# Hungry runners – low energy availability in male endurance athletes and its impact on performance and testosterone: mini-review

Martin Cupka, Milan Sedliak

*Comenius University in Bratislava, Faculty of Physical Education and Sport, Department of Biological and Medical Sciences, Bratislava, Slovakia.*



***Abstract***

Low Energy Availability (LEA) arises from the inability to cover energy needs and requirements of training or normal physiological functions. This value differs from the energy balance, which takes into account the total daily energy intake compared to all the energy expended, regardless of the amount of fat-free mass. Insufficient energy consumption affects recovery, adaptation processes, increases the risk of injury or illness, so all of this can negatively affect performance. This mini-review is written on research articles in Pubmed database related to LEA in endurance-trained men and its impact on performance and testosterone. This article also clarifies the prevalence of LEA in male endurance athletes and its correlation to Relative Energy Deficiency in Sports (RED-S). LEA occurs in male endurance athletes and correlates with decreased testosterone levels, decreased bone density and also Resting Metabolic Rate. In endurance-trained men, there is great potential for the negative consequences of low energy availability. It can also be said that there are possibilities for primary screening, so we recommend regular check-ups of blood markers, body structure and keeping not only training but also dietary records, which can increase awareness of an adequate energy balance.

**Key Words**: energy availability, endurance, testosterone, male hypogonadism, sports performance, hormones.

*Eur J Transl Myol 33 (2) 11104, 2023 doi: 10.4081/ejtm.2023.11104*

Lower body weight can be beneficial for some athletes, especially in endurance, weight-bearing and aesthetic sports disciplines. Sundgot-Borgen and Torstveit (2010)[1] recognised few cases of intentional weight loss or limitation of energy intake to increase endurance performance, relative strength or aesthetics. On the other hand, in this context, we are aware of several risks and consequences of insufficient energy intake for athletes. The effort to achieve the best possible body composition for sport performance may result in Low Energy Availability (LEA). Chronic low energy intake in sport and its consequences for health and performance have been the subject of several studies, most often due to the potential to increase the risk of injury or illness. In the context of exercise-related health risks, LEA has been extensively described in female athletes as a part of the female athlete triad in relation to bone health and menstrual function.[2] Recently, the International Olympic Committee (IOC) has expanded the triad concept with the term Relative Energy Deficiency in Sports (RED-S) to address the accompanying consequences with LEA on health and performance in both sexes.[3] For the purpose of this review, we understand RED-S as a wider spectrum of manifestations affecting components such as the level of resting metabolism, immunity, proteosynthesis, cardiovascular health or other psychological, endocrine and gastrointestinal factors in general. The etiology of RED-S is very complex, but a major aspect of the syndrome is low energy availability, whether associated with or without eating disorders or disordered eating. Research on LEA in male athletes has gained popularity since their official inclusion in the RED-S model by the IOC.[3] At the same time, it was described and became the subject of research within the American College of Sports Medicine (ACSM), where this model is recognized as the "Male Sports Triad".[4,5] Despite the slight difference between the concepts from the IOC and ACSM, the term RED-S syndrome will be used in this review. LEA occurs when an energy deficit exists to such an extent that the body has insufficient energy available to meet the needs of training and normal physiological functioning. This is different from energy balance, which takes into account total energy intake compared with all energy expended irrespective of fat-free mass.[6] Energy

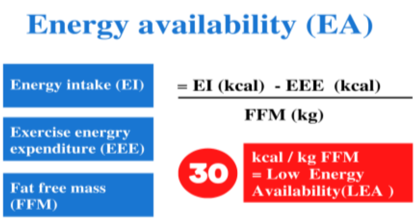


***Fig 1.*** *Formula for calculating Energy Availability (Ackerman et al., 2018.[3] Koehler et al., 2016).[10]*

Availability (EA) was defined as the amount of energy that remained available to support bodily functions and physiological processes after deducting the energy required for training. It is calculated using the energy intake, subtraction of the energy needed for training and subsequently divided by the value of fat-free mass in kilograms.[7]

EA = Dietary energy intake (kcal) minus Exercise energy expenditure (kcal) divided by Fat-Free Mass (kg)

Initially, LEA leads to a negative energy balance and thereby weight loss because the body's energy reserves (*e.g.*, adipose tissue and body proteins) substantially contribute to fuel needs. Energy availability value of less than 30 kcal/kg/FFM/day for five consecutive days has been shown to disrupt hypothalamic-pituitary axis, resulting in elevated cortisol levels, decreased Triiodothyronine (T3) and Luteinizing Hormone (LH), as well as decreased blood markers of bone formation and reduced blood glucose levels.[8] However, Loucks (2004)[9] claims that long-term LEA causes metabolic and physiological adaptations in order to reduce total energy expenditure to prevent further weight loss and promote survival, whereby the body obtains a new energy balance steady state. Therefore, an athlete may be weight stable and not excessively low in body mass or body fat levels yet have impaired physiological function secondary to LEA. As we can see there is no difference if LEA occurs due to low dietary energy intake or energy expanded through exercise is too high. In a study investigating EA in female and male athletes from a mix of sports, more than one-half of the athletes had EA values below the suggested threshold of 30 kcal/kgFFM.[10] The concept of adequate energy availability is under-studied in male athletes, although nutritional deficits have been identified in a subset of athletes. The largest pioneering nutritional study which spanned 8 years and evaluated the diet and nutritional adequacy of the diets using 4 to 7-day food logs among 419 elite male and female Dutch athletes competing in endurance, strength, and team sports. The majority of athletes in all sports consumed inadequate levels of carbohydrates, and athletes of both sexes participating in sports emphasizing leanness were observed to exhibit dieting and under-eating throughout the year.[11] LEA research in male athletes has gained popularity since their official inclusion in the RED-S model by the IOC.[3] Despite the apparent simplicity of the calculation of energy availability, there are several limitations and pitfalls in the exact quantification of each of the components. There is currently no universal agreement on how to precisely quantify these components, and thus across methodologies we can see discrepancies that need to be taken into account.[12] The first is the reliability and objectivity of energy intake in athletes. It turns out that more often it is a tendency to underestimate energy intake with an error rate of up to 21%.[13] Furthermore, we recognize the measurement of the energy demand of exercise in the free-living conditions of athletes. The method of doubly labeled water appears to be the most reliable, but its availability for athletes is limited. Another option is accelerometers showing a relatively high agreement with the previous method[14] and then there are popular and easiest available devices such as "smart watches" where the error rate can range up to 600 kcal per day.[15] Several authors emphasize that the use of EA as an absolute value and threshold for determining the development of RED-S conditions of the male athletic triad may not be sufficient due to individual variability and tolerance to EA.[4,5]
In conclusion, the assessment of LEA may face several methodological issues, however, we still consider it as an important concept of nutritional counseling in sports.

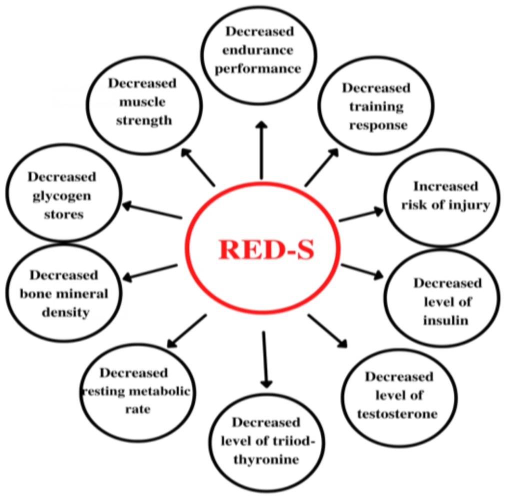


***Fig 2.*** *Potential influence of Relative Energy Deficiency in Sports on hormones and sports performance - modified and adapted to male endurance athletes (Mountjoy, 2018).[3]*

### *Prevalence of LEA*

Chronic low energy intake can stem from a variety of reasons: i) lack of knowledge about proper nutrition and nutritional sources to achieve energy balance, ii) lack of time to prepare meals, iii) lack of skills in preparing meals, iv) financial reasons, or v) physiological reasons like loss of appetite after training due to suppression of ghrelin production.[16] In these cases, it is not necessarily a matter of intentionally regulating energy income. In general, it does not matter whether it is an intentional or unintentional restriction of energy income. The consequences are identical in both cases. In the case of intentional control or restriction of energy intake, the most common reasons are dissatisfaction with your body and the desire to change body composition.[17] While most LEA and body image studies have focused primarily on women, on the other hand, there is growing evidence that problems with body image and eating habits are also common in male athletes - as we would like to describe in this minireview. Investigations among sport types demonstrated that athletes who participate in sports emphasizing leanness, including endurance sports (cycling and running), appear to have a greater prevalence of Disordered Eating (DE). Among a sample male cyclists and male non-cyclists, cyclists exhibited a significantly higher overall score on the Eating Attitudes Test (EAT)-26 (indicating more DE), and a higher score on the dieting and binge eating EAT-26 sub-factors.[18] In the largest epidemiological study to date which evaluated the prevalence of Eating Disorders (EDs) elite Norwegian male athletes (n=687) and non-athlete controls (n=629) were studied. Results reported an 8 % prevalence of EDs, including anorexia nervosa, bulimia nervosa, ED not otherwise specified, and anorexia athletica, among the 687 male athletes compared with a 0.5 % prevalence among the 629 male non-athlete controls. Ferrand and Brunet (2004)[19] evaluated a sample of 42 elite male cyclists and found that over 57% had an EAT-26 score. Among a sample of male cyclists, Filaire et al. (2007)[20] found that 67% were not satisfied with their weight, 41% dieted to lose weight, and others reported laxative use and increased exercise for weight-control purposes. Three investigations in male runners and cyclists identified low caloric intake in athletes, although food and fluid intake surrounding and during competition largely met recommended levels in most reports.[21-23] Similar to weight class and aesthetic sports, several studies have identified similar deficits in male endurance athletes. One report evaluating 37 male adolescent cyclists and controls found that, despite cyclists exercising fivefold more hours per week than controls, their energy intake (2300 kcal/day) did not significantly exceed that of control subjects and appeared to fall below recommended intake levels based on their level of training. Additionally, intake of calcium, vitamin D, iron, and B vitamins were below recommendations for both cyclists and controls. As we could see in the previous chapter LEA is a widespread phenomenon across several sports for both men and women. It seems that there is a lower risk of low EA in team sports and ball games. Studies investigating EA among male adolescent athletes competing in ball or team sports, such as football, soccer, and ice hockey, indicate sufficient absolute (kcal) and relative (kcal/kg) energy intake, ranging from 40 to 60 kcal/kg FFM.[24,25] In this minireview, we focused on the prevalence of low energy availability of endurance-trained men. Details are given in Table 1 below. The concept of adequate energy availability has not been sufficiently studied in male athletes. Despite the fact that women can be considered risky in terms of the consequences of LEA, for men, LEA, hypogonadism and bone health are three interconnected components.[4] An electronic database of "Pubmed" was chosen to search for relevant studies. This also included backward search according to the references in the included articles. The keywords "energy availability, endurance, testosterone, male hypogonadism, sports performance, hormones" were used to search for relevant resources. The main selection criterion was that the studies had to deal with low energy availability in endurance-trained men. Furthermore, there was a requirement for a publication date between 2017-2022 and the availability of full-text.

### *Hypogonadism and testosterone disturbances*

The Endocrine Society defines male hypogonadism as a clinical syndrome resulting from the failure of the testis to produce physiological levels of testosterone (androgen deficiency) and a normal number of spermatozoa. Hypogonadism (primary, secondary or mixed) is caused by disruption of one or more levels of the hypothalamic–pituitary–gonadal axis.[26] Boloña et al. (2007)[27] claim that testosterone is associated with various processes in the male organism including androgenic-anabolic it is thought, but not universally accepted that it is a crucial factor for male sexual libido. As has been noted, the definition of hypogonadism in medicine[28] differs from the ambiguous definition in the field of sports, where it can be a functional condition and, importantly, this condition is relatively quickly reversible to a normal condition.[29-31] The prevalence of exercise-associated hypogonadotropic hypogonadism and its impact on skeletal health in male athletes is not well understood. This is partly due to the lack of research on this topic and also because the identification of hypogonadism in men is not as clear as in women, where the situation is facilitated by the so-called menstrual dysfunction. In some cases, decreased testosterone levels may still be within the clinically normal range and may be considered an exercise-induced functional state.[32] In terms of sports performance, testosterone provides physiological benefits such as increased muscle development, increased erythropoiesis, increased hemoglobin levels, which facilitate the transfer of oxygen in the blood and, last but not least, increased aerobic capacity.[32] There are pioneering studies in animal models where has been shown that food deprivation suppresses spermatogenesis. If negative energy balance is associated with disturbances in reproductive function in male runners remains speculative but very likely.[33,34] De Souza (2021)[5] assumes that alterations in testosterone concentration and spermatogenesis are an initial physiological adaptation caused by insufficient energy intake. When there is a state of chronic negative energy balance, reproductive function might be suppressed in order to prevent energy loss. Further evidence suggests that endurance-exercising males can develop a similar suppression of the reproductive function which we know from women. It is called Exercise Hypogonadal Male Condition (EHMC). EHMC can be viewed as overreaching or overtraining, when the amount of training was not adequately balanced by rest, resulting in physiological or psychological symptoms of maladaptation. Despite the obvious similarities between EHMC, overtraining, the women's athletic triad and RED-S, the differences should be put into perspective. The European College of Sport Science and the American College of Sports Medicine agree that when overreaching or overtraining is suspected, it is important to rule out other hypothetical causes related to negative energy balance or low energy availability. If the cause of the symptoms is an energy deficit, we do not classify this situation in the area of overreaching or overtraining, but it falls under RED-S. Being more physically active has been shown to be beneficial reproductively for men who are sedentary (or have a very low physical activity levels) as it results in improved testosterone levels and libido.[35] Conversely, there are many reports suggesting that men who participate in large amounts of endurance exercise training (*e.g.*, marathon running) can have suppressed testosterone and libido.[36-39] The study about associations between endurance training and sexual libido in health men suggest that men with the lowest and mid-range training intensities or with the shorter and mid-range training volumes had greater odds of libido score in compare to their counterparts.[40] We have strong evidence that male endurance athletes across a range of different disciplines have been shown to exhibit lower levels of reproductive hormones including testosterone.[38,41-43] When Hackney et al. (1998)[44] compared endurance athletes with sedentary men, they reported significantly lower serum levels of testosterone. As for endurance athletes, levels of testosterone were in the normal clinical range but represented only 55% to 85% of their sedentary counterparts. A cross-sectional study, which is mentioned in Table 1, reported reduced testosterone levels in middle and long-distance runners and race walkers with clinical LEA.[12] It seems that long-term endurance running is also crucial for testosterone levels since 30% reduction in testosterone levels has been reported in athletes with at least 5 years of endurance running compared with athletes with fewer years of training (Hackney & Lane, 2018).[40] A study of elite long-distance runners showed a correlation between LEA and reduced testosterone levels. Runners who covered 81±14 km per week showed lower levels of total testosterone (9.2±2.3 *vs* 16.2±3.4 nmol/L) as well as lower EA (27.2±12.7 *vs* 45.4±18.2 kcal/kg/FFM/day) compared to their inactive counterparts.[45] In a study of 24 elite distance runners low testosterone levels appeared in 40% (n=10) of athletes and also bone injuries were 4.5 times more prevalent in low-T athletes.[45] Every subject ran more than 100 km per week. Similarly in a study of 50 road cyclists, there were 10 males with low EA and they had lower testosterone levels than those with adequate EA.[46] Also, RMR was suppressed in 65% of professional males cyclists despite similar EA and 24-hr energy balance compared with subjects with normal RMR, they spent more time in a severe energy deficit and had larger single-hour energy deficit, which was associated with higher cortisol levels and lower testosterone:cortisol ratio.[47]

### *Energy availability and endurance performance in males*

The overall amount of research examining endocrine dysfunctions due to low EA in men is only limited compared to research in women. The most evidence is provided by research into the effect of LEA on the reproductive abilities of men, which we mentioned in the previous text. Ultra-endurance exercise can cause acute decreases in testosterone levels as well as increases in cortisol, suggesting significant suppression of hypothalamic-pituitary axis functions.[48] Cortisol as one of the markers of endocrine stress is often associated with reduced testosterone circulation. This was seen in male endurance athletes who were exposed to low EA. It was also observed that a higher short-term energy deficit (24 hours) was associated with higher cortisol levels in performance endurance athletes compared to their counterparts with sufficient EA.[47] A study of elite rowers who underwent a four-week intensive training block with reduced energy supply found worsened regeneration and worsened performance on a 5,000-meter track.[49] Decreased aerobic and anaerobic performance, weight loss, and reduced RMR have also been shown in trained cyclists with insufficient energy intake during the intense training period.[49] In male cyclists, long-term low EA at the current higher training load resulted in reduced performance, and no benefit in terms of performance was found due to the amount of body fat.[50] Regarding the effect on muscle proteins, we know that the stimulation of muscle protein synthesis is supported by anabolic hormones such as insulin and testosterone. On the other hand, glucocorticoids, such as cortisol, increase the turnover of proteins in the body and initiate the breakdown of skeletal muscle proteins.[51] As described by Šarabon et al., (2022),[52] muscle strength and especially eccentric load is important for runners. The effect of low EA on performance may be more difficult to identify due to the significant effect of lower body weight on performance, thus even leading to a relative improvement in performance. Disease-related training failure is shown to be three times higher in athletes at low EA risk. These athletes lose more than 22 days of training per year, with an average of 7 days for risk-free athletes.[53] When evaluating the association between endurance training and sexual libido in men, it has been shown that libido scores are related to the duration and intensity of training, and thus the ability to train longer or harder.[40] Athletes usually follow a strict regimen and a hard training regimen to optimize athletic performance. In this endeavor, athletes may be malnourished enough to enter a state of low energy availability due to consuming too little energy compared to overpowering over a long period of time.[3] This can have devastating effects, including damage to multiple organ systems, lower Bone Mineral Density (BMD), decreased testosterone levels, increased risk of injury, impaired coordination, and decreased athletic performance in many ways.[54,45,50,55]

### *Final considerations*

The LEA seems to be a significant factor affecting the hormonal system and sports performance of endurance trained men. There is a fine line between the benefits of lower body weight and the negative consequences of LEA. This is linked with insufficient testosterone production, reduced libido, decreased bone mineral density. As we can see, the problem of low energy availability is better documented in women and on the contrary understudied in men. Its manifestations in men are more difficult to detect, and that is why we perceive a high need to include screening for nutritional risks as part of regular check-ups with a sports or physical education doctor. At the same time, we dare to say that there is a need for an easily accessible screening tool that can also be used outside of laboratory conditions. The athlete himself may see this as sudden weight changes, performance stagnation, fatigue fractures and digestive problems. It will be crucial for further research to reveal the relationships between a particular level of energy availability per organism - not just during the exercise itself and especially in the long term. More research is also needed for assessing long-term effects of LEA that result from various periods of sports training during the season.

## List of acronyms

ACSM - American College of Sports Medicine
BC - Body composition
LEA- Low energy availability
BMD - Bone Mineral Density
DE - Disordered eating
DXA - Dual energy x-ray absorptiometry
EA - Energy Availability
ED - Eating disorders
EEE - Exercise Energy Expenditure
EI - Energy Intake
FFM - Fat Free Mass
IOC - International Olympic Committee
RED-S - Relative Energy Deficiency in Sports
RMR - Resting Metabolism Rate
SHBG - Sex-hormone binding globuline
TST - Testosterone

## Funding

None.

## Conflict of Interest

The authors disclose no conflicts of research and publication interest or any specific endorsements of the products referenced in this manuscript.

## Ethical Publication Statement

We confirm that we have read the Journal’s position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

## Corresponding Author

Martin Cupka, Comenius University in Bratislava, Faculty of Physical Education and Sport, Department of Biological and Medical Sciences, Bratislava, Slovakia.
ORCID ID: https://orcid.org/0009-0004-2767-693X
E-mail: martin.cupka@uniba.sk

*E-mails and ORCID iD of co-author*

*Milan Sedliak: milan.sedliak@uniba.sk*
ORCID ID: https://orcid.org/0000-0002-2324-154X

## References

1. Sundgot-Borgen J, Torstveit MK. Aspects of disordered eating continuum in elite high-intensity sports. Scand J Med Sci Sports. 2010 Oct;20 Suppl 2:112-21. doi: 10.1111/j.1600-0838.2010.01190.x. PMID: 20840569.
2. Slater J, Brown R, McLay-Cooke R, Black K. Low Energy Availability in Exercising Women: Historical Perspectives and Future Directions. Sports Med. 2017 Feb;47(2):207-220. doi: 10.1007/s40279-016-0583-0. PMID: 27430502.
3. Mountjoy M, Sundgot-Borgen JK, Burke LM, Ackerman KE, Blauwet C, Constantini N, Lebrun C, Lundy B, Melin AK, Meyer NL, Sherman RT, Tenforde AS, Klungland Torstveit M, Budgett R. IOC consensus statement on relative energy deficiency in sport (RED-S): 2018 update. Br J Sports Med. 2018 Jun;52(11):687-697. doi: 10.1136/bjsports-2018-099193. PMID: 29773536.
4. De Souza MJ, Koltun KJ., Williams, NI. What is the evidence for a Triad-like syndrome in exercising men? Current Opinion in Physiology. 2019 Apr; 10. doi:10.1016/j.cophys.2019.04.002
5. Nattiv A, De Souza MJ, Koltun KJ, Misra M, Kussman A, Williams NI, Barrack MT, Kraus E, Joy E, Fredericson M. The Male Athlete Triad-A Consensus Statement From the Female and Male Athlete Triad Coalition Part 1: Definition and Scientific Basis. Clin J Sport Med. 2021 Jul 1;31(4):345-353. doi:

10.1097/JSM.0000000000000946. PMID: 34091537.

6. Loucks AB, Kiens B, Wright HH. Energy availability in athletes. J Sports Sci. 2011;29 Suppl 1:S7-15. doi: 10.1080/02640414.2011.588958. Epub 2011 Jul 28. PMID: 21793767.
7. Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, Warren MP; American College of Sports Medicine. American College of Sports Medicine position stand. The female athlete triad. Med Sci Sports Exerc. 2007 Oct;39(10):1867-82. doi: 10.1249/mss.0b013e318149f111. PMID: 17909417.
8. Loucks AB, Thuma JR. Luteinizing hormone pulsatility is disrupted at a threshold of energy availability in regularly menstruating women. J Clin Endocrinol Metab. 2003 Jan;88(1):297-311. doi: 10.1210/jc.2002-020369. PMID: 12519869.
9. Loucks AB. Energy balance and body composition in sports and exercise. J Sports Sci. 2004 Jan;22(1):1-14. doi: 10.1080/0264041031000140518. PMID: 14974441.
10. Koehler K, Achtzehn S, Braun H, Mester J, Schaenzer W. Comparison of self-reported energy availability and metabolic hormones to assess adequacy of dietary energy intake in young elite athletes. Appl Physiol Nutr Metab. 2013 Jul;38(7):725-33. doi: 10.1139/apnm-2012-0373. Epub 2013 Jan 30. PMID: 23980730.
11. van Erp-Baart AM, Saris WH, Binkhorst RA, Vos JA, Elvers JW. Nationwide survey on nutritional habits in elite athletes. Part I. Energy, carbohydrate, protein, and fat intake. Int J Sports Med. 1989 May;10 Suppl 1:S3-10. doi: 10.1055/s-2007-1024947. PMID: 2744927.
12. Heikura IA, Burke LM, Bergland D, Uusitalo ALT, Mero AA, Stellingwerff T. Impact of Energy Availability, Health, and Sex on Hemoglobin-Mass Responses Following Live-High-Train-High Altitude Training in Elite Female and Male Distance Athletes. Int J Sports Physiol Perform. 2018 Sep 1;13(8):1090-1096. doi: 10.1123/ijspp.2017-0547. Epub 2018 Sep 13. PMID: 29431548.
13. Stubbs RJ, O'Reilly LM, Whybrow S, Fuller Z, Johnstone AM, Livingstone MB, Ritz P, Horgan GW. Measuring the difference between actual and reported food intakes in the context of energy balance under laboratory conditions. Br J Nutr. 2014 Jun 14;111(11):2032-43. doi: 10.1017/S0007114514000154. Epub 2014 Mar 17. PMID: 24635904.
14. Shephard RJ, Aoyagi Y. Measurement of human energy expenditure, with particular reference to field studies: an historical perspective. Eur J Appl Physiol. 2012 Aug;112(8):2785-815. doi: 10.1007/s00421-011-2268-6. Epub 2011 Dec 11. PMID: 22160180.
15. Murakami H, Kawakami R, Nakae S, Nakata Y, Ishikawa-Takata K, Tanaka S, Miyachi M. Accuracy of Wearable Devices for Estimating Total Energy Expenditure: Comparison With Metabolic Chamber and Doubly Labeled Water Method. JAMA Intern Med. 2016 May 1;176(5):702-3. doi: 10.1001/jamainternmed.2016.0152. PMID: 26999758.
16. Heaney S, O’Connor H, Naughton G, Gifford J. Towards an understanding of the barriers to good nutrition for elite athletes. International Journal of Sports Science&Coaching. 2008 Sep; 3(3), 391–401. https://doi.org/10.1260/174795408786238542
17. Melin AK, Heikura IA, Tenforde A, Mountjoy M. Energy Availability in Athletics: Health, Performance, and Physique. Int J Sport Nutr Exerc Metab. 2019 Mar 1;29(2):152-164. doi: 10.1123/ijsnem.2018-0201. Epub 2019 Feb 26. PMID: 30632422.
18. Eichstadt M, Luzier J, Cho D, Weisenmuller C. Eating Disorders in Male Athletes. Sports Health. 2020 Jul/Aug;12(4):327-333. doi: 10.1177/1941738120928991. Epub 2020 Jun 11. PMID: 32525767; PMCID: PMC7787561.
19. Ferrand C, Brunet E. Perfectionism and risk for disordered eating among young French male cyclists of high performance. Percept Mot Skills. 2004 Dec;99(3 Pt 1):959-67. doi: 10.2466/pms.99.3.959-967. PMID: 15648494.
20. Filaire E, Rouveix M, Pannafieux C, Ferrand C. Eating Attitudes, Perfectionism and Body-esteem of Elite Male Judoists and Cyclists. J Sports Sci Med. 2007 Mar 1;6(1):50-7. PMID: 24149224; PMCID: PMC3778699.
21. 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. 2012 Feb;44(2):344-51. doi: 10.1249/MSS.0b013e31822dc809. PMID: 21775906.

22. Glace BW, Murphy CA, McHugh MP. Food intake and electrolyte status of ultramarathoners competing in extreme heat. J Am Coll Nutr. 2002 Dec;21(6):553-9. doi: 10.1080/07315724.2002.10719254. PMID: 12480801.
23. Eden BD, Abernethy PJ. Nutritional intake during an ultraendurance running race. Int J Sport Nutr. 1994 Jun;4(2):166-74. doi: 10.1123/ijsn.4.2.166. PMID: 8054961.
24. Petrie HJ, Stover EA, Horswill CA. Nutritional concerns for the child and adolescent competitor. Nutrition. 2004 Jul-Aug;20(7-8):620-31. doi: 10.1016/j.nut.2004.04.002. PMID: 15212744.
25. Rico-Sanz J, Frontera WR, Molé PA, Rivera MA, Rivera-Brown A, Meredith CN. Dietary and performance assessment of elite soccer players during a period of intense training. Int J Sport Nutr. 1998 Sep;8(3):230-40. doi: 10.1123/ijsn.8.3.230. PMID: 9738133.
26. Bhasin S, Cunningham GR, Hayes FJ, Matsumoto AM, Snyder PJ, Swerdloff RS, Montori VM. Testosterone therapy in adult men with androgen deficiency syndromes: an endocrine society clinical practice guideline. J Clin Endocrinol Metab. 2006 Jun;91(6):1995-2010. doi: 10.1210/jc.2005-2847. Epub 2006 May 23. Erratum in: J Clin Endocrinol Metab. 2006 Jul;91(7):2688. Erratum in: J Clin Endocrinol Metab. 2021 Jun 16;106(7):e2843. PMID: 16720669.
27. Boloña ER, Uraga MV, Haddad RM, Tracz MJ, Sideras K, Kennedy CC, Caples SM, Erwin PJ, Montori VM. Testosterone use in men with sexual dysfunction: a systematic review and meta-analysis of randomized placebo-controlled trials. Mayo Clin Proc. 2007 Jan;82(1):20-8. doi: 10.4065/82.1.20. PMID: 17285782.
28. Kumar P, Kumar N, Thakur DS, Patidar A. Male hypogonadism: Symptoms and treatment. J Adv Pharm Technol Res. 2010 Jul;1(3):297-301. doi: 10.4103/0110-5558.72420. PMID: 22247861; PMCID: PMC3255409.
29. Henning PC, Scofield DE, Spiering BA, Staab JS, Matheny RW Jr, Smith MA, Bhasin S, Nindl BC. Recovery of endocrine and inflammatory mediators following an extended energy deficit. J Clin Endocrinol Metab. 2014 Mar;99(3):956-64. doi: 10.1210/jc.2013-3046. Epub 2013 Dec 11. PMID: 24423293.
30. Langan-Evans C, Germaine M, Artukovic M, Oxborough DL, Areta JL, Close GL, Morton JP. The Psychological and Physiological Consequences of Low Energy Availability in a Male Combat Sport Athlete. Med Sci Sports Exerc. 2021 Apr 1;53(4):673-683. doi: 10.1249/MSS.0000000000002519. PMID: 33105389.
31. Narla A, Kaiser K, Tannock LR. EXTREMELY LOW TESTOSTERONE DUE TO RELATIVE ENERGY DEFICIENCY IN SPORT: A CASE REPORT. AACE Clin Case Rep. 2018 Nov 1;5(2):e129-e131. doi: 10.4158/ACCR-2018-0345. PMID: 31967017; PMCID: PMC6873856.
32. Hackney AC. Hypogonadism in Exercising Males: Dysfunction or Adaptive-Regulatory Adjustment? Front Endocrinol (Lausanne). 2020 Jan 31;11:11. doi: 10.3389/fendo.2020.00011. PMID: 32082255; PMCID: PMC7005256.
33. Blank JL, Desjardins C. Spermatogenesis is modified by food intake in mice. Biol Reprod. 1984 Mar;30(2):410-5. doi: 10.1095/biolreprod30.2.410. PMID: 6704472.
34. Cameron JL, Nosbisch C. Suppression of pulsatile luteinizing hormone and testosterone secretion during short term food restriction in the adult male rhesus monkey (Macaca mulatta). Endocrinology. 1991 Mar;128(3):1532-40. doi: 10.1210/endo-128-3-1532. PMID: 1999171.
35. Cormie P, Newton RU, Taaffe DR, Spry N, Joseph D, Akhlil Hamid M, Galvão DA. Exercise maintains sexual activity in men undergoing androgen suppression for prostate cancer: a randomized controlled trial. Prostate Cancer Prostatic Dis. 2013 Jun;16(2):170-5. doi: 10.1038/pcan.2012.52. Epub 2013 Jan 15. PMID: 23318529.
36. Daly W, Seegers CA, Rubin DA, Dobridge JD, Hackney AC. Relationship between stress hormones and testosterone with prolonged endurance exercise. Eur J Appl Physiol. 2005 Jan;93(4):375-80. doi: 10.1007/s00421-004-1223-1. Epub 2004 Nov 20. PMID: 15618989.
37. Hackney AC, Szczepanowska E, Viru AM. Basal testicular testosterone production in endurance-trained men is suppressed. Eur J Appl Physiol. 2003 Apr;89(2):198-201. doi: 10.1007/s00421-003-0794-6. Epub 2003 Feb 28. PMID: 12665985.
38. Bennell KL, Brukner PD, Malcolm SA. Effect of altered reproductive function and lowered

testosterone levels on bone density in male endurance athletes. Br J Sports Med. 1996 Sep;30(3):205-8. doi: 10.1136/bjsm.30.3.205. PMID: 8889111; PMCID: PMC1332330.

39. Wheeler GD, Wall SR, Belcastro AN, Cumming DC. Reduced serum testosterone and prolactin levels in male distance runners. JAMA. 1984 Jul 27;252(4):514-6. PMID: 6429357.
40. Hackney AC, Lane AR. Low testosterone in male endurance-trained distance runners: impact of years in training. Hormones (Athens). 2018 Mar;17(1):137-139. doi: 10.1007/s42000-018-0010-z. Epub 2018 Apr 27. PMID: 29858867.
41. Roberts AC, McClure RD, Weiner RI, Brooks GA. Overtraining affects male reproductive status. Fertil Steril. 1993 Oct;60(4):686-92. doi: 10.1016/s0015-0282(16)56223-2. PMID: 8405526.
42. Arce JC, De Souza MJ, Pescatello LS, Luciano AA. Subclinical alterations in hormone and semen profile in athletes. Fertil Steril. 1993 Feb;59(2):398-404. PMID: 8425638.
43. Wheeler GD, Singh M, Pierce WD, Epling WF, Cumming DC. Endurance training decreases serum testosterone levels in men without change in luteinizing hormone pulsatile release. J Clin Endocrinol Metab. 1991 Feb;72(2):422-5. doi: 10.1210/jcem-72-2-422. PMID: 1899423.
44. Hackney AC, Fahrner CL, Gulledge TP. Basal reproductive hormonal profiles are altered in endurance trained men. J Sports Med Phys Fitness. 1998 Jun;38(2):138-41. PMID: 9763799.
45. Hooper DR, Kraemer WJ, Saenz C, Schill KE, Focht BC, Volek JS, Maresh CM. The presence of symptoms of testosterone deficiency in the exercise-hypogonadal male condition and the role of nutrition. Eur J Appl Physiol. 2017 Jul;117(7):1349-1357. doi: 10.1007/s00421-017-3623-z. Epub 2017 May 3. PMID: 28470410.
46. Keay N, Francis G, Entwistle I, Hind K. Clinical evaluation of education relating to nutrition and skeletal loading in competitive male road cyclists at risk of relative energy deficiency in sports (RED-S): 6-month randomised controlled trial. BMJ Open Sport Exerc Med. 2019 Mar 29;5(1):e000523. doi: 10.1136/bmjsem-2019-000523. PMID: 31191973; PMCID: PMC6539156.
47. Torstveit MK, Fahrenholtz I, Stenqvist TB, Sylta Ø, Melin A. Within-Day Energy Deficiency and Metabolic Perturbation in Male Endurance Athletes. Int J Sport Nutr Exerc Metab. 2018 Jul 1;28(4):419-427. doi: 10.1123/ijsnem.2017-0337. Epub 2018 Jun 26. PMID: 29405793.
48. Kupchak BR, Kraemer WJ, Hoffman MD, Phinney SD, Volek JS. The impact of an ultramarathon on hormonal and biochemical parameters in men. Wilderness Environ Med. 2014 Sep;25(3):278-88. doi: 10.1016/j.wem.2014.03.013. Epub 2014 Jun 13. PMID: 24931590.
**49.** Woods AL, Rice AJ, Garvican-Lewis LA, Wallett AM, Lundy B, Rogers MA, Welvaert M, Halson S, McKune A, Thompson KG. The effects of intensified training on resting metabolic rate (RMR), body composition and performance in trained cyclists. PLoS One. 2018 Feb 14;13(2):e0191644. doi: 10.1371/journal.pone.0191644. PMID: 29444097; PMCID: PMC5812577.
50. 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. 2018 Oct 4;4(1):e000424. doi: 10.1136/bmjsem-2018-000424. PMID: 30364549; PMCID: PMC6196965.
51. Sheffield-Moore M, Urban RJ. An overview of the endocrinology of skeletal muscle. Trends Endocrinol Metab. 2004 Apr;15(3):110-5. doi: 10.1016/j.tem.2004.02.009. PMID: 15046739.
52. Križaj L, Kozinc Ž, Löfler S, Šarabon N. The chronic effects of eccentric exercise interventions in different populations: an umbrella review. Eur J Transl Myol. 2022 Oct 21;32(4):10876. doi: 10.4081/ejtm.2022.10876. PMID: 36269123; PMCID: PMC9830406.
53. Logue DM, Madigan SM, Heinen M, McDonnell SJ, Delahunt E, Corish CA. Screening for risk of low energy availability in athletic and recreationally active females in Ireland. Eur J Sport Sci. 2019 Feb;19(1):112-122. doi: 10.1080/17461391.2018.1526973. Epub 2018 Oct 10. PMID: 30303470.
54. Hackney AC, Moore AW, Brownlee KK. Testosterone and endurance exercise: development of the "exercise-hypogonadal male condition". Acta Physiol Hung. 2005;92(2):121-37. doi: 10.1556/APhysiol.92.2005.2.3. PMID: 16268050.
55. Cesanelli L, Eimantas N, Iovane A, Messina G, Satkunskiene D. The role of age on neuromuscular performance decay induced by a maximal intensity

sprint session in a group of competitive endurance athletes. Eur J Transl Myol. 2022 Mar 10;32(1):10378. doi: 10.4081/ejtm.2022.10378. PMID: 35330561; PMCID: PMC8992664.

### Disclaimer

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

Submitted: December 19, 2022
Accepted for publication: March 17, 2023