Do sex-differences in physiology confer a female advantage in ultra-endurance sport?

Nicholas B. Tiller[1], Kirsty J. Elliott-Sale[2], Beat Knechtle[3,4], Patrick B. Wilson[5], Justin D. Roberts[6], Guillaume Y. Millet[7,8]

[1]Institute of Respiratory Medicine and Exercise Physiology, The Lundquist Institute for Biomedical Innovation at Harbor-UCLA Medical Center, Torrance, CA, USA.
[2]Musculoskeletal Physiology Research Group, Sport, Health, and Performance Enhancement Research Centre, School of Science and Technology, Nottingham Trent University, Nottingham, United Kingdom.
[3]Medbase St. Gallen Am Vadianplatz, 9001 St. Gallen, Switzerland.
[4]Institute of Primary Care, University of Zurich, 8091 Zurich, Switzerland.
[5]Department of Human Movement Sciences, Old Dominion University, Norfolk, VA 23529, USA
[6]Cambridge Centre for Sport and Exercise Sciences, School of Psychology and Sports Science, Anglia Ruskin University, Cambridge, UK.
[7]Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-40023, Saint-Etienne, France.
[8]Institut Universitaire de France (IUF).

Correspondence:
Nicholas B. Tiller, Ph.D. | 1124 W. Carson Street, CDCRC Building, Torrance, CA 90502 | Email: nicholas.tiller@lundquist.org | Tel: (+1) 310-980-8163 | Orchid: https://orcid.org/0000-0001-8429-658X

Funding Disclosures/conflicts of interest: The authors declare no conflicts of interest and do not have any financial disclosures.

ABSTRACT

Ultra-endurance has been defined as any exercise bout that exceeds 6 h. A number of exceptional, record-breaking performances by female athletes in ultra-endurance sport has roused speculation that they might be predisposed to success in such events. Indeed, while the male-to-female performance gap in traditional endurance sport (e.g., marathon) remains at ~10%, the disparity in ultra-endurance competition has been reported as low as 4% despite the markedly lower number of female participants. Moreover, females generally outperform males in extreme-endurance swimming. The issue is complex, however, with many sports-specific considerations and caveats. This review summarizes the sex-based differences in physiological functions and draws attention to those which likely determine success in extreme exercise endeavors. The aim is to provide a balanced discussion of the female versus male predisposition to ultra-endurance sport. Herein, we discuss sex-based differences in muscle morphology and fatigability, respiratory-neuromechanical function, substrate utilization, oxygen utilization, gastrointestinal structure and function, and hormonal control. The literature indicates that while females exhibit numerous phenotypes that would be expected to confer an advantage in ultra-endurance competition (e.g., greater fatigue-resistance, greater substrate efficiency, and lower energetic requirements), they also exhibit several characteristics that unequivocally impinge on performance (e.g., lower O_2-carrying capacity, increased prevalence of GI distress, and sex-hormone effects on cellular function/ injury risk). Crucially, the advantageous traits may only manifest as ergogenic in the extreme endurance events which, paradoxically, are the races that females less often contest. The title question should be revisited in the coming years when/if the number of female participants increases.

KEY POINTS

- Females exhibit numerous physiological characteristics that would be expected to confer an advantage in ultra-endurance competition. However, these traits may only manifest in the extreme distance events that females less often contest
- Several aspects of female physiology unequivocally inhibit performance making it unlikely that the fastest females will surpass the fastest males in this sport
- More direct physiological comparisons between male and female ultra-endurance athletes are needed, particularly when/if female participation numbers increase

1.0 INTRODUCTION

A 1992 correspondence published in the journal *Nature* posed the question '*Will women soon outrun men?*' The analysis of distance-running records throughout the 1900s revealed an essentially linear chronological increase in mean running velocity ($\bar{V}$-slope), which was considerably steeper in the women's marathon relative to the men's (~37.8 vs. 9.2 m[insert raised dot]min^{-1}[insert raised dot]decade^{-1}) [1]. From this historical trend, Whipp and Ward calculated that the intersection for the men's and women's marathon would occur in the late 1990s [1]. Although linear models have accurately described performance trends in ultra-distance swimming [2], their utility predicting the "gender" gap in other sports has been criticized on the basis that athletic adaptation and performance rarely, if ever, follow a linear progression [3]. In 1989, using a non-linear (hyperbolic) model, Peronnet *et al.* calculated a ~10% disparity between male and female running performances, owing primarily to greater maximal aerobic capacities ($\dot{V}O_2max$) in the former. The model also predicted that males would retain a biological distance-running advantage well into the future [4]. In point of fact, a contemporary analysis of ~92,000 marathon finishes revealed a ~10% discrepancy between non-elite male and female finish times (males = 4 h 28 min ± 53 min; females = 4 h 54 min ± 52 min; [5]). Thus, if females are to further diminish the endurance performance gap, it is most likely in those contests which depend less on maximal aerobic capacities.

Participation in ultra-endurance sport (which has been defined as an exercise bout that exceeds 6 h; [6]) has steadily increased over the last 30 years [7,8]. Success in these events is determined by a complex interplay among various factors, including: oxidative capacity, the energy cost of locomotion, substrate efficiency, fatigue-resistance and musculoskeletal conditioning, race nutrition, gastrointestinal (GI) function, age/experience, pain management, decision-making, and motivation and psychological disposition [9–15]. Furthermore, extreme endurance exercise evokes considerable perturbations in respiratory, neuromuscular, cardiovascular, digestive, and immune functions [12,13,16,17]. Accordingly, the most successful competitors are those who not only exhibit the most diverse range of ergogenic attributes, but who also best endure the high training volumes and extreme physiological strain of participation.

Males and females compete side-by-side in ultra-endurance sport. Males are generally faster than females over any given distance [2,18,19], but the data may be confounded by the considerably lower number of female participants, particularly in the very long-distance races. For instance, while modern marathons comprise fairly equal numbers of males and females (54% and 46%, respectively; [20]), only 20% of ultra-marathon finishes since the 1970s have been accomplished by females [7,18]. In ultra-distance cycling (Race Across America; RAAM), females comprised only ~11% of finishers between 1982 - 2011 [19]. Notwithstanding, some have calculated the performance gap to be as low as 4% in ultra-marathon [21], 6% in ultra-distance open-water swimming [2], and negligible in cycling events of >200 miles [22]. In rare instances (yet, more often in ultra-endurance events than in shorter races) females may surpass their male counterparts [23]. Pertinently, the performance disparity between males and females is generally smallest in those events of greatest duration [19,21,24], and in those races with the highest number of female contestants [18,25]. At present, it is unclear what physical/physiological attributes underpin female ultra-endurance performance, and whether females might surpass males in this sport should their participation numbers equalize.

In recent years, these unknowns have been deliberated *ad nauseam* in the mainstream media [26–32], but while each publication has argued that females may outperform males in ultra-endurance sport, most have only speculated on the mechanisms, or provided cursory overviews of the empirical/published data. Thus, to address the title question, this paper will review the sex-mediated differences in human physiological function, and draw attention to those attributes which facilitate or impinge on female success in extreme duration exercise. The aim is to provide a balanced discussion of the female versus male physiological propensity for ultra-endurance sport.

1.1 Performance Trends

It has been argued that the disproportionate improvement in women's endurance performance in recent decades is attributable largely to sociocultural reform [33]. Women were prohibited from competing at the first modern Olympic Games in 1896, whereas women comprised ~36% of athletes at the Olympic Games a century later [34]. Thus, while it is unequivocal that success in ultra-endurance competition has a strong biological component, the performance trends may partially reflect factors such as greater participation and training opportunities. The published competition data are complex and difficult to interpret owing to the variety of sports examined, the considerable range in distances/durations, age-group categories, and varying participation numbers. Nevertheless, to contextualize the forthcoming discussions on physiological differences, what follows is a summary of the trends in male versus female ultra-endurance performance.

When viewed in its entirety, the data show that males generally outperform females in most sports, irrespective of distance, although the range in the performance disparity is large (0 – 17%) and there are several notable exceptions. In an analysis of world-record running performances ranging from 100 m to 200 km, males were on average 12.4% faster than females [35]. Moreover, in 24-h ultra-marathon, a gap of ~17% was reported between the annual fastest male and female finishers, ~11% for the annual 10 fastest, and ~14% for the annual 100 fastest [24]. These data are likely confounded by the lower numbers of female contestants. Studies that account for the participation disparity show a slightly diminished performance gap. For example, in a multiple linear regression analysis of >93,000 ultra-marathon finishes between 1975 and 2013 (across the range of distances), the sex difference in performance was generally <10%, and the discrepancy in finish time was lowest in events where females participated in greater numbers [18].

The data also indicate that the magnitude of the male-to-female performance discrepancy is influenced by sport, distance, and age category. For instance, females have reduced the performance gap to less than 10% in ultra-endurance (Ironman) triathlon, and to just ~7% in the marathon stage of the event [36]. In terms of race distance, the sex difference in running speed for the fastest ever women and men was higher in 50 km (~15%) relative to 100 km (5.0%) [37]. Moreover, in a study of ~13,000 cycling races, males were generally faster than females in events of 100 and 200 miles, but no difference was found in the 400- and 500-mile races [22]. Others make similar observations of a diminished performance disparity over longer distances in endurance running [38]. From 1977 to 2012, the sex-difference in 24-hour ultra-marathon was as low as 4.6 ± 0.5% for all women and men [24], with other reports of a similar difference (~4% over 100 miles) in footraces up to 2017 [21]. Interestingly, although the difference in running speed between the fastest males and females over 100 miles has been reported as ~17% [39], the decrease in the sex difference observed for 50 and 100-mile footraces suggests that females are reducing the performance gap [39]. With respect to age categories, the difference in average cycling speed between men and women, across all race distances, decreased with increasing age [22], and a recent ultra-marathon analysis similarly showed that sex differences in performance were attenuated with increasing distance and age [21].

To account for absolute differences in athlete ability, several studies have compared ultra-marathon performances between males and females whose race times had been matched over a given distance. One study concluded that equivalent performances were retained in longer races, and two studies showed the opposite. Specifically, Hoffman examined race results over three distances (50, 80, and 161-km) between 1990 and 2007, finding that females and males who were time-matched for 50-km performed similarly in running races of 80- and 161-km [40]. By contrast, a study by Bam *et al.* [23] compared the fastest male and female running speeds over distances ranging from 5 – 90 km, and showed that men were quicker over 5 – 42.2 km but not over 90 km (mean velocity = 2.8 vs. 2.9 m[insert raised dot]s^{-1}). Additionally, females with marathon times equivalent to males have been shown to produce significantly quicker times in a 90-km ultra-marathon [41]. The notion that female endurance runners may be closing the gap to males in longer distance/duration races is supported by a recent unpublished analysis of trends in ultra-marathon running over the last 23 y, which showed that females were 0.6% faster than males in races >195 miles [42].

Finally, performances in ultra-distance swimming appear paradoxical to the trend, showing a general female dominance. Indeed, while in 10-km open-water swimming the annual fastest males were ~6% quicker than the fastest females [2], the top 20 females in extreme-endurance competition (46 km) were ~12 – 14% faster than their male counterparts [43]. This observation does not appear anomalous. A recent review assessing male and female performances in several extreme-endurance, open-water swimming events, showed that females were on average 0.06 $km \cdot h^{-1}$ faster than males [44]. Female dominance in ultra-distance swimming, and the possible explanations, are discussed later.

When taken collectively, the data suggest that males generally outperform females in most ultra-endurance events and over most distances, with the exception of extreme-distance swimming. However, when scrutinizing the performance trends, the disparity is generally smallest in very long-distance races, and when there is a relatively greater number of female participants.

2.0 PHYSIOLOGICAL CONSIDERATIONS

The following discussion summarizes the sex-based differences in physiological functions, specifically those which are mostly relevant to ultra-endurance performance. Much of the literature has erroneously employed the terms “sex” and “gender” interchangeably. For clarity, a brief description of these terms, and how they will be used henceforth, is warranted. According to the National Institute of Health (NIH) [45] and the Canadian Institute of Health Research (CIHR) [46], “sex” is a biological constituent which comprises the genetic complement of chromosomes, including cellular and molecular differences [47]. By contrast, “gender” has been described as a social (rather than a biological) construct which varies with the roles, norms and values of a given society or era [48]. It has been suggested that because sex is reflected physiologically, the terms “male” and “female” should be employed when describing the sex of human subjects or when referring to other sex-related biological/physiological factors [49]. Accordingly, the term “sex-based differences” and the nouns “male” and “female” will be employed throughout this manuscript, except when referring to pre-defined race categories (e.g., the women’s marathon).

2.1 Muscle Morphology and Fatigability

Fatigue can be defined as a disabling symptom in which physical and cognitive function is limited by interactions between *perceived* fatigability and *performance* fatigability [50]. The latter of these, also known as neuromuscular fatigue (NMF), results from diminished voluntary activation (central component) and/or contractile function (peripheral component) [51]. We presently focus on the sex-differences in acute NMF, and how it might mediate performance in ultra-endurance competition. In controlled studies, females generally exhibit greater fatigue resistance than males [52,53]. Furthermore, in a detailed review of sex differences in fatigability, Hunter *et al.* made two specific observations: (i) females typically outperform males during exercise performed at submaximal intensities; and (ii) the magnitude of the difference is attenuated as contraction intensity increases [52].

As aforementioned, the sex-based differences in fatigue have been assessed in ultra-marathons of up to 90 km, showing equivocal results [23,40,41]. However, a more comprehensive exploration requires the objective assessment of fatigue using electrical and/or magnetic nerve stimulation to artificially stimulate the locomotor muscles. Several studies have made such assessments following 24-h treadmill running [54], field-based ultra-marathon [55], and ultra-distance road cycling [56]. Nevertheless, a paucity of data in females - owing to the low number of female ultra-endurance athletes - makes a direct male/female comparison problematic. To the best of our knowledge, only one study has examined sex differences in NMF following a bout of ultra-endurance exercise. Temesi *et al*. used superimposed transcranial magnetic stimulation and peripheral nerve stimulation to assess contractile fatigue in males and females matched by relative performance level [57]. After a 110-km ultra-marathon with a large cumulative ascent (Ultra-Trail du Mont-Blanc®, Alps) the authors showed that: (i) males exhibited greater peripheral fatigue in the plantar flexors; (ii) the magnitude of central fatigue in the plantar flexors and knee extensors was similar between sexes; and (iii) there were no between-sex differences in changes in corticospinal excitability or inhibition. Thus, while there were no overt differences in central fatigue between males and females, the latter exhibited less peripheral fatigue following the race. There are several mechanisms that may underpin the potential disparity in male/female muscle fatigability, including sex-differences in muscle fiber type, muscle mass, and neuromuscular control [52] (see Fig. 1).

2.1.1 Muscle fiber type.

Human skeletal muscle fibers are classified as oxidative type-I (slow-twitch), oxidative type-II and glycolytic type-II (fast-twitch) [58]. Type-I fibers are more fatigue-resistant, partially owing to a greater myoglobin/mitochondrial content [59]. In an analysis of mRNA in male and female lower-limbs, type-I fibers accounted for 44% of the total biopsy area in females but only 36% in males [60]. Moreover, of the four myosin-heavy chains (MyHC) which dominate gene expression in adult mammalian skeletal muscle, females express ~35% more type-I MYH mRNA (those that are smaller and of a more oxidative phenotype) when compared to males who express more type-II MYH mRNA (those that are larger and richer in glycolytic enzymes) [61]. The greater proportion of type-I fibers in females is associated with greater vasodilatory capacity [62] and capillarization [63]. Pertinent to the present discussion, individual fibers are 'typed' by a particular isoform which determines characteristics like contractile velocity and enzymatic makeup [59] (Table 1). Thus, the greater relative distribution of slow-twitch fibers in females may partially explain their greater contractile fatigue-resistance compared to males; although speculative, this offers a compelling argument for a sex-based physiological predisposition for ultra-endurance performance.

Insert Table 1

2.1.2 Muscle mass and strength.

As is the case for age-related discrepancies in muscle fatigue, muscle mass and strength may partially explain the sex-related differences. Over 3,000 genes are differentially expressed in male versus female skeletal muscles (e.g. *GRB10* and *ACVR2B*) [61] and largely mediate sexual dimorphism in muscularity and strength, in addition to interactions among sex-specific hormones (see *2.4 Endocrine Function*). It is the greater fiber diameter in males, rather than fiber number, that results in muscle mass differences [64]. Pertinently, stronger muscles exert higher intramuscular pressures onto the feed arteries, thereby restricting blood flow and rendering them more fatigable during submaximal isometric exercise [52,65]. Subsequently, the attributes that confer males an advantage in strength- and power-based sports, may be a potential disadvantage in events of extreme endurance in which peripheral NMF is an important determinant.

2.1.3 Central command.

The greater relative fatigability observed in males has been associated with greater central deficits in motor output [66,67], although it should be noted that these findings were made largely during maximal efforts and may not extend to submaximal tasks or sustained dynamic contractions. One explanation for the smaller deficits in female central motor output is a lesser accumulation of anaerobic metabolites during sustained, submaximal exercise (owing to more oxidative fibers), resulting in attenuated type-III and IV muscle afferent feedback; i.e., less inhibitory inputs to the motoneuronal pool. Although this may evoke less subsequent impairment of voluntary activation, this is considered an unlikely mechanism to explain central fatigue in ultra-marathon [68]. Given that ultra-marathons, particularly those contested on trail or mountainous terrain, encompass long downhill sections and exacerbated eccentric contractions in lower-limb extensors, it is worth examining sex differences in maximal force reduction after repeated lengthening contractions. The literature on this topic is somewhat equivocal: animal studies suggest that females are more resistant to muscle damage, while human studies suggest that females exhibit greater force decline when compared to males following eccentric contractions [52]. Thus, no firm conclusions can be made at this stage.

When interpreting the data on NMF, an important consideration is that the magnitude and prevalence of fatigue is task-dependent; i.e., different neuromuscular sites will be stressed when the requirements of the task are altered, and the stress on these sites can differ for males and females [52]. As such, while females may exhibit less muscle fatigue than males during maximal voluntary (isometric) contractions [69], such localized responses may be of little relevance to dynamic, whole-body activities [70] including ultra-endurance exercise. The greater muscle mass involved in such activities evokes greater demands on cardiorespiratory and central nervous systems (e.g., greater afferent feedback and central drive), resulting in lower end-exercise impairments in contractile function [71] and, more generally, different NMF etiology compared to isolated exercises. In studies evaluating fatigue responses during dynamic, submaximal exercise, sex differences in fatigability are less consistent [72–74].

Accordingly, while females exhibit various characteristics that associate with better fatigue resistance, supported by data from nerve stimulation studies [57], more research is needed to compare the phenomenon directly between males and females during and following ultra-endurance exercise. It is also likely that psychological/sociological factors (e.g., competitiveness and risk-taking) may be masking a true understanding of the sex-based differences in performance and fatigability.

2.1.4 Respiratory muscle fatigue.

Extending the fatigue data from the locomotor muscles, numerous studies support the notion of better fatigue resistance in the female respiratory muscles. The primary muscles of inspiration and expiration are the diaphragm and major abdominals, respectively, which have concurrent roles in ventilating the lungs and postural control. Respiratory muscle fatigue is a phenomenon whereby muscles attached to the thoracic cage exhibit a reduced force-generating capacity relative to baseline, usually following exhaustive exercise [75–78]. In male versus female comparisons, resistive breathing evoked a slower rate of inspiratory muscle fatigue in the latter, a finding that was independent of muscle strength [79], although both groups exhibited a similar relative decline in maximal inspiratory pressure (15%). In another study using cervical magnetic stimulation to artificially activate the diaphragm before and after constant work-rate cycling, diaphragm fatigue occurred in 11 out of 19 males (58%) and 8 out of 19 females (42%) [80]; however, contractile function diminished to a greater extent in the males (31 vs. 21%). Collectively, these data point to a female diaphragm that may be more fatigue-resistant, and this phenomenon might be partially attributed to a greater reliance on accessory inspiratory muscles for ventilation during dynamic exercise [81]. During high-intensity exercise, respiratory muscle fatigue may compromise ventilatory capacity and endurance, exacerbate dyspnea (sensations of breathlessness), and compromise limb-locomotor blood flow through "respiratory steal" [75]. However, its effects on ultra-endurance performance have not been adequately studied. Due to the expiratory muscles' important role in postural control [82], it has been speculated that fatigue of the abdominals during ultra-marathon could place the runner at an increased risk of injury due to a relative inability to sustain the rigors of competition, particularly on challenging terrain [16]. A fatigue resistance in the respiratory muscles may, therefore, be advantageous to ultra-marathon performance.

These observations should be balanced against the fact that, when compared to males, females exhibit a greater resistive work of breathing at a given level ventilation during exercise, attributed to innate sex-based differences in lung size and the diameter of conducting airways [83]. As a result, females are more likely to exhibit expiratory flow limitation and exercise-induced arterial hypoxaemia [84]. The respiratory muscles of females also utilize a greater relative percentage of $\dot{V}O_2$ during exercise [85] which may, at least in part, diminish oxygen economy (see *2.3 Oxygen Utilization*).

2.1.5 Pacing strategies.

A relative fatigue-resistance in female muscles has been postulated to influence pacing strategies during racing. A comprehensive analysis of marathon finish times in the United States revealed that females were 1.46-times more likely to maintain their running pace (defined as a decrease in velocity of <10%) and 0.36-times as likely to exhibit marked slowing (defined as a decrease of >30%) compared to males [5]; the mean change in pace was 15.6% and 11.7% for male and females, respectively (p<0.001). Similar observations – of more 'even' pacing strategies in female marathon runners - have been reported elsewhere [86,87]. To our knowledge, only one study has assessed sex-differences in pacing during ultra-endurance sport. In a 100-km ultra-marathon, Renfree *et al.* [88] assessed the difference between male and female velocities at 10-km splits, finding that females exhibited a slower relative starting speed but a higher finishing speed than males. These findings suggest that females may pace better than their male counterparts during both marathon and ultra-marathon running, certainly in the non-elite category.

The mechanisms underpinning the differences in pacing may extend beyond differences in fatigue resistance. Males have been observed to slow significantly more than females in short-distance running races (5 km), even when accounting for differences in absolute finish times [89]. Although peripheral neuromuscular fatigue may still manifest over such short distances, other aspects of localized fatigue such as glycogen depletion and dehydration can be discounted in the population at large. The authors supposed, therefore, that sex-differences in pacing may reflect disparities in decision making, such as overconfidence, risk perception, or willingness to tolerate discomfort [89]. Compared to females, males consistently overestimate their abilities in endurance sport, congruent with a greater degree of slowing in the latter stages of racing [90]. Individuals with a greater proclivity for risk appear to slow more considerably in distance running, even in regression models which account for other psychological constructs, training, and experience [91]. Testosterone concentrations have been associated with risk-taking behavior [92], and we speculate this as an additional explanation. Accordingly, the sex differences in pacing may be attributable to differences in physiology, decision making, or both [5], but likely play a crucial role in ultra-endurance performance.

Insert Fig. 1

2.2 Substrate Utilization.

Carbohydrate and fat provide the majority of energy to fuel muscle metabolism during prolonged, submaximal exercise. Ultra-endurance exercise depends heavily on oxidative metabolism for the efficient use of glucose and lipids, and there is a substantial increase in the use of free fatty acids (FFA) with increasing race distance [93]. Fat is also more energy dense than carbohydrate (containing 9 versus 4 kcal[insert raised dot]g^{-1}), and improved substrate efficiency towards better lipid use exerts a glycogen-sparing effect to prevent early-onset fatigue [94]. Thus, the ability to better mobilize and oxidize lipids during ultra-endurance exercise would be considered advantageous and should be a focus of the periodized ultra-endurance training program [12].

During exercise, muscle contractions signal the translocation of clusters of differentiation-36 (CD36)/fatty acid binding protein to plasma and mitochondrial membranes, thereby facilitating FFA transport and metabolism [95]. The overexpression of CD36 is associated with a fourfold greater fatty acid oxidation by contracting muscle in mice [96]. In humans, females exhibit greater mRNA expression of genes associated with fatty acid metabolism, including *CD36* [97,98]. Females are generally known to exhibit larger estrogen-mediated reserves of intramyocellular lipids (IMCL) to support fuel demands for endurance exercise, as well as a greater percentage of IMCL in contact with mitochondria following a bout of endurance exercise when compared to males (indicative of greater capacity) [99]. These genotypes may be primarily responsible for the sex-based differences in lipid oxidation rates.

A whole-room calorimeter study over a 24-h period showed that, irrespective of physical activity levels, females exhibited 24 - 56% greater fat oxidation normalized to fat-fee mass (FFM) when compared to males, and that the former had an enzymatic profile which favored cellular β-oxidation [100]. Such differences are also apparent during submaximal exercise. When exercising at a constant work-rate of ~65% $\dot{V}O_2$max, Tarnopolsky *et al.* [101] showed that males utilized 25% more muscle glycogen and exhibited significantly higher respiratory exchange ratios than females, even when accounting for differences in diet, training status, and hormonal status relating to female menstrual phase. Others have made similar observations throughout the range of submaximal exercise intensities up to 85% $\dot{V}O_2$max [102], and that the exercise intensity eliciting the highest rate of fat oxidation occurs at a higher percentage of $\dot{V}O_2$max in females relative to males (58 versus 50% $\dot{V}O_2$max) [102]. As a result, at any submaximal relative exercise intensity, the female fat oxidation curve is rightward- and upward of the male curve [103]. This is a similar pattern one would expect to see in a more highly-endurance-trained individual. Females may also exhibit greater metabolic flexibility [104]. These collective differences may confer a metabolic advantage for females during exercise of extreme duration.

There are important caveats to the interpretation of these data. Firstly, the metabolic advantage of greater lipid oxidation in females may be partially negated by the obligatory feeding that occurs during ultra-endurance races. In ultra-marathon, for example, runners may need to consume between 200 – 400 kcal[insert raised dot]h^{-1} from various food sources [12]. Relatively greater proportions of carbohydrate are recommended for ultra-distance triathlon [105] which, in turn, may decrease the expression of genes involved in lipid metabolism for at least 4 h [106]. Males oxidize more fat than females post-exercise when fasted, but the difference is nullified when food is consumed to facilitate recovery [107]. Secondly, when expressed in absolute terms, males generally exhibit greater lipid oxidation rates owing to greater active muscle mass, lower fat mass, and greater overall energy expenditure during exercise; thus, the female metabolic advantage may be limited to weight-dependent sports (e.g., running, cycling, triathlon, etc.) in which lipid oxidation relative to FFM is pertinent. Finally, the magnitude of the sexual dimorphism in lipid oxidation is small, and any potential benefit should be framed in the context of ultra-endurance performance. For instance, while a greater reliance on lipid metabolism by females may spare muscle glycogen during prolonged exercise (e.g., marathon), this may not confer a considerable advantage during ultra-endurance exercise which is characterized by lower relative work rates and slower rates of glycogen depletion. Accordingly, we propose that the better substrate efficiency in females may instead confer an advantage by attenuating caloric requirements (which may be considerable during a 24 – 48 h event), and by reducing the need to consume exogenous carbohydrate which has been shown to be a primary nutrition-related cause of GI distress (see *2.5 Gastrointestinal Distress*).

2.3 Oxygen Utilization.

2.3.1 Maximal oxygen uptake ($\dot{V}O_2max$). Maximal oxygen uptake sets the upper-limit for aerobic metabolism and predicts most of the variance in middle-to-long distance endurance events including running [108] and cycling [109]. A study in female marathon runners found that $\dot{V}O_2max$ was the strongest predictor of performance (r = -0.74, p<0.01) explaining 56% of the variance in finish time [110]. The superior performances of males compared to females in standard endurance events may be largely explained by their higher $\dot{V}O_2max$ values, in both trained [111] and untrained states [112].

It is generally accepted that a lower $\dot{V}O_2max$ in females is the result of sex-differences in fat mass, and hemoglobin and hematocrit levels [113,114]. When $\dot{V}O_2max$ in males and females was adjusted to FFM, some showed the sex differences to disappear [115] while others found that males retained higher values [116]. Equalizing hemoglobin concentrations between sexes via blood withdrawal also failed to completely equalize absolute VO_2max [115], thus suggesting that the sex-differences in aerobic capacity are likely attributable to a combination of the aforementioned factors. The sex-mediated disparity in oxygen utilization may also be determined at a cellular level (see *2.1.1 Muscle fiber type*). For example, the rate of oxidative phosphorylation is influenced by mitochondrial density, and while respiration in isolated mitochondria is higher in female muscles compared to male [117], the latter tend to have a higher expression of genes encoding mitochondrial proteins [61]. Importantly, mitochondrial function, as well as membrane microviscosity, may depend to a large extent on estrogen concentrations, with lowered levels associated with diminished mitochondrial function [118] (See *2.4 Endocrine Function*).

Pertinent to the present discussion is that although $\dot{V}O_2max$ is important in ultra-marathon - correlating positively with the distance run in a timed laboratory simulation [9] - its predictive power on performance diminishes with increasing race distance [119]. Indeed, when females outperformed males in 90-km ultra-marathon, their performances were not attributed to greater maximal aerobic capacity or running economy, but rather a greater fraction of $\dot{V}O_2max$ sustained during racing [41]. In cycling, the peak power-to-weight ratio did not correlate with bike finish time in an ultra-endurance triathlon [120] and, in Ironman triathlon more broadly, factors such as hydration and energy homeostasis are considered the most prominent predictors of performance [121]. Consequently, while maximal aerobic capacities and work rates are generally lower in females, this may not represent the distinct disadvantage in ultra-endurance competition that it does in the ‘standard’ endurance events like marathon and Olympic-distance triathlon.

2.3.2 Oxygen economy and energy efficiency. Aside from $\dot{V}O_2max$, several other factors underpin middle-to-long distance endurance performance including velocity at $\dot{V}O_2max$

($v\dot{V}O_2max$), lactate threshold, and oxygen economy/work efficiency [108,122–124]. Although the greater relative adiposity in females would be expected to diminish their oxygen economy and work efficiency in weight-dependent sports, the data pertaining to sex-differences in these characteristics are inconsistent. Some suggest that females tend to have poorer oxygen economy at a given submaximal work rate [125,126] despite generally exhibiting a lower body mass. By contrast, at various relative intensities of lactate threshold, Fletcher *et al.* found no sex-mediated differences in running economy [127], and there are several reports of lower (better) values for running economy in trained adult females versus trained adult males [128,129]. In terms of gross energy efficiency - defined as the ratio of work accomplished to total energy expended – Yasuda *et al*. observed no sex-differences during cycling or arm-cranking across a range of submaximal relative exercise intensities, even in males and females who were matched for $\dot{V}O_2$ at the gas exchange threshold [130]. Similar observations of no sex-differences in energy efficiency have been made in cross-country skiing [131,132] and in distance running when comparing elite male and female athletes [133,134].

Notwithstanding, the importance of oxygen economy/work efficiency in ultra-endurance footraces has been contested. In a race with considerable cumulative ascent (that prolonged exercise time), performance was not correlated with the energy cost of running, nor with any post-race changes in running economy [135]. It has also been suggested that ultra-marathon runners make tactical decisions (e.g., developing lower-body musculature, changing stride frequencies, using robust footwear, using poles, etc.) that sacrifice running economy in favor of mitigating the musculoskeletal damage and fatigue that more prominently impinge on performance [10]. These strategies may be crucial for very long races, especially those contested on mountainous and/or technical terrain that are associated with the greatest muscle damage and peripheral fatigue.

Consequently, in weight-bearing endurance events of ‘standard’ distance, the male/female performance disparity may in large part be associated with differences in maximal aerobic capacities and work rates. However, these attributes may be less important in ultra-endurance sport, with performance therein underpinned by a complex interplay among physiological, neuromuscular, biomechanical, and psychological factors. Fatigue-resistance, substrate efficiency, mitigating muscle damage, and avoiding GI distress may be just as relevant as aerobic capacities in the ultra-endurance model [10] (Fig. 2). Although speculative, it may be that in this context female athletes exhibit a more complete complement of ergogenic attributes.

Finally, given that females generally outperform males in swimming events of extreme duration, the various factors that underpin ultra-distance swimming performance warrant independent consideration. It is unlikely that female success in this sport is due to a superior maximal oxygen uptake. Indeed, male open-water swimmers have been shown to exhibit considerably higher $\dot{V}O_2max$ values than females (5.51 vs. 5.06 $L.min^{-1}$, respectively) [136]. Moreover, despite the lactate thresholds occurring at speeds equivalent to 89 and 95% $\dot{V}O_2max$ for males and females, respectively, the absolute $\dot{V}O_2$ at lactate threshold was still higher in males (4.90 vs. 4.81 $L.min^{-1}$). Thus, female dominance in this sport is likely due to factors other than oxygen utilization, and may instead relate to differences in the energy cost of swimming, second to lower hydrodynamic resistance [137]. Indeed, although increases in body mass have been shown to diminish oxygen economy during running [138], a higher fat mass may be ergogenic in swimming. Fat has a lower density than muscle, and the greater relative female adiposity - as well as important differences in adipose tissue distribution - likely increases buoyancy and reduces drag [139]. The generally smaller body size of females confers a further decrease in hydrodynamic drag, as do shorter lower limbs that result in a more horizontal and streamlined position in the water [140,141]. Others speculate that female success in ultra-distance swimming may also be associated with better pacing strategies [44]. Evidently, the extent to which a biological trait (e.g., lower body fat) can be considered ergogenic, is determined by the specific demands and characteristics of the event in question.

Insert Fig. 2

2.4 Endocrine Function.

Estrogens, progestogens, and androgens regulate human reproductive function, but also act on non-reproductive tissues (e.g., muscle and bone) in numerous ways that affect both health and exercise performance, and which are specific to the respective male and female physiological environments [142]. However, the data are extremely complex and often equivocal; as such, what follows is an abridged summary of the intricate and interrelated functions of the sex hormones, and the extent to which they might impact on the organism's capacity for ultra-endurance exercise.

Testosterone is the primary male sex hormone which facilitates increases in muscle strength and power [143] and decreases in body fat in a dose- and concentration-dependent fashion [144]. It also appears to act on substrates in the brain to increase aggression and competitiveness [145]. While not studied directly, higher testosterone concentrations may be ergogenic in ultra-endurance competition: directly, due to its association with hemoglobin concentrations [144], mitochondrial function [146], and lipid metabolism [147]; and indirectly, by augmenting muscle protein synthesis and thereby facilitating recovery [148]. Importantly, males exhibit a 30-fold increase in circulating testosterone from puberty, resulting in levels that are 15 – 20 times higher in adult males than females [149]. This sexual dimorphism is thought to largely account for the sex-based differences in athletic performance. Interestingly, Storer *et al.* failed to observe a dose-dependent relationship between testosterone and muscle fatigability; as such, the higher testosterone concentrations exhibited by male athletes may not strictly regulate this aspect of exercise performance [143].

In females, estrogen and progesterone exhibit large fluctuations throughout the monthly menstrual cycle [150] (Fig. 3). Estrogen augments muscle size, strength, and collagen content, all of which are conducive to sporting performance [151] (for a review of the effects of female sex hormones on the nervous system and muscle strength, see [152]). Paradoxically, elevated estrogen concentrations reduce tendon and ligament stiffness [151], which may impinge on ultra-endurance performance in two ways. First, there is a significant positive correlation between tendon stiffness and running economy in females [127], such that an estrogen-mediated decrease in stiffness might also deteriorate running economy. Second, there are cyclical changes in anterior knee laxity throughout the menstrual cycle [153], and while there is no consensus that female injury rates are necessarily hormone-mediated, it is possible that fluctuating sex-hormone concentrations may partially explain the higher prevalence of anterior cruciate ligament (ACL) ruptures in eumenorrheic females compared to males [154]. Worthy of note, the knee is one of the most frequently injured body parts in ultra-endurance athletes [155], and the risk may be greater when traversing technical/challenging terrain that increases impact and shear forces through the lower limbs. A greater propensity for injury would certainly attenuate the ability to both train and compete.

2.4.1 Estrogen and substrate metabolism. There are data to suggest that the lower female dependence on carbohydrate during exercise (and, therefore, their superior relative rates of lipid oxidation) may be estrogen-mediated. For instance, a study by Hamadeh *et al.* showed that males who were supplemented with estrogen, exhibited an enhanced lipid oxidation both at rest and during submaximal exercise [156]. Moreover, postprandial lipid oxidation is lower in postmenopausal females (i.e., those with diminished estrogen concentrations) [157], thereby supporting the notion that hypogonadism/estrogen deficiency negatively impacts on fat oxidation. There are methodological difficulties in quantifying such effects (e.g., differences in exercise modality, sex-hormone concentrations, and training status of participants), but the paradoxical effects of estrogen and progesterone on exercise metabolism further obfuscates the matter: estrogen appears to impede glucose kinetics in females while progesterone appears to potentiate it [158]. It has also been suggested that estrogen-progesterone interactions may influence substrate metabolism to a greater extent than either hormone independently, and that the estrogen-to-progesterone ratio must be sufficiently elevated to evoke metabolic changes (for review, see [159]).

The flux in lipid oxidation with estrogen concentrations may be partly due to changes in mitochondrial function and membrane microviscosity, both of which associate with the estrogen steroid hormone 17β-estradiol [118]. As a result, female ultra-endurance performance would be expected to fluctuate congruent with monthly perturbations in estrogen, even if only trivially. Some have reported that the sex-based discrepancy in ultra-marathon performance begins to widen at around 45 y, after which female performances diminish [18]; this coincides with the increased body fat percentage, decreased lipid oxidation, and decreased mitochondrial function occurring with the menopause and the associated reduction in estrogen levels. As an aside, a secondary consequence of an estrogen-mediated mitochondrial dysfunction is an increased hydrogen peroxide production [160], and decreased levels of antioxidant genes [160,161]. This may be of particular relevance for ultra-endurance events which exacerbate oxidative stress and reactive oxygen species in a linear fashion with exercise duration [162], although it is yet to be decisively determined if alternations in redox homeostasis affect performance in ultra-endurance sport.

2.4.2 Energy availability. An important consideration for the female ultra-endurance athlete is the effect of energy availability on sex hormone concentrations, and the combined manifestations. The foremost nutritional challenge facing ultra-endurance athletes is the ability to meet their daily caloric demands [12]. Low energy availability – resulting from high training volumes and/or unintentional or deliberate restriction of dietary energy intake - can affect both male [163] and female endurance athletes [164]. There is, however, less evidence to support the magnitude of its effects on male health and performance. The consequences of low energy availability likely affect females more profoundly and rapidly owing to its synergism with menstrual dysfunction (i.e., amenorrhea) that, in turn, reduces bone health (as described in the Female Athlete Triad [165]). Given that estrogen associates positively with bone mineral density via osteoblast activity [166], females with diminished estrogen levels (e.g., amenorrheic athletes) are at an increased risk of stress fracture [167], and this may have implications for the high-mileage running that characterizes ultra-marathon, ultra-distance triathlon, and adventure racing. Even eumenorrheic females appear to be more susceptible than males to adverse changes in bone health following short-term low energy availability [168]. For a detailed summary of endocrine changes in the hypothalamic pituitary gonadal axis, using markers of low energy availability in males and females, see Elliott-Sale *et al.* [169].

On balance, there is a wealth of literature on the effects of estrogen and progesterone on female musculoskeletal, metabolic, and cellular function, and all such effects directly or indirectly influence ultra-endurance performance. However, the data are confounded by large inter- and intraindividual variability in sex hormone concentrations. From puberty to menopause, female sex-hormone concentrations are in a constant state of flux: (i) across any given menstrual cycle; (ii) as a result of perturbations in the menstrual cycle (e.g., anovulation); (iii) during pregnancy; (iv) due to clinical conditions (e.g., polycystic ovarian syndrome); (v) as a consequence of low energy availability and subsequent amenorrhea; and (vi) in response to external supplementation (e.g., hormonal contraceptives which are used by approximately half of elite female athletes [170]). As such, while ultra-endurance performance may not be inhibited by the female sex hormones, *per se,* it is the perturbations in estrogen concentrations manifesting across the lifespan that likely contribute to the male/female performance disparity. More high-quality, well-controlled studies are needed to explore the effects of endogenous/exogenous estrogen and progesterone on ultra-endurance performance.

Insert Fig. 3

2.5 Gastrointestinal Distress.

Ultra-endurance exercise is associated with widespread reporting of gastrointestinal symptoms [171–173]. The most well-documented, performance-altering GI disturbances are nausea/vomiting [174] and abdominal cramping [175,176], although other symptoms include reflux, bloating, loose stools, and flatulence [177]. GI distress is often cited as a reason for non-completion and/or attenuated performance, particularly in single stage running races [178]. The mechanisms that underpin GI distress during ultra-endurance exercise are complex and multi-faceted, but likely include impairments to gut perfusion and neuroendocrine alterations [179]. Gastrointestinal symptoms may also be triggered or exacerbated by aggressive and/or unaccustomed nutritional intake [180]. Certainly, a biological propensity for less frequent/severe GI distress, and/or a greater ability to tolerate/mitigate the symptoms, would be considered ergogenic in ultra-endurance competition.

2.5.1 Gut anatomy and physiology. To contextualize the forthcoming overview of sex differences in the character and prevalence of GI distress during exercise, a brief discussion of the general differences in gut structure and function is warranted. On average, the female stomach is ~10% smaller than the male stomach [181] and may, therefore, be less capable of gastric accommodation after consuming a given food volume [182]. As a result, females are likely to exhibit greater postprandial fullness following a standardized feeding [183]. Whole-gut and colonic transit times are longer in females when compared to males [184,185], and females exhibit attenuated rates of gastric emptying [186] for both solid foods and fluids [187]. These latter findings may have important implications for fueling during prolonged exercise. While the precise mechanisms for sex-differences in gastric emptying are unclear, it has been hypothesized to be related to female sex-hormone effects on the gastrointestinal tract [187], speculation which has been supported empirically only in rodent models [188]. There are data on sex-differences in the gut microbiome that is thought to influence gut function and GI symptoms [189], but most of this research is also from animal models which may not closely reflect human physiology and behavior. Finally, there may also be sex-differences in gut barrier function which has been speculated to play a role in the development of endotoxemia (bacterial translocation into the blood), congruent with systemic inflammation and GI symptoms [190]. This may be particularly relevant to the present discussion owing to the positive association of endotoxemia biomarkers with the frequency and/or severity of GI symptoms (particularly nausea) during ultra-endurance competition [191,192], although this is not a universal finding [193]. To the authors' knowledge, sex differences in the vulnerability to GI permeability and endotoxemia has not been systematically studied in ultra-endurance exercise. However, in studies assessing the phenomenon in various resting conditions - via the postprandial measurement of urine or blood levels of non-metabolizable sugars - gut permeability was shown to be higher in males versus females [194–196].

2.5.2 Symptomology. In population-based research, females report a higher frequency of GI symptoms [197–199], most commonly nausea, bloating, abdominal pain, and constipation. While a greater prevalence of bloating and constipation in females may be due to slower whole-gut and colonic transit times [184,185] - thereby contributing to greater fermentation of dietary fiber and reabsorption of colonic water - the greater frequency of nausea and abdominal pain may be associated with the onset of monthly menses in individuals with eumenorrhea [200]. The observations of population-based studies generally extend to those made during exercise, although the most informative data stem from research in standard- as opposed to ultra-endurance competition [172,201–203]. For example, in a 1984 survey of >700 marathon runners (85% male), females more commonly reported symptoms of lower-GI distress (e.g., abdominal cramping, urge to defecate, diarrhea, bloody defecation) [203]. While interesting, these data may be confounded by external factors (e.g., training experience), particularly given that years of training associates negatively with GI symptoms [201]. A multivariate analysis of >1,200 endurance runners contesting races from 10 - 42 km also observed female sex to independently associate with increased prevalence of GI complaints [201].

Notwithstanding, reports on sex-differences in GI distress during ultra-endurance exercise are sparse. This can be attributed to lower female participation numbers and/or the failure of most studies to differentiate GI distress prevalence by sex (e.g., [204,205]). In reports that do make such distinctions, the data are less equivocal than for marathon. For instance, there was little difference in the frequency and/or severity of most GI symptoms between males and females during a 161-km ultra-marathon, with the exception of stomach bloating which was more common in females [173]. Furthermore, over a similar distance, Stuempfle *et al.* [191] reported no sex-mediated differences in nausea. When interpreting these data it should be noted that neither study was specifically designed to assess sex-differences in GI distress. In addition, both had a relatively low number of female participants, congruent with the trend in ultra-endurance participation numbers. Thus, more research is warranted to establish if the greater female propensity for GI distress extends to ultra-endurance competition. Such a predisposition would negatively impact on an athlete's ability to perform: directly, due to pain and discomfort associated with lower-GI issues; and/or indirectly owing to the difficulty of adequately fueling and hydrating.

2.5.3 Gut training. There is a growing interest in the concept of "training the gut" to enhance the digestion of, and tolerance to, exogenous carbohydrate and fluid intake during prolonged exercise. Such gut-training strategies are premised on the notion that high intakes of carbohydrate (at rest or during exercise) will increase the density and activity of intestinal glucose transports, thereby facilitating greater carbohydrate absorption and oxidation during exercise [206]. These adaptations would be expected to mitigate the magnitude and prevalence of GI distress during exercise. Gut training may be particularly relevant for ultra-endurance competition given the large energetic demands and nutritional intakes associated with training and racing [12]. Although anecdotal accounts of "speed eaters" show the GI tract to be highly adaptable [207], studies focused on the physiological and ergogenic appraisal of gut-training strategies are still relatively scarce. One such study on a group of trained cyclists and triathletes showed that a 28-d period of aggressive in-task fueling facilitated metabolic adaptations (including increased exogenous carbohydrate oxidation during exercise) [208]. Others report that gut-training evoked reductions in GI symptoms and carbohydrate malabsorption [209]. Nevertheless, the ergogenic effects of these strategies are mixed. The two studies that comprised mixed-sex cohorts showed that females were more likely to report GI symptoms during exercise when challenged with high rates of carbohydrate intake (90 $g \cdot h^{-1}$) [209,210]. Furthermore, following two weeks of gut training in a small group (5 male, 5 female), the magnitude of the reduction in GI symptoms associated with in-task fueling was lower in females relative to males [209]. Clearly, more data from larger samples are needed in order to make more robust direct comparisons.

Females report being less accustomed to feeding during exercise when compared to males [209]; therefore, it may be that integrating gut-training into periodized race preparation may still be beneficial for the female athlete, particularly if they intend on aggressively fueling with carbohydrate when racing. Perhaps the more relevant consideration is whether high rates of carbohydrate ingestion (>60 $g \cdot h^{-1}$) - after a period of gut training - are likely to enhance ultra-endurance performance for the female athlete when compared to more modest intakes (30 - 60 $g \cdot h^{-1}$) that are less likely to provoke GI symptoms in the first instance. This may be particularly relevant in light of a recent study showing the feasibility of very high rates of carbohydrate intake (120 $g \cdot h^{-1}$) in elite ultra-marathon runners who had previously undergone nutritional and gut-training [211]. Rather predictably, the study comprised an exclusively male cohort, and so whether such nutritional strategies are viable, or even possible, in female ultra-marathon runners remains unclear. Given the aforementioned sex-differences in the rates of gastric emptying and gut transit time, not to mention the existing data in endurance events of shorter duration, it is likely that females may be somewhat less tolerant to such high rates of intake. Moreover, the appropriate gut-training strategy is almost certainly to differ between sexes.

A final consideration is the extent to which sex-differences in substrate efficiency and body mass impact on race nutrition and the propensity for nutrition-induced GI distress. Owing to their greater dependence on lipid oxidation during exercise (see *2.2 Substrate Utilization*), female endurance athletes may be less susceptible to glycogen degradation [212] and its debilitating effects. Better substrate efficiency may also explain, at least in part, the lower carbohydrate and general caloric intakes of females during ultra-endurance competition [213,214]. Lower caloric intakes in females is also a factor of a smaller average body size, smaller stomach, and possibly deliberate strategies aimed at mitigating GI symptoms. A lesser need to consume exogenous carbohydrate to sustain a given work rate may be pertinent given that the primary nutritional cause of GI distress during endurance exercise is the high intake of carbohydrate, particularly hyperosmolar solutions [171]. The lower average body mass of the female athlete may also explain their lower sweat rates at both absolute and relative work rates [215]. This may, in turn, attenuate their fluid requirements during exercise, and decrease the need to ingest high volumes that provoke GI distress. Therefore, while it may be that female athletes are more prone to GI distress during exercise, it remains unclear whether this extends to the durations typical of ultra-endurance and whether this might be partially mitigated by their reduced caloric, carbohydrate, and fluid requirements. More studies are needed to further explore this complex issue in the context of ultra-endurance performance.

3.0 BEYOND PHYSIOLOGY

There are several considerations that should accompany the discussions presented in this paper. Firstly, this review has not discussed sex differences in all aspects of human physiology, just those that are prominent predicters of ultra-endurance performance. That said, in the interest of concision, there were several omissions including sex-differences in thermoregulation [215], the effects of sleep deprivation [216], and the responses to nutritional and training regimens [99]. Furthermore, while physiology is certainly a crucial determinant of performance in ultra-endurance sport, we did not explore sex-differences in psychological attributes that are arguably the greatest predictors of success in such events. At the least, we would expect there to be sex-based differences in sporting motivation, competitiveness, and risk taking [217]; as such, these psychological characteristics and their impact on the propensity for ultra-endurance performance warrant further consideration.

Second, we earlier reviewed the male and female performance trends in a number of ultra-distance sports, finding that the sex-based disparity was generally smallest in the events of longest distance/duration and when females were represented more numerously. It has been postulated that females may have lesser interest in competitive sports, and that the lower number of athletes may not simply be due to sociocultural factors and fewer opportunities [217]. Thus, there may exist a degree of selection bias, in that those females competing in the extreme endurance events may be self-selecting as the fittest, strongest, and most motivated among their sex. This might, in turn, lead to a skewed interpretation of the performance trends. Accordingly, direct comparisons remain problematic until participation numbers equalize.

Finally, this review discussed numerous physiological attributes that may facilitate or impede ultra-endurance performance. However, ultra-endurance events are highly variable in terms of the exercise mode (e.g., running, cycling, swimming, adventure racing, etc.), distance/duration, cumulative ascent/descent, terrain, and environmental extremes. It stands to reason, therefore, that the physical/physiological attributes of individuals will be differentially suited to different events. For instance, those contested on relatively flat, non-technical terrain may favor athletes with larger maximal aerobic capacities and higher ventilatory thresholds, whereas individuals with smaller frames and greater peripheral conditioning/robustness may excel on technical terrain with downhill running components. As such, the nuances of each event should be considered before arbitrarily designating a physical/physiological trait as advantageous. Certainly, optimal performances will stem from matching individual physiological profiles with individual race types.

4.0 CONCLUSION

When compared to their male counterparts, females exhibit numerous phenotypes that would be expected to confer an advantage in ultra- and/or extreme-endurance competition. These include a greater relative distribution of type-I (oxidative) fibers, greater fatigue-resistance owing to neuromuscular, contractile, and metabolic factors, better substrate efficiency (higher rates of lipid oxidation), lower energetic requirements, and higher subcutaneous body fat which is likely beneficial in ultra-distance swimming. The data also suggest that females may be better at pacing. These factors may explain why the sex-mediated performance disparity is lowest in ultra-endurance sport than in any other. However, there are two caveats. First, these collective traits may only manifest as ergogenic in the extreme endurance events which, paradoxically, are the races that females less-often contest. Second, several important characteristics of female physiology - including mechanical-ventilatory function, O_2-carrying capacity, prevalence of GI distress, and sex-hormone effects on both cellular function and injury risk – unequivocally impinge on female ultra-endurance performance, making it unlikely that the fastest females will ever outperform the fastest males (ultra-distance swimming a notable exception). In light of these caveats and the numerous considerations proposed in our discussion, we urge a skeptical approach to cursory or simplified answers to this complex question. We encourage more research into the physiological determinants of ultra-endurance sport, as well as more direct comparisons of male versus female ultra-endurance physiology, particularly when/if the number of female participants increases.

Acknowledgements

The authors wish to thank Professor Sue Ward (University of Leeds, UK) for her guidance in developing the manuscript.

Declarations

Funding. No funding was received in developing this manuscript. Nicholas B. Tiller is funded by a postdoctoral fellowship from the Tobacco-Related Disease Research Program (TRDRP; award no. T31FT1692).

Conflicts of interest. Nicholas B. Tiller, Kirsty J. Elliott-Sale, Beat Knechtle, Patrick B. Wilson, Justin D. Roberts and Guillaume Y. Millet declare that they have no conflicts of interest relevant to the content of this review.

Authors' contributions. NBT, GYM, KJES, and PBW drafted the manuscript; JDR and BK provided additional comments and contributions; all authors approved the final version

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TABLES AND FIGURES

Table 1. Comparison of contractile and metabolic properties of the various skeletal muscle fiber types. All values are expressed as a fold-change relative to ST oxidative fibers [59]. ST = slow-twitch; FT = fast-twitch.

Fig. 1. Proposed physiological mechanisms underpinning the sex difference in muscle fatigue, these include differences in: 1) motor neuron activation; 2) contractile function of the activated fibers; and 3) the magnitude of metabolites accumulating that interfere with contractile function. Mechanisms are stipulated with large arrows. Black boxes indicate processes within the muscle, white boxes are processes in the nervous system, and the grey are hormonal/ sympathetic actions. Negative signs indicate physiological variables/processes that are exhibited less by females; positive signs indicate physiological variables/processes that are exhibited more by females Reproduced from Hunter [52], with permission.

Fig. 2. Determinants of performance in ultra-endurance events, and the compromise between energy cost and lower-limb tissue damage (dashed lines). The principal determinants are in bold. Reproduced from Millet et al [10], with permission. GI = gastrointestinal; NM = neuromuscular; $\dot{V}O_2max$ = maximal oxygen uptake.

Fig. 3. Schematic showing the hormonal fluctuations across an idealized 28-d menstrual cycle, with ovulation occurring at day 14 [150].

Table 1.

Characteristic	ST Oxidative	FTa Oxidative	FTb Glycolytic
Contractile			
Time to peak tension	1.0	0.4	0.4
Ca^{2+} myosin ATPase	1.0	3.0	3.0
Mg^{2+} actomyosin ATPase	1.0	2.8	2.8
Enzymatic	1.0		
Creatine phosphokinase	1.0	1.3	1.3
Phosphofructokinase	1.0	1.5	2.1
Glycogen phosphorylase	1.0	2.1	3.1
Citrate synthase	1.0	0.8	0.6
Morphological			
Capillary density	1.0	0.8	0.6
Mitochondrial density	1.0	0.7	0.4
Metabolic			
Oxidative potential	1.0	0.7	0.2
Glycolytic potential	1.0	1.5	2.0
Phosphocreatine	1.0	1.2	1.2
Glycogen	1.0	1.3	1.5
Triacyglycerol	1.0	0.4	0.2

Figure 1.

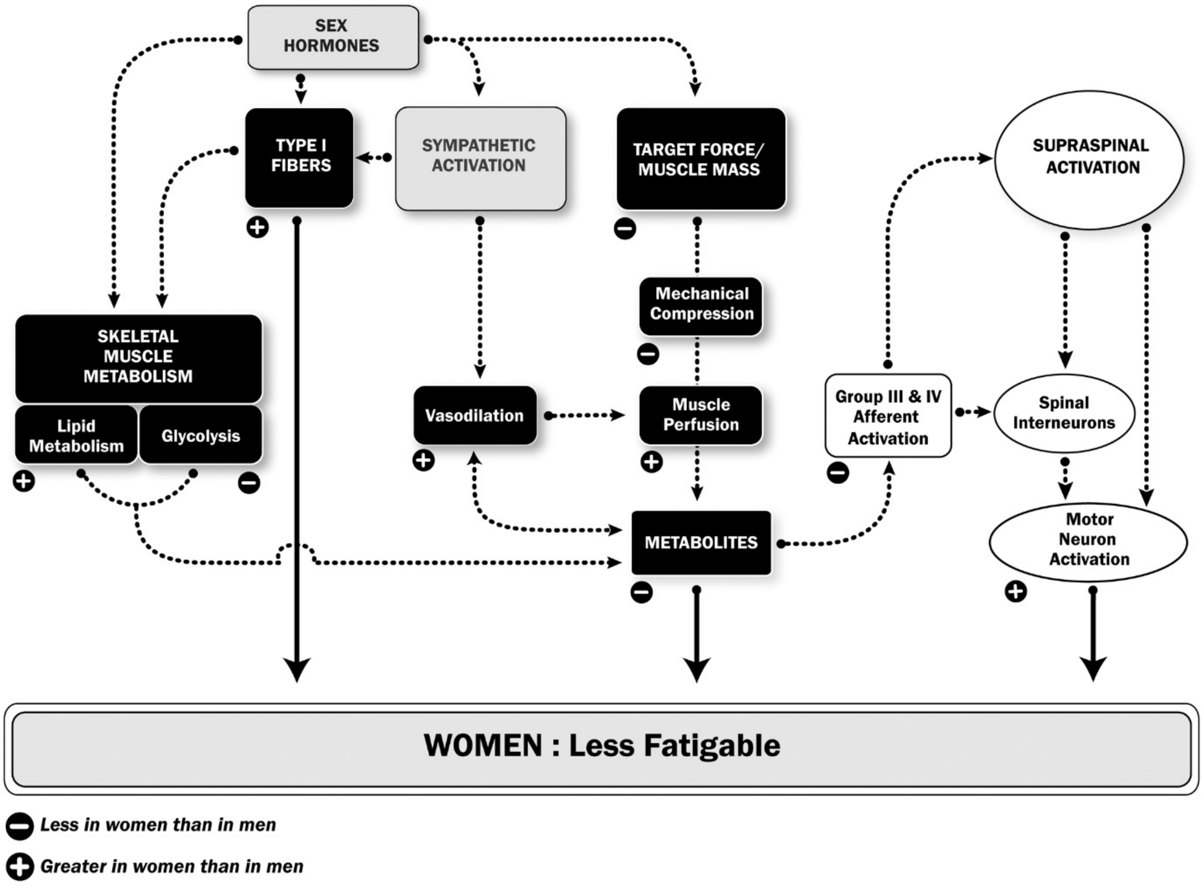

SEX HORMONES
TYPE I FIBERS
SYMPATHETIC ACTIVATION
TARGET FORCE/ MUSCLE MASS
SUPRASPINAL ACTIVATION
SKELETAL MUSCLE METABOLISM
Lipid Metabolism
Glycolysis
Mechanical Compression
Vasodilation
Muscle Perfusion
Group III & IV Afferent Activation
Spinal Interneurons
METABOLITES
Motor Neuron Activation
WOMEN : Less Fatigable
Less in women than in men
Greater in women than in men

Figure 2.

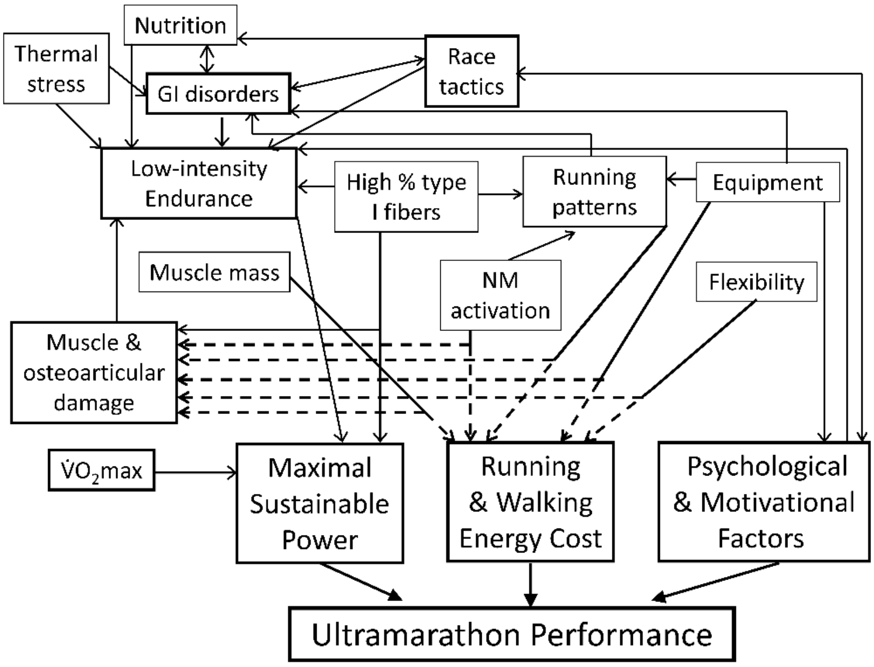
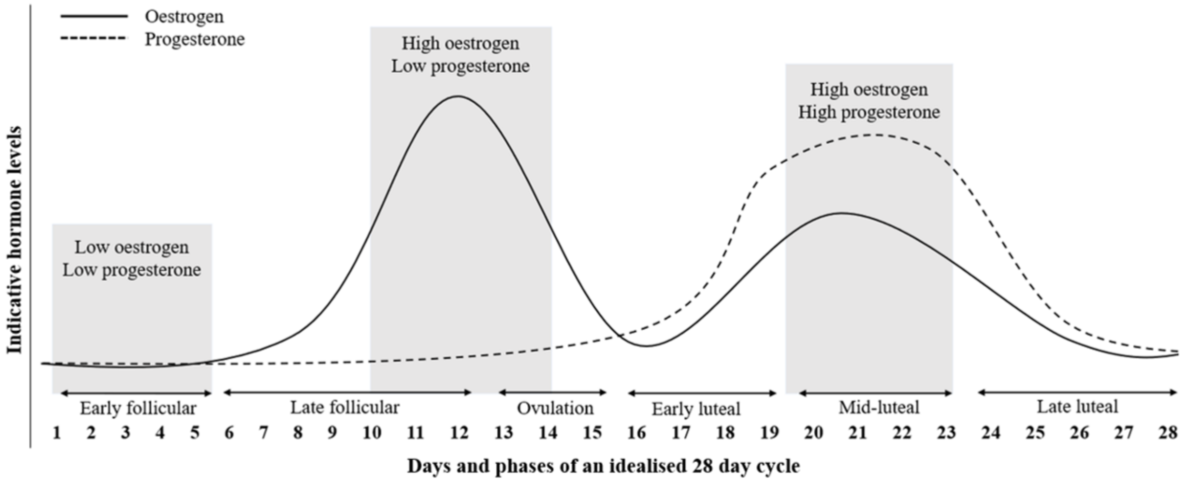

Nutrition
Thermal stress
GI disorders
Race tactics
Low-intensity Endurance
High % type I fibers
Running patterns
Equipment
Muscle mass
NM activation
Flexibility
Muscle & osteoarticular damage
V̇O$_2$max
Maximal Sustainable Power
Running & Walking Energy Cost
Psychological & Motivational Factors
Ultramarathon Performance

Figure 3.


Oestrogen
Progesterone
Low oestrogen
Low progesterone
High oestrogen
Low progesterone
High oestrogen
High progesterone
Indicative hormone levels
Early follicular
Late follicular
Ovulation
Early luteal
Mid-luteal
Late luteal
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Days and phases of an idealised 28 day cycle