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INVITED REVIEW

Physiological employment standards IV: integration of women in combat units physiological and medical considerations

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Abstract Anthropometric and physiological factors place the average female soldier at a disadvantage relative to male soldiers in most aspects of physical performance. Aerobic and anaerobic fitness levels are lower in women than in men. Thus, women have a lower overall work capacity and must therefore exert themselves more than men to achieve the same output. The lower weight and fat-free mass and the higher body fat of women are associated with lower muscle strength and endurance, placing them at disadvantage compared with men in carrying out military tasks such as lifting and carrying weights or marching with a load. Working at a higher percentage of their maximal capacity to achieve the same performance levels as men, women tire earlier and are at increased risk of overuse injuries. Their smaller size, different bone geometry and lower bone strength also predispose women to a higher incidence of stress fractures. Although training in gender-integrated groups narrows the gaps in fitness, significant differences between the genders after basic training still remain. Nevertheless, integration of women into military combat professions is feasible in many cases. Some 'close combat roles' will still be an exception, mainly because of the extreme physical demands that are required in those units that are beyond the physiological adaptability capacities of an average female. There is no direct evidence that women have a negative impact on combat effectiveness. Once the gender differences are acknowledged and operational doctrines adjusted accordingly, female soldiers in mixed-gender units can meet the physical standards for the assigned missions.

Keywords Soldiers · Combat · Females · Physiological strain · Adaptation

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Introduction

The integration of women in traditionally manly profession has raised the question of their physical and physiological capabilities to perform equally effective. In this review, it is our intention to provide an overview of the essential gender differences which are relevant to workers in physically demanding occupations. In so doing, our aim is to provide a sound physiological basis that may facilitate the development of physiological and physical employment standards. This background will be provided within the context of military environment, with specific reference to women within combat units.

Historical perspective

Integration of women into professions in the armed forces, especially in combat-oriented units, has been a controversial issue under discussion for many years. In all societies worldwide, the military has traditionally been considered one of the manliest institutions, and accordingly has been reserved exclusively for men.

Even though the mythology and folklore of many nations throughout history have glorified women serving as warriors and women leading armies in war, it is only since World War I (WWI) that the service of women in the army has become more organized. Most of the female in that war served in non-combat professions such as nursing and administrative positions, and served even in separate military frameworks (Harrell and Miller 1997). World War II (WWII) represented a turning point in this attitude (Binkin and Bach 1977). In the Soviet army, 400,000 women were recruited, many of whom served in front lines and in combat positions. Similarly, in the US military forces the number of female soldiers in that war reached 350,000. Nevertheless, none of these US female soldiers served in direct combat occupations. Immediately after the war ended, the number of female soldiers on active duty dropped to fewer than 20,000.

In a study conducted during WWII to examine how well American female soldiers could perform in an anti-aircraft unit, it was concluded that 'in contradiction to generally existing stereotypes of females being physically too weak to perform combat jobs, females met the physical, intellectual and psychological standards for this mission' (Campbell 1993). Although the results of the experiment were positive, the Army needed those female soldiers for other high priority assignments—clerical and administrative positions. General Marshall, Chief of Staff of the US Armed Forces, therefore terminated the experiment, ordered the results kept confidential and never used women in combat (Campbell 1993).

The decision made in 1972 by the US Armed Forces to increase the numbers of enlisted females and to expand military occupations for women represented a second major turning point in the integration of women into combat professions. Over a 30-year period, the percentage of women in the US Armed Forces increased from 1.6 % in 1972 to 15 % in 2001 (Elspeth 2001; McNeary and Lomalesick 2000). Today, women make up to 13 % of the active US Armed Forces (Cawkill et al. 2009). (For more details on combat military service by women in many other countries, the interested reader is referred to the survey by Cawkill et al. 2009.)

Throughout the years of its existence as a modern state, Israel experienced several large-scale military conflicts and low-intensity wars, in which women have taken part. During the War of Independence of the State of Israel (December 1947–March 1949), 10 % of the entire Jewish population (males and females) was drafted. A minority of women served in front line 'close combat roles' and only in the early stages of the war. Most served in supporting duties: nurses, radio operators, drivers and other essential auxiliary professions.

Israel is the only country in the world with a mandatory military service requirement for women. Service in the Israel Defence Forces (IDF) is compulsory for males and females from the age of 18 years. However, after the IDF was established in 1948, removal of women from front line positions was decreed, and until the mid 1990s most combat positions were closed to them. A landmark High Court appeal lodged by a young female aviation engineer in 1994 forced the Air Force to accept female pilot cadets on the basis of their right to gender equality. In the summer of 1996, the first seven female pilot cadets were accepted, but none of them successfully finished the demanding course. Although all seven were highly motivated and were physically fit, they failed owing to physical difficulties, and it was only in 2001 that Israel's first female combat pilot received her wings. This breakthrough soon spread to other combat positions in the IDF. In 1999, a gender-integrated light-infantry company was formed and was substantially expanded into a battalion in which 68 % of the combatants today are females. Since then, further combat positions have been opened to females. Cawkill et al. (2009), in their detailed review on the experience of many nations with respect to the inclusion of female soldiers in ground forces trained for close combat pointed out that in 2006, 88 % of IDF positions were open to women, and 2.5 % of conscripted female soldiers served in 14 combat positions including light infantry, artillery, field intelligence, shallow water diving, search and rescue, non-conventional warfare (NBC) purification units, border patrol, dog handling (K-9 unit), armoured vehicle instructors and anti-aircraft warfare. Only close combat roles with high probability of direct engagement and extreme physical fitness requirements (e.g. elite infantry and SEALS) are closed to women. Since 2003, part of the IDF Officers' Course was unified for male and female soldiers, and the rates of success in passing this demanding course do not differ between the genders. It is noteworthy that the absolute physical demands from females in most gender-integrated units and courses are adjusted to the average female physiological capacities. Although these demands are about 20 % lower than for men, in relative terms, they are similar.

Recent operational deployments to the Middle East and elsewhere have blurred both the distinction of the traditional 'front line' and the definition of 'combat zone'. In current conflicts the enemy is dispersed across national boundaries and employs irregular tactics leading to asymmetric warfare. Given that in such situations there are no truly safe zones free from possible combat action, and consequently that all service members in all specialties are at risk (e.g. from rocket or mortar fire as well as ambushes), frequently women also find themselves involved in active fighting in various aspects.

Combat fitness and performance

'Combat fitness' refers to the ability of a soldier to effectively perform military-oriented tasks. This is achieved by acquiring specific military skills and meeting military-oriented physical fitness requirements. Earlier definitions of fitness were commonly expressed in terms of the capacity to carry out daily physical activities without undue fatigue. This was amended, and the current understanding of the term includes concepts of effectiveness and efficiency; thus, task-oriented fitness is a person's ability to perform a specific activity with acceptable efficiency (Caspersen et al. 1985).

A common concept is that of the Soldier Athlete. Although in some aspects this expression is justified, and despite certain similarities between athletes and combat soldiers, combat fitness is not analogous to athletic fitness. In contrast to training for athletic fitness, which is aimed specifically at cutting seconds off running time, jumping a few centimetres higher or lifting heavier weights, military fitness training focuses on the physical and mental ability required to accomplish all aspects of a combat mission while remaining healthy and uninjured. To accomplish military missions, the basic fitness requirements are cardiopulmonary capacity, muscle strength and muscle endurance, and to these components it is accustomed to add flexibility and mobility. Specific training programs prepare soldiers to perform well to accomplish their missions. Other factors that are classified as components of 'motor' fitness, and which affect a soldier's survivability on the battlefield, are speed, agility, muscle power, eye–hand coordination and eye–foot coordination. All of these can be improved by appropriate training within the limits of each soldier's potential. Furthermore, whereas many athletes train and compete as individuals, a soldier works as a part of a team in which cohesion and mutual reliance are dominant components in the successful achievement of a mission.

In every measurable sport discipline (except maybe in ultramarathon), the records attained by women are lower than those of men. Among elite athletes in all disciplines, gender generally accounts for an attainment difference of approximately 10 % (Ransdell et al. 2009), a gap which has remained stable over the last three decades. A recently stated conclusion is that the athletic performance of females at the highest level will never match that of males (Thibault et al. 2010). Is this conclusion relevant also in the case of combat fitness and the ability of females to serve in an integrated combat unit?

In the context of daily routine tasks, physiological gender-related differences are usually insignificant. In contrast, military routines are unique and soldiers are required to accomplish missions which are often physically demanding and must be carried out under harsh environmental conditions. In several studies of workload tolerance and injury frequency in the military, females soldiers were reported to exert themselves considerably more than males when carrying out typical military tasks aimed at reaching a specified output, and are fatigued earlier than males. Furthermore, fatigue is a major underlying cause of injuries, and female soldiers are more prone to be injured than males when conducting similar military tasks (Cline et al. 1998; Friedl et al. 2008; Kelly et al. 2000; Libster et al. 1999). Under military scenarios, the question is whether inherent gender-related differences will limit, a priori, a female soldier's ability to effectively accomplish a given military mission without jeopardizing herself and her comrades, especially when the action takes place in small fighting units such as team, squad or platoon, where reliance on one another is crucial to the mission's success.

In the following sections, we discuss gender-related physiological differences relevant to the fulfilment of military missions, and their possible effect on the integration of female soldiers in combat professions. It should be noted that the paper addresses gender as a group and that findings will not apply to individual cases (e.g. the top female may well fit in the average male performance). We focus only on physiological aspects; other important issues, including enabling environment, sociological and psychological aspects (such as cohesion and motivation), are not within the scope of this review.

Body composition

Basic gender-related military differences in performance of military relevance stem from the sexually dimorphic maturation during puberty and adolescence. The hallmark of this dynamic period of development is the sexual differentiation involving rapid changes in body size, shape and composition, all of which are highly correlated with changes in individual hormone levels that act independently or in concert (Rogol et al. 2002).

On average (across ethnic origin, genetic and nutritional effects), females enter puberty 2 years earlier than males corresponding to a biological age of approximately 11 in girls and 13 in boys (Tanner 1965). At this stage, the hormonal regulation of growth becomes increasingly complex. In addition to the influence of adequate levels of thyroid hormone and cortisol, which are prerequisites for normal growth, independent effects on growth and body composition are exerted by the gonadal steroid hormones, by dramatic activation of the growth hormone (GH) and insulin growth factor-1 (IGF-1) axis, and possibly by other hormones as well (e.g. leptin). Many of the growth-promoting effects induced by the gonadal steroid hormones are mediated through estrogens rather than androgens, either via direct secretion of estrogens or through the conversion of androgens to estrogens by peripherally located aromatase (Rogol et al. 2002).

The central role of estrogens on growth is related to their effect on the dynamics of growth hormone secretion (Mauras et al. 1987). In women, an intact menstrual cycle is fundamental. This can be exemplified by the delay in puberty development and growth spurt in young female athletes who compete in sports in which leanness or low body weight or both are considered important. In these elite athletes, the incidence of amenorrhoea is significantly higher (and estrogen levels are lower) than in the general population, and is particularly evident in those who begin physical training before rather than after menarche (Frisch et al. 1981).

Amenorrhoea, as a marker for hypothalamus-pituitary-gonadal dysfunction that is related to sustained intensive exercise from childhood or as part of the 'female athlete triad', is less common among females in the military than among athletes. More frequent among these soldiers is secondary amenorrhoea, regarded as 'stress-induced' amenorrhoea, which prevails, according to Cline et al. (1998), in 40 to 50 % of females during basic training. Those female recruits, who in response to everyday life stress (social and metabolic) develop menstrual cycle disturbances, are stress-sensitive. In contrast to these stress-sensitive individuals, other recruits are more stress resilient. Earlier studies attributed the 'stress-induced' amenorrhoea to heightened activity of the hypothalamic-pituitary-adrenal axis (Berga et al. 1997), but the serotonergic system may also be involved (Bethea et al. 2005). 'Stress-induced' amenorrhoea in most of the cases is transient, and as summarized by Berga and Loucks (2006), 'it all depends upon developing healthy attitudes and healthy behaviors.'

Body height

The adolescent growth spurt characteristic of mid-puberty occurs earlier in girls, typically at Tanner breast stage 3, and does not reach the magnitude of that in boys. Girls average a peak height velocity of 9 cm/year at age 12 and a total gain in height of 25 cm during the pubertal growth period (Marshall and Tanner 1969). Boys attain, on average, a peak height velocity of 10.3 cm/year, usually 2 years later than girls, during Tanner genital stage 4, and during the pubertal growth period they gain 28 cm in height (Marshall and Tanner 1970). The additional 2-year duration of pre-pubertal growth in combination with a greater peak height velocity results in an average adult height difference of 13 cm between men and women (Rogol et al. 2002).

Longitudinal growth of the long bones occurs at the growth plate (epiphysis). During childhood, the growth plate matures and by the end of puberty it disappears, after undergoing epiphyseal fusion and consequently complete replacement by bone, resulting in cessation of longitudinal growth (Emons et al. 2011). Sex steroids (estrogens and androgens) play a major role in growth plate maturation, not only via their classical endocrine pathway but also through local paracrine/autocrine mechanisms (Oz et al. 2001). The pivotal role of estrogen in growth plate senescence is attributed to its effect on earlier chondrocytes proliferative exhaustion, and hence to earlier fusion (Weise et al. 2001). The androgenic effect on longitudinal growth is mediated through the conversion of androgens into estrogen in the growth plate (Emons et al. 2011). Growth plate maturation is also dominated by a complex of growth factors, which indirectly are also regulated by estrogens (Kronenberg 2003).

Body mass

Puberty is also a time of significant weight gain with 50 % of adult body weight gained during adolescence. In girls, peak weight gain lags behind peak height velocity by approximately 6 months and reaches 8.3 kg/year at about the age of 12.5. In boys, peak weight velocity occurs at about the same time as peak height velocity and averages 9 kg/year (Barnes 1975; Tanner 1965).

Under the influence of testosterone, boys gain muscle tissue at greater rate and for a longer time than girls do (Tanner 1965). Consistent with their significantly higher serum testosterone levels, males have larger and stronger muscles with a greater potential for muscle development. Consequently, most of the adult amount of free-fat mass is attained between the ages of 15 and 16 years in females, but at 19–20 years in males (Malina and Bouchard 1991). During the third decade of life, the upper body muscle mass is 50 % higher and the lower body muscle mass 30 % higher in men than in women, which corresponds to 14 % more and 35 % larger muscle fibres (Miller et al. 1993). In addition, men have greater fast-twitch muscle fibre size and a higher ratio of fast-twitch to slow-twitch fibres than women, both of which contribute to gender-related differences in muscular strength.

During puberty, in females, the percentage of body fat is increased and fat mass is accumulated at a rate of 1.14 kg/year, while in males the percentage of body fat is decreased by 1.15 kg/year (Rogol et al. 2002). Ultimately, fat mass relative to body mass averages 20 to 25 % in females in comparison to 13 to 16 % in males (Wells and Plowman 1983). Essential fat in females (12 %) is also higher than in males (3 %). As height velocity declines, fat accumulation resumes in both genders but is twice as rapid in females. Hence, as adults, males have twice the number of muscle cells and their lean body mass is 150 % greater compared with the average female. Plasma leptin levels, thought to regulate body fat content, increase in girls and decrease in boys after Tanner stage 2 as pubertal development proceeds. Although concentrations of circulating free leptin levels increase with age, a significant gender difference persists even after adjustment for body mass index (BMI) or percent body fat, indicating that women may be more resistant to the effects of leptin and therefore accumulate more fat (Saad et al. 1997; Wong et al. 2004). The lower levels of leptin in males may be explained, at least in part, by a suppressive effect of androgens (Blum et al. 1997).

At the age of 20 women weigh less than males (by 14–18 kg on average), and their lean body mass is approximately 30 % lower than that of men (Malina and Bouchard 1991). Even after adjustment of lean body mass to height, these differences remain; at the age of 20, the mean lean body mass is 0.36 kg/cm for men and 0.26 kg/cm for women (Malina and Bouchard 1991). Nevertheless, despite real and perceived association between the inherent differences in body composition (BMI and lean body mass to fat mass ratio) on physical performance, there is low specific predictive value of body size and body composition for soldiers' performance within a wide range of healthy weights and adiposity (Friedl 2012).

Bone growth

During the 2 years of peak skeletal growth, adolescents accumulate over 25 % of adult bone mass, and usually by the age of 18 more than 90 % of peak skeletal mass has been reached (Rogol et al. 2002). The process of bone mineral accrual is hormone dependent with both androgens and estrogens promoting deposition of bone minerals. In women, a normal menstrual cycle is crucial for calcium deposition, as can be learned from the low levels of estrogens and the accompanying calcium deficiency in amenorrheic women. Estrogen deficiency in this case has a dual effect on bone: first, homeostasis of intestinal and renal calcium is less efficient, resulting in a need for increased calcium intake to maintain calcium balance; second, estrogen deficiency permits osteoclasts to reabsorb bone with greater efficiency, resulting in a weaker bone (Eriksen et al. 1988).

A gender-related difference is evident in the dynamics of bone mineralization. Males have a marked age-related delay in bone mineralization compared with females and the age of maximal peak bone mineral content velocity is approximately 12 in girls and 14 in boys (Whiting et al. 2004). Furthermore, after the age of peak height velocity there is a more rapid gain in bone in boys than in girls, and bone mineral content is 22 % higher in males than in females by the age of 18 (Whiting et al. 2004). Gender difference in the bone mineral accumulation that accompanies pubertal development deserves further investigation, but is explained, in part at least, by the higher efficiency of calcium absorption in males than in females (Eriksen et al. 1988; Whiting et al. 2004). Consequently, in addition to the differences in bone length discussed above (subsection 'Body height'), bone dimensions also differ between genders with males having 75 % higher humeral and 85 % higher femoral surface bone areas than females (Miller et al. 1993) (For further discussion see the section on 'Musculoskeletal system: bone strength').

Cardiovascular system

Cardiac output

Three components of heart function influence cardiac output: left ventricular volume, blood volume and heart–muscle mass. Independent of body size, women have thinner left ventricular walls, less myocardial mass and smaller cavity size compared with males (Cain et al. 2009; Dalen et al. 2010; Whyte et al. 2004). These differences in cardiac structure may affect left ventricular diastolic function and ultimately filling pressure, resulting in a lower cardiac output and eventually affecting oxygen consumption. As stroke volume in women is smaller than in men, for a given oxygen consumption, this is compensated for by a higher heart rate. Given the fact that maximal heart rate is similar in both genders, maximal cardiac output in women is lower and is limited by stroke volume.

Oxygen extraction

Oxygen extraction by the tissues is influenced by the oxygen content in the blood and its consumption rate by the cells. Haemoglobin is a key factor in this regard, and although the large inter-individual differences are accompanied by large between-gender overlap, the average haemoglobin levels in women are 10 to 16 % lower than in men. Consequently, the lower haemoglobin levels in women reflect, a priori, lower oxygen-carrying capacity than that of men with similar anthropometry. Notably, for the present discussion, this is aggravated by a significantly higher prevalence of iron deficiency and anaemia among female soldiers than among the males (Merkel et al. 2008; Yanovich et al. 2011).

Iron deficiency by itself and iron deficiency anaemia have long been known to impair physical and mental performance (Brownlie et al. 2002; Friedman et al. 2001; Gardner et al. 1977; Hinton et al. 2000; Shaskey and Green 2000). The published prevalence of iron deficiency in population varies, depending on the cutoff values used for its definition, but its prevalence as well as the prevalence of the associated condition of anaemia in the general female population and among female military recruits is significant and is higher than in males (Dubnov et al. 2006; Israeli et al. 2008; McClung et al. 2006; Merkel et al. 2008; Yanovich et al. 2011). McClung et al. (2006) and Yanovich et al. (2011) showed that after basic training the prevalence of iron deficiency and the associated anaemia is even higher than pre-induction. A few months later, during permanent assignments (i.e. active combat duties), iron deficiency anaemia resolved to some extent (Yanovich et al. 2011).

The identified mechanisms underlying exercise-induced iron loss are mainly gastrointestinal bleeding, haematuria, sweating, haemolysis and inflammation (Ottomano and Franchini 2012; McClung 2012). Menstrual blood loss in women is a significant cause of iron deficiency with an inverse relationship between the amount of menstrual flow and serum ferritin levels (Rowland and Kelleher 1989). Low iron stores in women have been related to the suboptimal dietary intake of iron (Dubnov et al. 2006; Israeli et al. 2008; King et al. 1993; McClung et al. 2006). Dubnov et al. (2006) point out that a Western diet containing ~3,000 kcal is needed to supply the recommended daily intake of iron (18 mg), but that young women engaged in athletic activities usually do not reach those energy and nutrient intakes, and consume on average 2,000 kcal/day. According to one survey in the IDF, the average dietary intake of iron for female military recruits before induction is 83 % of the dietary reference intake (DRI) and that of male recruits, over 200 % (Israeli et al. 2008). It is recognized that external stressors during military service, including field and environmental conditions, the stress of training and emotional stress, types of military rations and soldiers' nutritional habits affect appetite and hence the amount and types of food consumed (Torres and Nowson 2007); as a consequence, the prevalence of iron deficiency is exacerbated (McClung et al. 2006; Yanovich et al. 2011).

Preventive measures to counteract iron deficiency to enhance performance include consumption of a balanced diet which includes the maximum possible amounts of enhancers of iron absorption (red meat and ascorbic acid). Iron supplements (iron capsules) have proved to be beneficial in attenuating declines in iron status during periods of military training (McClung et al. 2009). The latter measure, however, is effective only in individuals in whom iron deficiency is established or in those with low ferritin levels without anaemia (Ottomano and Franchini 2012). Such a practice was tested recently in the IDF, and preliminary results point to its beneficial effect in reducing the prevalence of anaemia.

Cardiopulmonary endurance

Cardiopulmonary endurance is the ability to perform continuous physical activity and is one of the three major components relevant for optimal military-related performance. This component of physical fitness is best represented by the cardiopulmonary capacity and is commonly expressed by maximal oxygen consumption. In general, the maximal oxygen consumption reported among trained female is between 15 and 30 % lower than among the trained males (Drinkwater 1973; Yanovich et al. 2008). However, maximal oxygen consumption within each gender varies considerably, and between the ages of 20 and 30 there is a large overlap between these two populations, especially among untrained individuals (Drinkwater 1973; Vogel et al. 1986). In this regard, Drinkwater (1973) reported that 76 % of untrained females had similar maximal oxygen consumption values to those in 47 % of untrained males, and that among athletes the corresponding values were about 22 and 7 %. This observation should be taken into account in the planning of adequate fitness training protocols.

Several attempts have been made to adjust the absolute values of oxygen consumption (expressed in litres per min) to anthropometric measures and haemoglobin concentrations to objectively compare between the genders (Saltin and Astrand 1967; Cureton et al. 1986; Shvartz and Reibold 1990). Although the gender difference in those studies was found to be narrowed, it did not disappear. According to Tarnopolsky and Saris (2001), when oxygen consumption values were expressed relative to body weight the gender difference was narrowed to 28 % and when initial oxygen consumption values were adjusted to lean body mass the difference was only 15 %. Even after the application of other allometric scaling (e.g. $kg^{0.56}$ or $kg^{0.75}$), gender-related differences in oxygen consumption were still apparent (Rowland et al. 2000; Eisenmann et al. 2001). A lower cardiopulmonary capacity has a profound effect on endurance. Oxygen consumption is directly correlated with workload; thus, for a given submaximal activity, females—who will use a higher percentage of their maximal oxygen consumption than males—will work at a higher relative intensity, resulting in earlier fatigue and lower tolerance time.

Musculoskeletal system

Muscle strength and anaerobic capacity

Activities involving high intensity and short duration, such as sprinting or lifting and carrying heavy loads, are typical of military tasks and are related to muscular strength. In several military-oriented studies, it was reported that women had up to 40 % less muscle strength than men in both the upper and lower body (Knapik et al. 2001; Yanovich et al. 2008). In another study, the absolute muscle strength in women was lower than that in men by up to 55 % in the upper body and by 40 % in lower body, which, when adjusted for body weight, was narrowed to 40 and 25 %, respectively (Beckett and Hodgson 1987). These differences in muscle strength are further narrowed if calculated for muscle cross-sectional area, but they do not disappear (Kanehisa et al. 1994). Overall, the lower muscle strength in women is reflected by a 40 % lower anaerobic power than in men when measured in absolute values and 17 % lower than in men when adjusted to lean body weight (Murphy et al. 1986).

Energy pathways for muscle contractions at intensities which are greater than 50 % of maximum voluntary contraction (MVC) are significantly more aerobic in females than in males (Kent-Braun et al. 2002). This is corroborated by other observations showing that at higher workloads, there is a greater contribution of anaerobic activity in males than in females (Morgan et al. 2003; Tarnopolsky 2000). In absolute values, anaerobic power abilities in males were reported to be 66.5 % higher than in females, which were narrowed to an insignificant 8.5 % when data were adjusted for lean body mass (Maud and Shultz 1986). Still, military-relevant anaerobic performance is lower in females than in males; for example, the effect of load carriage on the performance of an explosive, anaerobic military task was reported to be significantly larger in female than in male soldiers (36 vs. 29 %, respectively) (Treloar and Billing 2011).

Muscle endurance

Muscle endurance is the ability of a muscle or group of muscles to sustain repeated contractions against a submaximal resistance for an extended period of time. In other words, it is the ability of the muscle to resist fatigability as expressed in extended time to failure while maintaining a target resistance (Hicks et al. 2001). Hence, muscle endurance is among the most important physical requirements for many military tasks (e.g. loading ammunition, carrying backpacks).

Relative to body physique, women are more resistant to muscle fatigue in comparison to males. (Bam et al. 1997; Hunter and Enoka 2001; Maughan et al. 1986; Miller et al. 1993; West et al. 1995). The most obvious mechanism responsible for this finding is the lower muscle mass in women. Because their muscle mass is lower, women generate lower absolute muscle force than men do when performing the same relative work. This lower absolute forces involve a lower muscle oxygen demand and less mechanical compression of the local vasculature, resulting with delayed fatigue. Other suggested mechanisms are muscle morphology (the proportion of Type I muscle fibres is higher in women than in men), substrate utilization (higher fat oxidation in women than in men during submaximal endurance exercise and higher reliance of men than of women on glycolytic pathways) and probably a better preserved neuromuscular activity in women than in men after fatiguing exercise (Hicks et al. 2001). It should be noted, however, that the magnitude of female advantage in muscle endurance declines in a curvilinear manner as the contraction intensity increases, and it is only in the lower range of contraction intensity that a real advantage in fatigability of women over men can be exhibited (Hicks et al. 2001).

Muscular endurance of men in absolute terms is, however, greater than that of women because of their greater muscle mass and strength. This is of advantage for those military tasks in which the endurance level is fixed (e.g. loading, carrying absolute weights in a predefined pace and distance). Thus, tailoring the task to the women's physique and fitness may result in similar muscular endurance between the genders. It should be emphasised that task analysis in regard to gender and muscle endurance requires further studies.

As mentioned above, a major concern with regard to muscle fatigue in military performance has to do with the loads that soldiers carry. The load carried by a soldier in combat, regardless of body mass, can range from 30 to 60 kg (Knapik et al. 2004b; Nindl et al. 2013). A number of studies have described the effect of excessive load carriage on fatigue. Clarke et al. (1955) reported decreased MVC of trunk, knee and ankle flexor/extensor muscles in soldiers after walking for about 3 h while carrying loads of up to 27 kg ($\sim$30 % of body weight). Blacker et al. (2010) showed that carrying a 25-kg pack during 2 h of walking on a treadmill induced a 15 % loss in knee extensor MVC and was associated with moderate central (neural) and peripheral (muscular) fatigue. In this regard, women are more susceptible to fatigue than men even when carrying loads of 15–20 kg (Bhambhani and Maikala 2000). Therefore, to postpone fatigue and enhance performance, it is advisable to limit the load according to body mass. At present, the recommended load to be carried by fit soldiers is 30 to 50 % of body mass. Given the lower mass of women than that of men, under such recommendation, female soldiers will carry substantially lower loads than their male counterparts. This might cause a serious operational difficulty, but with thoughtful planning parts of the loads can differentially be divided between the soldiers. Though it is beyond the scope of the present review, we should mention that contemporary technological developments are underway in an attempt to reduce the load carried on the soldier's trunk, thereby allowing heavy loads to be carried without causing undue fatigue.

Bone strength

Bone strength is assessed in terms of bone mass, a combined measure of bone size and bone mineral density. The hormonal balance, which differs between males and females during adolescence, is a significant determinant of bone growth (Kasperk et al. 1997). During this period in life, the greatest bone mineral content accrual occurs and peak bone mass is achieved (Henry et al. 2004; Pérez-López et al. 2010). Because of gender-related differences in the dynamics of bone accrual, maximal bone mineral density is lower in women than in men (Wentz et al. 2011) and is achieved in the second decade of life, whereas in men it is achieved during the third decade (Lu et al. 1994). (For further details on hormonal effects on bone growth, see subsection 'Bone growth').

Bone strength is obviously affected by the bone's material properties, which depend in turn on dietary habits (Moreno et al. 2008; Pérez-López et al. 2010). In this regard, women are more vulnerable than men since their nutrition is generally more deficient in macro- and micronutrients (Etzion-Daniel et al. 2008). In the latter survey, men were found to consume a balanced diet before their recruitment, whereas women consumed significantly less than the military dietary reference intake (MDRI). This is in line with other publications reporting that the Western diet is poor in many of the important nutritional requirements for bone mass gain, and is often exacerbated by social eating habits (Moreno et al. 2008; Starkey et al. 2001).

The dietary intake of both male and female soldiers during basic training and combat missions is on average only 70 to 75 % of the MDRI (Burstein et al. 1996; Hoyt et al. 2006; Israeli et al. 2008; Moran et al. 2012; Yanovich et al. 2011). This intake was found to be associated with less than the recommended proportions of calcium, magnesium and vitamin D (Etzion-Daniel et al. 2008). A recent survey in an elite infantry unit in the IDF suggested that the rate of stress fractures is inversely related to the daily consumption of calcium and vitamin D (Moran et al. 2012). This general observation draws attention to the need for improved quality and variety of dietary components to ensure adequate levels of the nutrients required as a preventive measure for bone health. (For further discussion on the effects of calcium and vitamin D supplementations see the subsection 'Prevention'.)

From a biomechanical perspective, the strength of a bone is highly dependent on its geometry. Compared to those of men, the long bones of women have lower cross-sectional area and thinner cortices, are more slender (the tibial length to width ratio is higher and the moment of inertia to tibial length ratio is lower), and have smaller section modulus (ratio of the bone's cross-sectional moment of inertia to its outer diameter) (Beck et al. 2000; Evans et al. 2008; Tommasini et al. 2007). As a result of these characteristics, bending and torsional stiffness properties of tibias relative to body size in women are significantly lower than in men (by approximately 40 %), even after adjusting for body size (Beck et al. 2000; Evans et al. 2008; Jepsen et al. 2011; Tommasini et al. 2007). (For more information on the geometry and biomechanics of bone, see the review by Turner and Burr, 1993.)

Musculoskeletal injuries

Intense physical activity may increase the prevalence of acute and overuse musculoskeletal injuries, which comprise a broad array of medical conditions involving muscle, tendon, nerve, ligament and bone tissues (Kaufman and Brodine 2000; Rosendal et al. 2003; Zambraski and Yancosek 2012). Overuse injuries may be episodic (e.g. rhabdomyolysis), but can potentially advance to chronic conditions (e.g. brachial plexus palsy). Musculoskeletal injuries are a major concern in the military since they directly affect soldiers' combat readiness. In the US Armed Forces, musculoskeletal injuries were reported to be the leading cause of all medical consultations in 2006 (Jones et al. 2010) and according to the Armed Forces Health Surveillance Center (2011) in 2010 it accounted for 30 % of all medical consultations.

Female gender has been identified as a risk factor for overuse injuries, especially during basic training (Finestone et al. 2008; Kelly et al. 2000; Zambraski and Yancosek 2012). Female soldiers exercising under the same conditions as males are 1.2–10 times more susceptible to overuse injuries (Bijur et al. 1997; Evans et al. 2008; Ivković et al. 2007). Numerous factors underlie the enhanced susceptibility of women to musculoskeletal injuries that are related to physical activity in general, but are of greater relevance to a military lifestyle. Among these, the following risk factors have been described as significant: skeletal and anthropometric factors such as foot arch height, external rotation of the hip and gynecoid pelvis, overload of adipose tissue on the musculoskeletal system, nutritional calcium deficiency caused by eating disorders, ongoing mental and physical stressors and inactive lifestyle before recruitment (Drinkwater et al. 1984; Friedl et al. 2008; Ivković et al. 2007). Notably, however, in female and male soldiers matched for aerobic physical fitness, the injury rates are similar (Bell et al. 2000). It is still an open question whether this means, as concluded by Zambraski and Yancosek (2012), that the observed differences in injury rates are linked not to gender but to aerobic fitness.

Among overuse injuries, stress fracture has been identified as a leading medical condition affecting soldiers' combat readiness. This is because of the relative long recovery time, during which the soldier is prevented from engaging in weight-bearing activity. Cumulative data indicate that the prevalence of stress fractures is 1.5–9.5 times more prevalent in female than in male soldiers (Bijur et al. 1997; Gam et al. 2005; Jones et al. 1993; Wentz et al. 2011). Anthropometric data suggest that individuals with smaller, more slender bones are at greater risk for stress fractures (Moran et al. 2008; Tommasini et al. 2005). Thus, females, whose anatomy compared with that of males is characterized by smaller and narrower bones, with thinner bone cortices leading to lower bone mass, inherently have lower resistance than males to stress imposed by repetitive mechanical loading and are thus at greater risk of sustaining stress fractures (Evans et al. 2008). Muscles attached to the long bones function to oppose bending and torsional stress under load by converting tensile and shear stresses to compression, to which bone is intrinsically more resistant (Turner and Burr 1993). Thus, stronger muscles serve to protect the bone against the mechanical stresses leading to stress fractures, while weaker muscles or when muscles are fatigued during exercise their protective effect is impaired and stress fractures can more readily occur as a result of the unopposed tensile stress.

Thermoregulation

Heat exposures

Troops participating in military training and deployments will often encounter heat stress (metabolic and environmental), which might impair many aspects of normal military functioning and influence soldiers' health and performance. A key issue in this respect is the maintenance of body heat within a compensable range (Epstein and Roberts 2011). The ability to dissipate heat at a rate comparable to that of heat accumulation will ensure that the body-core temperature is maintained within a restricted 'normal' range.

A large body of studies since the 1940s has shown that women thermoregulate less effectively than men when exposed to an acute heat stress (Dill et al. 1977; Druyan et al. 2012; Hardy and Dubois 1940; Kaciuba-Uscilko and Grucza 2001; Shoenfeld et al. 1978; Wyndham et al. 1965;). This was concluded from the observation that under exercise-heat stress, the body-core temperature of women is higher than that of men. While it is not a simple matter to compare the results of different studies, mainly because of methodological variability, it can be concluded that the observed gender-related differences in body-core temperature are related to differences in physical characteristics rather than to inherent differences in the whole-body thermoregulatory response (Gagnon et al. 2009; Shapiro et al. 1980, 1981). For a given change in body heat content, the lower body mass (and lower lean body mass) of women, together with their higher percentage of fat mass (i.e. lower specific heat) cause their body temperature to increase more than in males, (Cheung et al. 2000; Gagnon et al. 2009; Havenith 2001). It follows that engaging in exercise under similar conditions of metabolic heat production will expose women to a greater risk of experiencing heat-related injuries. However, in view of the higher body mass and higher maximal oxygen consumption in men, working at a given percentage of maximum oxygen consumption elicits greater metabolic heat production in men than in women. Thus, despite the fact that men have higher sweat rates and higher potential absolute rates of evaporative heat loss than women, in this case, the higher metabolic heat content in men will result in a higher body-core temperature than in women (Gagnon et al. 2008; Shapiro et al. 1980).

Changes in the concentrations of estrogen and progesterone during the menstrual cycle have long been thought to modify the resting body-core temperature threshold for sweating and peripheral vasodilation (Stephenson and Kolka 1993). Specifically, the higher progesterone levels during the luteal phase have been associated with the increase in resting body-core temperature and temperature threshold for sweating, whereas the elevation in estrogen levels during the follicular phase was associated with a decrease in these parameters (Stephenson and Kolka 1993, 1999; Tankersely et al. 1992). Furthermore, sensitivity of sweating (per change in body temperature) is lower during the luteal phase than during the follicular phase (and both are lower than sensitivity of sweating in males) (Inoue et al. 2005). Whether these differences during the menstrual cycle are of practical significance is not clear, but a recent study in the IDF concluded that there are no apparent thermoregulatory differences between the follicular and the luteal phases during exposure to a heat challenge.

Cold exposure

Gender-related differences in body size, body shape and body composition contribute to a disparity in cold tolerance between men and women. In general, the greater fat content and subcutaneous fat thickness in women accounts for the greater maximal tissue insulation and lower critical temperature (the temperature when shivering ensues) in women than in men. During exposure to cold, women have a lower skin temperature than men, as well as a reduced thermal gradient for metabolic heat removal, a lower rate of body-core cooling and reduced cardiovascular and metabolic responses (McArdle et al. 1992).

Nevertheless, their greater fat content does not necessarily provide women with a thermoregulatory advantage over men. Body heat production and heat content are lower in women than in men because of their smaller body mass. In addition, the larger surface area-to-mass ratio in women results in a greater heat loss in women than in men. Therefore, although their insulation might be equivalent, in women, the body-core temperature falls more rapidly than in men for any given thermal gradient and metabolic rate (Kaciuba-Uscilko and Grucza 2001). However, when subjects were subgrouped according to similar body fatness and immersed in water, there were no significant gender differences in the rate of change in body-core temperature (Tikuisis et al. 2000).

Whether anthropometry and body composition by themselves can explain thermal response in the cold is still an open question. Glickman-Weiss concluded that differences in anthropometric characteristics alone could not explain the gender-related differences in thermoregulatory responses even though thermosensitivity between the genders is similar (Glickman-Weiss et al. 1993, 2000).

Protective garments

In military settings, not only are both genders required to meet similar physical demands but also to wear protective clothing. These suits impose an additional thermal stress owing to their high thermal and water vapour resistances that impair adequate heat dissipation (Havenith 1999; Holmer 2006). Wearing protective garments impose also an increase in energy cost during continuous tasks, which is attributed to the clothing weight and impaired biomechanics (Murphy et al. 2001).

Gender differences in tolerance time, while wearing protective garments, are not well established. McLellan (1998) concluded that women are at a thermoregulatory disadvantage compared with men when wearing protective clothing and exercising in a hot environment. He attributed this disadvantage to the higher fat percentage (and hence the lower specific heat) in women. Furthermore, it was reported that the effect of protective garments is more demanding, both physiologically and psychologically, for women than for men working at the same absolute intensity and duration (Murphy et al. 2001). This was attributed by Murphy et al. (2001) to the lower aerobic capacity of females than that of males, which required females to work at a higher percentage of their maximum aerobic capacity.

Although much of the sweat is retained within the clothing, resulting in reduced thermoregulatory efficiency and greater discomfort, it is only rarely that the evaporative heat loss is nil, except when the clothing is totally impermeable. Therefore, an absolute increase in sweat rate in individuals wearing protective clothing will eventually lead to an increased evaporative heat loss if the tolerance time is long enough to allow significant quantities of water vapour to diffuse through the clothing layers into the dryer ambient environment (McLellan and Aoyagi 1996). Hence, the higher absolute sweating rate of males may be a thermoregulatory advantage in promoting evaporative heat loss when protective clothing is worn (McLellan 1998). However, the data on tolerance time of women wearing protective garments are limited and deserve further investigation.

Adaptation to environmental stress and injury prevention

The mere fact that soldiers' physical performance can be intense and can be carried out under extreme environmental conditions, increase the vulnerability of soldiers to overuse injuries and to heat-related injuries. Recently, Roy (2011) concluded that the major cause (over 20 %) for musculoskeletal encounters, in an Infantry Brigade deployed to Afghanistan, was overuse injuries. While all combat soldiers are at risk, women soldiers might be more susceptible (Jones et al. 1993; Knapik et al. 2011). Thus, an important goal during military training of both male and female soldiers is to reduce the incidence of injuries, which poses a substantial health hazards to the individual and reduces the unit military readiness, by taking the appropriate preventive measures.

Education, leader responsibility and accountability, and surveillance have all been found effective in this connection. Educating commanders and trainees with regard to the implications of overuse injuries and the feasibility of preventing them by adopting a few simple behavioural measures has proved to be extremely important (Epstein et al. 2000; Knapik et al. 2004a). Knapik et al. (2004a) reported a 30 % reduction in overuse injuries in initial entry trainees when such education was made an integral component of an injury prevention program. Similarly, the rate of fatal exertional heat stroke in the IDF was dramatically been reduced by education and by implementing and enforcing adequate preventing measures (Epstein et al. 1999). In this respect, commanders and primary health providers should be educated on gender-related physiological and physical differences that might be of relevance in enhancing performance and preventing injuries.

Musculoskeletal injuries

Changing the concept of physical fitness training to 'physical readiness training', which includes gradual progression in physical training, scheduling periods of recovery from weight-bearing exercises (every 2–3 weeks), reducing running distances and including proprioception, balance and agility components (Knapik et al. 2009; Jones et al. 2002; Friedl et al. 2008). By changing the physical training protocols, the incidence of stress fractures in the IDF has been reduced from ~30 % to less than 10 %, and the severity of injuries has also been dramatically reduced (Finestone and Milgrom 2008).

Another line of prevention is through adequate and appropriate food intake to counteract glycogen depletion, restore energy balance, overcome fatigue, minimize muscle damage and protect against hyponatremia. Calcium and vitamin D supplementations appear to have positive effects on bone density and in reducing the rate of stress fractures in the young active population. Lappe et al. (2008) provided female recruits with 2,000 mg calcium and 800 IU vitamin D daily during basic training. Compared with placebo, the intervention was successful in reducing the rate of stress fractures by 27 %. It was also reported that women whose daily calcium consumption was less than 800 mg had nearly six times the stress fracture rate of women who consumed more than 1,500 mg of calcium daily and more than double the rate for women whose daily consumption was between 800 and 1,500 mg (Nieves et al. 2010). This association was stronger in women with menstrual irregularities, emphasizing the role of estrogens in the process and suggesting that high calcium intake may be particularly important for this group.

Footwear modification has been considered as a potentially useful way to prevent overuse injuries and stress fractures in the military, as this type of intervention can be easily enforced and implemented. However, several well-designed studies have not yet yielded any significant effects of basketball shoes, military boots or orthotics on injury rates (Milgrom et al. 1992; Gardner et al. 1988; Schwellnus et al. 1990). An early study by Milgrom et al. (1985) in the IDF revealed only a minor effect of shoe-shock attenuation in reducing metatarsal stress fractures, while specific arch supports were associated with fewer femoral stress fractures (Milgrom et al. 1985). These interventions, however, have not shown sufficient overall reduction of injuries to justify their use (Finestone et al. 2004). While the effects of footwear were tested mainly in male soldiers, current knowledge gives no reason to believe that females would respond differently but this deserves further investigation.

Heat-related injuries

Heat-related injuries is a spectrum from a mild condition of heat-related fatigue to the serious, life-threatening condition of exertional heat injuries; the latter is a continuum between heat exhaustion and heatstroke which are related to body heat balance. While the cumulative data suggest that there are no apparent gender differences in thermoregulatory function or in whole-body thermoregulatory responses, there are quantitative differences, especially in regard to sweat rate, which may affect performance and thus should be outlined.

Prolonged physical exercise, especially when performed in the heat will often incur significant hypohydration, when sweating exceed fluid intake. Dehydration increases physiological strain, decreases exercise performance and can mediate exertional heat illnesses (Carter et al. 2005; Armstrong et al. 2007). Women sweat less than men (Bar-Or 1998; Sawka et al. 1983). Plotting sweat rate against work rate (absolute exercise intensity) show that there is almost a linear relationship between them (Schwiening et al. 2011). Furthermore, the mean number of activated sweat glands is an exponential function of absolute work rate with maximal activated sweat glands of approximately 120 glands/cm^2 at a work rate of approximately 120 W (Schwiening et al. 2011). It follows that women sweat less than men not because of gender-related difference, e.g. higher sweating threshold), but because of their lower body mass and lower physical capacity. Therefore, women may incur lower levels of dehydration and its undesired consequences. However, women are at a higher risk to develop hyponatremiam, mainly because of the increased risk of women to overhydrate (Almond et al. 2005; Eijsvogels et al. 2011). It follows from the above that adhering to fluid replacement guidelines is critical. General guidelines for fluid replacement have been published based on male physical characteristics (Epstein et al. 2012; O'Brien et al. 2006). Those guidelines should, however, be used with caution when applied to women, and further research is needed in this respect.

Heat acclimatisation denotes physiological and perceptual change that occur over a period of several days to weeks in a person newly exposed to heat In general, these changes reflect an improved thermoregulatory effectiveness and heat tolerance. There is no apparent difference in the acclimatisation process or benefit between men and women (Avellini et al. 1980; Frye and Kamon 1981; Shapiro et al. 1980; Wyndham et al. 1965). Therefore, newly recruits, males and females, should start exercising gradually until acclimatised and should be assigned to military missions in a gradual manner during deployment to warm areas in order to maximise their effectiveness.

Integration of women in combat professions

The current tendency worldwide is to acknowledge that integration of women into combat professions is achievable. As a consequence, in many military organizations today, female soldiers are integrated into many combat professions that in the past were restricted to males. However, in most militaries, women are still being excluded from positions in which their combat effectiveness is questioned mainly on physical grounds (Cawkill et al. 2009; Tarrasch et al. 2011). Historically, physical standards for soldiers' combat readiness have been set for male soldiers. Therefore, the question arises whether female soldiers, given the implementation of proper military-relevant training programs, can adapt to military physical and combat demands. Not less important are the questions of whether, and if so to what extent, adapting the physical fitness standards for female soldiers, which would be lower than for male soldiers, will compromise the unit's readiness for combat.

As outlined above, the physiological and anthropometric differences between male and female soldiers limit the absolute weight female soldiers can carry. There are also significant gender-related differences in biomechanics. At a given marching pace, females walk with shorter stride length and greater stride frequency than men (Martin and Nelson 1986). Furthermore, as loads increase, females' stride length decreases, whereas men's stride length does not show significant change. With increasing load, females also show a more pronounced linear increase in the time that both feet are on the ground (double support time) than do males (Martin and Nelson 1986). To bring the centre of the load mass over the feet (base of support), females tend to hyperextend their necks and bring their shoulders farther forward than do males, possibly to compensate for their inferior upper body strength (Ling et al. 2004). Many of these differences between males and females persist even when differences in body size and composition are taken into account (Ling et al. 2004; Martin and Nelson 1986). Furthermore, when male and female soldiers were asked to complete a 10-km road march as quickly as possible, while carrying different loads, men were about 21 % faster (Harper et al. 1997). Will these differences compromise unit combat effectiveness?

Because combat requirements differ from the requirements of athletic performance, direct projection of the lower records achieved by women athletes and the prediction made by Thibault et al. (2010) that females' physical performance at the highest level will never match that of males is irrelevant for soldiers. It is plausible that by thoughtful planning and adaptation of proper training doctrines that will be mission oriented while also taking account on body characteristics and physical fitness, females can be integrated in almost all combat front line missions. Yanovich et al. (2008) investigated the physical capacity of all soldiers in a gender-integrated light-infantry battalion, where the physical requirements for both female and male soldiers through all stages of service were supposed to be equal. All soldiers served under the same environmental conditions and underwent similar basic training regimens. Following basic and advanced training they participated equally in all combat duties (e.g. patrols, pursuits, ambushes and surveillance). This survey showed that the overall physical fitness of these soldiers was lower than that of other infantry battalions. Furthermore, although the physiological advantage of male soldiers over their female counterparts was lowered by almost 4 % during basic training, the overall gender differences were still evident with males having 20 % higher aerobic capacity and 25 % higher anaerobic capacity than females (Yanovich et al. 2008). Nevertheless, the lower fitness in this light-infantry battalion did not prevent accomplishment of the specific missions assigned, which were carried out successfully by both female and male soldiers. Thus, although females have an initial disadvantage physiologically in comparison to males, the IDF experience is that a thoughtful doctrine, which takes account of the soldiers' physical abilities, enables successful integration of females in combat professions. Similar conclusions have been drawn in other militaries as well (Cawkill et al. 2009).

Ergonomic considerations should not be overlooked. Traditionally, military standards have focused on male soldiers. Therefore, many of the working environments and much of the equipment are designed accordingly. Some of the required modifications are trivial, e.g. redesigning apparel, and not just scaling down male-proportioned armour vests and combat vests, to accommodate women's physique in terms of height, chest-waist-hip ratios and breast tissue. The following two examples will demonstrate how ergonomics can reduce injuries and enhance performance. The first, described by Knapik et al. (2004b), concerns load carriage. Because the design of pack systems was based primarily on the anthropometry of men, females have commented more often than men that the pack straps were uncomfortable, that the pistol belts fit poorly and that the rucksacks were unstable. Furthermore, an independent predictor of march-time while carrying loads (when gender is included in the equation) is shoulder breadth (Harper et al. 1997). On the other hand, a well-padded hip belt improves load carriage performance by allowing a better transfer of the load to the hips so that females can use the stronger muscles of the legs to carry the load (Lafiandra and Harman 2004; Ling et al. 2004). The second observation was made by Yanovich and colleagues (personal communication) after 75 % of female Hummer drivers were found experiencing overuse injuries, such as low-back and neck pains. These were attributed to unsuitable protective equipment for the driver (e.g. helmet and eye protectors) and ergonomics of the driver's seat. Firstly, the drivers' helmets, which were designed for the average male anthropometry, did not fit the average female head size, leading to excess strain on the cervical vertebrae and muscles (such as trapezius and levator scapulae) with resulting neck pain. Secondly, the original pneumatic chair in the vehicle had been replaced by a solid nonadjustable seat, which was too high for most females and not aligned to the gas and brake pedals. This forced female drivers to compensate by straining the latissimus dorsi and gluteus maximus muscles, causing low-back pain. All the above were solved after the adequate adjustments were made.

Despite the considerable physiological and anthropometric differences between the genders, the integration of women in many combat professions is feasible. To successfully accomplish this goal, military organizations should define appropriate positions at which the exact physical demands are realistic for female body structure and physiology. An adjustable training program should be adopted that will improve the physical fitness of female soldiers to the level required for fulfilment of the units' specified combat missions. One successfully implemented program in the gender-integrated Officers Course in the IDF is training in 'ability groups' rather than training in gender-separated groups. Such a doctrine was also been suggested recently by Knapik et al. (2006). In some cases, changes in doctrine should also be considered with the object of narrowing the anthropometric and physiological gaps without compromising the specified mission.

Little information is available on the effect exerted by women in combat professions on the military effectiveness of a fighting unit. However, already during WWII, it was proved that women could serve equally in some combat positions side by side with men. The conclusion of the study conducted by General Marshall, then US Chief of Staff, that female soldiers met the physical, intellectual and psychological standards for the mission under study should be a beacon for the future. Similarly, years later, Harries-Jenkins (2002) found no direct evidence that women are likely to have a negative impact on combat effectiveness. The IDF experience suggests that cohesion, an important factor in combat unit effectiveness, is preserved in gender-integrated combat units. Furthermore, attrition rates (excluding medical reasons) in those units are lower for women than for men. While physical fitness requirements are task dependent, in many cases, the level of physical fitness required during the training stage is much higher than the level actually required during the field (combat) stage of service, where the principal factor is professionalism. By assigning tasks on the basis of physical capabilities, no differences between female and male combatants' performance were reported. Only a minority of the close combat roles professions will still be closed to women, mainly because of their extreme physical requirements that are beyond the physiological adaptability capacity of the average female.

Conclusions

The present review concentrated on the physiological differences between genders and their effects on the potential for successfully integrating women in combat missions. Many other aspects of this issue, which might be detrimental, are not reviewed here. Even within the limited scope of this review, many questions are still open for further investigations and many aspects concerning the successful integration of females into combat units warrant further research. There are still knowledge gaps about how to prevent overuse injuries and enhance performance by implementing proper training protocols, redesigning pieces of equipment (e.g. boots and backpacks), and adjusting diet, including micro- and macronutrient supplementations, to meet the body's needs under stressful military duties. A crucial issue is modern life style that is not supportive of routine physical activity and is not encouraging balanced dietary intake during adolescent. More research initiatives focusing on the importance to military demands in preventing injuries are required. The extent to which gene expression during military-oriented physical tasks can be helpful in better selecting females for combat positions is still in question. Finally, the vast body of information in the literature with regard to female versus male physiological differences have on military competence should be reviewed with caution. Differences in studies' methodology can blur the conclusions and can even be contradictory. A meta-analysis on this issue that accounts for methodological differences is a challenge for future research.

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References

Almond CS, Shin AY, Fortescue EB, Mannix RC, Wypij D, Binstadt BA, Duncan CN, Olson DP, Salerno AE, Newburger JW, Greenes DS (2005) Hyponatremia among runners in the Boston Marathon. N Engl J Med 352:1550–1556

Armed Forces Health Surveillance Center (2011) Brief report: morbidity burdens attributable to illnesses and injuries in deployed (per Theater Medical Data Store [TMDS]) compared to nondeployed (per Defense Medical Surveillance System [DMSS]) settings, active component, US Armed Forces, 2010. MSMR 18:14–15

Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO (2007) American College of Sports Medicine position stand. Exertional heat illness during training and competition. Med Sci Sports Exerc 39:556–572

Avellini BA, Kamon EK, Krajewski JT (1980) Physiological responses of physically fit men and women to acclimation to humid heat. J Appl Physiol 49:254–261

Bam J, Noakes TD, Juritz J, Dennis SC (1997) Could women outrun men in ultramarathon races? Med Sci Sports Exerc 29:244–247

Barnes HV (1975) Physical growth and development during puberty. Med Clin North Am 59:1305–1317

Bar-Or O (1998) Effects of age and gender on sweating pattern during exercise. Int J Sports Med 19:S106–S107

Beck TJ, Ruff CB, Shaffer RA, Betsinger K, Trone DW, Brodine SK (2000) Stress fracture in military recruits: gender differences in muscle and bone susceptibility factors. Bone 27:437–444

Beckett MB, Hodgson JA (1987) Lifting and carrying capacities relative to physical fitness measures. Report No 87–26, Naval Health Research Center, San Diego, CA

Bell NS, Mangione TW, Hemenway D, Amoroso PJ, Jones BH (2000) High injury rates among female army trainees: a function of gender? Am J Prev Med 18(Suppl):141–146

Berga SL, Loucks TL (2006) Use of cognitive behavior therapy for functional hypothalamic amenorrhea. Ann NY Acad Sci 1092:114–129

Berga SL, Daniels TL, Giles DE (1997) Women with functional hypothalamic amenorrhea but not other forms of anovulation display amplified cortisol concentrations. Fertil Steril 67:1024–1030

Bethea CL, Pau FK, Fox S, Hess DL, Berga SL, Cameron JL (2005) Sensitivity to stress-induced reproductive dysfunction linked to activity of the serotonin system. Fertil Steril 83:148–155

Bhambhani Y, Maikala R (2000) Gender differences during treadmill walking with graded loads: biomechanical and physiological comparisons. Eur J Appl Physiol 81:75–83

Bijur PE, Horodyski M, Egerton W, Kurzon M, Lifrak S, Friedman S (1997) Comparison of injury during cadet basic training by gender. Arch Pediatr Adolesc Med 151:456–461

Binkin M, Bach SJ (1977) Women and the Military. Brookings Institute, Washington

Blacker SD, Fallowfield JL, Bilzon JL, Willems ME (2010) Neuromuscular function following prolonged load carriage on level and downhill gradients. Aviat Space Environ Med 81:745–753

Blum WF, Englaro P, Hanitsch S, Juul A, Hertel NT, Müller J, Skakkebaek NE, Heiman ML, Birkett M, Attanasio AM, Kiess W, Rascher W (1997) Plasma leptin levels in healthy children and adolescents: dependence on body mass index, body fat mass, gender, pubertal stage, and testosterone. J Clin Endocrinol Metab 82:2904–2910

Brownlie T 4th, Utermohlen V, Hinton PS, Giordano C, Haas JD (2002) Marginal iron deficiency without anemia impairs aerobic adaptation among previously untrained women. Am J Clin Nutr 75:734–742

Burstein R, Coward AW, Askew WE, Carmel K, Irving C, Shpilberg O, Moran D, Pikarsky A, Ginot G, Sawyer M, Golan R, Epstein Y (1996) Energy expenditure variations in soldiers performing military activities under cold and hot climate conditions. Mil Med 161:750–754

Cain PA, Ahl R, Hedstrom E, Ugander M, Allansdotter-Johnsson A, Friberg P, Arheden H (2009) Age and gender specific normal values of left ventricular mass, volume and function for gradient echo magnetic resonance imaging: a cross sectional study. BMC Med Imaging 9:2. doi:10.1186/1471-2342-9-2

Campbell D (1993) Women in Combat: the world war two experience in the United States, Great Britain, Germany, and the Soviet Union. J Mil Hist 57:301–323

Carter R 3rd, Cheuvront SN, Williams JO, Kolka MA, Stephenson LA, Sawka MN, Amoroso PJ (2005) Epidemiology of hospitalizations and deaths from heat illness in soldiers. Med Sci Sports Exerc 37:1338–1344

Caspersen CJ, Powell KE, Christenson GM (1985) Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. Public Health Rep 100:126–131

Cawkill P, Rogers A, Knight S, Spear L (2009) Women in ground close combat roles: the experiences of other nations and a review of the academic literature, DSTL/CR37770 V3-0. Defence Science and Technology Laboratory, Porton Down

Cheung SS, McLellan TM, Tenaglia S (2000) The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. Sports Med 29:329–359

Clarke HH, Shay CT, Mathews DK (1955) Strength decrements from carrying various army packs on military marches. Res Q 26:253–265

Cline AD, Jansen GR, Melby CL (1998) Stress fractures in female army recruits: implications of bone density, calcium intake, and exercise. J Am Col Nutr 17:128–135

Cureton K, Bishop P, Hutchinson P, Newland H, Vickery S, Zwiren L (1986) Sex difference in maximal oxygen uptake: effect of equating haemoglobin concentration. Eur J Appl Physiol 54:656–660

Dalen H, Thorstensen A, Vatten LJ, Aase SA, Stoylen A (2010) Reference values and distribution of conventional echocardiographic Doppler measures and longitudinal tissue Doppler velocities in a population free from cardiovascular disease. Circ Cardiovasc Imaging 3:614–622

Dill DB, Soholt LF, McLean DC, Drost TF Jr, Loughran MT (1977) Capacity of young male and females for running in desert heat. Med Sci Sports 9:137–142

Drinkwater BL (1973) Physiological responses of women to exercise. Exerc Sport Sci Rev 1:125–153

Drinkwater BL, Nilson K, Chesnut CH III, Shainholtz S, Southworth MB, Drinkwater BL (1984) Bone mineral content of amenorrheic and eumenorrheic athletes. N Engl J Med 311:277–281

Druyan A, Makranz C, Moran D, Yanovich R, Epstein Y, Heled Y (2012) Heat tolerance in women—reconsidering the criteria. Aviat Space Environ Med 83:58–60

Dubnov G, Foldes AJ, Mann G, Magazanik A, Siderer M, Constantini N (2006) High prevalence of iron deficiency and anemia in female military recruits. Mil Med 171:866–869

Eijsvogels TM, Scholten RR, van Duijnhoven NT, Thijssen DH, Hopman MT (2011) Sex difference in fluid balance responses during prolonged exercise. Scand J Med Sci Sports doi:10.1111/j.1600-0838.2011.01371.x

Eisenmann JC, Pivarnik JM, Malina RM (2001) Scaling peak VO2 to body mass in young male and female distance runners. J Appl Physiol 90:2172–2180

Elspeth CR (2001) Issues for military females deploymalest: an overview. Mil Med 166:1033–1037

Emons J, Chagin AS, Sävendahl L, Karperien M, Wit JM (2011) Mechanisms of growth plate maturation and epiphyseal fusion. Horm Res Paediatr 75:383–391

Epstein Y, Roberts WO (2011) The pathopysiology of heat stroke: an integrative view of the final common pathway. Scand J Med Sci Sports 21:742–748

Epstein Y, Moran DS, Shapiro Y, Sohar E, Shemer J (1999) Exertional heat stroke: a case series. Med Sci Sports Exerc 31:224–228

Epstein Y, Shani Y, Moran DS, Shapiro Y (2000) Exertional heat stroke—the prevention of a medical emergency. J Basic Clin Physiol Pharmacol 11:395–401

Epstein Y, Druyan A, Heled Y (2012) Heat injury prevention—a military perspective. J Strength Cond Res 26:S82–S86

Eriksen EF, Colvard DS, Berg NJ, Graham ML, Mann KG, Spelsberg TC, Riggs BL (1988) Evidence of estrogen receptors in normal human osteoblast-like cells. Science 241:84–86

Etzion-Daniel Y, Constantini N, Finestone AS, Shahar D, Israeli E, Yanovich R, Moran DS (2008) Nutrition consumption of female combat recruits in army basic training. Med Sci Sports Exerc 40:S677–S684

Evans KR, Negus C, Antxzak AJ, Yanovich R, Israeli E, Moran DS (2008) Sex differences in parameters of bone strength in new recruits: beyond bone density. Med Sci Sports Exerc 40:S645–S653

Finestone A, Milgrom C (2008) How stress fracture incidence was lowered in the Israeli army: a 25-yr struggle. Med Sci Sports Exerc 40:S623–S629

Finestone A, Novack V, Farfel A, Berg A, Amir H, Milgrom C (2004) A prospective study of the effect of foot orthoses composition and fabrication on comfort and the incidence of overuse injuries. Foot Ankle Int 25:462–466

Finestone A, Milgrom C, Evans R, Yanovich R, Constantini N, Moran DS (2008) Overuse injuries in female infantry recruits during low-intensity basic training. Med Sci Sports Exerc 40:S630–S635

Friedl KE (2012) Body composition and military performance—many things to many people. J Strength Cond Res 26:S87–S100

Friedl KF, Evans RK, Moran DS (2008) Stress fracture and military medical readiness: bridging basic and applied research. Med Sci Sports Exerc 40:S609–S622

Friedman B, Weller E, Mairbauri H, Baertsch P (2001) Effects of iron repletion on blood volume and performance capacity in young athletes. Med Sci Sports Exerc 33:741–746

Frisch RE, Gotz-Welbergen AV, McArthur JW, Albright T, Witschi J, Bullen B, Birnholz J, Reed RB, Hermann H (1981) Delayed menarche and amenorrhea of college athletes in relation to age of onset of training. JAMA 246:1559–1563

Frye AJ, Kamon E (1981) Responses to dry heat of men and women with similar aerobic capacities. J Appl Physiol 54:972–977

Gagnon D, Jay O, Lemire B, Kenny GP (2008) Sex-related differences in evaporative heat loss: the importance of metabolic heat production. Eur J Appl Physiol 104:821–829

Gagnon D, Dorman LE, Jay O, Hardcastle S, Kenny GP (2009) Core temperature differences between males and females during intermittent exercise: physical considerations. Eur J Appl Physiol 105:453–461

Gam A, Goldstein L, Karmon Y, Mintser I, Grotto I, Guri A, Goldberg A, Ohana N, Onn E, Levi Y, Bar-Dayan Y (2005) Comparison of stress fractures of male and female recruits during basic training in the Israeli anti-aircraft forces. Mil Med 170:710–712

Gardner GW, Edgerton VR, Senewiratne B, Barnard RJ, Ohira Y (1977) Physical work capacity and metabolic stress in subjects with iron-deficient anemia. Am J Clin Nutr 30:910–917

Gardner LI Jr, Dziados JE, Jones BH, Brundage JF, Harris JM, Sullivan R, Gill P (1988) Prevention of lower extremity stress fractures: a controlled trial of a shock absorbent insole. Am J Public Health 78:1563–1567

Glickman-Weiss EL, Nelson AG, Hearon CM, Goss FL, Robertson RJ, Cassinelli DA (1993) Effects of body morphology and mass on thermal responses to cold water: revisited. Eur J Appl Physiol 66:299–303

Glickman-Weiss EL, Cheatman C, Caine N, Blegen M, Marcinkiewicz J, Mittleman KD (2000) The influence of gender and menstrual phase on thermosensitivity during cold water immersion. Aviat Space Environ Med 71:715–722

Hardy JD, Dubois EF (1940) Differences between men and women in their responses to heat and cold. Proc Natl Acad 26:389–398

Harper W, Knapik JJ, dePontbriand R (1997) An investigation of female load carriage capability. Technical Report ARL-TR-1176, USArmy Research Laboratory, Aberdeen Proving Ground, MD

Harrell MC, Miller LL (1997) New opportunities for military women: effects upon readiness, cohesion and morale, MR-896-OSD. RAND Co, Santa Monica

Harries-Jenkins G (2002) Women in extended roles in the military: legal issues. Curr Sociol 50:745–769

Havenith G (1999) Heat balance when wearing protective clothing. Ann Occup Hyg 43:289–296

Havenith G (2001) Human surface to mass ratio and body core temperature in exercise heat stress—a concept revisited. J Themal Biol 26:387–393

Henry YM, Fatayerji D, Eastell R (2004) Attainment of peak bone mass at the lumbar spine, femoral neck, and radius in men and women: relative contributions of bone size and volumetric bone mineral density. Osteoporos Int 15:263–273

Hicks AL, Kent-Braun J, Ditor DS (2001) Sex differences in human skeletal muscle fatigue. Exerc Sports Sci Rev 29:109–112

Hinton PS, Giordano C, Brownlie TIV, Haas JD (2000) Iron supplementation improves endurance after training in iron-depleted, nonanemic women. J Appl Physiol 99:1103–1111

Holmer I (2006) Protective clothing in hot environments. Indust Health 44:404–413

Hoyt RW, Opstad PK, Haugen AH, DeLany JP, Cymerman A, Friedl KE (2006) Negative energy balance in male and female rangers: effects of 7 d of sustained exercise and food deprivation. Am J Clin Nutr 83:1068–1075

Hunter SK, Enoka RM (2001) Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. J Appl Physiol 91:2686–2694

Inoue Y, Tanaka Y, Omori K, Kuwahara T, Ogura Y, Ueda H (2005) Sex- and menstrual cycle-related differences in sweating and cutaneous blood flow in response to passive heat exposure. Eur J Appl Physiol 94:323–332

Israeli E, Merkel D, Constantini N, Yanovich R, Evans RK, Shahar D, Moran DS (2008) Iron deficiency and the role of nutrition among female military recruits. Med Sci Sports Exerc 40: S685–S690

Ivković A, Franić M, Bojanić I, Pećina M (2007) Overuse injuries in female athletes. Croat Med J 48:767–778

Jepsen KJ, Centi A, Duarte GF, Galloway K, Goldman H, Hampson N, Lappe JM, Cullen DM, Greeves J, Izard R, Nindl BC, Kraemer WJ, Negus CH, Evans RK (2011) Biological constraints that limit compensation of a common skeletal trait variant lead to inequivalence of tibial function among healthy young adults. J Bone Miner Res 26:2872–2885

Jones BH, Bovee MW, Harris JM 3rd, Cowan DN (1993) Intrinsic risk factors for exercise-related injuries among male and female army trainees. Am J Sports Med 21:705–710

Jones BH, Thacker SB, Gilchrist J, Kimsey CD Jr, Sosin DM (2002) Prevention of lower extremity stress fractures in athletes and soldiers: a systematic review. Epidemiol Rev 24:228–247

Jones BH, Canham-Chervak M, Canada S, Mitchener TA, Moore S (2010) Medical surveillance of injuries in the US Military descriptive epidemiology and recommendations for improvement. Am J Prev Med 38:S42–S60

Kaciuba-Uscilko H, Grucza R (2001) Gender differences in thermoregulation. Curr Opin Clin Nutr Metab Care 4:533–536

Kanehisa H, Ikegawa S, Fukunaga T (1994) Comparison of muscle cross-sectional area and strength between untrained women and men. Eur J Appl Physiol 68:148–154

Kasperk CH, Wakley GK, Hierl T, Ziegler R (1997) Gonadal and adrenal androgens are potent regulators of human bone cell metabolism in vitro. J Bone Miner Res 12:464–471

Kaufman KR, Brodine S, Shaffer R (2000) Military training-related injuries: surveillance, research, and prevention. Am J Prev Med 18(Suppl):54–63

Kelly EW, Jonson SR, Cohen ME, Shaffer R (2000) Stress fractures of the pelvis in female navy recruits: an analysis of possible mechanisms of injury. Mil Med 165:142–146

Kent-Braun JA, Ng AV, Doyle JW, Towse TF (2002) Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. J App Physiol 93:1813–1823

King N, Fridlund KE, Askew EW (1993) Nutrition issues of military women. J Am Coll Nutr 12:344–348

Knapik JJ, Sharp MA, Canham-Chervak M, Hauret K, Patton JF, Jones BH (2001) Risk factors for training-related injuries among men and women in basic combat training. Med Sci Sports Exerc 33:946–954

Knapik JJ, Bullock SH, Canada S, Toney E, Wells JD, Hoedebecke E, Jones BH (2004a) Influence of an injury reduction program on injury and fitness outcomes among soldiers. Inj Prev 10:37–42

Knapik JJ, Reynolds KL, Harman E (2004b) Soldier load carriage: historical, physiological, biomechanical, and medical aspects. Mil Med 169:45–56

Knapik JJ, Scott SJ, Sharp MA, Hauret KG, Darakjy S, Rieger WR, Palkoska FA, VanCamp SE, Jones BH (2006) The basis for prescribed ability group run speeds and distances in US Army basic combat training. Mil Med 171:669–677

Knapik JJ, Rieger W, Palkoska F, Van Camp S, Darakjy S (2009) United States Army physical readiness training: rationale and evaluation of the physical training doctrine. J Strength Cond Res 23:1353–1362

Knapik JJ, Spiess A, Swedler D, Grier T, Hauret K, Yoder J, Jones BH (2011) Retrospective examination of injuries and physical fitness during federal bureau of investigation new agent training. J Occup Med Toxicol 6:26. doi:10.1186/1745-6673-6-26

Kronenberg HM (2003) Developmental regulation of the growth plate. Nature 423:332–336

Lafiandra M, Harman E (2004) The distribution of forces between the upper and lower back during load carriage. Med Sci Sports Exerc 36:460–467

Lappe J, Cullen D, Haynatzki G, Recker R, Ahlf R, Thompson K (2008) Calcium and vitamin D supplementation decreases incidence of stress fractures in female navy recruits. J Bone Miner Res 5:741–749

Libster D, Heled Y, Shapiro Y, Epstein Y (1999) Physiological aspects of females in combat. Harefuah 137:521–525

Ling W, Houston V, Tasi YS, Chui K, Kirk J (2004) Women's load carriage performance using modular lightweight load-carrying equipment. Mil Med 169:914–919

Lu PW, Briody JN, Ogle GD, Morley K, Humphries IR, Allen J, Howman-Giles R, Sillence D, Cowell CT (1994) Bone mineral density of total body, spine, and femoral neck in children and young adults: a cross-sectional and longitudinal study. J Bone Miner Res 9:1451–1458

Malina RM, Bouchard C (1991) Growth, maturation, and physical activity. Human Kinetics, Champaign, pp 101–120

Marshall WA, Tanner JM (1969) Variations in pattern of pubertal changes in girls. Arch Dis Child 44:291–303

Marshall WA, Tanner JM (1970) Variations in the pattern of pubertal changes in boys. Arch Dis Child 45:13–23

Martin PE, Nelson RC (1986) The effect of carried loads on the walking patterns of men and women. Ergonomics 29:1191–1202

Maud PJ, Shultz BB (1986) Gender comparison in anaerobic power and anaerobic capacity tests. Br J Sports Med 20:51–54

Maughan RJ, Harmon M, Leiper JB, Sale D, Delman A (1986) Endurance capacity of untrained males and females in isometric and dynamic muscular contractions. Eur J Appl Physiol Occup Physiol 55:395–400

Mauras N, Blizzard RM, Link K, Johnson ML, Rogol AD, Veldhuis JD (1987) Augmentation of growth hormone secretion during puberty: evidence for a pulse amplitude-modulated phenomenon. J Clin Endocrinol Metab 64:596–601

McArdle WD, Toner MM, Magel JR, Spina RJ, Pandolf KB (1992) Thermal responses of men and women during cold-water immersion: influence of exercise intensity. Eur J Appl Physiol 65:265–270

McClung JP (2012) Iron status and the female athlete. J Trace Elem Med Biol 26:124–126

McClung JP, Marchitelli LJ, Friedl KE, Young AJ (2006) Prevalence of iron deficiency and iron deficiency anemia among three populations of female military personnel in the US army. J Am Coll Nutr 25:64–69

McClung JP, Karl JP, Cable SJ, Williams KW, Nindl BC, Young AJ, Lieberman HR (2009) 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 90:124–131

McLellan TM (1998) Sex-related differences in thermoregulatory responses while wearing protective clothing. Eur J Appl Physiol 78:28–37

McLellan TM, Aoyagi Y (1996) Heat strain in protective clothing following hot-wet or hot-dry heat acclimation. Can J Appl Physiol 21:90–108

McNeary AM, Lomalesick TS (2000) Military duty: risk factor for preterm labor? A review. Mil Med 165:612–615

Merkel D, Moran DS, Yanovich R, Evans RK, Finestone AS, Constantini N, Israeli E (2008) The association between hematological and inflammatory factors and stress fractures among female military recruits. Med Sci Sports Exerc 40:S691–S697

Milgrom C, Giladi M, Kashtan H, Simkin A, Chisin R, Margulies J, Steinberg R, Aharonson Z, Stein M (1985) A prospective study of the effect of a shock-absorbing orthotic device on the incidence of stress fractures in military recruits. Foot Ankle 6:101–104

Milgrom C, Finestone A, Shlamkovitch N, Wosk J, Laor A, Voloshin A, Eldad A (1992) Prevention of overuse injuries of the foot by improved shoe shock attenuation. A randomized prospective study. Clin Orthop Relat Res 281:189–192

Miller AE, MacDougall JD, Tarnopolsky MA, Sale DG (1993) Gender differences in strength and muscle fiber characteristics. Eur J Appl Physiol Occup Physiol 66:254–262

Moran DS, Israeli E, Evans RK, Yanovich R, Constantini N, Shabshin N, Merkel D, Luria O, Erlich T, Laor A, Finestone A (2008) Prediction model for stress fracture in young female recruits during basic training. Med Sci Sports Exerc 40:S636–S644

Moran DS, Heled Y, Arbel Y, Israeli E, Finestone A, Evans RK, Yanovich R (2012) Dietary intake and stress fractures among elite male combat recruits. J Int Soc Sports Nutr 9:6. doi:10.1186/1550-2783-9-6

Moreno LA, González-Gross M, Kersting M, Molnár D, de Henauw S, Beghin L, Sjöström M, Hagströmer M, Manios Y, Gilbert CC, Ortega FB, Dallongeville J, Arcella D, Wärnberg J, Hallberg M, Fredriksson H, Maes L, Widhalm K, Kafatos AG, Marcos A (2008) Assessing, understanding and modifying nutritional status, eating habits and physical activity in European adolescents: the HELENA (healthy lifestyle in europe by nutrition in adolescence) study. Pub Health Nutr 11:288–299

Morgan B, Woodruff SJ, Tiidus PM (2003) Aerobic energy expenditure during recreational weight training in females and males. J Sports Sci Med 2:117–122

Murphy MM, Patton JL, Frederick BS (1986) Comparative anaerobic power of men and women. Aviat Space Environ Med 57:636–641

Murphy MM, Patton J, Mello R, Bidwell T, Harp M (2001) Energy cost of physical task performance in men and women wearing

chemical protective clothing. Aviat Space Environ Med 72:25–31
Nieves JW, Melsop K, Curtis M, Kelsey JL, Bachrach LK, Greendale G, Sowers MF, Sainani KL (2010) Nutritional factors that influence change in bone density and stress fracture risk among young female crosscountry runners. PM R 2:740–750
Nindl BC, Sharp MA, Castellani JW, Warr B, Henning P, Spiering P Scofield D (2013) Physiological employment standards III: Physiological challenges and consequences encounterd during international military deployments, Eur J Appl Physiol (accepted for publication)
O'Brien KK, McPherson MK, Alsip B, Sawka MN (2006) Exertional heat sroke. In: DeKoning BL (ed) Textbook of military medicine: recruit medicine. Borden Institute, Washington, pp 493–516
Ottomano C, Franchini M (2012) Sports anaemia: facts or fiction? Blood Transfus 10:252–254
Oz OK, Millsaps R, Welch R, Birch J, Zerwekh JE (2001) Expression of aromatase in the human growth plate. J Mol Endocrinol 27:249–253
Pérez-López FR, Chedraui P, Cuadros-López JL (2010) Bone mass gain during puberty and adolescence: deconstructing gender characteristics. Curr Med Chem 17:453–466
Ransdell LB, Vener J, Huberty J (2009) Masters athletes: an analysis of running, swimming and cycling performance by age and gender. J Exerc Sci Fit 7:S61–S73
Rogol AD, Roemmich JN, Clark PA (2002) Growth at puberty. J Adolesc Health 31:S192–S200
Rosendal L, Langberg H, Skov-Jensen A, Kjær M (2003) Incidence of injury and physical performance adaptations during military training. Clin J Sport Med 13:157–163
Rowland TW, Kelleher JF (1989) Iron deficiency in athletes. Insights from high school swimmers. Am J Dis Child 143:197–200
Rowland T, Goff D, Martel L, Ferrone L (2000) Influence of cardiac functional capacity on gender differences in maximal oxygen uptake in children. Chest 117:629–635
Roy TC (2011) Diagnoses and mechanisms of musculoskeletal injuries in an infantry brigade combat team deployed to Afghanistan evaluated by the brigade physical therapist. Mil Med 176:903–908
Saad MF, Damani S, Gingerich RL, Riad-Gabriel MG, Khan A, Boyadjian R, Jinagouda SD, el-Tawil K, Rude RK, Kamdar V (1997) Sexual dimorphism in plasma leptin concentration. J Clin Endocrinol Metab 82:579–884
Saltin B, Astrand PO (1967) Maximal oxygen uptake in athletes. J Appl Physiol 23:353–358
Sawka MN, Toner MM, Francesconi RP, Pandolf KB (1983) Hypohydration and exercise: effects of heat acclimation, gender, and environment. J Appl Physiol 55:147–1153
Schwellnus MP, Jordaan G, Noakes TD (1990) Prevention of common overuse injuries by the use of shock absorbing insoles. A prospective study. Am J Sports Med 18:636–6416
Schwiening CJ, Mason MJ, Thompson M (2011) Absolute power, not sex, promotes perspiration. Exp Physiol 96:556–558
Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF (1980) Physiological responses of men and women to humid and dry heat. J Appl Physiol 49:1–8
Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF (1981) Heat balance and transfer in men and women exercising in hot-dry and hot-wet conditions. Ergonomics 24:375–386
Shaskey DJ, Green GA (2000) Sports haematology. Sports Med 29:27–38
Shoenfeld Y, Udassin R, Shapiro Y, Ohri A, Sohar E (1978) Age and sex difference in response to short exposure to extreme dry heat. J Appl Physiol 44:l–4
Shvartz E, Reibold RC (1990) Aerobic fitness norms for males and females aged 6–75: a review. Aviat Space Environ Med 61:3–11
Starkey LJ, Johnson-Down L, Gray-Donald K (2001) Food habits of Canadians: comparison of intakes in adults and adolescents to Canada's food guide to healthy eating. Can J Diet Pract Res 62:61–69
Stephenson LA, Kolka MA (1993) Thermoregulation in women. In: Holloszy JO (ed) Exercise and sport sciences reviews, 21st edn. Williams and Wilkins, Baltimore, pp 231–262
Stephenson LA, Kolka MA (1999) Esophageal temperature threshold for sweating decreases before ovulation in premenopausal women. J Appl Physiol 86:22–28
Tankersely CG, Nicholas WC, Deaver DR, Mikita D, Kenney WL (1992) Estrogen replacement in middle-aged women: thermoregulatory responses to exercise in the heat. J Appl Physiol 73:1238–1245
Tanner JM (1965) The relationship of puberty to other maturity indicators and body composition in man. Symp Soc Stud Hum Biol 6:211
Tarnopolsky MA (2000) Gender differences in substrate metabolism during endurance exercise. Can J Appl Physiol 25:312–327
Tarnopolsky MA, Saris WH (2001) Evaluation of gender differences in physiology: an introduction. Curr Opin Clin Nutr Metab Care 4:489–492
Tarrasch R, Lurie O, Yanovich R, Moran DS (2011) Psychological aspects of the integration of women into combat roles. Pers Individ Dif 50:305–309
Thibault V, Guillaume M, Berthelot G, El-Helou N, Schaal K, Quinquis L, Nassif H, Tafflet M, Escolano S, Hermine O, Toussaint JF (2010) Women and men in sport performance: the gender gap has not evolved since 1983. J Sports Sci Med 9:214–223
Tikuisis P, Jacobs I, Moroz D, Vallerand AL, Martineau L (2000) Comparison of thermoregulatory responses between men and women immersed in cold water. J Appl Physiol 89:1403–1411
Tommasini SM, Nasser P, Schaffler MB, Jepsen KJ (2005) Relationship between bone morphology and bone quality in male tibias: implications for stress fracture risk. J Bone Miner Res 20:1372–1380
Tommasini SM, Nasser P, Jepsen KJ (2007) Sexual dimorphism affects tibia size and shape but not tissue-level mechanical properties. Bone 40:498–505
Torres SJ, Nowson CA (2007) Relationship between stress, eating behavior, and obesity. Nutrition 23:887–894
Treloar AK, Billing DC (2011) Effect of load carriage on performance of an explosive, anaerobic military task. Mil Med 176:1027–1031
Turner CH, Burr DB (1993) Basic biomechanical measurements of bone: a tutorial. Bone 14:595–608
Vogel JA, Patton JL, Mello RP, Daniels WL (1986) An analysis of aerobic capacity in a large United States population. J Appl Physiol 60:494–500
Weise M, De-Levi S, Barnes KM, Gafni RI, Abad V, Baron J (2001) Effects of estrogen on growth plate senescence and epiphyseal fusion. Proc Natl Acad Sci USA 98:6871–6886
Wells CL, Plowman SA (1983) Sexual differences in athletic performance: biological or behavioral? Phys Sportsmed 11:52–63
Wentz L, Liu PY, Haymes E, Ilich JZ (2011) Females have a greater incidence of stress fractures than males in both military and athletic populations: a systemic review. Mil Med 176:420–430
West W, Hicks A, Clements L, Dowling J (1995) The relationship between voluntary electromyogram, endurance time and intensity of effort in isometric handgrip exercise. Eur J Appl Physiol 71:301–305

Whiting SJ, Vatanparast H, Baxter-Jones A, Faulkner RA, Mirwald R, Bailey DA (2004) Factors that affect bone mineral accrual in the adolescent growth spurt. J Nutr 134:696S–700S

Whyte GP, George K, Sharma S, Firoozi S, Stephens N, Senior R, McKenna WJ (2004) The upper limit of physiological cardiac hypertrophy in elite male and female athletes: the British experience. Eur J Appl Physiol 92:592–597

Wong SL, DePaoli AM, Lee JH, Mantzoros CS (2004) Leptin hormonal kinetics in the fed state: effects of adiposity, age, and gender on endogenous leptin production and clearance rates. J Clin Endocrinol Metab 89:2672–2677

Wyndham CH, Morrisson JF, Williams CG (1965) Heat reactions of males and females Caucasians. J Appl Physiol 21:357–364

Yanovich R, Evans R, Israeli E, Constantini N, Sharvit N, Merkel D, Epstein Y, Moran DS (2008) Differences in physical fitness of male and female recruits in gender-integrated army basic training. Med Sci Sports Exerc 40:S654–S659

Yanovich R, Merkel D, Israeli E, Evans RK, Erlich T, Moran DS (2011) Anemia, iron deficiency, and stress fractures in female combatants during 16 months. J Strength Cond Res 25:3412–3421

Zambraski EJ, Yancosek KE (2012) Prevention and rehabilitation of musculoskeletal injuries during military operations and training. J Strength Cond Res 26:S101–S106