Journal of Science and Medicine in Sport 24 (2021) 995–1001

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Review

Feeding female soldiers: Consideration of sex-specific nutrition recommendations to optimise the health and performance of military personnel

Sophie L. Wardle [a,b,1,*], Thomas J. O'Leary [a,b], James P. McClung [c,1], Stefan M. Pasiakos [c,1], Julie P. Greeves [a,b,d]

[a] Army Health and Performance Research, Army Headquarters, United Kingdom
[b] Division of Surgery and Interventional Science, University College London, United Kingdom
[c] Military Nutrition Division, US Army Research Institute of Environmental Medicine, United States of America
[d] Norwich Medical School, University of East Anglia, United Kingdom

ARTICLE INFO

Article history:
Received 29 June 2020
Received in revised form 25 June 2021
Accepted 11 August 2021
Available online 18 August 2021

Keywords:
Feeding strategies
Sex-differences
Muscle mass
Energy deficit
Reproductive health
Bone health

ABSTRACT

Appropriate nutrition recommendations are required to optimise the health and performance of military personnel, yet limited data are available on whether male and female military personnel have different nutrition requirements.
Objectives: To consider the evidence for sex-specific nutrition requirements to optimise the health and performance of military personnel.
Design: Narrative review.
Methods: Published literature was reviewed, with a focus on sex-specific requirements, in the following areas: nutrition for optimising muscle mass and function, nutrition during energy deficit, and nutrition for reproductive and bone health.
Results: There are limited data on sex differences in protein requirements but extant data suggest that, despite less muscle mass, on average, in women, sex-specific protein feeding strategies are not required to optimise muscle mass in military-aged individuals. Similarly, despite sex differences in metabolic and endocrine responses to energy deficit, current data do not suggest a requirement for sex-specific feeding strategies during energy deficit. Energy deficit impairs health and performance, most notably bone and reproductive health and these impairments are greater for women. Vitamin D, iron and calcium are important nutrients to protect the bone health of female military personnel due to increased risk of stress fracture.
Conclusions: Women have an increased incidence of bone injuries, less muscle mass and are more susceptible to the negative effects of energy deficit, including compromised reproductive health. However, there are limited data on sex differences in response to various nutrition strategies designed to improve these elements of health and performance. Future studies should evaluate whether sex-specific feeding recommendations are required.

Practical implications

Based on limited data directly addressing sex-specific feeding requirements (Fig. 1), the authors suggest the following recommendations would make best practise for female military personnel for bone, muscle and reproductive health. Although these recommendations are not based on a quantitative evaluation or meta-analysis, they are the result of a comprehensive search of the available literature coupled with the authors' significant experience in the field. We suggest that these recommendations may also benefit other athlete and physically arduous occupational groups, where appropriate.

- Consume at least 20 g of high-quality protein in an energy-sufficient state to optimally stimulate MPS following whole-body resistance exercise;
- Consume 4 to 8 $g \cdot kg \cdot d^{-1}$ carbohydrate and 1.5 to 2.0 $g \cdot kg \cdot d^{-1}$ protein to preserve performance and muscle mass during energy deficit;
- Ensure an energy availability of 45 $kcal \cdot kgFFM \cdot d^{-1}$, where possible, to preserve HPO function;
- Consume 18 $mg \cdot d^{-1}$ of dietary iron; consider providing multivitamin formulations with iron during basic military training;
- Consume at least 600 $IU \cdot d^{-1}$ vitamin D and 1000 $mg \cdot d^{-1}$ calcium; consider providing supplemental vitamin D and calcium during basic military training.

* Corresponding author.
E-mail address: sophielwardle@gmail.com (S.L. Wardle).
[1] The opinions or assertions contained herein are the private views of the author and are not to be construed as official or as reflecting the views of the US Army or the US Department of Defense.

https://doi.org/10.1016/j.jsams.2021.08.011
1440-2440/

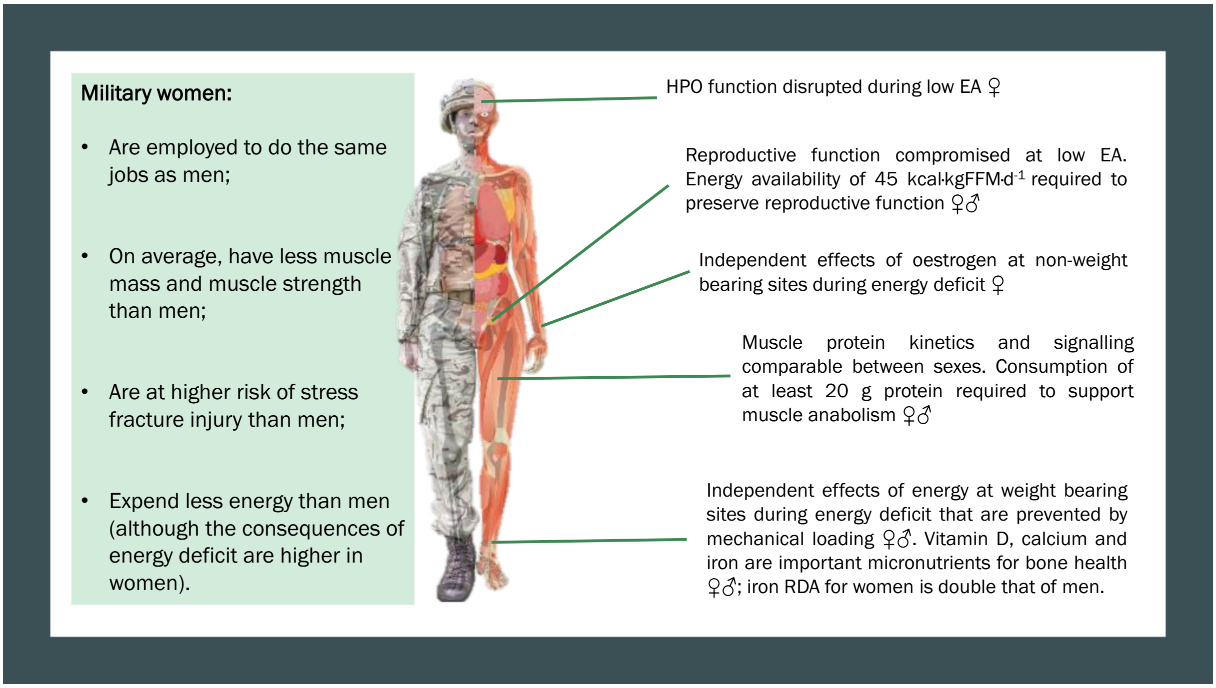

Fig. 1. Nutrition requirements of military women. Where ♀ indicates findings in women and ♂ indicates findings in men.

1. Introduction

Military training and employment can be physically and psychologically demanding. High total daily energy expenditures (TDEE) and/or energy deficits are commonly reported during military training courses.[1–6] Energy deficit is associated with negative whole-body protein balance,[7,8] decreased lean body mass[3,9] and muscle performance,[3,9–13] impaired endocrine function,[3,4,9,14] uncoupled bone turnover[15,16] and a loss of bone mass.[4,16] Appropriate nutritional strategies are important for military personnel to prevent maladaptive effects of high TDEE on health and performance, and to promote muscle, bone and physical performance adaptations to high volumes of exercise.

Men and women demonstrate phenotypic and physiological differences, mediated in part by differences in sex steroid concentrations from puberty. Women typically are shorter, have more body fat, less lean muscle mass, relatively fewer type II muscle fibres, less bone mass, and smaller bones (narrower cross-sectional area and thinner cortex) than men.[17,18] Women also oxidise more fat and less carbohydrate and amino acids than men during exercise at the same relative intensity.[19] These physiological sex differences result in women, on average, demonstrating poorer physical performance than men.[17,18] Although men and women must complete identical military tasks in the UK and US Armed Forces, women have lower TDEE but higher physiological strain,[20,21] and a two- to three-fold higher risk of musculoskeletal injury[22–24] and stress fracture,[25] compared with men in military training. Women may also be more susceptible to the maladaptive effects of military training in energy deficit on endocrine[12] and reproductive function.[26] Lower TDEE in women may, however, confer an advantage by attenuating energy deficits and lean mass losses compared with men.[12,27]

Women across many nations are now allowed to operate in arduous ground close combat roles, which demand high levels of physical fitness to meet the physical employment standards for their role. Training for the extreme operating environments of combat roles involves regular exposure to the physiological challenges of high levels of physical activity, restricted eating, sleep loss and psychological stress. Given the anatomical, hormonal and physical performance sex differences, and sex differences in the physiological responses and musculoskeletal injury risk during military training, it is reasonable to question whether feeding strategies in the military should differ between men and women. The effects of nutritional interventions on physical performance, endocrine and musculoskeletal adaptations to military training are well studied,[4,7,9,11,14,28] but sex-specific requirements have not been considered. The aim of this review is to consider the evidence for sex-specific nutrition requirements to optimise the health and performance of military personnel.

2. Nutrition for muscle mass and function

There are clear differences in skeletal muscle mass between men and women that appear from puberty and continue into older age.[29] Women, on average, have less skeletal muscle mass than men, particularly in the upper body,[30] and demonstrate poorer physical performance in several athletic and occupational tasks. Differences in skeletal muscle mass can almost exclusively explain the performance variance between men and women in generating muscle force[31] and power.[32] Beyond physical performance, skeletal muscle also plays an important role in metabolic health and provides a vital amino acid reservoir during periods of nutritional deficit.[33] With many militaries now permitting women to serve in combat roles, nutritional strategies that can increase, or preserve, skeletal muscle mass during periods of intense training or energy deficit may have important implications for female performance in these physically demanding occupations.

Skeletal muscle mass is regulated by the continual metabolic processes of muscle protein synthesis (MPS) and muscle protein breakdown (MPB). Muscle accrual occurs when the rate of MPS exceeds MPB, whereas muscle loss occurs when the rate of MPB exceeds MPS. Food, particularly protein, intake and resistance exercise are the main regulators of MPS in healthy people.[29] In the post-absorptive state, there is no difference in basal MPS, measured as mixed-muscle fractional synthetic rate (FSR)[34–37] or whole-body protein kinetics[38] between young men and women, despite sex differences in older (>65 y) individuals (reviewed in Smith & Mittendorfer[29] and Trommelen et al.[39]). Similarly, no differences in mixed-muscle FSR or mammalian target of rapamycin complex 1 (mTORC1) — a primary regulator of muscle anabolism — signalling are reported between young men and women in response to a hyperinsulinemic-hyperaminoacidemic clamp[36] or resistance exercise,[35] and muscle mass changes following resistance training[40,41] and disuse[42] are largely comparable between sexes. Similar responses of myofibrillar FSR and p70S6K1 — a signalling protein downstream of mTORC1 — signalling to combined resistance exercise and amino acid provision in men and women are also reported, despite a 45-fold greater post-exercise serum testosterone concentration and greater mTORC1 phosphorylation (activation) in men.[37] Although women in this study demonstrated a similar MPS response to combined resistance exercise and protein as men, the 25 g absolute protein dose administered resulted in women consuming a higher relative protein dose.

The optimal protein dose achieves a balance between maximally stimulating MPS by exceeding the leucine threshold[43] without consuming excess amino acids beyond the point at which the muscle can no longer utilise the additional amino acids, termed the muscle full effect.[44] The optimal dose of protein for maximising MPS following resistance exercise in young individuals has been derived from studies predominantly conducted in men, and is considered to be 20 to 40 g of high-quality protein (~10 to 15 g essential amino acids).[45–48] A relative protein dose recommendation of 0.31 $g{\cdot}kgBM^{-1}$ was derived from cut-point analysis of several protein feeding with resistance exercise studies.[49] However, to derive optimal protein recommendations for female soldiers, several questions remain: 1) what is the impact of lean mass (across a greater range than previously studied) on these responses, and; 2) what is the impact of whole-body exercise on protein dose requirements. Better understanding of the effect of lean mass and a whole-body exercise stimulus is essential for understanding military specific protein requirements for men and women. Macnaughton et al.[48] demonstrated 40 g whey protein intake was more effective than 20 g for stimulating MPS following whole-body resistance exercise irrespective of lean body mass (men with <65 kg *vs* >70 kg lean mass). However, the difference in FSR between doses was comparable to other studies and the results require replication. The saturating protein dose for MPS following whole-body exercise, and thus the notion of protein requirements based on lean mass, remains to be fully determined. These studies are also limited by the measurement of acute responses in isolated muscle samples.

Recent advancement of the Indicator Amino Acid Oxidation technique has provided valuable data on whole-body protein requirements of men and women in specific exercising contexts, for example during resistance and endurance exercise. Estimated protein requirements of 1.71 to 1.93 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ for trained women performing variable-intensity intermittent exercise[50] and resistance exercise,[51] are comparable to estimates of 1.64 to 2.00 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ in men performing the same exercise modalities,[52,53] suggesting women performing exercise training have similar protein requirements to men. However, these studies did not directly compare men and women doing the same exercise and thus we cannot decisively conclude whether there are any sex differences in protein requirements. Further studies are required to establish whether different protein feeding recommendations are required for men and women, or individuals with varying muscle mass, and to determine the protein requirements of individuals engaged in military relevant physically arduous exercise to optimise whole-body and muscle protein turnover.

3. Nutrition during energy deficit

Recommendations for optimising muscle mass are grounded in the premise that individuals are consuming sufficient energy to meet their metabolic demands. However, military personnel engaged in strenuous training and combat operations routinely experience periods of energy deficit (*i.e.*, percent of dietary energy intake needed to achieve energy balance and maintain body mass), caused by high TDEE and limited energy intake.[1,2] For example, US Marines participating in the US Marine Corps Forces Special Operations Command Individual Training Course expended 6376 $kcal{\cdot}d^{-1}$ during a 9 day simulated combat operation, but only consumed 2410 $kcal{\cdot}d^{-1}$, resulting in a 62% daily energy deficit. The energy deficits observed in US Marines were comparable to those recently demonstrated in US Army Special Forces Soldiers (52%)[6] and Norwegian Army Infantry Soldiers (50 to 54%)[7,10] participating in similar training exercises. Although these data are largely from men, high energy deficits are observed in both men and women during operational demands and field-based training.[54–56] The physiological consequences associated with severe energy deficits are, in large part, dictated by the duration and magnitude of the deficit incurred and its subsequent effects on body composition.[13,57] Sustained or repeated exposure to severe energy deficits can rapidly deplete endogenous energy stores (*i.e.*, muscle and liver glycogen and body fat) and accelerate muscle protein catabolism. If energy deficits are not attenuated by increasing dietary energy intake or by modifying dietary composition, muscle mass loss may occur and physical performance may be impaired.[13]

The physiological consequences of severe energy deficit and the development of nutritional strategies to mitigate muscle loss and sustain physical performance have been studied extensively. In recent years, studies have focused on the amount of dietary protein necessary to meet whole-body protein requirements and limit the catabolic effects of energy deficit on muscle mass (reviewed in Carbone et al.[58]). The amount of dietary carbohydrate required to maintain glycogen status and fuel exercise metabolism during military operations has also been thoroughly studied (reviewed in Montain & Young[59]). As a result, carbohydrate intakes of 4 to 8 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ (>55% total energy intake) and protein intakes of 1.5 to 2.0 $g{\cdot}kg^{-1}{\cdot}d^{-1}$ are recommended for military personnel exposed to energy deficit during strenuous operations.[59,60] However, studies that formed the basis of carbohydrate and protein recommendations for strenuous military operations were conducted mostly in men and do not account for the potential that men and women may respond differently to physiological stress. Whether these putative differences affect nutrition recommendations for strenuous military operations also remains to be understood. These questions are of practical relevance to modern militaries, as combat roles are no longer exclusive to men; a growing number of women are taking on combat occupations and are more likely to be exposed to energy deficits.

The effect of sex on energy expenditure and substrate metabolism responses to exercise may have implications for dietary requirements on strenuous military operations. Absolute TDEEs ($kcal{\cdot}d^{-1}$) during military operations are lower for women than men because of their lower body mass,[27,55] and the lower energy requirements may make energy balance more attainable for women than men when subsisting on the same foods. Women also oxidise proportionately more fat and men more carbohydrate and protein during low-to-moderate intensity prolonged exercise, regardless of training status.[61,62] Interestingly, the inverse is observed in recovery whereby fat oxidation is higher in men than women,[63] and these differences are no longer evident at higher exercise intensities.[64] There also appears to be no sex differences in capability to resynthesise muscle glycogen after exercise.[65,66] Nevertheless, greater reliance on body fat to fuel low-to-moderate intensity exercise suggests women may be more resilient to muscle loss during energy deficit than men. In support, Hoyt et al.,[54] demonstrated greater fat oxidation and less fat-free mass loss in female *versus* male soldiers participating in a 7 day training exercise in severe energy deficit. These findings have not been confirmed, yet they do provide some evidence that women may respond differently, at least metabolically, to strenuous military operations than men.

Most of the observed sex differences in exercise and post-exercise metabolism that could affect how women should be fed during military operations are attributable, in large part, to fluctuations in oestrogen and progesterone during the menstrual cycle.[19] For example, men exhibited the same substrate oxidative responses to exercise (*i.e.*, greater fat and lower glucose and protein oxidation) as women when supplemented with oestrogen.[67,68] In addition, while muscle protein turnover responses to resistance exercise and protein feeding are similar between sexes,[37] whole-body protein catabolism may be higher when women perform moderate-to-vigorous aerobic exercise during the luteal phase than during the follicular phase of their menstrual cycle.[69] Although there is limited evidence to suggest men and women respond physiologically differently to strenuous military operations, the endocrine-mediated disparities in exercise and post-exercise metabolism, between sexes, support the need to study sex-specific operational nutritional requirements as militaries continue to integrate women into combat occupations. Women may also be at increased risk of some of the negative consequences of energy deficit on health, notably reproductive health.[70,71]

4. Nutrition for reproductive health

The impact of employment in the physically demanding combat roles on female soldier physiology is not yet clear. Chronic, episodic exposure to reduced energy availability and psychological stress likely impairs hypothalamic-pituitary-adrenal (HPA) and hypothalamic-pituitary-ovarian (HPO) axis function, leading to low circulating oestrogen.[26] The physiological impact of altered HPA and HPO signalling include bone stress injuries, exacerbated by heavy load carrying activities of infantry soldiering,[17,72] and women suffer an increased risk of bone stress injuries than men during basic military training.[25,72] Men experience greater energy deficits than women undertaking the same training because of their larger body size,[54] but women may still experience a greater clinical impact of even modest reductions in energy availability on reproductive function and bone.[73,74]

The complex relationship between energy deficiency, reproductive status, and bone health, is a widely recognised clinical syndrome in female athletes. Disordered eating, amenorrhoea and osteoporosis in women typically engaged in arduous, weight-bearing sports, are the clinical endpoints of the Female Athlete Triad ('Triad'),[75] but exist along a spectrum of reduced energy availability, menstrual disturbances and decreased bone mass/stress fractures.[76] The 'Triad' is a clinical phenomenon originally identified as unique to women; insufficient energy availability disrupts HPO signalling, characterised by altered luteinising pulsatility, and suppresses oestrogen production that, in turn, causes mineral loss from bone.[76] More recently, the potential widespread effects of energy deficiency on health and performance have been recognised in the *relative energy deficiency in sports* (RED-S) syndrome, which acknowledges the negative effects of energy deficit in both women and men,[77,78] but the clinical evidence is currently still strongest for reproductive and bone health. A threshold of optimal energy availability to sustain physiological function — adjusted for exercise energy expenditure — is 45 $\text{kcal}\cdot\text{kgFFM}\cdot\text{d}^{-1}$, and *non-essential* physiological systems such as the menstrual cycle stop functioning below this threshold to conserve energy.[76,78,79] The classic 'Triad' has not been detected in female service personnel,[26,80] but several studies have demonstrated menstrual cycle disturbances or compromised bone health in this population.[71,80–83]

Early menstrual cycle disturbances (luteal phase deficiency, anovulation) can occur when cycle lengths are still 'regular' (24 to 35 days), but chronic low energy availability results in menstrual irregularity *(oligomenorrhoea)* and complete suppression of menses *(amenorrhoea)*.[26] The prevalence of menstrual disturbances in military populations is not well studied. Cross sectional studies have reported menstrual irregularities in 11 to 15% of cohorts.[80,81] Retrospective and prospective studies of basic military training studies reported menstrual cycle changes or irregularities in ≥90% of women, coincident with increased energy expenditure and psychological stress; most women (73%) reported a regular menstrual cycle prior to training.[82,83] The quality of these studies is poor, however; hormonal contraceptive use and energy status are not measured or controlled for, and methods of measuring menstrual irregularities are inconsistent, limiting the interpretation of these findings. A prospective study in British Army Officer Cadets during 44 weeks of basic training observed: an increase in the prevalence of menstrual disturbances from 25% at week 14 to 65% at week 28; cessation of ovulation in almost all women; and, suppression of the HPO axis (determined from *gonadorelin* infusion) at week 28.[84] The development of menstrual dysfunction in these women occurred in concert with high TDEE sustained during the whole training course, and low energy availability measured intermittently during in-barrack and field exercise.[84,85] Function of the HPA axis was preserved,[86] which supports a greater role of energy availability than psychological stress in the pathogenesis of menstrual dysfunction.

Amenorrhoea, a clinical endpoint of severe and prolonged energy restriction, is associated with impaired bone health; bone mass,[87,88] architecture and strength,[87–90] are deteriorated in amenorrhoeic athletes compared with eumenorrhoeic counterparts. Menstrual disturbances in servicewomen are accompanied by an increased risk of stress fractures[81,91–94] and musculoskeletal injuries,[95] and low bone mass,[96] although these findings are not supported by all studies.[80,97–101] Less severe energy restriction (≥30 $\text{kcal}\cdot\text{kgFFM}\cdot\text{d}^{-1}$), however, impairs bone metabolism independent of reproductive and oestrogen status in a dose-dependent manner by suppressing bone formation.[102] Low insulin-like growth factor I (IGF-I) and leptin, and elevated cortisol, can decrease bone formation.[76] Decreased IGF-I, a surrogate biochemical marker of low EA and an important mediator of bone formation, has been detected in female stress fracture cases but not in non-injured control recruits,[103] although a causal link has not been confirmed. Recent studies also suggest site-specific effects of oestrogen *and* energy deficiency on the skeleton, modulated by protective effects of mechanical loading. Low oestrogen affects the non-weight bearing radius,[87,89,90] whereas energy deficiency selectively affects the weight-bearing tibia; but, mechanical loading preserves tibial bone strength under conditions of energy[16] and oestrogen deficiency.[87,89]

Adequate energy intake is required for women in arduous roles to preserve menstrual function, prevent skeletal injuries and optimise bone health, particularly at *pinch point* periods of heightened energy expenditure; better evidence is required to determine when these periods might be. Adequate energy intake, matching the physical demands of training and operations, will also more likely provide recommended intakes of the bone protective nutrients calcium, iron, protein and vitamin D.

5. Nutrition for bone health

Musculoskeletal injury is a leading cause of lost duty days and attrition from military service. Stress fractures, associated with overuse and unaccustomed physical activities during basic military training, are among the most common musculoskeletal injuries and may affect up to 5% of male recruits and 21% of female recruits.[91,104] Stress fractures have a significant impact on military readiness, burden the military healthcare system, and come at a great personal cost to female military personnel, as over half of female recruits that experience stress fractures during basic military training attrite from military service.[104] Many innate factors contribute to stress fracture risk, including sex, genetics, and race.[105] Optimising nutrition may reduce stress fracture risk and improve the health and performance of military personnel. In addition to adequate energy, iron, calcium, and vitamin D are important nutrients for bone health and are of particular importance to female military personnel.

Iron, a nutritionally essential mineral, confers physiological function through incorporation into a series of proteins and enzymes. Proteins include haemoglobin and myoglobin, critical for the transport and storage of oxygen. Enzymes include cytochrome *c*, NADH oxidase, and others that function in energy metabolic pathways. Due to the critical roles of these proteins and enzymes in oxygen transport, storage and energy metabolism, the physiological consequences of poor iron status, particularly iron deficiency anaemia (IDA, diminished haemoglobin) on physical and cognitive performance are stark and have been well described.[106] Iron also functions in the maintenance of bone health. Iron is a mineral component of bone and contributes to the synthesis of collagen, a significant component of bone protein. Although clinical trials directly evaluating the role of iron in bone health are limited, animal studies suggest a link between iron status and bone strength, mineralization, and density,[107,108] and studies with healthy postmenopausal women suggest a relationship between dietary iron and bone mineral density.[109] Studies have linked iron status to stress fracture in female military personnel; female recruits serving in the Israeli Defense Force (IDF) that suffered stress fractures had reduced biomarkers of iron status,[110] and stress fracture incidence is increased in female personnel with IDA.[111]

Dietary iron is of particular importance for female military personnel as the requirement is more than double for women as compared with men. Significant reductions in iron status of female military recruits have been reported during basic military training and have been linked to physical performance, including running time.[112,113] Iron supplementation provides some benefit to female recruits during basic military training, as randomised, controlled trials have demonstrated positive effects on physical and cognitive performance, particularly in recruits that begin training with IDA.[28] Identifying feeding solutions to optimise iron status in military personnel is challenging due to sex differences in dietary requirements and poor iron bioavailability in fortified food products. In recent years the US and other nations have focused on providing increased education regarding iron nutrition to female recruits, along with the option to consume a daily multivitamin supplement containing iron. Although controlled trials have not assessed the efficacy of such programs, an observational study in US Air Force recruits noted positive impacts on medical attrition and stress fracture.[114]

Calcium and vitamin D are critical for the optimisation of bone health and the prevention of stress fracture in military personnel, as calcium is the largest mineral component of bone (over 99%), and vitamin D regulates calcium metabolism. Although the dietary requirements for calcium and vitamin D are not different between women and men, research has focussed on the role of these nutrients in preventing stress fracture in female military personnel due to the significantly increased risk for injury in this population. A study of female US Navy recruits reported that higher vitamin D status was associated with protection from stress fracture.[115] Further, a systematic review and meta-analysis reported the association between vitamin D status and stress fracture incidence; 8 studies were included in the analyses, vitamin D status at time of both entry to training and at the time of diagnosis was lower in recruits that suffered stress fractures during basic military training compared with those that did not.[116] Randomised, controlled trials have demonstrated the efficacy of vitamin D supplementation for the prevention of stress fracture and optimisation of bone health. Lappe and colleagues[117] enrolled over 5200 female US Navy recruits and provided 2000 mg calcium and 800 IU vitamin D per day or placebo during basic military training; calcium and vitamin D reduced stress fracture incidence by 20%. In a more recent trial, Gaffney-Stomberg and colleagues[118] enrolled over 200 male and female US Army recruits and provided 2000 mg calcium and 1000 IU vitamin D per day or placebo during basic military training; calcium and vitamin D improved bone structure as assessed using peripheral quantitative computed tomography.

Studies demonstrating the efficacy of vitamin D and calcium to prevent stress fracture and optimise bone health have led to the development of fortified food products for use during basic military training. In the US, the "Performance Readiness Bar", a product containing approximately 2000 mg of calcium and 1000 IU of vitamin D is now provided once daily to all US Army recruits. The impact of this program on stress fracture incidence has not yet been assessed, although studies are underway.

6. Conclusions

Data directly addressing sex differences in nutrient requirements are lacking and should be prioritised in future studies. Based on the available evidence, women would benefit from ensuring adequate iron, vitamin D and calcium intake to protect bone health, and adequate protein and energy to support muscle mass growth/preservation and reproductive function.

Funding information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of interest statement

No conflicts of interest.

Confirmation of ethical compliance

This paper is a review and did not require ethical compliance.

Acknowledgements

None.

References

1. Barringer ND, Pasiakos SM, McClung HL et al. Prediction equation for estimating total daily energy requirements of special operations personnel. *J Int Soc Sports Nutr* 2018;15:15.
2. Tassone EC, Baker BA. Body weight and body composition changes during military training and deployment involving the use of combat rations: a systematic literature review. *Br J Nutr* 2017;117(6):897-910.
3. Nindl BC, Barnes BR, Alemany JA et al. Physiological consequences of U.S. Army Ranger training. *Med Sci Sports Exerc* 2007;39(8):1380-1387.
4. Friedl KE, Moore RJ, Hoyt RW et al. Endocrine markers of semistarvation in healthy lean men in a multistressor environment. *J Appl Physiol (1985)* 2000;88(5):1820-1830.
5. Richmond VL, Horner FE, Wilkinson DM et al. Energy balance and physical demands during an 8-week arduous military training course. *Mil Med* 2014;179(4):421-427.
6. Margolis LM, Rood J, Champagne C et al. Energy balance and body composition during US Army special forces training. *Appl Physiol Nutr Metab* 2013;38(4):396-400.
7. Margolis LM, Murphy NE, Martini S et al. Effects of supplemental energy on protein balance during 4-d Arctic military training. *Med Sci Sports Exerc* 2016;48(8):1604-1612.
8. Pasiakos SM, Margolis LM, Orr JS. Optimized dietary strategies to protect skeletal muscle mass during periods of unavoidable energy deficit. *FASEB J* 2015;29(4):1136-1142.
9. Fortes MB, Diment BC, Greeves JP et al. Effects of a daily mixed nutritional supplement on physical performance, body composition, and circulating anabolic hormones during 8 weeks of arduous military training. *Appl Physiol Nutr Metab* 2011;36(6):967-975.
10. Margolis LM, Murphy NE, Martini S et al. Effects of winter military training on energy balance, whole-body protein balance, muscle damage, soreness, and physical performance. *Appl Physiol Nutr Metab* 2014;39(12):1395-1401.
11. Ofsteng SJ, Garthe I, Josok O et al. No effect of increasing protein intake during military exercise with severe energy deficit on body composition and performance. *Scand J Med Sci Sports* 2020;30(5):865-877.
12. Vikmoen O, Teien HK, Raustøl M, Aandstad A, Tansø R, Gulliksrud K, Skare M, Raastad T. Sex differences in the physiological response to a demanding military field exercise. *Scand J Med Sci Sports* 2020 Aug;30(8):1348-1359. doi:10.1111/sms.13689. Epub 2020 May 4. PMID: 32311789.
13. Murphy NE, Carrigan CT, Philip Karl J et al. Threshold of energy deficit and lower-body performance declines in military personnel: a meta-regression. *Sports Med* 2018;48(9):2169-2178.
14. Opstad PK, Falch D, Oktedalen O et al. The thyroid function in young men during prolonged exercise and the effect of energy and sleep deprivation. *Clin Endocrinol (Oxf)* 1984;20(6):657-669.
15. Hughes JM, Smith MA, Henning PC et al. Bone formation is suppressed with multi-stressor military training. *Eur J Appl Physiol* 2014;114(11):2251-2259.
16. O'Leary TJ, Gifford RM, Double RL et al. Skeletal responses to an all-female unassisted Antarctic traverse. *Bone* 2019;121:267-276.
17. Greeves JP. Physiological implications, performance assessment and risk mitigation strategies of women in combat-centric occupations. *J Strength Cond Res* 2015;29(Suppl 11):S94-100.
18. Nindl BC, Jones BH, Van Arsdale SJ et al. Operational physical performance and fitness in military women: physiological, musculoskeletal injury, and optimized physical training considerations for successfully integrating women into combat-centric military occupations. *Mil Med* 2016;181(1 Suppl):50-62.
19. Tarnopolsky MA. Sex differences in exercise metabolism and the role of 17-beta estradiol. *Med Sci Sports Exerc* 2008;40(4):648-654.
20. O'Leary TJ, Saunders SC, McGuire SJ et al. Sex differences in training loads during British Army basic training. *Med Sci Sports Exerc* 2018;50(12):2565-2574.

21. Blacker SD, Wilkinson DM, Rayson MP. Gender differences in the physical demands of British Army recruit training. *Mil Med* 2009;174(8):811-816.
22. Jones BH, Bovee MW, Harris 3rd JM et al. Intrinsic risk factors for exercise-related injuries among male and female army trainees. *Am J Sports Med* 1993;21(5):705-710.
23. Knapik JJ, Sharp MA, Canham-Chervak M et al. Risk factors for training-related injuries among men and women in basic combat training. *Med Sci Sports Exerc* 2001;33(6):946-954.
24. Blacker SD, Wilkinson DM, Bilzon JL et al. Risk factors for training injuries among British Army recruits. *Mil Med* 2008;173(3):278-286.
25. Wentz L, Liu PY, Haymes E et al. Females have a greater incidence of stress fractures than males in both military and athletic populations: a systemic review. *Mil Med* 2011;176(4):420-430.
26. Gifford RM, Reynolds RM, Greeves J et al. Reproductive dysfunction and associated pathology in women undergoing military training. *J R Army Med Corps* 2017;163(5):301-310.
27. Hoyt RW, Friedl KE. Field studies of exercise and food deprivation. *Curr Opin Clin Nutr Metab Care* 2006;9(6):685-690.
28. McClung JP, Karl JP, Cable SJ et al. Randomized, double-blind, placebo-controlled trial of iron supplementation in female soldiers during military training: effects on iron status, physical performance, and mood. *Am J Clin Nutr* 2009;90(1):124-131.
29. Smith GI, Mittendorfer B. Sexual dimorphism in skeletal muscle protein turnover. *J Appl Physiol (1985)* 2016;120(6):674-682.
30. Janssen I, Heymsfield SB, Wang ZM et al. Skeletal muscle mass and distribution in 468 men and women aged 18-88 yr. *J Appl Physiol (1985)* 2000;89(1):81-88.
31. Miller AE, MacDougall JD, Tarnopolsky MA et al. Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol* 1993;66(3):254-262.
32. Perez-Gomez J, Rodriguez GV, Ara I et al. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol* 2008;102(6):685-694.
33. Wolfe RR. The underappreciated role of muscle in health and disease. *Am J Clin Nutr* 2006;84(3):475-482.
34. Fujita S, Rasmussen BB, Bell JA et al. Basal muscle intracellular amino acid kinetics in women and men. *Am J Physiol Endocrinol Metab* 2007;292(1):E77-E83.
35. Dreyer HC, Fujita S, Glynn EL et al. Resistance exercise increases leg muscle protein synthesis and mTOR signalling independent of sex. *Acta Physiol (Oxford)* 2010;199(1):71-81.
36. Smith GI, Atherton P, Reeds DN et al. No major sex differences in muscle protein synthesis rates in the postabsorptive state and during hyperinsulinemia-hyperaminoacidemia in middle-aged adults. *J Appl Physiol (1985)* 2009;107(4):1308-1315.
37. West DW, Burd NA, Churchward-Venne TA et al. Sex-based comparisons of myofibrillar protein synthesis after resistance exercise in the fed state. *J Appl Physiol (1985)* 2012;112(11):1805-1813.
38. Volpi E, Lucidi P, Bolli GB et al. Gender differences in basal protein kinetics in young adults. *J Clin Endocrinol Metab* 1998;83(12):4363-4367.
39. Trommelen J, Betz MW, van Loon LJC. The muscle protein synthetic response to meal ingestion following resistance-type exercise. *Sports Med* 2019;49(2):185-197.
40. Staron RS, Karapondo DL, Kraemer WJ et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *J Appl Physiol (1985)* 1994;76(3):1247-1255.
41. Hubal MJ, Gordish-Dressman H, Thompson PD et al. Variability in muscle size and strength gain after unilateral resistance training. *Med Sci Sports Exerc* 2005;37(6):964-972.
42. Yasuda N, Glover EI, Phillips SM et al. Sex-based differences in skeletal muscle function and morphology with short-term limb immobilization. *J Appl Physiol (1985)* 2005;99(3):1085-1092.
43. Churchward-Venne TA, Breen L, Di Donato DM et al. Leucine supplementation of a low-protein mixed macronutrient beverage enhances myofibrillar protein synthesis in young men: a double-blind, randomized trial. *Am J Clin Nutr* 2014;99(2):276-286.
44. Atherton PJ, Etheridge T, Watt PW et al. Muscle full effect after oral protein: time-dependent concordance and discordance between human muscle protein synthesis and mTORC1 signaling. *Am J Clin Nutr* 2010;92(5):1080-1088.
45. Moore DR, Robinson MJ, Fry JL et al. Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *Am J Clin Nutr* 2009;89(1):161-168.
46. Witard OC, Jackman SR, Breen L et al. Myofibrillar muscle protein synthesis rates subsequent to a meal in response to increasing doses of whey protein at rest and after resistance exercise. *Am J Clin Nutr* 2014;99(1):86-95.
47. Symons TB, Sheffield-Moore M, Wolfe RR et al. A moderate serving of high-quality protein maximally stimulates skeletal muscle protein synthesis in young and elderly subjects. *J Am Diet Assoc* 2009;109(9):1582-1586.
48. Macnaughton LS, Wardle SL, Witard OC et al. The response of muscle protein synthesis following whole-body resistance exercise is greater following 40 g than 20 g of ingested whey protein. *Physiol Rep* 2016;4(15).
49. Moore DR. Maximizing post-exercise anabolism: the case for relative protein intakes. *Front Nutr* 2019;6:147.
50. Wooding DJ, Packer JE, Kato H et al. Increased protein requirements in female athletes after variable-intensity exercise. *Med Sci Sports Exerc* 2017;49(11):2297-2304.
51. Malowany JM, West DWD, Williamson E et al. Protein to maximize whole-body anabolism in resistance-trained females after exercise. *Med Sci Sports Exerc* 2019;51(4):798-804.
52. Packer JE, Wooding DJ, Kato H et al. Variable-intensity simulated team-sport exercise increases daily protein requirements in active males. *Front Nutr* 2017;4:64.
53. Mazzulla M, Sawan SA, Williamson E et al. Protein intake to maximize whole-body anabolism during postexercise recovery in resistance-trained men with high habitual intakes is severalfold greater than the current recommended dietary allowance. *J Nutr* 2020;150(3):505-511.
54. Hoyt RW, Opstad PK, Haugen AH et al. Negative energy balance in male and female rangers: effects of 7 d of sustained exercise and food deprivation. *Am J Clin Nutr* 2006;83(5):1068-1075.
55. Castellani JW, Delany JP, O'Brien C et al. Energy expenditure in men and women during 54 h of exercise and caloric deprivation. *Med Sci Sports Exerc* 2006;38(5):894-900.
56. Conkright WR, O'Leary TJ, Wardle SL et al. Sex differences in the physical performance, physiological, and psycho-cognitive responses to military operational stress. *Eur J Sport Sci* 2021:1-34.
57. Friedl KE, Moore RJ, Martinez-Lopez LE et al. Lower limit of body fat in healthy active men. *J Appl Physiol (1985)* 1994;77(2):933-940.
58. Carbone JW, McClung JP, Pasiakos SM. Recent advances in the characterization of skeletal muscle and whole-body protein responses to dietary protein and exercise during negative energy balance. *Adv Nutr* 2019;10(1):70-79.
59. Montain SJ, Young AJ. Diet and physical performance. *Appetite* 2003;40(3):255-267.
60. Force DANA. Nutrition and menu standards for humna performance optimization, In: DANA F, ed. *AR40-25*, 2017. (Washington, DC).
61. Tarnopolsky LJ, MacDougall JD, Atkinson SA et al. Gender differences in substrate for endurance exercise. *J Appl Physiol (1985)* 1990;68(1):302-308.
62. Maher AC, Akhtar M, Vockley J et al. Women have higher protein content of beta-oxidation enzymes in skeletal muscle than men. *PLoS One* 2010;5(8):e12025.
63. Forsyth JJ, Burt D. Sex differences in recovery from sprint interval exercise. *J Strength Cond Res* 2019 Dec 27. doi:10.1519/JSC.0000000000003460. Epub ahead of print. PMID: 31895284.
64. Nathalie B, Laurie I. Substrate metabolism during exercise: sexual dimorphism and women's specificities. *Eur J Sport Sci* 2021:1-21.
65. Tarnopolsky MA, Bosman M, Macdonald JR et al. Postexercise protein-carbohydrate and carbohydrate supplements increase muscle glycogen in men and women. *J Appl Physiol (1985)* 1997;83(6):1877-1883.
66. Flynn S, Rosales A, Hailes W et al. Males and females exhibit similar muscle glycogen recovery with varied recovery food sources. *Eur J Appl Physiol* 2020;120(5):1131-1142.
67. Devries MC, Hamadeh MJ, Graham TE et al. 17beta-estradiol supplementation decreases glucose rate of appearance and disappearance with no effect on glycogen utilization during moderate intensity exercise in men. *J Clin Endocrinol Metab* 2005;90(11):6218-6225.
68. Hamadeh MJ, Devries MC, Tarnopolsky MA. Estrogen supplementation reduces whole body leucine and carbohydrate oxidation and increases lipid oxidation in men during endurance exercise. *J Clin Endocrinol Metab* 2005;90(6):3592-3599.
69. Lamont LS, Lemon PW, Bruot BC. Menstrual cycle and exercise effects on protein catabolism. *Med Sci Sports Exerc* 1987;19(2):106-110.
70. De Souza MJ, Koltun KJ, Williams NI. The role of energy availability in reproductive function in the female athlete triad and extension of its effects to men: an initial working model of a similar syndrome in male athletes. *Sports Med* 2019;49(Suppl 2):125-137.
71. O'Leary TJ, Wardle SL, Greeves JP. Energy deficiency in soldiers: the risk of the athlete triad and relative energy deficiency in sport syndromes in the military. *Front Nutr* 2020;7:142.
72. O'Leary TJ, Wardle SL, Greeves JP. Energy deficiency in soldiers: the risk of the athlete triad and relative energy deficiency in sport syndromes in the military. *Front Nutr* 2020 Aug 25;7:142. doi:10.3389/fnut.2020.00142. PMID: 32984399; PMCID: PMC7477333.
73. De Souza MJ, Williams NI, Nattiv A et al. Misunderstanding the female athlete triad: refuting the IOC consensus statement on Relative Energy Deficiency in Sport (RED-S). *Br J Sports Med* 2014;48(20):1461-1465.
74. Papageorgiou M, Elliott-Sale KJ, Parsons A et al. Effects of reduced energy availability on bone metabolism in women and men. *Bone* 2017;105:191-199.
75. Otis CL, Drinkwater B, Johnson M et al. American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc* 1997;29(5):i-ix.
76. Nattiv A, Loucks AB, Manore MM et al. American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc* 2007;39(10):1867-1882.
77. Mountjoy M, Sundgot-Borgen J, Burke L et al. The IOC consensus statement: beyond the Female Athlete Triad–Relative Energy Deficiency in Sport (RED-S). *Br J Sports Med* 2014;48(7):491-497.
78. Mountjoy M, Sundgot-Borgen J, Burke L et al. International Olympic Committee (IOC) consensus statement on Relative Energy Deficiency In Sport (RED-S): 2018 update. *Inter J Sport Nutr Exer Metab* 2018;28(4):316-331.
79. De Souza MJ, Nattiv A, Joy E et al. 2014 female athlete triad coalition consensus statement on treatment and return to play of the female athlete triad: 1st International Conference held in San Francisco, California, May 2012 and 2nd International Conference held in Indianapolis, Indiana, May 2013. *Br J Sports Med* 2014;48(4):289.
80. Lauder TD, Williams MV, Campbell CS et al. The female athlete triad: prevalence in military women. *Mil Med* 1999;164(9):630-635.
81. Friedl KE, Nuovo JA, Patience TH et al. Factors associated with stress fracture in young army women: indications for further research. *Mil Med* 1992;157(7):334-338.
82. Schneider MB, Fisher M, Friedman SB et al. Menstrual and premenstrual issues in female military cadets: a unique population with significant concerns. *J Pediatr Adolesc Gynecol* 1999;12(4):195-201.

83. Schneider MB, Bijur PE, Fisher M et al. Menstrual irregularity in female military cadets: comparison of data utilizing short-term and long-term recall. *J Pediatr Adolesc Gynecol* 2003;16(2):89-93.
84. Gifford RM, Greeves JP, Wardle SL, O'Leary TJ, Double RL, Venables M, Boos C, Langford J, Woods DR, Reynolds RM. Measuring the exercise component of energy availability during arduous training in women. *Med Sci Sports Exerc* 2021 Apr 1;53 (4):860-868. doi:10.1249/MSS.0000000000002527. PMID: 33017351.
85. Gifford RM, Greeves JP, Wardle SL et al. Measuring the exercise component of energy availability during arduous training in women. *Med Sci Sports Exerc* 2021;53 (4):860-868.
86. Gifford RM, O'Leary TJ, Double RL et al. Positive adaptation of HPA axis function in women during 44 weeks of infantry-based military training. *Psychoneuroendocrinology* 2019;110:104432.
87. Ackerman KE, Cano Sokoloff N, G DENM et al. Fractures in relation to menstrual status and bone parameters in young athletes. *Med Sci Sports Exerc* 2015;47(8):1577-1586.
88. Ackerman KE, Nazem T, Chapko D et al. Bone microarchitecture is impaired in adolescent amenorrheic athletes compared with eumenorrheic athletes and nonathletic controls. *J Clin Endocrinol Metab* 2011;96(10):3123-3133.
89. Ackerman KE, Putman M, Guereca G et al. Cortical microstructure and estimated bone strength in young amenorrheic athletes, eumenorrheic athletes and non-athletes. *Bone* 2012;51(4):680-687.
90. Southmayd EA, Mallinson RJ, Williams NI et al. Unique effects of energy versus estrogen deficiency on multiple components of bone strength in exercising women. *Osteoporos Int* 2017;28(4):1365-1376.
91. Rauh MJ, Macera CA, Trone DW et al. Epidemiology of stress fracture and lower-extremity overuse injury in female recruits. *Med Sci Sports Exerc* 2006;38(9): 1571-1577.
92. Shaffer RA, Rauh MJ, Brodine SK et al. Predictors of stress fracture susceptibility in young female recruits. *Am J Sports Med* 2006;34(1):108-115.
93. Cosman F, Ruffing J, Zion M et al. Determinants of stress fracture risk in United States Military Academy cadets. *Bone* 2013;55(2):359-366.
94. Winfield AC, Moore J, Bracker M et al. Risk factors associated with stress reactions in female Marines. *Mil Med* 1997;162(10):698-702.
95. Knapik JJ, Graham B, Cobbs J et al. A prospective investigation of injury incidence and injury risk factors among Army recruits in military police training. *BMC Musculoskelet Disord* 2013;14:32.
96. Ruffing JA, Nieves JW, Zion M et al. The influence of lifestyle, menstrual function and oral contraceptive use on bone mass and size in female military cadets. *Nutr Metab (Lond)* 2007;4:17.
97. Lappe JM, Stegman MR, Recker RR. The impact of lifestyle factors on stress fractures in female Army recruits. *Osteoporos Int* 2001;12(1):35-42.
98. Cline AD, Jansen GR, Melby CL. Stress fractures in female army recruits: implications of bone density, calcium intake, and exercise. *J Am Coll Nutr* 1998;17(2):128-135.
99. Lauder TD, Dixit S, Pezzin LE et al. The relation between stress fractures and bone mineral density: evidence from active-duty Army women. *Arch Phys Med Rehabil* 2000;81 (1):73-79.
100. Kelly EW, Jonson SR, Cohen ME et al. Stress fractures of the pelvis in female navy recruits: an analysis of possible mechanisms of injury. *Mil Med* 2000;165(2):142-146.
101. Armstrong 3rd DW, Rue JP, Wilckens JH et al. Stress fracture injury in young military men and women. *Bone* 2004;35(3):806-816.
102. Ihle R, Loucks AB. Dose-response relationships between energy availability and bone turnover in young exercising women. *J Bone Miner Res* 2004;19(8):1231-1240.
103. Strohbach CA, Scofield DE, Nindl BC et al. Female recruits sustaining stress fractures during military basic training demonstrate differential concentrations of circulating IGF-I system components: a preliminary study. *Growth Horm IGF Res* 2012;22(5): 151-157.
104. Jones BH, Thacker SB, Gilchrist J et al. Prevention of lower extremity stress fractures in athletes and soldiers: a systematic review. *Epidemiol Rev* 2002;24(2):228-247.
105. Knapik J, Montain SJ, McGraw S et al. Stress fracture risk factors in basic combat training. *Int J Sports Med* 2012;33(11):940-946.
106. McClung JP, Murray-Kolb LE. Iron nutrition and premenopausal women: effects of poor iron status on physical and neuropsychological performance. *Annu Rev Nutr* 2013;33:271-288.
107. Medeiros DM, Plattner A, Jennings D et al. Bone morphology, strength and density are compromised in iron-deficient rats and exacerbated by calcium restriction. *J Nutr* 2002;132(10):3135-3141.
108. Medeiros DM, Stoecker B, Plattner A et al. Iron deficiency negatively affects vertebrae and femurs of rats independently of energy intake and body weight. *J Nutr* 2004;134(11):3061-3067.
109. Harris MM, Houtkooper LB, Stanford VA et al. Dietary iron is associated with bone mineral density in healthy postmenopausal women. *J Nutr* 2003;133(11):3598-3602.
110. Merkel D, Moran DS, Yanovich R et al. The association between hematological and inflammatory factors and stress fractures among female military recruits. *Med Sci Sports Exerc* 2008;40(11 Suppl):S691-S697.
111. Yanovich R, Merkel D, Israeli E et al. Anemia, iron deficiency, and stress fractures in female combatants during 16 months. *J Strength Cond Res* 2011;25 (12):3412-3421.
112. McClung JP, Karl JP, Cable SJ et al. Longitudinal decrements in iron status during military training in female soldiers. *Br J Nutr* 2009;102(4):605-609.
113. Martin NM, Conlon CA, Smeele RJM et al. Iron status and associations with physical performance during basic combat training in female New Zealand Army recruits. *Br J Nutr* 2019;121(8):887-893.
114. Barnes KR, Tchandja JN, Webber BJ et al. The effects of prenatal vitamin supplementation on operationally significant health outcomes in female air force trainees. *Mil Med* 2015;180(5):554-558.
115. Burgi AA, Gorham ED, Garland CF et al. High serum 25-hydroxyvitamin D is associated with a low incidence of stress fractures. *J Bone Miner Res* 2011;26 (10):2371-2377.
116. Dao D, Sodhi S, Tabasinejad R et al. Serum 25-hydroxyvitamin D levels and stress fractures in military personnel: a systematic review and meta-analysis. *Am J Sports Med* 2015;43(8):2064-2072.
117. Lappe J, Cullen D, Haynatzki G et al. Calcium and vitamin d supplementation decreases incidence of stress fractures in female navy recruits. *J Bone Miner Res* 2008;23(5):741-749.
118. Gaffney-Stomberg E, Lutz LJ, Rood JC et al. Calcium and vitamin D supplementation maintains parathyroid hormone and improves bone density during initial military training: a randomized, double-blind, placebo controlled trial. *Bone* 2014;68:46-56.