bicycle (Figure 2B).

Application of Exercise Energy Expenditure to Estimate Target Energy Intake

Resting metabolic rate predicted based on equations derived from healthy lean and athletic populations was 1,556 ± 168 $kcal \cdot d^{-1}$ and produced an FFM relative energy equivalent of 32.2 ± 1.4

Table 2

Validation statistics of physics-derived average power, total work, and exercise energy expenditure compared with power meter-measured values.*†

	Power meter measured	Physics-derived	Physics-Meter difference	*SEM* of diff	CV, %	*p*-value of diff	ICC (95% CI)
Average power (W)							
All training	135 ± 27	134 ± 28	−1.0 ± 10.4 (−3.1 to 1.0)	1.0	4.2	0.3176	0.93 (0.90–0.95)
Road bike only	152 ± 34	151 ± 36	−1.1 ± 13.8 (−6.0 to 3.9)	2.5	4.5	0.6692	0.93 (0.86–0.96)
MTB bike only	127 ± 19	126 ± 20	−1.0 ± 8.4 (−3.1 to 1.0)	1.0	4.0	0.3128	0.91 (0.86–0.94)
Total work (kcal)							
All training	295 ± 166	293 ± 170	−2 ± 24 (−7 to 3)	2.4	4.2	0.2151	0.99 (0.98–0.99)
Road bike only	272 ± 179	272 ± 184	0 ± 28 (−10 to 10)	4.9	4.5	0.6003	0.99 (0.98–0.99)
MTB bike only	306 ± 160	304 ± 160	−3 ± 22 (−8 to 3)	2.7	4.0	0.2394	0.99 (0.98–0.99)
EEE (kcal)							
All training	1,315 ± 756	1,305 ± 763	−10 ± 120 (−33 to 14)	12.0	4.7	0.2026	0.99 (0.98–0.99)
Road bike only	1,214 ± 815	1,214 ± 840	−1 ± 138 (−50 to 49)	24.3	5.1	0.5972	0.99 (0.97–0.99)
MTB bike only	1,362 ± 729	1,348 ± 727	−14 ± 112 (−41 to 13)	13.6	4.6	0.2252	0.99 (0.98–0.99)

**SEM* of diff = standard error of the mean of differences; CV = coefficient of variability; ICC = intraclass correlation coefficient (and CI = 95% confidence interval of ICC); EEE = exercise energy expenditure; MTB = mountain bike.

†Data presented as mean ± *SD* or mean difference ± *SD* (95% confidence interval of the difference)

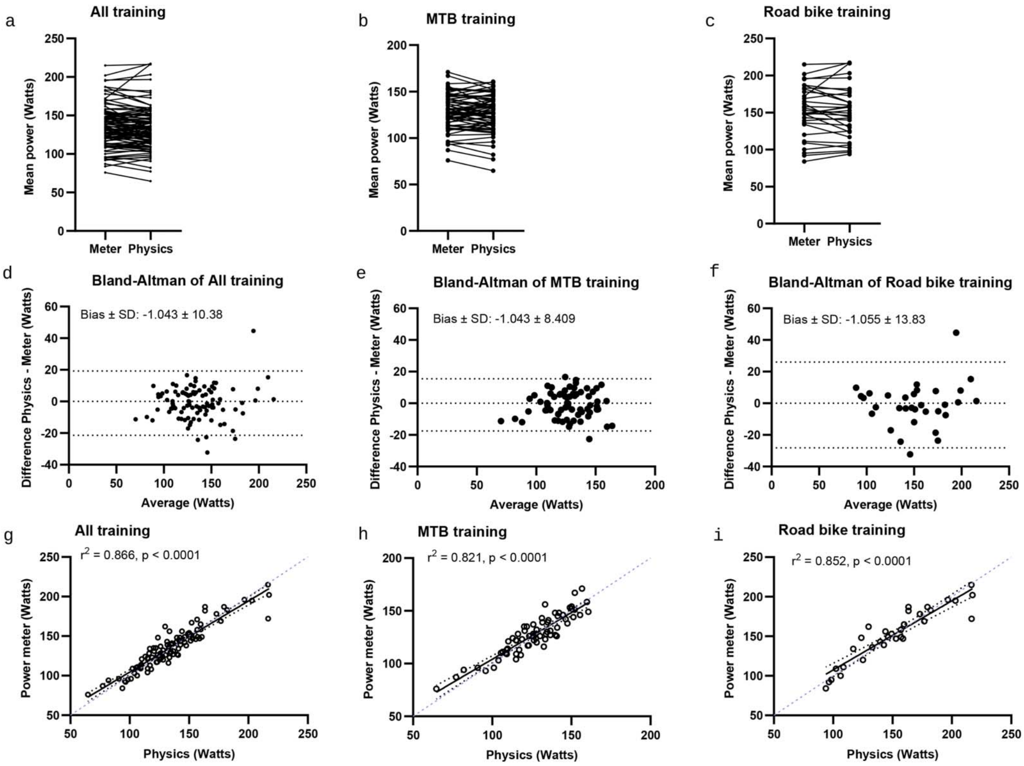

Figure 1. Comparison of average power during cycling training derived from the physics laws of mechanics (physics) with power meter measurements (meter) including all training sessions, mountain bike (MTB) only, and road bicycle only training showing individual data (A–C), Bland–Altman plots of bias and limits of agreement (D–F), and linear regression goodness-of-fit showing the best fit line (solid black), 95% confidence interval (dotted black lines), and the line of identity (blue dashed line) (G–I).

(range: 30.5–33.8) kcal·kg^{-1} FFM per day in this study cyclists. Therefore, during all training sessions, the sum of measured EEE (28.3 ± 15.7 kcal·kg^{-1} FFM) and predicted RMR consistently produced a basic target EI that when applied to the EA equation would result in an EA that equates to RMR and that marginally exceeds 30 kcal·kg^{-1} FFM by 2.5 ± 1.2 kcal·kg^{-1} FFM (95% CI: 2.2–2.7; where the difference from 30 kcal·kg^{-1} FFM attained significance at $p < 0.05$ level, producing an absolute $p < 0.0001$) (Figure 3A, B). When assuming an additional daily living non-exercise energy cost of seated work as 0.45-fold RMR, this equated to an extra 700 ± 76 kcal or 14.5 ± 0.6 (range: 13.7–15.2) kcal·kg^{-1} FFM. Therefore, during all training days, the sum of EEE, RMR plus an additional 0.45-fold RMR (or ~14.5 kcal·kg^{-1} FFM) produced a target EI that would result in an EA of 47.1 ± 1.8 (range: 44.3–49.0) kcal·kg^{-1} FFM, which marginally exceeds 45 kcal·kg^{-1} FFM by 2.1 ± 1.8 kcal·kg^{-1} FFM (95% CI: 1.7–2.4; where the difference from 45 kcal·kg^{-1} FFM attained significance at the $p < 0.05$ level, producing an absolute $p < 0.0001$) (Figure 3A, B).

Discussion

This study tested the validity of applying the physics laws of mechanics to estimate mean power, total work, and EEE for cycling in road bicycle or MTB disciplines. This physics-derived method is intended for application to the training metrics of cyclists lacking a bicycle-mounted power meter. The validation outcome shows that the physics-derived method produces good estimates of mean power, total work, and EEE compared with bicycle-mounted power meter measures. Second, a comparison of the components of total force produced in road bicycle and MTB training shows that the force to overcome gradient and rolling resistance is greater in MTB but the force to overcome air frictional drag is greater in road bicycle training. Although total force produced is greater in MTB than in road bicycle training, average power can be similar. Third, application of EEE to predict target EI shows that a target EI equating to the sum of EEE and predicted RMR is expected to achieve an EA of ~32 kcal·kg^{-1} FFM, while a target EI equating to the sum of EEE and predicted RMR plus an additional factor of 0.45-fold RMR as an estimate of non-exercising energy cost (~14.5 kcal·kg^{-1} FFM) is expected to achieve an EA of ~47 kcal·kg^{-1} FFM.

The use of power meter-derived measures of EEE is common practice in elite cyclists to guide target EI (18,50,54). Without a prescribed target EI, the average daily EI of elite cyclists during multiday stage racing (~5,500 kcal·d^{-1}) (3,36,41) is substantially less than the total daily energy expenditure measured by doubly labeled water in similar Grand Tour stage races, consistently reported as ~7,600 kcal·d^{-1} (3,38,54), consequently resulting in a significant reduction in fat mass (36,41) or body mass (3,36). Moreover, when EEE is increased on a given training day, there is a mismatch in the associated unguided EI, such that for every 1,000 kcal·d^{-1} increase in EEE, EI increased by only 210 kcal·d^{-1} in elite male road cyclists (50). Consequently, EA in these latter male cyclists was low (19.5 kcal·kg^{-1} FFM per day) and their body mass decreased in even the 7 days of evaluation (50). However, as indicated in the introduction, observations from our

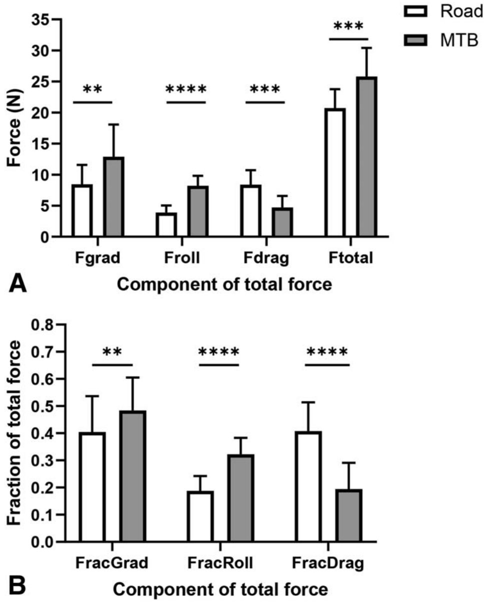

Figure 2. Comparison of the force to overcome gradient (F_{grad}), rolling resistance (F_{roll}), and drag due to air resistance (F_{drag}), and total force (F_{total}) during cycling training on a road bicycle (road) and mountain bike (MTB) expressed in absolute units (A); and as a fraction of total force for gradient (F_{racGrad}), rolling resistance (F_{racRoll}), and drag due to air resistance (F_{racDrag}) (B), presented as mean and *SD*, where all comparisons were significant and the effect size differences between road and MTB are denoted as **moderate effect; ***large effect; ****very large effect.

laboratory suggest that many cyclists who follow consistent, intense, and high-volume training do not have bike-mounted power meters, but most do use GPS altimeter devices to record their general training metrics of distance, time, and accumulated vertical gain. This study is the first to validate the application of the physics laws of mechanics to derive the average power output of cycling training sessions and EEE, and for application when training on road bicycles and MTBs. This physics-based method provides close estimates to power meter-generated EEE. A useable spreadsheet is available as a tool for researchers, coaches, and cyclists to generate daily physics-derived average power, total work, and EEE from basic cycling training metrics (see Supplemental Digital Content 2, http://links.lww.com/JSCR/A669 for the Excel spreadsheet template).

Prior training metrics from professional and elite under 23 road cyclists for a season report average training duration of 2.6 and 2.2 hours per training session, vertical gain per distance of 13.8 and 10.6 m·km^{-1}, and annual accumulated mechanical work of 1,376 and 1,259 kcal·kg^{-1} (or 5.9 and 4.7 kcal·kg^{-1} per training session), respectively (17). By calculation, this translates to an estimated average training power of 2.6 and 2.5 W·kg^{-1}, respectively (17), and is similarly reported from 4 years of training records in male (2.6 W·kg^{-1}) and female (2.3 W·kg^{-1}) professional road cyclists (53). These average training values for professional and U23 elite cyclists fall within the range of the road bicycle and MTB training metrics recorded in this study from amateur competitive cyclists, albeit with notably higher vertical gain per distance in this study MTB training data. Likewise, the group average power reported for daily stages of an 8-day MTB stage race was between 2.2 and 3.1 W·kg^{-1} for amateur competitive MTB cyclists, where in that MTB race, the mean vertical gain per distance was 23 m·km^{-1} (39). Therefore, the applied training data in this study, on which the validation of the physics-derived method is based, suitably match the reported training practices of competitive cyclists.

The noted differences in the force components making up total force during road bicycle versus MTB training are relevant for training prescription and equipment choices. The greater force to overcome gradient, rolling resistance, and total force produced during MTB training emphasizes a greater strength required in MTB than in road bicycle training. In fact, the force to overcome gradient is a major energy cost in cycling and gradients greater than 13–16% result in cycling becoming more energy expensive than walking or running at a matched speed (2). In this study, overcoming gradient contributed 48 and 40% of total force in MTB and road bicycle training, respectively, while overcoming rolling resistance contributed 32% of total force in MTB but only 19% in road bicycle training. Conversely, overcoming frictional air drag is comparatively minor in MTB, requiring 20% of total force but is a major contributor in road bicycle training (41% of total force) matching the demand of overcoming gradient in this discipline. Producing an equal average power despite overcoming a lower total force in road cycling might indicate a greater focus for speed training in road cycling training. In addition, optimizing posture on the road bicycle to minimize project frontal area is a well-accepted performance-enhancing tactic (15,26). This is emphasized again in this study by the dominant force component of drag due to air resistance when training on a road bicycle but not MTB. Moreover, the advantage of drafting in road cycling is well acknowledged (37) and cycling in a peloton can dramatically reduce the required power to maintain a given speed (8). A possible limitation of this physics-derived method is that it cannot account for a drafting effect and could potentially overstate power in big bunch/peloton riding. The current road bicycle training data are from training solo or in small groups. Conversely, the force to overcome drag due to air resistance is comparatively small in MTB and the opportunity for drafting is limited. The current physics-validated method did include data from some MTB racing and is valid for big group MTB riding.

The use of average power in variable intensity cycling on a road bicycle on tarmac surfaces is expected to produce valid calculations of EEE (18,54). However, average power measured during MTB on off-road surfaces is expected to underestimate true EEE whether measured by a power meter or using the current physics-derived method. The use of portable indirect calorimetry during MTB has produced high rates of oxygen consumption ($\dot{V}O_2$) when descending on MTB cross-country (19,32) or downhill (9,11) tracks despite the lack of pedaling and yielding concurrent power readings of zero (19,32). In fact, accelerations experienced in the arms, legs, and at the seat post and $\dot{V}O_2$ are higher for both ascending (28) and descending (32) on MTB cross-country trails than on an equal gradient tar or forest road. During MTB, bike handling to negotiate obstacles (29) and the dampening of vibrations (32) necessitate upper and lower body isometric muscle contractions often with the rider maintaining a standing flexed posture. These associated additional energy costs of MTB cannot be accounted for in measured power or even heart rate recordings (19,45). Therefore, power meter or physics-derived total work and EEE for MTB must be regarded as a minimum estimate.

Measured total work and EEE can be used to quantify training load or to determine a daily target EI to support bodily functions, repair, and recovery, and thereby ensure the ongoing quality of training, performance, and maintenance of long-term health (34).

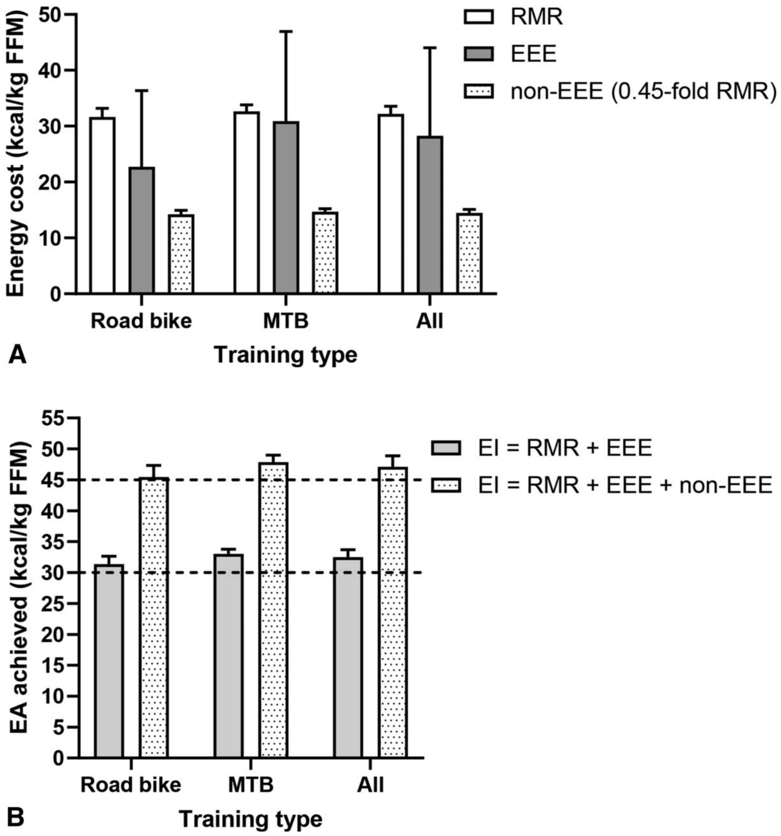

Figure 3. The energy cost of predicted resting metabolic rate (RMR), exercise energy expenditure (EEE) plus the nonexercise energy cost of daily living (non-EEE) estimated as 0.45-fold RMR from all training data, mountain bike (MTB) training only, and road bicycle training only (A); and the achieved energy availability (EA) when applying a target EI as the sum of RMR and EEE, and as the sum of RMR, EEE plus a nonexercise daily living energy cost of 0.45-fold RMR (non-EEE) (B), presented as mean and *SD*, showing the historical low and optimal EA thresholds of 30 kcal·kg^{-1} FFM and 45 kcal·kg^{-1} FFM, respectively. EI = energy intake; FFM = fat-free mass.

Studies investigating recommendations to determine a target EI that matches total daily energy expenditure in cyclists have proposed summing EEE and a nonexercising energy cost (54). The nonexercising energy cost is the additional energy cost of daily living that includes RMR plus the energy required for other daily activities. This composite nonexercising energy cost is estimated as 1.45-fold RMR for lightly active people with seated work (43) and has been measured to be 1.8- and 2.0-fold RMR in elite cyclists during a 3-week Grand Tour or for 8 days that included three 1-day classic races, respectively (54). However, whether the latter measures in cyclists can be applied to regular training weeks without extreme energy demanding race days remains to be investigated. Findings from this study's cyclists show that a target EI equating to the sum of EEE and predicted RMR will produce an EA of, or modestly higher than, the previously suggested low EA threshold (4,35). Notably, this is because the FFM relative energy value of predicted RMR equates to ~32 kcal·kg^{-1} FFM. Likewise, this is also reported for measured RMR in male runners (32.7 kcal·kg^{-1} FFM) where the measured/predicted RMR ratio is at unity, but measured RMR was modestly $<$30 kcal·kg^{-1} FFM in male cyclists (26 kcal·kg^{-1} FFM) when the measured/predicted RMR ratio was $<$0.9 (10). Previously reported values for predicted RMR when expressed relative to FFM also approximates 30 kcal·kg^{-1} FFM in premenopausal female athletes of varying menstrual status (ovulatory cycles 31.1 kcal·kg^{-1} FFM, amenorrhea 31.5 kcal·kg^{-1} FFM, and menstrual disturbances 31.1 kcal·kg^{-1} FFM) (49). Therefore, if a nonexercising energy factor is uncertain, then it might be prudent to calculate the sum of predicted RMR and EEE to achieve a primary target EI on which an additional EI proportion is needed to cover nonexercise energy costs. For cyclists, where cycling training comprises their only physical effort and other daily living includes only very light movement and mainly seated work, then the addition of the nonexercise energy factor of 0.45-fold RMR might be appropriate (43). Interestingly, in this study, this nonexercise factor equated to an extra 14.5 kcal·kg^{-1} FFM, which when added to the sum of EEE and RMR resulted in a target EI that would achieve an EA of 47 kcal·kg^{-1} FFM, modestly higher than the initially suggested threshold for an optimal EA (4,35). More recently, use of these EA thresholds has been abandoned based on the need for more supporting evidence (34). Therefore, the latter is with the understanding that the derived EA values based on the target EIs are not firm indications of EA status and further studies are necessary to validate whether such a target EI is suitable for cyclists engaging in regular cycling training with no other energy-demanding activities.

The physics-derived method has some limitations. It is unable to adjust for the drafting effect in big peloton bunch riding in road cycling, as already discussed, but is suitable for individual or small group road training. The effectiveness of the physics-derived model supports its application when cycling on circular or out-and-back routes in the wind speeds encountered in this study, where countering wind directions negates the complexity of including wind direction and wind speed in the model. Considering that all cyclists in this study used circular or out-and-back routes might suggest that this is a more typical route choice. However, further investigation is required to derive a model suitable for use when cycling in a single direction on a point-to-point route in strong winds. In addition, as already discussed, all current methods are unable to account for the additional energy cost of isometric contractions in bike handling and vibration dampening in MTB, and, therefore, this is a mutual limitation when using physics-derived or power meter data. Finally, extreme surface conditions, such as extended distances over thick sand, might require a higher Crr correction factor for surface rolling resistance of +0.03 (or +0.028 greater than tarmac), rather than the current applied +0.006 (or +0.004 greater than tarmac) for more regular dirt or gravel surfaces (48).

Practical Applications

Although power-meter data are still the preferred method, the physics laws of mechanics can be used to calculate cycling forces, average power, total work, and EEE in road bicycle and MTB training in most training conditions when power-meter data are not available, by applying the current reported methodology (see Content, Supplemental Digital Content 2, http://links.lww.com/JSCR/A669 for a template spreadsheet). Notable differences exist in the fractional force components of road bicycle and MTB training that can guide training prescription. The forces to overcome gradient and rolling resistance and total force produced are greater in MTB, while the force to overcome drag due to air resistance is greater in road training. Application of the current methodology to calculate these respective forces could be useful for understanding training demands and equipment adjustments to optimize performance, even in cyclists with bike-mounted power meters. Furthermore, knowing the individual force components for a cyclist on a particular course could be valuable in selecting appropriate training gradients and surface types to maximize effect for guiding on-the-bike strength-focused training. Total work as a measure of training load could be used to avoid overtraining. Exercise energy expenditure can be useful in guiding target EI to avoid over- or undernutrition, where the sum of EEE and predicted RMR produces an EA value of ~32 kcal·kg^{-1} FFM, and plus an additional estimated nonexercise energy cost of 0.45-fold RMR produces an EA value of ~47 kcal·kg^{-1} FFM.

Acknowledgments

The authors thank the photographer, Jordan Oosthuyse, for capturing and processing the photographs for the measurement of pixel area. This study did not require any funding. The results of this study do not constitute endorsement of the product by the authors or the National Strength and Conditioning Association. The authors have no conflicts of interest to disclose. T. Oosthuyse and A. N. Bosch conceived and designed the study; T. Oosthuyse, N. Bownes and L. A. Wiemers conducted data collection, data analysis, and statistical analyses; all authors interpreted the findings; T. Oosthuyse wrote the first draft; all authors reviewed/edited the article and approved the final version.

References

1. Ainsworth BE, Haskell WL, Herrmann SD, et al. 2011 compendium of physical activities: A second update of codes and MET values. *Med Sci Sports Exerc* 43: 1575–1581, 2011.
2. Ardigò LP, Saibene F, Minetti AE. The optimal locomotion on gradients: Walking, running or cycling? *Eur J Appl Physiol* 90: 365–371, 2003.
3. Areta JL, Meehan E, Howe G, Redman LM. Energetics of a world-tour female road cyclist during a multistage race (Tour de France Femmes). *Int J Sport Nutr Exerc Metab* 34: 253–257, 2024.
4. Areta JL, Taylor HL, Koehler K. Low energy availability: History, definition and evidence of its endocrine, metabolic and physiological effects in prospective studies in females and males. *Eur J Appl Physiol* 121: 1–21, 2021.
5. Bergman RN, Stefanovski D, Buchanan TA, et al. A better index of body adiposity. *Obesity (Silver Spring)* 19: 1083–1089, 2011.
6. Bertucci WM, Rogier S, Reiser RF. Evaluation of aerodynamic and rolling resistances in mountain-bike field conditions. *J Sports Sci* 31: 1606–1613, 2013.
7. Bierman J. Bicycle rolling resistance. Available at: https://www.bicyclerollingresistance.com/. Accessed August 1, 2021–November 30, 2023.
8. Blocken B, van Druenen T, Toparlar Y, et al. Aerodynamic drag in cycling pelotons: New insights by CFD simulation and wind tunnel testing. *J Wind Eng Ind Aerodyn* 179: 319–337, 2018.
9. Burr JF, Drury CT, Ivey AC, Warburton DE. Physiological demands of downhill mountain biking. *J Sports Sci* 30: 1777–1785, 2012.
10. Chen Z, Sherk VD, Sharma-Ghimire P, Bemben MG, Bemben DA. Site-specific bone differences and energy status in male competitive runners and road cyclists. *J Clin Densitom* 25: 150–159, 2022.
11. Chidley JB, MacGregor AL, Martin C, Arthur CA, MacDonald JH. Characteristics explaining performance in downhill mountain biking. *Int J Sports Physiol Perform* 10: 183–190, 2015.
12. Cunningham JJ. A reanalysis of the factors influencing basal metabolic rate in normal adults. *Am J Clin Nutr* 33: 2372–2374, 1980.
13. Czernia D, Szyk B. Air density calculator. Available at: https://www.omnicalculator.com/physics/air-density. Accessed August 1, 2021–November 30, 2023.
14. De Lorenzo A, Bertini I, Candeloro N, et al. A new predictive equation to calculate resting metabolic rate in athletes. *J Sports Med Phys Fitness* 39: 213–219, 1999.
15. Debraux P, Bertucci W, Manolova AV, Rogier S, Lodini A. New method to estimate the cycling frontal area. *Int J Sports Med* 30: 266–272, 2009.
16. Fenre MD, Klein-Paste A. Rolling resistance measurements on cycleways using an instrumented bicycle. *J Cold Reg Eng* 35: 04021001, 2021.
17. Gallo G, Leo P, March MM, et al. Differences in training characteristics between junior, under 23 and professional cyclists. *Int J Sports Med* 43: 1183–1189, 2022.
18. Haakonssen EC, Martin DT, Burke LM, Jenkins DG. Energy expenditure of constant- and variable-intensity cycling: Power meter estimates. *Med Sci Sports Exerc* 45: 1833–1840, 2013.
19. Hays A, Devys S, Bertin D, Marquet LA, Brisswalter J. Understanding the physiological requirements of the mountain bike cross-country Olympic race format. *Front Physiol* 9: 1062, 2018.
20. Heil DP. Body size as a determinant of the 1-h cycling record at sea level and altitude. *Eur J Appl Physiol* 93: 547–554, 2005.
21. Hopker JG, Coleman DA, Wiles JD. Differences in efficiency between trained and recreational cyclists. *Appl Physiol Nutr Metab* 32: 1036–1042, 2007.
22. Hopkins WG. Spreadsheet for analysis of validity and reliability. *Sportsscience* 19: 36–42, 2015.
23. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.

24. Jeukendrup AE, Areta JL, Van Genechten L, et al. Does relative energy deficiency in sport (REDs) syndrome exist? *Sports Med* 54: 2793–2816, 2024.
25. Keay N, Francis G, Hind K. Low energy availability assessed by a sport-specific questionnaire and clinical interview indicative of bone health, endocrine profile and cycling performance in competitive male cyclists. *BMJ Open Sport Exerc Med* 4: e000424, 2018.
26. Lim AC, Homestead EP, Edwards AG, et al. Measuring changes in aerodynamic/rolling resistances by cycle-mounted power meters. *Med Sci Sports Exerc* 43: 853–860, 2011.
27. Lundstrom CJ, Foreman NA, Biltz G. Practices and applications of heart rate variability monitoring in endurance athletes. *Int J Sports Med* 44: 9–19, 2023.
28. Macdermid PW, Fink PW, Stannard SR. The effects of vibrations experienced during road vs. off-road cycling. *Int J Sports Med* 36: 783–788, 2015.
29. Macdermid PW, Miller MC, Fink PW, Stannard SR. The effectiveness of front fork systems at damping accelerations during isolated aspects specific to cross-country mountain biking. *Sports Biomech* 16: 527–539, 2017.
30. Maier T, Müller B, Schmid L, Steiner T, Wehrlin JP. Reliability of the virtual elevation method to evaluate rolling resistance of different mountain bike cross-country tyres. *J Sports Sci* 36: 156–161, 2018.
31. Maier T, Schmid L, Müller B, Steiner T, Wehrlin JP. Accuracy of cycling power meters against a mathematical model of treadmill cycling. *Int J Sports Med* 38: 456–461, 2017.
32. Miller MC, Macdermid PW, Fink PW, Stannard SR. Performance and physiological effects of different descending strategies for cross-country mountain biking. *Eur J Sport Sci* 17: 279–285, 2017.
33. Moseley L, Achten J, Martin JC, Jeukendrup AE. No differences in cycling efficiency between world-class and recreational cyclists. *Int J Sports Med* 25: 374–379, 2004.
34. Mountjoy M, Ackerman KE, Bailey DM, et al. 2023 International Olympic Committee's (IOC) consensus statement on relative energy deficiency in sport (REDs). *Br J Sports Med* 57: 1073–1097, 2023.
35. Mountjoy M, Sundgot-Borgen J, Burke L, et al. The IOC consensus statement: Beyond the female athlete triad--relative energy deficiency in sport (RED-S). *Br J Sports Med* 48: 491–497, 2014.
36. Muros JJ, Sánchez-Muñoz C, Hoyos J, Zabala M. Nutritional intake and body composition changes in a UCI World Tour cycling team during the Tour of Spain. *Eur J Sport Sci* 19: 86–94, 2019.
37. Phillips KE, Hopkins WG. Determinants of cycling performance: A review of the dimensions and features regulating performance in elite cycling competitions. *Sports Med Open* 6: 23, 2020.
38. Plasqui G, Rietjens G, Lambriks L, Wouters L, Saris WHM. Energy expenditure during extreme endurance exercise: The Giro d'Italia. *Med Sci Sports Exerc* 51: 568–574, 2019.
39. Reinpõld K, Bossi AH, Hopker JG. What does it take to complete the Cape Epic? *J Strength Cond Res* 36: 3513–3520, 2022.
40. Roza AM, Shizgal HM. The Harris Benedict equation reevaluated: Resting energy requirements and the body cell mass. *Am J Clin Nutr* 40: 168–182, 1984.
41. Sánchez-Muñoz C, Zabala M, Muros JJ. Nutritional intake and anthropometric changes of professional road cyclists during a 4-day competition. *Scand J Med Sci Sports* 26: 802–808, 2016.
42. Schaal K, VanLoan MD, Hausswirth C, Casazza GA. Decreased energy availability during training overload is associated with non-functional overreaching and suppressed ovarian function in female runners. *Appl Physiol Nutr Metab* 46: 1179–1188, 2021.
43. Shetty P. Energy requirements of adults. *Public Health Nutr* 8: 994–1009, 2005.
44. Shirley MK, Longman DP, Elliott-Sale KJ, et al. A life history perspective on athletes with low energy availability. *Sports Med* 52: 1223–1234, 2022.
45. Smekal G, von Duvillard SP, Hörmandinger M, et al. Physiological demands of simulated off-road cycling competition. *J Sports Sci Med* 14: 799–810, 2015.
46. Spragg J, Leo P, Swart J. The relationship between training characteristics and durability in professional cyclists across a competitive season. *Eur J Sport Sci* 23: 489–498, 2023.
47. Stellingwerff T, Heikura IA, Meeusen R, et al. Overtraining syndrome (OTS) and relative energy deficiency in sport (RED-S): Shared pathways, symptoms and complexities. *Sports Med* 51: 2251–2280, 2021.
48. Steyn WJ, Warnich J. Comparison of tyre rolling resistance for different mountain bike tyre diameters and surface conditions. *S Afr J Res Sport Phys Educ Recreation* 36: 179–193, 2014.
49. Strock NCA, Koltun KJ, Southmayd EA, Williams NI, De Souza MJ. Indices of resting metabolic rate accurately reflect energy deficiency in exercising women. *Int J Sport Nutr Exerc Metab* 30: 14–24, 2020.
50. Taylor HL, Garabello G, Pugh J, et al. Patterns of energy availability of free-living athletes display day-to-day variability that is not reflected in laboratory-based protocols: Insights from elite male road cyclists. *J Sports Sci* 40: 1849–1856, 2022.
51. ten Haaf T, Weijs PJ. 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, 2014.
52. Time and Date. *Weather*. Available at: https://www.timeanddate.com/weather/. Accessed August 1, 2021–November 30, 2023.
53. van Erp T, Sanders D, de Koning JJ. Training characteristics of male and female professional road cyclists: A 4-year retrospective analysis. *Int J Sports Physiol Perform* 15: 534–540, 2020.
54. Van Hooren B, Cox M, Rietjens G, Plasqui G. Determination of energy expenditure in professional cyclists using power data: Validation against doubly labeled water. *Scand J Med Sci Sports* 33: 407–419, 2023.
55. Viner RT, Harris M, Berning JR, Meyer NL. Energy availability and dietary patterns of adult male and female competitive cyclists with lower than expected bone mineral density. *Int J Sport Nutr Exerc Metab* 25: 594–602, 2015.