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Energy Requirements of Paralympic Athletes: Insights from the Doubly Labeled Water Approach

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ABSTRACT

WEIJER, V. C. R., K. L. JONVIK, L. VAN DAM, L. RISVANG, G. PLASQUI, Ø. SANDBAKK, T. RAASTAD, L. J. C. VAN LOON, and J.-W. VAN DIJK. Energy Requirements of Paralympic Athletes: Insights from the Doubly Labeled Water Approach. *Med. Sci. Sports Exerc.*, Vol. 56, No. 5, pp. 963–971, 2024. **Purpose:** Advanced insight in energy requirements of Paralympic athletes is imperative for optimizing their nutritional counseling. Given the lack of accurate data on total daily energy expenditure (TDEE) of Paralympic athletes, this study aimed to assess energy expenditure and nutritional intake of a large cohort of Paralympic athletes, across different sports and disabilities. **Methods:** In this cross-sectional study, 48 Dutch and Norwegian Paralympic athletes (19 male/29 female) with various disabilities, competing in Para cycling, wheelchair tennis, wheelchair basketball, Para Nordic skiing, and alpine skiing participated. TDEE was assessed by the gold standard doubly labeled water method over a 14-d period, resting metabolic rate by ventilated hood indirect calorimetry, energy intake by three unannounced 24-h dietary recalls, body composition by dual-energy x-ray absorptiometry, and exercise training duration by a training log. **Results:** Mean TDEE was 2908 ± 797 kcal·d^{-1}, ranging from 2322 ± 340 kcal·d^{-1} for wheelchair basketball players to 3607 ± 1001 kcal·d^{-1} for Para cyclists. Regression analysis identified fat-free mass, exercise duration, and the presence of a spinal cord disorder as the primary predictors of TDEE, explaining up to 73% of the variance in TDEE. Athletes' energy intake (2363 ± 905 kcal·d^{-1}) was below their TDEE, whereas their body mass remained constant, indicating underreporting. Carbohydrate intake (4.1 ± 1.9 g·kg^{-1} body mass) was low, even when considering underreporting, whereas protein intake (1.8 ± 0.6 g·kg^{-1} body mass) was relatively high. **Conclusions:** Paralympic athletes display moderate- to high-energy expenditure, varying across sports and individuals. Much of the variation in TDEE can be attributed to individual differences in fat-free mass and exercise duration. This study establishes the benchmarks for energy requirements of Paralympic athletes, serving as the foundation for future dietary guidelines within this population. **Key Words:** ATHLETES, DISABILITY, ENERGY EXPENDITURE, EXERCISE, INDIRECT CALORIMETRY, SPINAL CORD INJURY

Despite a wealth of information available on energy requirements of athletes across various sport disciplines, little information is available on the energy requirements of Paralympic athletes. Notably, no assessments of the energy requirements have been made by the gold standard doubly labeled water (DLW) approach. Currently, estimates of total daily energy expenditure (TDEE) in disabled athletes are limited to measurements or estimations of resting metabolic rate (RMR) with an activity allowance based on activity logs (1–3). However, this approach is complicated by the limited information on the energy costs of exercise and habitual physical activity in disabled athletes, potentially leading to inaccurate TDEE estimates. This warrants attention, given the potential differences in energy requirements between Paralympic athletes and their able-bodied counterparts.

Paralympic athletes may have a lower fat-free mass (FFM) due to factors like amputations or muscle degeneration from

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nerve innervation loss (e.g., spinal cord injury (SCI) or spina bifida (SB)), potentially affecting their absolute energy requirements (4). In support, individuals with SCI have been reported to have a lower RMR when compared with matched controls (5). In contrast, athletes with cerebral palsy or SCI may experience spasms, during which involuntary muscle contractions could potentially increase RMR (6). Furthermore, gait imbalances or ambulation with braces or crutches may increase the physical activity energy expenditure (PAEE) (7,8), whereas for wheelchair users, the energy costs of habitual physical activities, such as dusting, grocery shopping, or vacuuming, are generally lower compared with able-bodied individuals (9). In addition, the exercise energy expenditure has been shown to be lower in SCI athletes compared with able-bodied athletes, which could be due to lower peak oxygen uptakes ($\dot{V}O_{2peak}$) (10), the amount of active muscle mass used, and lower maximal heart rates (11).

The energy requirements of athletes largely determine the macronutrient needs, that is, carbohydrates, fats, and proteins. The current macronutrient intake guidelines for Paralympic athletes are largely based on nutritional guidelines for abled-bodied athletes (12). Hence, the recommended carbohydrate intake for Paralympic athletes ranges from 3 to 5 $g \cdot kg^{-1}$ body mass on days with low exercise volume up to 8 to 12 $g \cdot kg^{-1}$ body mass on days with high exercise volume, whereas the recommended protein intake ranges from 1.2 to 1.8 $g \cdot kg^{-1}$ body mass (13). Studies evaluating macronutrient intake in Paralympic athletes based on these guidelines (14–16) generally indicated inadequate energy and carbohydrate intakes compared with the recommendations. It should be noted, however, that neither energy nor carbohydrate intakes of Paralympic athletes has been evaluated in the light of the total energy requirements. Hence, it is unknown whether current guidelines are feasible within the energy budget of Paralympic athletes.

To gain advanced insight in the energy requirements of Paralympic athletes, we assessed energy expenditure and dietary intake in a large cohort of Paralympic athletes participating in diverse sports, encompassing athletes with a broad spectrum of disabilities. For this purpose, TDEE was assessed in Paralympic athletes by the DLW method, along with the assessment of RMR by indirect calorimetry and energy and macronutrient intake by multiple 24-h recalls.

METHODS

Design. The current cross-sectional study involved assessments of TDEE, dietary intake, and training load assessed over a 14-d period, whereas RMR and body composition measurements were conducted on a single test day within 1 month. The 14-d period was selected in consultation with the coaching staff, aiming to reflect a representative training period. The study was preapproved by the Medical Ethical Committee Zuyd (NL72682.096.20) in the Netherlands and the Regional Committee for Medical and Health Research Ethics (REK 102284) in Norway, and conducted according to the principles of the Declaration of Helsinki. All participants signed a written informed consent form before participation.

Participants. In this study, 48 male (n = 19) and female (n = 29) Paralympic athletes participated. These athletes competed in Para cycling (n = 13, male/female: 8/5), wheelchair tennis (n = 10, male/female: 5/5), wheelchair basketball (n = 13, male/female: 0/13), Para Nordic skiing (n = 7, male/female: 4/3), and Para alpine skiing (n = 5, male/female: 2/3). The Nordic skiers, one Para cyclist and one alpine skier, originated from and were measured in Norway, whereas all other athletes were Dutch and measured in the Netherlands. Participants (16–50 yr) competing at the highest (inter)national level were recruited through ongoing partnerships with the Dutch Olympic Committee and Norwegian national sport associations. Multiple disabilities were included, ranging from SCI to visual impairments (Table 1). The athletes were classified as being wheelchair users if more than 50% of their ambulatory activities outside of sports were performed in a wheelchair. Exclusion criteria were pregnancy or an injury that disrupted the regular training schedule. The participants were in preparation for either the 2020 Summer Paralympics in Tokyo or the 2022 Winter Paralympics in Beijing and won

TABLE 1. Participant characteristics.

	Total (n = 48)	Para Cycling (n = 13)	Wheelchair Tennis (n = 10)	Wheelchair Basketball (n = 13)	Nordic Skiing (n = 7)	Alpine Skiing (n = 5)
Male/Female	19/29	8/5	5/5	0/13	4/3	2/3
Disability n						
SCD	17	2	4	7	2	2
Neurological disorder	4	2	0	0	2	0
Limb deficiency	16	4	5	4	1	2
Visual impairment	4	2	0	0	1	1
Other	7	3	1	2	1	0
Wheelchair user (no/yes)	22/26	9/4	2/8	5/8	4/3	2/3
Age (yr)	27 (23–33)	28 (24–32)	29 (23–36)	27 (21.5–33.5)	23.0 (19.0–34.0)	33 (21–38)
Body height (cm)	169.1 (160.8–180.0)	177.9 (164.2–190.9)	169.5 (147.4–177.6)	170.0 (141.5–181.1)	165.0 (151.1–180.0)	171.1 (146.4–181.3)
Body mass (kg)	63.2 (55.4–72.1)	70.6 (59.4–72.4)	65.2 (54.5–72.7)	60.0 (54.6–73.7)	59.2 (51.0–72.5)	63.3 (57.5–69.7)
BMI ($kg \cdot m^{-2}$)	22.4 (19.9–26.1)	22.1 (20.0–25.7)	23.4 (21.4–27.8)	21.7 (18.6–32.5)	22.4 (22.0–24.3)	19.6 (18.4–34.1)
Body fat (%)	23.2 ± 8.5	17.8 ± 6.8	22.3 ± 6.2	27.4 ± 8.3*	25.3 ± 9.2	25.4 ± 10.5
FFM (kg)	49.2 ± 10.0	54.5 ± 12.1	48.6 ± 8.2	46.1 ± 8.5	47.3 ± 10.9	46.7 ± 7.1
Exercise duration ($min \cdot d^{-1}$)	104 ± 41	103 ± 35	129 ± 46	71 ± 13**	125 ± 26	61 ± 15**

Frequencies are presented as number of cases (n). Normally distributed data are presented as mean ± SD, whereas nonnormally distributed data are presented as median (Q1–Q3).
*Significantly different from Para cycling, $P < 0.05$.
**Significantly different from wheelchair tennis, $P < 0.05$.
BMI, body mass index.

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a total of 20 medals (11 gold, 4 silver, and 7 bronze) during these games.

Resting metabolic rate. Participants arrived at the laboratory by car or public transport between 7:30 and 9:00 AM in an overnight fasted state. The RMR was measured by indirect calorimetry using a ventilated hood (Q-NRG (Cosmed, Rome, Italy) for the Dutch participants and Oxycon Pro (Jaeger System, Frankfurt, Germany) for the Norwegian participants). Before each test, the indirect calorimetry device was calibrated according to the manufacturer's instructions. The RMR measurements were conducted in a quiet room in thermoneutral conditions (~22.5°C). Participants were rested in seated position for at least 20 min before being placed on a bed in supine position. The RMR measurements were conducted over a 30-min period with data points being collected every 30 s. RMR was determined as follows. The first 5 min of data was discarded. From the remaining 25 min, the average energy expenditure was determined, but only if the average variation in $\dot{V}O_2$ and $\dot{V}CO_2$ was lower than 10%. If the variation in $\dot{V}O_2$ or $\dot{V}CO_2$ exceeded 10%, the duration of the measurement was reduced with 5-min increments until a period with a variation less than 10% was obtained (e.g., 20, 15, 10, or 5 min). If even the shortest 5-min interval displayed a variation above 10%, steady state was considered absent and the measurement was excluded from the analysis.

Body composition. After the RMR measurement, participants' body composition was assessed with a whole-body dual-energy x-ray absorptiometry (DXA) scan. Three DXA systems were used in the current study, that is, Hologic Horizon and Hologic Discovery A (Hologic, Marlborough, MA) in the Netherlands and Lunar iDXA (GE Healthcare, Madison, WI) in Norway. Whole-body fat and FFM were determined with the participants positioned according to National Health and Nutrition Examination Survey procedures (17,18). If the procedures could not be followed because of a disability, participants were placed in a position they could maintain for the duration of the scan. Analyses were conducted using the system's software package (Hologic Horizon: Apex version 5.6.0.5, Hologic Discovery A: Apex version 4.5.3, Lunar iDXA: enCORE version 18). The height of the participants was measured with a stadiometer (Seca 213i and Seca 437, Hamburg, Germany) with an accuracy of 0.001 m. If the participant was unable to stand upright because of a disability, the height was measured in supine position measuring the height from heel to the top of the head with a tape measure. Body mass was measured with a scale (Seca 770 and Seca 887) with an accuracy of 0.1 kg.

Total daily energy expenditure. The TDEE was assessed over a 14-d period by the DLW method according to the Maastricht protocol (19). In brief, before ingesting the DLW, the participants provided a baseline urine sample on day 0. All participants received a dose of $^{2}H_2^{18}O$, based on their individual body mass index, age, and sex (20), targeting an initial body water enrichment of ~130 ppm for ^{2}H and ~230 ppm for ^{18}O. The participants ingested the DLW on day 0 at ~10:00 PM, before going to bed. Participants measured and recorded their body mass on days 1, 8, and 15 directly after voiding, but before breakfast. Urine samples of the second void of the day were collected by the participants on days 1, 8, and 15. For validation purposes, a second urine sample was taken on these days at least 3 h after the first sample. All exact time points of the urine samples were recorded. Urine samples were either frozen immediately or stored in a refrigerator (~4°C) and collected by the researcher within 36 h. Urine was aliquoted into two 2-mL glass vials and stored at −20°C. All samples were analyzed by isotope ratio mass spectrometry at Maastricht University, the Netherlands. A regression line of the elimination of ^{18}O and ^{2}H was made from the six samples (not the baseline sample). Based on this regression line, the ratio of elimination of ^{18}O and ^{2}H was calculated, from which the CO_2 production was calculated. TDEE was calculated from the CO_2 production where a respiration quotient of 0.85 was assumed. Furthermore, the isotope dilution spaces were calculated using the intercept method, meaning that the regression line obtained from all urine samples postdosing was extrapolated back to time 0 (21).

PAEE and physical activity level. The PAEE was calculated as TDEE minus the diet-induced thermogenesis (DIT) and measured RMR. The DIT was assumed to be 10% of the TDEE (22). Furthermore, the physical activity level (PAL) of the participants was calculated as TDEE divided by RMR.

Nutritional analysis. The dietary intake of the participants was assessed by three unannounced 24-h dietary recalls. The recalls were conducted for a competition day, training day, and rest day, when applicable. If no competition days were available within the 14-d period, recalls were conducted for 2 training days and 1 rest day. The recalls were conducted via video calls by nutritionists or dietitians who were specifically trained for this task. To increase accuracy, the recalls were assessed with the validated five-step multipass method with a checklist at the end (23). The raw data were processed with Compl-eat software (Wageningen University, Division of Human Nutrition) in the Netherlands and Kostberegningssystem (version 7.4; KBS, Oslo) in Norway, by a single researcher in each country respectively. Numbers of competition, training, and rest days were not equally distributed over the 14-d period. Therefore, weighted means, taking into account the number of competition, training, and rest days for each individual, were calculated to estimate the mean daily energy and macronutrient intake over the 14-d period.

Exercise training. All participants were asked to keep a training log with information on the timing, type, and duration of all training sessions or competitions during the 14-d period. Some participants already tracked such data in a digital app, whereas the other participants were provided a written training log to record training data. Exercise duration was extracted from all exercise training logs and mean daily exercise duration served as a universal exercise training metric across sports.

Statistical analysis. All data were analyzed with SPSS (IBM SPSS Statistics, version 27) and checked for normal distribution. Normal distributed data were described as mean ± SD, whereas nonnormal distributed data were described as median

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TABLE 2. Various components of energy expenditure.

	Total	Para Cycling	Wheelchair Tennis	Wheelchair Basketball	Nordic Skiing	Alpine Skiing
TDEE (kcal·d^{-1})	2908 ± 797	3607 ± 1001	3082 ± 381	2322 ± 340*	2727 ± 678	2521 ± 256*
TDEE (kcal·kg FFM^{-1}·d^{-1})	59.2 ± 10.0	65.8 ± 9.4	65.2 ± 8.9	50.9 ± 4.8*,**	58.0 ± 9.3	54.6 ± 7.1
RMR (kcal·d^{-1})	1484 ± 277	1683 ± 276	1540 ± 224	1374 ± 203*	1258 ± 283*	1412 ± 246
RMR (kcal·kg FFM^{-1}·d^{-1})	30.5 ± 3.9	31.4 ± 3.9	31.6 ± 5.5	30.2 ± 3.6	28.0 ± 3.0	30.2 ± 2.3
PAEE (kcal·d^{-1})	1127 ± 555	1564 ± 736	1234 ± 317	715 ± 210*	1117 ± 410	857 ± 244
PAEE (kcal·kg FFM·$^{-1}$·d^{-1})	22.9 ± 8.6	27.8 ± 9.8	27.0 ± 5.3	15.6 ± 4.1*,**	24.8 ± 7.6	18.9 ± 7.0
PAL	2.0 ± 0.4	2.1 ± 0.4	2.0 ± 0.3	1.7 ± 0.2*	2.1 ± 0.3	1.8 ± 0.3

All outcomes are presented as mean ± SD. Differences between sports categories were analyzed using one-way ANOVA.
*Significantly different from Para cycling, $P < 0.05$.
**Significantly different from wheelchair tennis, $P < 0.05$.

(Q1–Q3). The difference in TDEE, RMR, PAEE, PAL, and energy and macronutrient intake between the different sports disciplines were analyzed with a one-way ANOVA with Bonferroni correction. Because it was not feasible to perform a 24-h recall on a rest, training, and competition day for all athletes, the differences in energy and macronutrient intake between the various days (rest, training, competition days) were analyzed with a paired *t*-test with multiple comparisons correction. Pearson correlations were conducted between energy expenditure (TDEE, RMR, PAEE) and FFM and exercise duration. Multiple regression analyses with backward selection were conducted with TDEE, PAEE, and PAL as dependent variables. Exercise duration, FFM, age, the presence of spasms, and the presence of spinal cord disorders (SCD; SCI or SB) were included as independent variables. Exercise duration was not recorded properly by 12 athletes, whereas FFM could not be assessed in one other athlete. Therefore, the regression analyses were performed with 35 athletes. Based on the regression analyses, three prediction equations for TDEE were formulated. The prediction equations were analyzed for accuracy by calculating the proportion of athletes within 10% of measured TDEE and the root mean square error of the predicted TDEE. Statistical significance was set at $P < 0.05$.

RESULTS

Athlete characteristics. The physical characteristics of the participants are shown in Table 1. Participants were classified as either having an SCD (including SB, and traumatic and nontraumatic SCI; ranging from T4 to L3 complete and incomplete lesions; $n = 17$), neurological disorder (including cerebral palsy and other neurological disorders; $n = 4$), limb deficiency (including dysmelia and amputations; $n = 16$), a visual or hearing impairment ($n = 4$) or other disabilities ($n = 7$). Among the seven athletes in the other disabilities group were athletes with nerve damage in the lower extremities, hip dysplasia, muscular dystrophy, complex regional pain syndrome, or a connective tissue disease. Of all participants, 54% were classified as wheelchair users.

Energy expenditure. During the 14-d period of TDEE measurements of the wheelchair basketball players, one of the players got infected by COVID and the whole team was quarantined from day 11. Therefore, only days 1 to 8 were analyzed for the TDEE of the wheelchair basketball players, except for one player who started the 14-d period 1 month later because of personal circumstances.

Results on energy expenditure are reported in Table 2. The mean RMR of participants was 1484 ± 277 kcal·d^{-1}. The RMR correlated strongly with the TDEE ($r = 0.73$; $P < 0.001$) and with the FFM (49.2 ± 10.0 kg; $r = 0.80$; $P < 0.001$). When expressing the RMR relative to FFM, no significant differences between sports were observed.

Mean TDEE of all athletes was 2908 ± 797 kcal·d^{-1} (Fig. 1A and Table 2). Para cyclists had a significantly higher TDEE compared with wheelchair basketball players ($P < 0.001$) and alpine skiers ($P = 0.025$). TDEE of wheelchair tennis players and Nordic skiers was not significantly different from any other

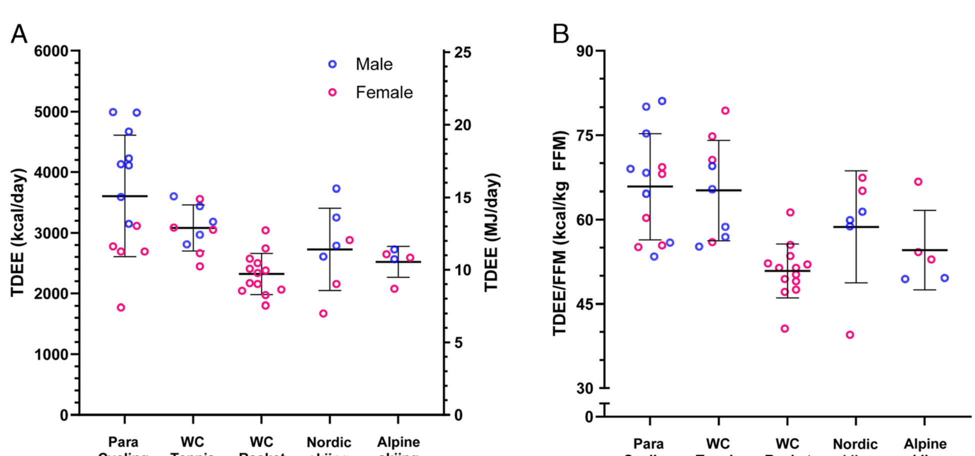

FIGURE 1—The absolute TDEE (A) and TDEE divided by the FFM (B) for male (blue circles) and female (pink circles) athletes categorized by sport. The horizontal lines and error bars represent the mean ± SD for each sports category.

sports category. The TDEE correlated strongly with the FFM ($r = 0.76$; $P < 0.001$). When expressed relative to FFM (Fig. 1B), both Para cyclists and wheelchair tennis players exhibited a higher energy expenditure compared with wheelchair basketball players ($P < 0.01$ for both comparisons). Nordic skiers and alpine skiers did not significantly differ from any other sport. When comparing the various disabilities, SCD athletes (2379 ± 522 kcal·d^{-1}) exhibited a lower TDEE compared with both athletes with a limb deficiency (3140 ± 837 kcal·d^{-1}; $P = 0.027$) and visual impaired athletes (3882 ± 1003 kcal·d^{-1}; $P = 0.003$). However, no differences were found when TDEE is expressed relative to FFM. Furthermore, TDEE expressed relative to FFM correlated moderately with the exercise duration ($r = 0.50$; $P = 0.002$).

Mean PAEE of the Paralympic athletes was 1127 ± 555 kcal. Again, Para cyclists had a significantly greater PAEE compared with wheelchair basketball players ($P < 0.01$), whereas wheelchair tennis players, Nordic skiers, and alpine skiers did not significantly differ from any other sport. When expressed relative to FFM, PAEE correlated moderately with exercise duration ($r = 0.60$; $P < 0.001$).

The mean PAL value of the Paralympic athletes was 2.0 ± 0.4. However, large differences were observed between sports. Para cyclists showed the highest PAL value followed by Nordic skiers, wheelchair tennis players, alpine skiers, and wheelchair basketball players. The PAL value correlated moderately with the exercise duration of the athletes ($r = 0.58$; $P < 0.001$).

Regression analyses. In the regression analyses presented in Table 3, it is shown that 73% of the variability in TDEE can be attributed to the independent variables FFM, exercise duration, and the presence of SCD. More specific, both FFM and exercise duration exhibited a positive relationship with TDEE, whereas SCD demonstrated a negative relationship. These variables were also responsible for explaining 62% of the variance in PAEE. With regard to PAL, FFM and exercise duration accounted for 42% of the variance.

Prediction of TDEE. Based on the regression models, the TDEE can be predicted with three different prediction equations, in which TDEE and RMR are expressed in kilocalories per day, mean daily exercise duration in minutes per day, and FFM in kilograms, and presence of SCD is binary (presence is 1, absence is 0):

Equation 1 Direct prediction of TDEE

$$\text{Predicted TDEE} = -323.921 + (57.660 \times \text{FFM}) + (6.203 \times \text{exercise duration}) - (441.684 \times \text{SCD})$$

Equation 2 Measured RMR with predicted PAEE and a 10% allowance for DIT (1.111)

$$\text{Predicted TDEE} = (\text{measured RMR} + (-861.931 + (30.893 \times \text{FFM}) + (6.345 \times \text{exercise duration}) - (266.949 \times \text{SCD}))) \times 1.111$$

Equation 3 Measured RMR × predicted PAL

$$\text{Predicted TDEE} = \text{measured RMR} \times (0.975 + (0.011 \times \text{FFM}) + (0.005 \times \text{exercise duration})$$

Regressing the observed versus predicted TDEE resulted in R^2 values of 0.752, 0.799, and 0.773 for prediction equations 1, 2, and 3, respectively (Fig. 2). Prediction equation 2 showed the highest accuracy, with 63% of the athletes predicted within 10% of the measured TDEE, whereas 20% and 17% were overpredicted and underpredicted, respectively. Prediction equations 1 and 3 predicted 60% and 51% correctly, respectively. The root mean square error was lowest for equation 2 at 272 kcal, followed by equation 3 (312 kcal) and equation 1 (314 kcal).

Energy and macronutrient intake. As shown in Table 4, the weighted mean energy intake was 2363 ± 905 kcal. As such, the energy intake was found to be 19% ± 20% lower compared with the TDEE. As the athletes were relatively weight stable throughout the 14-d assessment period (65.8 ± 11.5 kg on

TABLE 3. Backward stepwise multiple regression model with TDEE, PAEE, and PAL as dependent variables.

	Unstandardized Coefficients		Standardized Coefficients			
Outcome Variable: TDEE	***B***	**SE**	***β***	***t***	R^2_{adj}	***P***
Model					0.728	**<0.001**
(constant)	−323.921	463.041		−0.700		0.489
Exercise duration	6.203	1.809	0.307	3.430		**0.002**
FFM	57.660	7.974	0.683	7.231		**<0.001**
SCD	−441.684	166.773	−0.250	−2.648		**0.013**
	Unstandardized Coefficients		**Standardized Coefficients**			
Outcome Variable: PAEE	***B***	**SE**	***β***	***t***	R^2_{adj}	***P***
Model					0.617	**<0.001**
(constant)	−861.931	374.266		−2.303		**0.028**
Exercise duration	6.345	1.462	0.461	4.340		**<0.001**
FFM	30.893	6.445	0.537	4.793		**<0.001**
SCD	−266.949	134.799	−0.222	−1.980		0.057
	Unstandardized Coefficients		**Standardized Coefficients**			
Outcome Variable: PAL	***B***	**SE**	***β***	***t***	R^2_{adj}	***P***
Model					0.419	**<0.001**
(constant)	0.975	0.259		3.771		**<0.001**
Exercise duration	0.005	0.001	0.600	4.627		**<0.001**
FFM	0.011	0.005	0.301	2.320		**0.027**

The values in bold represent the significant *P*-values of the independent variables in the regression analyses.

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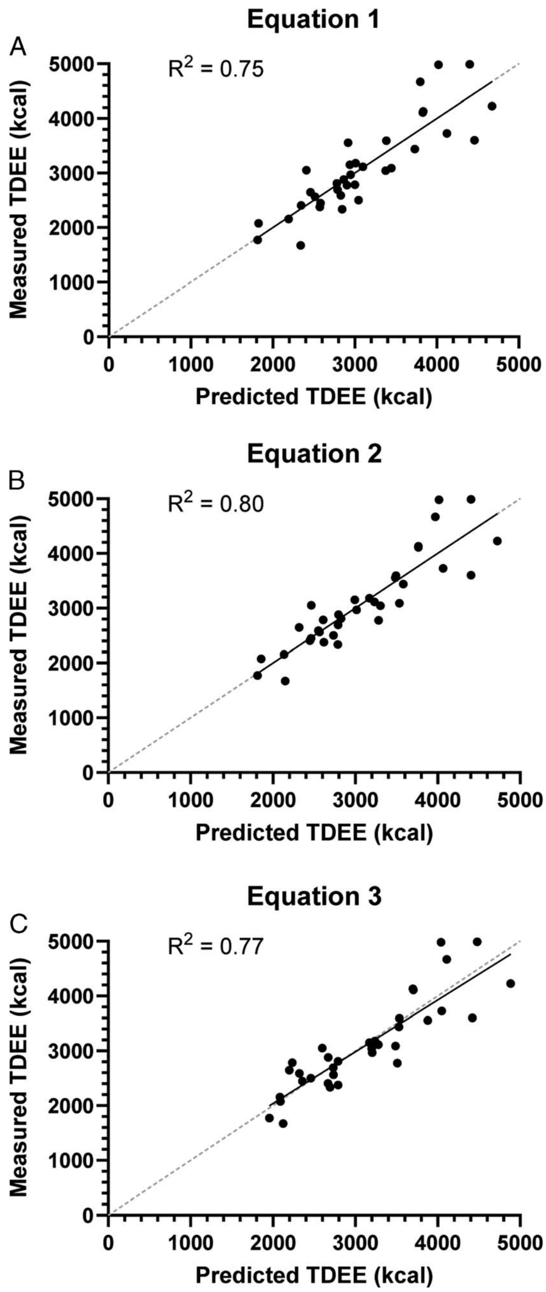

FIGURE 2—Predicted versus measured TDEE. TDEE was predicted according to three prediction equations, that is, direct prediction of TDEE (A; equation 1), TDEE predicted from measured RMR plus predicted PAEE (B; equation 2), and TDEE predicted from measured RMR multiplied with predicted PAL (D; equation 3). The solid line represents the linear regression line of the prediction equations, with the corresponding R^2. The gray dashed line is the regression line through origin with a slope of 1.

day 1 to 65.6 ± 11.6 kg on day 15; median change, −0.1 kg (interquartile range, −0.8 to +0.4)), the discrepancy between energy expenditure and energy intake can be considered as underreporting rather than substantial undereating. When expressed relative to FFM, the weighted mean energy intake of wheelchair basketball players (34.5 ± 9.9 kcal·kg^{-1} FFM) was significantly lower compared with Para cyclists (56.2 ± 15.2 kcal·kg^{-1} FFM; P < 0.001) and Nordic skiers (59.1 ± 15.3 kcal·kg^{-1} FFM; P = 0.002). The energy intake of wheelchair tennis players (49.0 ± 11.5 kcal·kg^{-1} FFM) and alpine skiers (45.8 ± 7.9 kcal·kg^{-1} FFM) did not differ from any other sport. Although it was not feasible to conduct a 24-h recall on a rest, training, and competition day for all participants, energy intake was numerically highest during competition days (2578 ± 1444 kcal), followed by training days (2330 ± 922 kcal) and rest days (2298 ± 860 kcal). However, no significant differences were observed between different day types.

As shown in Table 4, the weighted mean carbohydrate intake was 4.1 ± 1.9 g·kg^{-1} body mass, whereas the mean protein intake was 1.8 ± 0.6 g·kg^{-1} body mass and the mean fat intake was 32% ± 6% of energy intake. The carbohydrate intake per kilogram body mass was highest for Para cyclists followed by Nordic skiers, wheelchair tennis players, alpine skiers, and wheelchair basketball players. Relative protein and fat intake did not significantly differ between the sport disciplines. With respect to the type of day, protein intake of the total group was significantly higher on training days compared with rest days (P = 0.012). No differences in carbohydrate intake were found between type of days.

DISCUSSION

The current study aimed to assess energy expenditure and intake of a large cohort of Paralympic athletes, across different sports and disabilities. The TDEE was moderate to high, ranging from 2322 ± 340 kcal·d^{-1} for wheelchair basketball players to 3607 ± 1011 kcal·d^{-1} for Para cyclists. Regression analysis identified FFM, exercise duration, and SCD as the primary predictors of TDEE. Athletes' energy intake and carbohydrate intake were relatively low, whereas protein intake was sufficient.

Energy expenditure. No previous studies have assessed the TDEE using the DLW approach in a representative group of Paralympic athletes. Our data revealed an average TDEE of approximately 2900 kcal·d^{-1}, which aligns with a recent case study of a wheelchair tennis player, where the TDEE measured by DLW was reported to be between 3118 and 3368 kcal·d^{-1} (24). These TDEE data of Paralympic athletes are considerably higher than estimates of the energy requirements derived from analyzing the energy intake of weight-stable athletes with SCI (16) and wheelchair athletes (14), with energy intakes ranging from 1500 to 2300 kcal·d^{-1}. Therefore, the novel, high-quality data provided by the DLW approach in our study indicate that previous literature relying on energy intake may have severely underestimated the actual energy requirements of Paralympic athletes.

FFM was the strongest predictor for both TDEE and PAEE in the multiple regression analyses. The major contribution of FFM to the energy expenditure can be explained by the high metabolic activity of the tissues it encompasses, including vital organs and skeletal muscle (25). In addition to FFM, the mean daily exercise duration was identified as a significant predictor of TDEE, PAEE, and PAL. Although it may seem intuitive that a higher exercise duration would lead to an increased TDEE, the constrained energy expenditure model proposed by Pontzer and colleagues (26) suggests that as daily physical

TABLE 4. Energy and macronutrient intake.

	Total	Para Cycling	WC Tennis	WC Basketball	Nordic Skiing	Alpine Skiing
Weighted mean						
n	48	13	10	13	7	5
Energy (kcal)	2363 ± 905	3062 ± 1029*	2322 ± 490	1554 ± 402	2776 ± 853*	2152 ± 518
Carbohydrate (g)	263 ± 127	369 ± 141*	259 ± 99	155 ± 51	300 ± 116*	228 ± 49
Carbohydrate (g·kg^{-1} BM)	4.1 ± 1.9	5.5 ± 1.9*	4.1 ± 1.7	2.5 ± 0.9	4.9 ± 2.0*	3.6 ± 0.6
Protein (g)	118 ± 41	139 ± 39	113 ± 51	99 ± 29	121 ± 41	118 ± 41
Protein (g·kg^{-1} BM)	1.8 ± 0.6	2.1 ± 0.5	1.7 ± 0.7	1.6 ± 0.5	2.0 ± 0.7	1.9 ± 0.8
Fat (g)	85 ± 37	106 ± 40*	84 ± 24	54 ± 17*	114 ± 42*	76 ± 27
Fat (EN%)	32 ± 6	31 ± 6	32 ± 6	31 ± 7	37 ± 5	31 ± 5
Rest day						
n	32	8	7	10	3	4
Energy (kcal)	2298 ± 860	2956 ± 1001*	2410 ± 722	1779 ± 422	2249 ± 1344	2118 ± 634
Carbohydrate (g)	246 ± 104	327 ± 114*	251 ± 95	177 ± 47	259 ± 177	240 ± 47
Carbohydrate (g·kg^{-1} BM)	3.9 ± 1.7	5.0 ± 1.6	4.0 ± 1.6	2.8 ± 0.9	4.4 ± 3.5	3.7 ± 0.7
Protein (g)	110 ± 35**	133 ± 26	105 ± 41**	105 ± 26	90 ± 43	97 ± 44**
Protein (g·kg^{-1} BM)	1.7 ± 0.6**	2.1 ± 0.4	1.7 ± 0.6**	1.6 ± 0.5	1.5 ± 0.8	1.5 ± 0.7**
Fat (g)	89 ± 45	114 ± 55	100 ± 42	66 ± 34	88 ± 53	80 ± 42
Fat (EN%)	34 ± 9	34 ± 8	37 ± 8	32 ± 10	35 ± 9	32 ± 13
Training day						
n	48	13	10	13	7	5
Energy (kcal)	2330 ± 922	2992 ± 975*	2312 ± 494	1483 ± 448	2806 ± 1014*	2178 ± 519
Carbohydrate (g)	260 ± 127	359 ± 130*	254 ± 111	151 ± 57	303 ± 125*	232 ± 74
Carbohydrate (g·kg^{-1} BM)	4.0 ± 1.9	5.3 ± 1.7*	4.0 ± 1.9	2.5 ± 1.0	4.9 ± 2.0*	3.6 ± 0.9
Protein (g)	120 ± 44	136 ± 42	120 ± 57	100 ± 37	123 ± 43	128 ± 37
Protein (g·kg^{-1} BM)	1.9 ± 0.7	2.0 ± 0.6	1.9 ± 0.8	1.6 ± 0.6	2.0 ± 0.7	2.0 ± 0.7
Fat (g)	83 ± 39	104 ± 43*	83 ± 23	47 ± 14	115 ± 45*	75 ± 21
Fat (EN%)	32 ± 7	31 ± 7	32 ± 6	29 ± 7	37 ± 6	31 ± 3
Competition day						
n	20	6	0	11	3	0
Energy (kcal)	2578 ± 1444	4168 ± 1569*	N.A.	1669 ± 519	2731 ± 374	N.A.
Carbohydrate (g)	305 ± 227	562 ± 257*	N.A.	166 ± 61	300 ± 43	N.A.
Carbohydrate (g·kg^{-1} BM)	4.6 ± 3.1	8.1 ± 3.4*	N.A.	2.6 ± 1.0	5.0 ± 1.2	N.A.
Protein (g)	124 ± 51	172 ± 42*	N.A.	98 ± 43	122 ± 22	N.A.
Protein (g·kg^{-1} BM)	1.9 ± 0.7	2.5 ± 0.5*	N.A.	1.5 ± 0.6	2.0 ± 0.4	N.A.
Fat (g)	88 ± 42	125 ± 48*	N.A.	62 ± 21**	108 ± 14	N.A.
Fat (EN%)	32 ± 6	27 ± 5	N.A.	33 ± 5	35 ± 2	N.A.

Data are presented as mean ± SD or number of athletes included. Differences in energy and macronutrient intake between sports within day type were analyzed using one-way ANOVA. Differences in energy and macronutrient intake between day types within sports were analyzed using paired t-tests with multiple comparisons corrections.
*Significantly different from wheelchair basketball, $P < 0.05$.
**Significantly different from training day within group, $P < 0.05$.
BM, body mass; EN%, energy percentage; WC, wheelchair.

activity levels rise, other energy-demanding processes are downregulated, resulting in only minimal impact on TDEE. However, in contrast, the current study's linear correlation (r = 0.51) between the exercise duration and TDEE (relative to FFM) suggests a largely additive effect of physical activity on TDEE. It could even be speculated that exercise volume, as a product of exercise duration and intensity, would explain even more of the variation in PAEE and TDEE than exercise duration alone. However, because of the diverse range of sport disciplines and training regimens in our study and the challenges associated with objectively measuring exercise intensity, it was not feasible to collect uniform data on exercise intensity and consequently exercise volume.

Previous literature reported that individuals with SCI exhibit a lower RMR compared with controls (5), which likely translates to a lower TDEE as well. Although some studies completely attribute the lower RMR to low FFM (27,28), others have shown that the reduced RMR in individuals with SCI (5) and SB (29) extends beyond low FFM. In agreement, we found that individuals with SCD exhibited a lower TDEE, even when accounting for FFM. One explanation could be a decreased sympathetic nervous system activity in individuals with SCD (30). As shown by pharmacological intervention studies with β-adrenergic blockers, a reduced sympathetic nervous system activity leads to a lower overall metabolic rate (31,32) and thus lower TDEE. Another explanation is a reduction in exercise energy expenditure. Previous studies have reported that athletes with SCI exhibit lower maximal heart rates (11) and $\dot{V}O_{2peak}$ (10) during exercise compared with able-bodied elite athletes. This leads to a lower exercise energy expenditure at the same relative exercise intensity (i.e., a percentage of $\dot{V}O_{2peak}$ or heart rate) compared with able-bodied athletes (11) and likely also compared with disabled athletes without SCD.

In this study, the TDEE was assessed by the DLW method, providing an accurate measurement of the TDEE. However, because of the high costs associated with this measurement method, it is not feasible for routine use in daily practice. To allow for estimations of TDEE in Paralympic athletes, by using practical, easy-to-use methods, we developed prediction equations based on prediction factors that are relatively easy to obtain by practitioners. In this regard, the preferred equation to predict the TDEE relies on the measured RMR together with the predicted PAEE (equation 2), in which FFM, exercise duration, and the presence of SCD are used to predict the PAEE. If RMR cannot be assessed accurately, TDEE can also be predicted directly based on FFM, exercise duration, and the presence of SCD (equation 1). Both equations presented an accuracy greater than 60%, with equation 2 exhibiting a slightly higher accuracy compared with equation 1. These findings are promising, suggesting that the newly developed equations hold potential as tools for estimating TDEE in Paralympic athletes. It is important to acknowledge, however, that the evaluation of the accuracy was conducted with the same cohort of athletes, whose characteristics were used for the initial regression analyses. This might have inflated the predictive accuracy (33).

Energy intake. The 19% underreporting of energy intake observed in the current study is commonly seen in nutrition research (34) and underlines that energy intake data should be evaluated with caution. Although the common sport nutritional guidelines (13) and those specific for Para cyclists (35) indicate that carbohydrate intake should be tailored according to the daily needs, observed carbohydrate intakes were generally low and did not differ significantly between the different day types. Even when considering 19% underreporting, most athletes had inadequate carbohydrate intakes according to the guidelines. Multiple reasons for a low carbohydrate intake have been identified in previous studies, including inadequate practical nutrition skills or nutritional knowledge, poor availability of carbohydrate-rich foods in the immediate eating environment, or a chaotic lifestyle with frequent travel commitments (36). However, the most important reason for low carbohydrate intake may be the desire to restrict energy intake for weight maintenance or loss (37). The use of the DLW method in the present study allows for the evaluation of carbohydrate intake in the light of TDEE. Considering the athletes' current protein intake (1.8 $g \cdot kg^{-1}$ body mass) and the common sports nutrition recommendations for fat intake (30% of total energy intake), we can determine feasible carbohydrate intake levels based on the measured TDEE for various sports. Consequently, Para cyclists could aim for a mean daily carbohydrate intake of 6–10 $g \cdot kg^{-1}$ body mass, whereas wheelchair tennis players could target 5–8 $g \cdot kg^{-1}$ body mass. Nordic skiers should consider 4–8 $g \cdot kg^{-1}$ body mass, and alpine skiers and wheelchair basketball players could aim for 4–6 $g \cdot kg^{-1}$ body mass.

The mean protein intake (1.8 $g \cdot kg^{-1}$ body mass) was in the higher range of current sports nutrition guidelines for nondisabled athletes (1.2–1.8 $g \cdot kg^{-1}$ body mass) (13). Furthermore, the protein intake was significantly higher on training days compared with rest days. It has been suggested that Paralympic athletes can benefit from a higher protein intake during the healing of ulcers (38). However, none of the participants reported to have ulcers during the measurement period, and no other surplus benefits of a high-protein diet have been demonstrated in Paralympic athletes yet. Altogether, our data suggest that the emphasis should be placed more on carbohydrates rather than protein.

Strengths and limitations. The main strength of this study is the use of the DLW method to assess energy requirements of Paralympic athletes. This is the first study to provide such novel and valuable insights into the energy requirements of Paralympic athletes. Still, we should also acknowledge some limitations of this study that are also included in the interpretations of our results.

This international study was conducted at two different research sites to allow for a large number of Paralympic athletes to participate. However, RMR and FFM were assessed using different equipment at these sites. Standardized operating procedures were implemented across research sites to minimize potential measurement errors, although the risk for systematic errors between research sites cannot be completely eliminated.

The assessment of energy expenditure by DLW requires several assumptions. More specifically, to translate CO_2 production to energy expenditure, we assumed a respiratory quotient (RQ) of 0.85. However, the RQ could have been higher or lower based on the macronutrient composition of the diet of the participants. Another approach considered was calculating the food quotient based on the nutritional intake and using that in the estimation of RQ (39). However, because of the 19% underreporting of energy intake and the possibility that carbohydrates are more susceptible to underreporting compared with fat and protein (40), the food quotient and therefore the RQ would be biased. As a result, a single RQ value was used for all athletes, instead of individual values, which could have caused a small overestimation or underestimation of the TDEE of less than 5%. In addition, PAEE was derived from TDEE by subtracting RMR and DIT. Although RMR was measured, DIT was assumed to be 10% of TDEE. Because the actual DIT may range between 5% and 15% of TDEE (22), PAEE may be slightly underestimated or overestimated.

Despite the relatively large cohort of male and female Paralympic athletes competing in various large Paralympic sports in the Netherlands and Norway, not all Paralympic sports were represented. Hence, the prediction equations generated in the current study were based on the athletes and sports included in this particular study. It remains to be established whether the prediction equations are also valid in other Paralympic populations comprising a wider selection of Paralympic sports.

The influence of wheelchair dependence on TDEE was not analyzed. Most of the athletes with SCD were wheelchair users (94%), whereas this proportion was substantially lower in other groups. Because SCD is a known modulator of RMR and TDEE (5,29), we selected SCD rather than wheelchair dependence as a predictor of TDEE.

CONCLUSIONS

The energy expenditure of Paralympic athletes presented here can be regarded moderate to high, although substantial variations between sports and individuals are observed. Much of this variation in TDEE between sports and individuals can be attributed to individual differences in FFM and exercise duration, whereas the presence of SCD negatively affects TDEE. Consequently, we developed prediction equations that can estimate the TDEE of Paralympic athletes based on RMR, FFM, exercise duration, and the presence of SCD. Regarding dietary intake, there is room to increase carbohydrate intake while maintaining energy balance. Furthermore, protein intake is relatively high for most Paralympic athletes. Taken together, this comprehensive study establishes the benchmarks for energy requirements of Paralympic athletes, serving as the foundation for future dietary guidelines and nutritional counseling within this population.

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