Training volume and total energy expenditure of an Olympic and Ironman world champion: approaching the upper limits of human capabilities

Marcus S. Dasa [1,2*], Olav Aleksander Bu [3,4], Øyvind Sandbakk [5], Bent R. Rønnestad [6], Guy Plasqui [7], Hilde Gundersen [8], Morten Kristoffersen [8,2*]

Affiliations:

[1] Department of Health and Care Sciences, UiT - The Arctic University of Norway, Tromsø, Norway
[2] Norwegian Olympic Federation, Bergen, Norway
[3] Entalpi, Askvoll, Norway
[4] Santara Technology, Askvoll, Norway
[5] School of Sport Sciences, UiT - The Arctic University of Norway, Tromsø, Norway
[6] Section for Health and Exercise Physiology, Department of Public Health and Sport Sciences, Inland Norway University of Applied Sciences, Lillehammer, Norway
[7] Department of Nutrition and Movement Sciences, Maastricht University, Maastricht, Netherlands
[8] Department of Sport, Food and Natural Sciences, Western Norway University of Applied Sciences, Campus Bergen, Norway

Correspondence to:
Morten Kristoffersen, PhD, E-mail: Morten.kristoffersen@hvl.no or Marcus S. Dasa, PhD, E-mail: Marcus.smavik.dasa@gmail.com

RUNNING HEAD: Training and energy expenditure of a world-class triathlete

Abstract

Research on world-class athletes in endurance events, such as cycling Grand Tours, has reported extreme levels of total energy expenditure. However, it has been argued that over extended periods, such as months, sustained energy expenditure is capped at approximately 2.5 times the basal metabolic rate. Triathlon is particularly notable for its high energetic demands due to its multimodal nature, requiring athletes to maintain high training volumes. In this case study, we analyzed the total energy expenditure of world-class triathlete Kristian Blummenfelt using doubly labelled water over two specific periods, along with three years of training data. Total energy expenditure ranged from 7,019-8,506 kcal/day. Reported energy intake ranged from 4,899 to 6,360 kcal/day. The annual training volumes for the years 2020-2022 were 1,480, 1,350 and 1,308 hours, respectively, following a pyramidal intensity distribution. Approximately 53% of the entire three-year period matched with the doubly labeled water measurement periods in terms of training volume, indicating that the recorded total energy expenditure is representative of the majority of the observed data. Hence, the greater part of the three-year period likely exceeds the proposed metabolic ceiling for sustained total energy expenditure. This not only questions the validity of the current metabolic limits but also suggests a new perspective on what is physiologically achievable in world-class athletes.

Key words: Energy Expenditure; Endurance; Triathlon; Doubly Labeled Water; Exercise.

New and noteworthy: The current paper presents unprecedented data on the training volume and intensity distribution of a world-class triathlete. Further, using doubly labeled water measurements and training data, we argue that our findings challenge the proposed alimentary limit for sustained energy expenditure, thereby raising the upper boundary of what is physiologically possible in humans.

Introduction

Triathlon is a multi-discipline endurance sport where athletes compete in varying events extending from the Olympic to the Ironman discipline, with varying distances in swimming, biking and running. Irrespective of the discipline, success necessitates a significant training volume across all three modalities, accompanied by adequately calibrated energy intake (EI) to offset substantial energy expenditure (EE).

Total energy expenditure (TEE) encompasses all biological processes, including basal metabolic rate (BMR), thermic effect of food, non-exercise activity thermogenesis and physical activity (1). The physical activity level (PAL) is defined as the factor by which TEE exceeds BMR, with levels in the general population ranging between 1.2-2.5 (2). TEE has been empirically assessed in a variety of sports, using the “gold standard method” doubly labeled water (DLW). For instance, a one week investigation of cross-county skiers found an average PAL of 3.4 and 4.0 for female and male athletes, respectively (3). Research from three-week endurance events such as the Tour de France, Giro d’Italia and Vuelta a España have identified PAL values reaching as high as 5.3 (4–6). The absence of weight loss during these events implies that sufficient energy consumption occurs.

Recently, Thurber et al. (7) suggested the existence of a “metabolic ceiling” situated at a PAL of ~ 2.5 and that sustained EE exceeding this alimentary limit necessitates utilization of energy reserves, a strategy that is unsustainable over time. This alimentary limit is based on the constrained EE model which posits that increased physical activity over time directly decreases other metabolic processes, causing a decrease in TEE (8). While the current body of research exploring TEE relies heavily on data from short-term training, competitions, and expeditions (7), longitudinal studies focusing on training settings where strategic manipulation of exercise and EI is designed to maximize training volumes and subsequently TEE, are lacking.

Training volume is regarded a critical element in the optimization of performance across most endurance sports, with a general consensus that the major part constitutes low-intensity training (LIT) (9). For world-class endurance athletes, the power output at LIT will remain notably high, yielding substantial energy turnover. Despite consensus on the importance of high amounts of LIT, there is an additional need for certain amounts of moderate- (MIT) and high-intensity training (HIT), although the exact distribution is a subject of ongoing debate (10, 11). Within this context, triathlon emerges as one of the most demanding sports. The aim of the current study is to investigate TEE across two representative training camps and three years of training in a world-class triathlete.

Materials and Methods

Subject

The athlete, Kristian Blummenfelt (KB) is a Norwegian triathlete born on January 14th, 1994 in Bergen, Norway. His career highlights include Olympic gold medal, world Triathlon champion, ironman™ world champion, ironman™ 70.3 world champion, and the ironman distance world record. He is classified as tier 5 or world-class according to the athlete classification framework (12). The study was reviewed by the regional ethics committee and approved by the Norwegian Agency for Shared Services in Education and Research (ref: 761888). Written informed consent was obtained from KB for the usage of training data, full name and publication of the study.

Research design

We present an overview of KB’s training data spanning from January 2020 to December 2022. During this timeframe, he underwent training for various competitions across different disciplines, ranging from Olympic distance to ironman events. To estimate KB’s TEE, two periods of doubly labeled water (DLW) measurements during two distinct training camps (from October 29th to November 8th, 2021 (DLW^1) and from January 26th to February 8th, 2022 (DLW^2)) were measured, both held at 2,320 m.a.s.l., as part of the preparatory period.

Energy expenditure

The subject specific DLW dose was calculated using estimated total body water i.e., body fat percentage was estimated based on body mass index, age, and gender (13). Assuming a constant hydration fraction of fat-free mass of 73% (14), TBW was then calculated. For both DLW periods, KB collected a baseline urine sample (day 0) before ingesting a weighted amount of ^2H_2O and $H_2{}^{18}O$, providing an excess body water enrichment of approximately 150 ppm for H^2 and 200 ppm for ^{18}O. The next morning, a urine sample was collected from the second voiding. An additional dose of DLW was ingested on the evening of day 7, after the collection of a new background sample, both during DLW^1 and DLW^2. Additional urine samples were collected every day following the first voiding. The urine samples were duly collected using standard urine cups, subsequently aliquoted into airtight glass vials, and then preserved at -40°C within the facility's storage. After each training camp, the vials were shipped with overnight express to the laboratory where they were analyzed.

The isotope dilution spaces were calculated using two different methods, i.e. the plateau method and the intercept method. These two methods, which to our knowledge only have been reported once during extreme TEE (4), have been shown to elicit different outcomes in these scenarios. Given the potential methodological implications for the current and future studies, we report both, thereby contributing to the limited data available. Using the plateau method, the isotopic dilution spaces for ^2H and ^{18}O were calculated from the background enrichment from the baseline urine sample in the evening and the urine sample in the morning after dosing, allowing overnight equilibration. Using the intercept method, the dilution space was calculated from the final (at the end of the observation period) and initial urine samples by extrapolating back to time 0. CO_2-production was then calculated using an updated equation of CO_2-production (15), whereas EE was determined using Weirs non-protein equation (16), while assuming a respiratory quotient of 0.90, reflecting the typical carbohydrate intake of elite-level endurance athletes (5, 6).

PAL was determined by the ratio of TEE to BMR. BMR was calculated by employing the equation developed by Van Hooren et al. (17) for elite endurance athletes. Specifically, the equation used was:

BMR (MJ/day) = 0.767 + 0.106*mass (kg) (17).

Energy intake

Since this study was conducted retrospectively and initially aimed to provide internal information on KB's EE, there was no pre-planned measurement of EI during DLW^1. However, after the conclusion of the first data collection period, the research team and head coach mutually decided to extend the data collection efforts. Consequently, during DLW^2, we were able to assess KB's energy intake across four consecutive days.

EI was assessed using 24-h diet recalls, conducted using a nutritional analysis software, developed for research purposes with access to the Norwegian nutritional register (Myfood24, Leeds, UK). The diet recalls were scheduled on consecutive days, including one rest day (easy training) to accurately depict KB's regular habitual EI.

Training

The training records were obtained from the KB's training computer (Garmin Edge 1040, Garmin Ltd., Kansas, USA) and smartwatch (Garmin Forerunner 945-955, Fenix 6) covering the period from January 1st, 2020, to December 31st, 2022. These records comprised 2782 observations, with each observation representing an individual training session or competition. The variables encompassed within the data set included duration of session, power (cycling), heart rate (cycling and running), and speed (running and swimming). Applicable variables were categorized in a three-zone model. Specifically, the zones were demarcated as below the first lactate threshold (LT^1), which is defined as the first infliction point where lactate concentrations begin to increase, between LT^1 and the second lactate threshold (LT^2), corresponding to the second infliction point, and above LT^2. These thresholds are based on testing completed in the laboratory during the 2021 season for cycling (LT^1: 310 W, 140 BPM; LT^2: 373 W, 161 BPM), running (LT^1: speed: 16.4 km/h, 148 BPM; LT^2: speed: 19.0 km/h, 167 BPM), and swimming (LT^1: speed: 1.32 m/s; LT^2: speed: 1.34 m/s), respectively. Given the overarching objective of this paper, a single test was deemed sufficient for the calculation of a three-zone model.

Anthropometric data

For similar reasons mentioned concerning EI, KB's body mass was only measured systematically during DLW^2. Throughout this period, KB recorded his body mass each morning (excluding one day) after the first voiding using a digital scale from Seca (Hamburg, Germany). Additionally, his body mass was measured sporadically throughout the designated period in relation to metabolic testing and body composition assessments.

Data analysis

Training data were imported into the statistical software R to facilitate comprehensive data visualization and subsequent analytical procedures. To contextualize the TEE derived from the DLW measurements, we analyzed the total training volume during each year of the overall observation period and the DLW periods specifically. As such, the period defined as "overall" refers to the period between January 1st 2020, and December 31st 2022, excluding DLW^1 and DLW^2. Since the DLW periods may not consist of complete weeks, we included full 7-day cycles within these periods for analytic purposes.

Results

Anthropometric data

KB's stature is 175 cm. During DLW^2, the body mass of KB was 79.2 ± 0.8 kg [range: 78.0-81.2 kg], indicating he was in energy balance or surplus during the time of measurement. Additional weight and anthropometric data, collected during lab testing and body composition measurements, are provided in the supplementary materials.

Energy expenditure

During DLW^1, the TEE was 7,715 ± 2,652 kcal/day for Days 1-6 and 8,028 ± 2,318 kcal/day for Days 7-12, using the intercept method. Using the plateau method, the TEE was 8,052 ± 2,772 kcal/day for days 1-6 and 8,506 ± 2,461 kcal/day for days 7-12. For DLW^{2,} the TEE was 7,019 ± 1,888 kcal/day for days 1-7 and 7,600 ± 2,772 kcal/day for days 8-14, using the intercept method. Using the plateau method, the TEE was 7,400 ± 1,993 kcal/day for days 1-7 and 8,078 ± 2,963 kcal/day for days 8-14.

The equation by Van Hooren et al.(17) gave an estimated BMR of 2,175 kcal/day for KB, yielding PAL values of 3.6 and 3.8 during DLW^1 for the intercept and plateau method, respectively. For DLW^2, the values were 3.4 and 3.6, respectively.

Energy intake

The EI ranged from 4,899 to 6,360 kcal/day. Table 1 provides an overview of the energy and macronutrient intake during four consecutive days of DLW^2.

Insert table 1 approx. here

Training data

In 2020, 2021, and 2022, the annual training volumes were 1,480 hours, 1,350 hours, and 1,308 hours, respectively. The training durations for DLW^1 and DLW^2 were 54.5 hours and 58.9 hours. The weekly average durations [range] for DLW^1, DLW^2, and the overall period were 31.6 hours [27.7-36.1], 29.7 hours [28.4-31.8], and 26.3 hours [1.2-42.6], respectively (Figure 1). 53% of all weeks fell within the volume range exhibited during the DLW periods. This shows that the majority of the overall period commensurate in energetic output compared to the DLW periods.

Insert Figure 1. Approx. here

No sessions with alternative training or strength training were recorded throughout either training camp. Excluding the two camps, a total of 41.4 h was registered as alternative training, which includes mobility- and core training. The mean session duration for DLW^1, DLW^2, and the overall period was 1.7 ± 1.6 h, 1.7 ± 1.0 h and 1.5 ± 0.9 h, respectively. The percentage zone allocation, based in a three-zone model derived from the metabolic testing for duration, heart rate, velocity, and power are delineated in Table 2 and 3, respectively.

Insert Table 2. Approx. here

Insert Table 3. Approx. here

Discussion

This case study aimed to quantify the TEE of KB, a world-class triathlete during two training camps representative of his general training, as well as the annual training regimen across a three-year period. The main findings revealed that KB exhibited PAL values notably exceeding the proposed alimentary limit for sustainable TEE during the DLW periods, which represents the majority of the three-year observation period. He did this by applying an intensity distribution resembling a pyramidal approach, averaging 1,379 hours annually, numbers unprecedented across any sport reported in the literature.

During DLW^1 and DLW^2, the average PAL ranged from 3.4-3.8, depending on the calculation used. During high energy turnover, the intercept method tends to overestimate the isotope concentrations at time 0, causing the dilution space and hence TEE to be underestimated. Therefore, the plateau method has been recommended during high energy turnover, a notion reinforced by our results (4, 18). Using the plateau method, TEE ranged between 7,400-8,506 kcal/day, which are values that commensurate with those reported in grand tours (4–6). Notably, the PAL values of KB are lower than several other reported numbers in elite athletes, including cyclists, cross country skiers and ultra-endurance runners, whose numbers ranges between 3.4 and 5.3 (3, 5, 17, 19). One contributing factor is KB's comparatively high body mass, causing his relative TEE to be constrained. Additionally, numerous studies on elite athletes have utilized BMR estimates that are substantially lower than those proposed by Van Hooren et al. (18), which likely do not accurately reflect this demographic (3, 19). For example, using the BMR formula applied by Best et al. (19) yields PAL values ranging between 4.0-4.5 for KB. Comparable results are observed when employing the formula from Sjödin et al (3). Hence, considering these methodological differences, KB appears to elicit similar relative TEE to the aforementioned studies on elite athletes. Notably, KB's data reflect his habitual TEE rather than extreme events like Grand Tours, making them more representative of his actual EE.

The corresponding EI of KB did not match the TEE, with values ranging between 4,889-6,360 kcal/day. However, analogous to data from Grand Tours, his body mass remained stable during DLW^2, indicating that KB was in energy balance. This suggests that his actual EI was significantly higher. Previous studies corroborate that self-reported EI tends to be underestimated by 20% on average in athletes, with greater discrepancies at higher intake (20). Thus, KB's EI were likely within the range of the reported TEE across the evaluated days. Despite the underestimation in EI, the data still provides a reliable proxy for macronutrient distribution (20). Extreme PAL values have been suggested to be concomitant with substantial tissue loss, implying that a proportion of the energy requirements is met through catabolism of body stores such as adipose tissue or muscle mass (7). Despite this, a critical distinction exist between EI and energy absorption, with world class athletes potentially possessing superior absorption capabilities due to biological traits, compared to the general population (21). These capabilities may enable them to sustain elevated PAL's over extended periods, unlike the general population (21, 22). As an example, current nutritional guidelines do not support exceeding 90 g/h of carbohydrates during exercise, as most research show little additional benefit beyond this threshold and high prevalence of gastrointestinal discomfort (23). However, contemporary elite athletes frequently consume quantities substantially exceeding 90 g/h of carbohydrate and appear to tolerate it well (24). This is also evident through KB's reported EI which exceeded 1000 g of carbohydrate on certain days, without adjusting for underreporting. It is therefore plausible that KB demonstrates enhanced tolerance for carbohydrates, which may also transfer to superior nutritional absorption relative to findings in non-world-class athletes. Interestingly, a high amount of the reported food consumption were high and ultra-processed foods, which may affect absorption and seems to be necessary to accommodate such carbohydrate quantities. Consequently, KB has been able to support a training volume likely exceeding the proposed metabolic ceiling of 2.5 x BMR for most of this three-year period, while seemingly remaining in energy balance.

The lowest weekly average training volume recorded during the DLW periods was 27.7 h. In the overall three-year period, 53% of all weeks had training volumes that either matched or exceeded this. Notably, for illustrative purposes, 67% of the weeks in the overall period had a training volume of at least 25 h, representing a 10% reduction from the aforementioned weekly training volume. Considering this distribution, it is reasonable to infer that the PAL's during the majority of the three-year period exceeds the suggested "metabolic ceiling". Since the TEE data from the DLW periods were collected in the latter part of the observational period, it is unlikely that we would observe further decreases in TEE over time. This stand in contrast to the proposed mechanisms of the constrained model of EE. Hence, if a compensation occurs, it likely would have decreased earlier in the period. While extended research is required to accurately determine PAL values over durations longer than those covered in this study, the present data suggests that EE greatly exceeding 2.5 x BMR for significant portions of the annual calendar is plausible. It should be mentioned that both DLW^1 and DLW^2 were altitude camps. There is mixed evidence suggesting that altitude camps around 2,000 m.a.s.l. both may (25) or may not (26) affect BMR. Although difficult to conduct, future studies should aim to apply DLW measurements over longer periods i.e., every other month and including altitude and sea-level training periods, allowing for confirmation of our findings. This would ideally include daily RMR measurements to offset potential fluctuations due to internal/external factors, as well as periods with curated food selections for increased accuracy of EI.

To achieve the reported EE values, KB averaged 1,380 training hours annually, using an intensity distribution resembling a pyramidal training approach. The majority of training was LIT, reflecting consensus on the importance of large quantities for elite endurance athletes (9). It has been suggested that combining large amounts of LIT with too much MIT may cause excess fatigue with less adaptational benefits compared to spending this time at HIT (10). However, in the present setting, KB performs substantially more MIT compared to HIT, which appears to be sustainable. Thus, KB's training data mainly resembles a pyramidal intensity distribution, similar to what has been reported in several world-class athletes from different sports (11). This indicates that high amounts of LIT is supplemented by notable quantities of so-called threshold training (i.e., MIT), comparable to what is seen during competition, while less attention is placed on HIT.

Conclusion

The present findings show that KB's PAL values during two distinct phases markedly exceed the proposed metabolic ceiling of 2.5 x BMR, representing the majority of the three-year period. Therefore, world class athletes, which are scarcely represented in the literature, may produce results that are not otherwise possible. Notably, he did this by applying a pyramidal training approach. Lastly, the methodological approach is essential when measuring TEE during high energy turnover, and our results reinforce that the plateau method should be adopted in such cases.

Data availability

Source data for this study are not publicly available due to privacy restrictions for the athlete. The source data may be available to verified researchers upon request by contacting the corresponding author.

Grants

The research by MSD was supported by Tromsø Research Foundation (Grant No. 19_FFC_SAP)

Disclosure

OAB serves as the coach of Kristian Blummenfelt and holds stake in the company's Entalpi and Santara Technology.

Authors contribution

OAB is the coach of KB and designed the training plan. MD, OAB, ØS, MK, BR and HG helped conceive the idea and design the outline. MD did the analysis of the training data, while GP analyzed TEE. All authors have been involved in the in the preparation and revisions of the manuscript and have authorized the final version.

Acknowledgments

The authors would like to thank Kristian Blummenfelt for participating in the study and allowing insight into his training. We would also like to thank Aart Gossens for his help in exporting training data involved in this project.

References

1. **Westerterp KR**. Diet induced thermogenesis. *Nutr Metab Lond* 1: 5, 2004. doi: 10.1186/1743-7075-1-5.

2. **Westerterp KR**. Pattern and intensity of physical activity. *Nature* 410: 539–539, 2001. doi: 10.1038/35069142.

3. **Sjödin AM**, **Andersson AB**, **Högberg JM**, **Westerterp KR**. Energy balance in cross-country skiers: a study using doubly labeled water. *Med Sci Sports Exerc* 26: 720–724, 1994.

4. **Plasqui G**, **Rietjens G**, **Lambriks L**, **Wouters L**, **Saris WH**. Energy expenditure during extreme endurance exercise: The Giro d'Italia. *Med Sci Sports Exerc* 51: 568–574, 2019.

5. **Westerterp K**, **Saris W**, **Van Es M**, **Ten Hoor F**. Use of the doubly labeled water technique in humans during heavy sustained exercise. *J Appl Physiol* 61: 2162–2167, 1986.

6. **Van Hooren B**, **Cox M**, **Rietjens G**, **Plasqui G**. Determination of energy expenditure in professional cyclists using power data: validation against doubly-labelled water. *Scand J Med Sci Sports* 33: 407–419, 2023. doi: 10.1111/sms.14271.

7. **Thurber C**, **Dugas LR**, **Ocobock C**, **Carlson B**, **Speakman JR**, **Pontzer H**. Extreme events reveal an alimentary limit on sustained maximal human energy expenditure. *Sci Adv* 5: eaaw0341, 2019. doi: 10.1126/sciadv.aaw0341.

8. **Pontzer H**, **Durazo-Arvizu R**, **Dugas LR**, **Plange-Rhule J**, **Bovet P**, **Forrester TE**, **Lambert EV**, **Cooper RS**, **Schoeller DA**, **Luke A**. Constrained total energy expenditure and metabolic adaptation to physical activity in adult humans. *Curr Biol* 26: 410–417, 2016. doi: 10.1016/j.cub.2015.12.046.

9. **Staff HC**, **Solli GS**, **Osborne JO**, **Sandbakk Ø**. Long-Term Development of Training Characteristics and Performance-Determining Factors in Elite/International and World-Class Endurance Athletes: A Scoping Review. *Sports Med* 53: 1595–1607, 2023. doi: 10.1007/s40279-023-01850-z.

10. **Foster C**, **Casado A**, **Esteve-Lanao J**, **Haugen T**, **Seiler S**. Polarized Training Is Optimal for Endurance Athletes. *Med Sci Sports Exerc* 54: 1028–1031, 2022. doi: 10.1249/MSS.0000000000002871.

11. **Burnley M**, **Bearden SE**, **Jones AM**. Polarized Training Is Not Optimal for Endurance Athletes. *Med Sci Sports Exerc* 54: 1032–1034, 2022. doi: 10.1249/MSS.0000000000002869.

12. **McKay AKA**, **Stellingwerff T**, **Smith ES**, **Martin DT**, **Mujika I**, **Goosey-Tolfrey VL**, **Sheppard J**, **Burke LM**. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform* 17: 317–331, 2022. doi: 10.1123/ijspp.2021-0451.

13. **Deurenberg P**, **Weststrate JA**, **Seidell JC**. Body mass index as a measure of body fatness: age- and sex-specific prediction formulas. *Br J Nutr* 65: 105–114, 1991. doi: 10.1079/BJN19910073.

14. **Pace N**, **Rathbun EN**. Studies on body composition: III. The body water and chemically combined nitrogen content in relation to fat content. *J Biol Chem* 158: 685–691, 1945. doi: 10.1016/S0021-9258(19)51345-X.

15. **Speakman JR**, **Yamada Y**, **Sagayama H**, **Berman ES**, **Ainslie PN**, **Andersen LF**, **Anderson LJ**, **Arab L**, **Baddou I**, **Bedu-Addo K**. A standard calculation methodology for human doubly labeled water studies. *Cell Rep Med* 2: 100203, 2021.

16. **Weir JB de V**. New methods for calculating metabolic rate with special reference to protein metabolism. *J Physiol* 109: 1–9, 1949.

17. **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. doi: 10.1111/sms.14271.

18. **Van Hooren B**, **Most J**, **Collombon E**, **Nieminen H**, **Plasqui G**. A new approach to improve the validity of doubly labeled water to assess co2 production during high-energy turnover. *Med Sci Sports Exerc* 54: 965–973, 2022.

19. **Best AW**, **McGrosky A**, **Swanson Z**, **Rimbach R**, **McConaughy K**, **McConaughy J**, **Ocobock C**, **Pontzer H**. Total Energy Expenditure and Nutritional Intake in Continuous Multiday Ultramarathon Events. .

20. **Capling L**, **Beck KL**, **Gifford JA**, **Slater G**, **Flood VM**, **O'Connor H**. Validity of dietary assessment in athletes: a systematic review. *Nutrients* 9: 1313, 2017. doi: 10.3390/nu9121313.

21. **Dolan E**, **Koehler K**, **Areta J**, **Longman DP**, **Pontzer H**. Energy constraint and compensation: Insights from endurance athletes. *Comp Biochem Physiol A Mol Integr Physiol* 285: 111500, 2023. doi: 10.1016/j.cbpa.2023.111500.

22. **Speakman JR**. An Evolutionary Perspective on Sedentary Behavior. *BioEssays News Rev Mol Cell Dev Biol* 42: e1900156, 2020. doi: 10.1002/bies.201900156.

23. **Podlogar T**, **Wallis GA**. New Horizons in Carbohydrate Research and Application for Endurance Athletes. *Sports Med* 52: 5–23, 2022. doi: 10.1007/s40279-022-01757-1.

24. **Pfeiffer B**, **Stellingwerff T**, **Hodgson AB**, **Randell R**, **Pöttgen K**, **Res P**, **Jeukendrup AE**. Nutritional intake and gastrointestinal problems during competitive endurance events. *Med Sci Sports Exerc* 44: 344–351, 2012. doi: 10.1249/MSS.0b013e31822dc809.

25. **Woods AL**, **Sharma AP**, **Garvican-Lewis LA**, **Saunders PU**, **Rice AJ**, **Thompson KG**. Four Weeks of Classical Altitude Training Increases Resting Metabolic Rate in Highly Trained Middle-Distance Runners. .

26. **Woods AL**, **Garvican-Lewis LA**, **Rice A**, **Thompson KG**. 12 days of altitude exposure at 1800 m does not increase resting metabolic rate in elite rowers. *Appl Physiol Nutr Metab Physiol Appl Nutr Metab* 42: 672–676, 2017. doi: 10.1139/apnm-2016-0693.

Figure legends

Figure 1. An overview of weekly training volume in hours during the entire three-year period along with a 4-week moving average (black line).

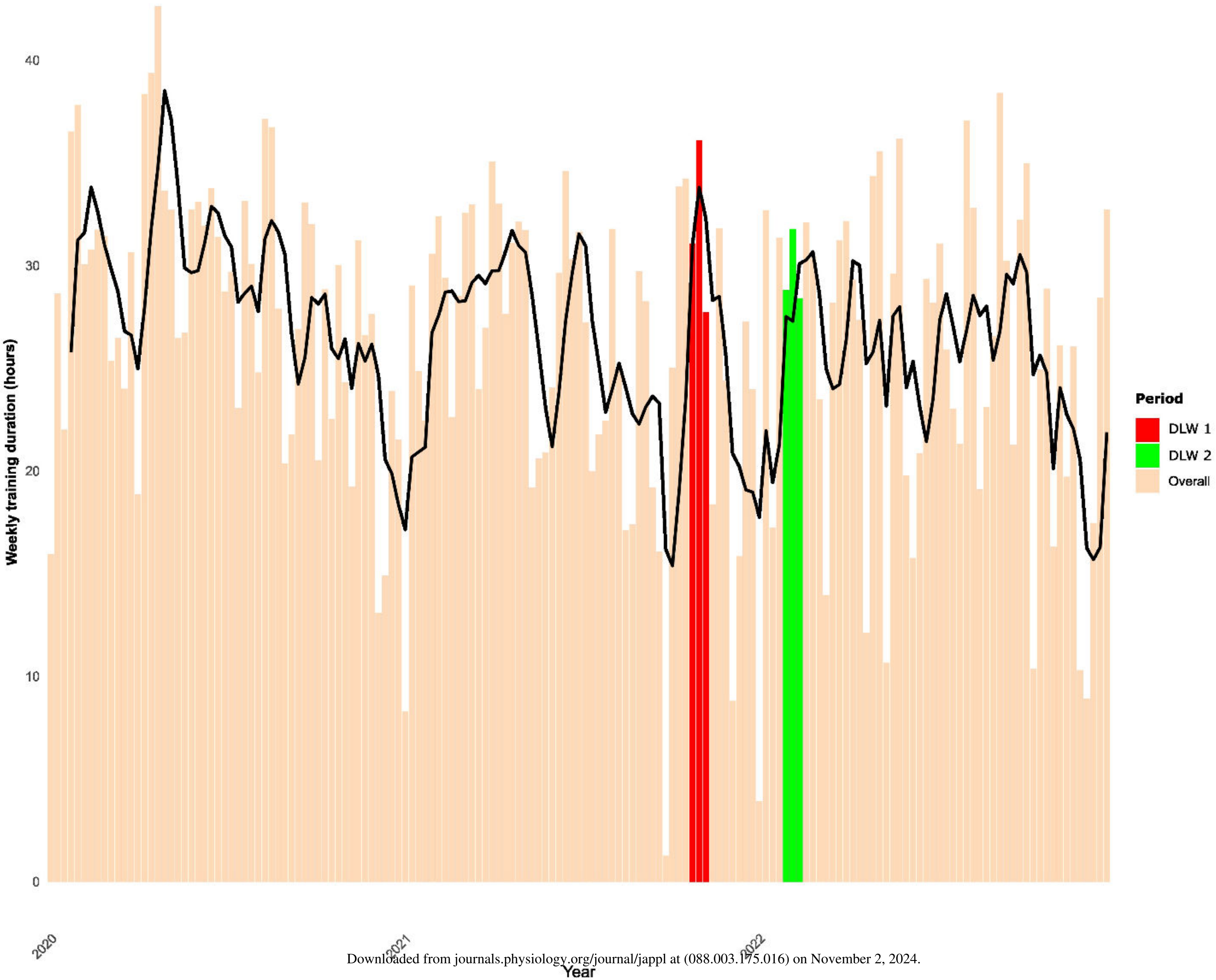
Weekly training duration (hours)
0
10
20
30
40
Year
2020
2021
2022
Period
DLW 1
DLW 2
Overall

Table 1. Energy intake (EI) during DLW[2] (January 26th-February 8th, 2022) on distinct training days, with day 4 categorized as easy by the coaching team.

		Day 1	Day 2	Day 3	Day 4 (easy)
EI	Kcal	5,630	6,360	5,393	4,889
Carbohydrate	g	878	1,181	565	780
	g/kg	11.1	14.9	7.1	9.8
Protein	g	214	160	239	166
	g/kg	2.7	2.0	3.0	2.1
Fat	g	134	99	226	112
	g/kg	1.7	1.2	2.8	1.4

Table 2. Percentage distribution across different exercise modalities during the three periods. DLW[1] (October 29th- November 8th, 2021), DLW[2] (January 26th – February 8th, 2022), and overall (the remainder of the time between January 1st, 2020 – December 31st, 2022). Doubly labeled water = DLW

Exercise modality	DLW[1]	DLW[2]	Overall
Cycling	57 %	45 %	46 %
Running	24 %	30 %	29 %
Swimming	19 %	25 %	24 %
Alternative training	0 %	0 %	1 %

Table 3. Intensity distribution (%) in a three-zone model for DLW^1, DLW^2, and the overall period, respectively. DLW = Doubly labeled water; Z = Zone; HR = Heart rate

** Cumulative intensity distribution for the entire 3-year period, excluding observations from DLW^1 and DLW^2.*

DLW^1	**Z1 HR**	**Z2 HR**	**Z3 HR**	**Z1 speed**	**Z2 speed**	**Z3 speed**	**Z1 power**	**Z2 power**	**Z3 power**
Cycling	71	29	0				84	12	4
Running	100	0	0	81	19	0			
Swimming				100	0	0			

DLW^2	**Z1 HR**	**Z2 HR**	**Z3 HR**	**Z1 speed**	**Z2 speed**	**Z3 speed**	**Z1 power**	**Z2 power**	**Z3 power**
Cycling	88	12	0				88	8	4
Running	87	13	0	93	7	0			
Swimming				100	0	0			

Overall *	**Z1 HR**	**Z2 HR**	**Z3 HR**	**Z1 speed**	**Z2 speed**	**Z3 speed**	**Z1 power**	**Z2 power**	**Z3 power**
Cycling	85	13	2				85	10	5
Running	85	12	3	88	7	5			
Swimming				95	0	5			