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Sex differences in world record performance: the influence of sport discipline and competition duration

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3 Figures***Abstract***

In the present review, we summarize scientific knowledge concerning sex differences in world record performance and the influence of sport discipline and competition duration. In addition, we discuss how physiological factors relate to sex dimorphism. While cultural factors played a major role in the rapid improvement of performance of women relative to men up until the 1990’s, sex differences between the world’s best athletes in most events have remained relatively stable at approximately 8-12%. The exceptions are events in which upper-body power is a major contributor, where this difference is more than 12%, and ultra-endurance swimming, where the gap is now less than 5%.

The physiological advantages in men include a larger body size with more skeletal muscle mass, a lower percentage of body fat, as well as greater maximal delivery of anaerobic and aerobic energy. The greater strength and anaerobic capacity in men normally disappears when normalized for fat-free body mass, whereas the higher hemoglobin concentrations leads to 5-10% greater maximal oxygen uptakes in men also with such normalization. The higher percentage of muscle mass in the upper-body of men results in a particularly large sex difference in power production during upper-body exercise. While the exercise efficiency of men and women is usually similar, women have a better capacity to metabolize fat and demonstrate better hydrodynamics and more even pacing, which may be advantageous in particular during long-lasting swimming competitions.

**Keywords:** anaerobic capacity, body composition, exercise efficiency, gender difference, maximal oxygen uptake, muscle mass

***Introduction***

The most obvious distinctions between men and women that explains differences in sport performance concern body size and composition, as well as physiological differences due to androgens and estrogens. Fortunately, cultural acceptance of women in sport has improved considerably during the past century, and the proportion of women’s participation in the Olympic Games rose from ~4% in 1924 to ~45% in 2016.[1](#_ENREF_1) At the same time, women have gradually gained the same possibilities to train and compete as men, and performance improvements during most of this time-period have thereby been greater for women.

For example, the sex differences of world records in running races from 100 m to the marathon declined gradually until the 1990’s,[2](#_ENREF_2),[3](#_ENREF_3) with similar trends in most other sports as well. In fact, their linear regressions predicted that women would soon outrun men. However, as expected from the sex differences in the established sexual dimorphisms in skeletal muscle mass and potential for producing metabolic power, more recent investigations have shown relatively steady sex differences in performance over the past couple of decades.[4-6](#_ENREF_4) Accordingly, an updated overview of sex differences in performance in connection with sport competitions of varying duration is called for.

In the present review, we summarize scientific knowledge concerning sex differences in world record performance and the influence of sport discipline and competition duration. Furthermore, we discuss how physiological factors relate to sex dimorphism.

***Sex differences in performance***

Our comparison of sex differences in performance is based on publicly available data from world record performances collected from the respective sports’ official websites in February 2017, as well as scientific peer-reviewed papers on events where men’s and women’s performance could be validly compared. Note that women’s performance is defined as 100% in connection with all sex comparisons.

*Sprint events*

The performance gap between men’s and women’s world records in sprint running races (100 m, 200 m, 400 m), speed skating (500 m) and swimming competitions (100-m freestyle and 100-m backstroke), events lasting 10–60 s, narrowed from 12-14% in 1950 to approximately 8-11% in 1980, before increasing again somewhat to 9-12% in 2005.[5](#_ENREF_5) Between 2005 and 2017, these performance differences with respect to sprint running and freestyle swimming were approximately 10-12%. However, the difference in men’s and women’s world records for 500-m speed skating was reduced to 7%.

For all Olympic running events longer than 100 m, the sex differences in world records are relatively stable at 10-12% without any clear effect of distance (Figure 1A). In the case of speed skating, sex differences in performance appear to increase with distance (Figure 1B), a pattern also observed for short track cycling events. This might reflect a female advantage of having relatively lower upper-body mass to accelerate, a proposal supported by the less pronounced sex differences associated with 50- and 60-m than 100- and 200-m running events.

In contrast, with swimming the pattern is the opposite, with smaller differences in performance over longer distances, probably due to the better hydrodynamic properties (i.e., less drag) and floating skills of women (Figure 1C). This pattern of reduced sex differences by increasing distance also appear in some upper-body dominant modes, such as canoeing and double poling cross-country skiing, whereas the sex differences in kayaking is relatively constant at 12-13%. This exemplifies the fact that upper-body dominant modes in general reveal somewhat larger sex differences than for leg- or whole-body exercise sports (Figure 2).

*Middle- and long-distance events*

For middle- and long-distance events, the magnitudes of sex differences in world record performance are relatively similar to those presented for sprint events, with the gap declining gradually from the 1950’s to the 1990’s, thereafter remaining relatively stable. Currently, the average sex difference in middle- and long-distance running is slightly more than 11% and the world record in the marathon for women is only 10% slower than for men (Figure 1A). This is comparable to the corresponding values for most other endurance sports, such as rowing (9%), speed skating (9-11%; Figure 1B), and cross-country skiing (10-12%). In freestyle swimming the difference decreases from 10.8% in 200 m to 6.3% in the 1500 m (Figure 1C), whereas in triathlon, the sex difference is around 11-12%, although swimming performance differentiates least.[7](#_ENREF_7)

The performance difference between male and female world record holders in middle distance kayaking (12-13%) and canoe (>20%) are relatively large in this context. This may largely be explained by the proportionally larger upper-body muscle mass of men, in which upper-body power generation may be more determining for performance than cardiovascular factors. Consequently, the sex differences in performance in these sports is larger than in those where the legs produce most of the propulsion. In addition, with canoeing men’s longer upper bodies may provide an additional advantage. This also appears to be the case in cross-country skiing, where the sex differences become more pronounced as the contribution from upper-body poling increases.[8](#_ENREF_8)

*Ultra-endurance events*

For most prolonged non-Olympic ultra-endurance events (cycling, running, swimming, and triathlon) the sex differences vary more widely than for Olympic long-distance events, probably due to the lower criteria for participation and resulting large variation in the performance of the participants. For example sex differences in ultra-endurance running competitions lasting from 50 to 1000 km[9](#_ENREF_9) or 6- to 240[10](#_ENREF_10) hours differ extensively. Therefore, it is difficult to draw firm conclusions about “true” sex differences and there is ongoing discussion concerning whether these increase or decrease with distance.[9](#_ENREF_9)

Although women generally do not outperform men in endurance events, open-water ultra-endurance swimming offers an exception. Over distances of 16-36 km, the sex differences are only 1-6% and in the 32-km ‘Catalina Channel Swim’ and 46-km ‘Manhattan Island Marathon Swim’, the fastest women ever were faster than best-performing men.[11](#_ENREF_11) Although these two races are currently the exceptions where women outperform men, the sex differences in open-water swimming are indeed smaller than in all other sports.

## *Factors that explain the differences in performance between men and women*

## *Body size and composition*

Sex differences in body size and composition begin to develop at the onset of puberty, driven by sex-specific changes in circulating levels of hormones, including testosterone, estrogen, progesterone, luteinizing hormone, follicle-stimulating hormone and growth hormone. Men become larger, with both more absolute and relative muscle mass and a lower percentage of body fat, and have superior muscle strength and power, as well as both anaerobic and aerobic production of energy (Figure 3). Normalization for fat-free mass (an approximation of skeletal muscle mass) has been repeatedly proven to abolish these sex differences in strength and power.[12](#_ENREF_12) For example, the main factor accounting for gender differences in peak power output during sprint cycling is the muscle mass of the lower extremities.[13](#_ENREF_13) However, such normalization of upper-body power gives less consistent results. For example, after normalization of power differences for lean upper-body mass during poling by cross-country skiers a sex gap of more than 30% remained.[14](#_ENREF_14) This is different from leg-dominant or whole-body exercise endurance sports, where the sex differences in the relative amounts of muscle and fat explains most of the difference in performance. However, a remaining 5-10% difference[8](#_ENREF_8),[15](#_ENREF_15) is due to higher level of hemoglobin concentration and thereby enhanced oxygen transport capacity of men.

The muscle mass of women is generally 25-40% less than for the men, and men generally have relatively more muscle mass located in the upper-body. For example, Janssen and co-workers reported that the skeletal muscle mass of men is 36% greater than in women, with 40% and 33% differences located in theupper- and lower-body, respectively.[16](#_ENREF_16) Similar differences are demonstrated by e.g. elite cross-country skiers that are relatively equally trained in their upper- and lower-extremities,[14](#_ENREF_14),[17](#_ENREF_17) which in part explains the conclusion that sex differences in performance are greater for sports that rely more heavily on upper-body power. The smaller sex difference in lower- than upper-body muscle mass and maximal strength reflects the lower power output in connection with sports that involve predominantly lower-body exertion than those that rely more on the upper-body. In addition, increased demands of strength during upper-body exercise accentuates the sex differences in power production,[17](#_ENREF_17) which may contribute to explain that swimming, canoeing and cross-country skiing reveal greater sex differences at short compared to long competitions.

However, certain aspects of women’s body composition are actually advantageous compared to men. For example, the small sex differences observed in connection with long-distance swimming are probably due to the better hydrodynamic properties and floating skills of women.[7](#_ENREF_7) There is a lower drag coefficient in women compared to men,[18](#_ENREF_18) and women may have superior ability to perform at long durations in cold water in ultra-endurance swimming compared to men with lower body fat.[19](#_ENREF_19)

*Maximal anaerobic power*

More contractile tissue can produce greater amounts of metabolic power anaerobically and the larger muscle mass of men explains their advantage in this respect. However, it is more difficult to measure anaerobic than aerobic energy production valid and reliably, so few studies on the sex difference in anaerobic power have yet appeared. Normalizing for body mass, the peak acceleration power after ~1 s of sprint running by world-class male and female competitors has been found to be ~30 W·kg-1 and ~25 W·kg-1, respectively,[20](#_ENREF_20) with similar sex differences typically being observed in connection with countermovement tests. These sex differences can be explained primarily by the relatively larger muscle mass used to accelerate men’s body. In the Wingate test, which is used to express the anaerobic power during cycling, the differences between men and women also appear to be primarily related to differences in working muscle mass.[13](#_ENREF_13)

In addition, anaerobic power production in connection with sports that involve both high aerobic and anaerobic demands has been assessed. For example, the accumulated oxygen (∑O2) deficit during self-paced tests to exhaustion. World-class female and male cross-country skiers demonstrate ∑O2 deficits of 55 and 70 mL·kg⁻¹, respectively.[21](#_ENREF_21),[22](#_ENREF_22) That 30% gap is somewhat more pronounced than the corresponding difference in aerobic power. Similar sex differences are found during cycling and running, although running ∑O2 is normally higher than in cycling for both sexes.[23](#_ENREF_23) However, the ∑O2 deficits method may have limitations as a valid and reliable measure of anaerobic capacity that may influence sex differences as well.[24](#_ENREF_24)

*Maximal aerobic power*

Maximal oxygen uptake (*V*O2max), which is considered to be the most valid index of aerobic endurance, appears to be the primary factor determining the sex difference in endurance performance. In the general population, *V*O2max differs between men and women by approximately 50% in absolute terms (L·min-1) and by 20-30% when normalized to body mass (mL·min-1·kg-1).[25](#_ENREF_25) In comparison to Saltin and Åstrand’s[26](#_ENREF_26" \o "Saltin, 1967 #17901) evaluation of the maximal aerobic capacity of athletes from numerous disciplines, the sex gap in this respect has decreased substantially since the 1960’s, which is consistent with the relatively greater improvement in women’s performance during this same period.[27](#_ENREF_27)

In the light of the equivalent training loads of male and female skiers and lack of any change in the sex difference with respect to *V*O2max during the past two decades, a 15-20% difference in this value relative to body mass among equally talented and well-trained men and women appears to be physiologically determined. The highest body mass-normalized *V*O2max values reported so far are ~90 and ~75-80 mL·min-1·kg-1 for men and women, respectively[21](#_ENREF_21),[28](#_ENREF_28) For male distance runners and cyclists, values in the range of 70–85 mL·min-1·kg-1 are frequently seen.{Joyner, 2008 #18095}[29](#_ENREF_29) Fewer data are available in truly elite women, but values ∼10-15% lower than those seen in men are typically reported when expressed as mL·min-1·kg-1.[30](#_ENREF_30) These differences are normally attributed to a combination of higher percentage of body fat in women and lower concentration of red cell mass.

At the same time, the sex difference in peak oxygen uptake using modes of exercise with low muscle mass involved are influenced by the amount of power produced by men and women. For example, female skiers attain less of their *V*O2max when using the upper-body, e.g., during isolated upper-body poling (76% versus 67%) due to relatively less muscle mass and power production by the upper extremities.[14](#_ENREF_14) This illustrate that the sex differences in endurance performance involving various modes of exercise are accompanied by equivalent differences in the production of aerobic power.

Variations in maximal cardiac output (the product of heart rate and stroke volume) are consistent with the sex differences in *V*O2max.[25](#_ENREF_25) Whereas there exists no sex difference in maximal heart rate, the cardiac output differences are explained by greater stroke volume of men’s larger heart. In addition, men have more blood (8-9 L in elite male endurance athletes,[31](#_ENREF_31) with few corresponding values being available for women). While most of the sex differences in cardiac and blood parameters disappear when normalized for body size,[32](#_ENREF_32) the concentration of hemoglobin in women is markedly lower than in men (12-16 versus 14-18 g/100 ml).

## *Fractional utilization of VO2max*

The performance VO2 (i.e., the amount of oxygen utilized during competition) is determined by both the absolute *V*O2max and its fractional utilization.[29](#_ENREF_29) Certain findings indicate that women can utilize a higher proportion of their *V*O2max at various estimates of anaerobic threshold (i.e., ventilatory or lactate thresholds), e.g., in the case of performance-matched female and male runners (86.4% versus 81.7%)[15](#_ENREF_15) and cross-country skiers (87.6% versus 81.3%),[8](#_ENREF_8) In contrast, men can utilize a greater % of *V*O2max in upper-body exercise.[17](#_ENREF_17) Indeed, the fractional utilization of *V*O2max is influenced to various degrees by numerous discipline-related factors, such as the maximal lactate steady state, oxygen kinetics and the ability to produce power with a given technique. To what extent these factors, individually and/or in combination, differ between men and women across different sports is currently unknown.

## *Energy utilization*

It has been proposed that larger fat stores in the muscles of women and their ability to rely more on fat oxidation are advantageous in connection with ultra-marathon races.[33](#_ENREF_33) In addition, the high rates of fat oxidation in women is shifted toward higher intensities compared to men.[34](#_ENREF_34) However, while greater fat oxidation can spare glycogen and potentially prolong the time to fatigue it can also increase the oxygen cost of a given workload,[30](#_ENREF_30) and the evidence in this respect remains inconclusive.

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## *Work economy/efficiency*

Work economy/efficiency is an important factor in all endurance disciplines and differences in this respect may influence performance considerably.[30](#_ENREF_30) However, findings on sex differences in exercise efficiency are contradictory and influenced by numerous factors, including body composition, physiological parameters, training status and technique. While some previous investigations on distance runners have reported that men are more economical,[35](#_ENREF_35),[36](#_ENREF_36) others[37](#_ENREF_37) found that women exhibit lower *V*O2 compared to men with equal marathon times when running at comparable submaximal velocities. However, in most recent studies no difference between elite male and female distance runners with respect to the energy cost of running has been observed.[38](#_ENREF_38),[39](#_ENREF_39) Similarly, there is no difference in the ability of male and female cross-country skiers to convert the rate of metabolism into work and speed.[17](#_ENREF_17) In the case of cycling, there is indications of better efficiency in women due to their lower upper-body mass,[8](#_ENREF_8),[40](#_ENREF_40) and the energy cost of freestyle swimming has been shown to be significantly higher (i.e. lower economy) in men compared with women.[7](#_ENREF_7)

Little information on sex differences related to technique in endurance sports is presently available. Some studies have concluded that sex differences in performance are due primarily to the production of less work per cycle by women (a measure closely related to cycle/stride length), rather than differences in cycle rate. For example, for male cross-country skiers, both larger force and more rapid movement velocity are associated with more work during each cycle.[8](#_ENREF_8),[17](#_ENREF_17)

*Pacing strategy*

In connection with sports, pacing is defined as a strategy to distribute the power output during the exercise. For both runners and cross-country skiers, faster performance is associated with more even pacing and in these disciplines women appear to pace themselves more evenly than men.[41-43](#_ENREF_41) Upon investigating men and women with equal levels of marathon performance, Speechly and co-workers[44](#_ENREF_44) found that the women could maintain higher speeds during the second half of the race. In addition, Trubee et al.[45](#_ENREF_45) reported that the sex difference in pacing during a race increases with temperature, with women becoming more conservative in warmer environments.

More rapid depletion of glycogen in men has been put forward as an explanation for these differences in pacing. However, Deaner et al.[46](#_ENREF_46) reported that the sex difference in pacing is also observed during shorter races (10 km), where glycogen depletion is usually not relevant. Thus, the sex difference in pacing appears to involve psychological factors, such as decision-making and level of competitiveness, in agreement with findings that male distance runners are more competitive than their female counterparts.[47](#_ENREF_47) In general, men take more risks, which is a key component of competitiveness.[48](#_ENREF_48)

***Methodological considerations***

As a result of the historically limited opportunities for women to participate in sports, the sex gap in performance previously appeared to be artificially large. Although more professional training by women has in general reduced the apparent gap in Western countries, there still exist sex differences in participation and professionalization for certain sports. For example, conflicting findings across the ultra-marathon competitions and cases where sexes are compared across increasing age and placement of the competition can certainly confound “true” sex differences in performance. In addition, there are much fewer data on elite women than men for almost all of the issues outlined above.

Moreover, it is not entirely clear how best to compare men and women. Most of the conclusions we present here are based on studies involving world record holders and/or scales that compare performance to that of the best athlete in the world (e.g., FIS points in cross-country skiing). Although this approach allows comparison of the maximal capacities of men and women, it provides less insight into the sex differences between athletes who perform at a lower level. Perhaps comparison of the most successful 100 competitors, for example, would lead to somewhat different conclusions of more general relevance.

Another fundamental problem in this connection is the ambiguity that is sometimes present concerning a women’s sex, typically women with higher than normal levels of testosterone that enhance muscle mass, cardiovascular capacity, strength, speed, and power. How this might influence the evaluation of sex differences in performance has been discussed in detail by Tucker and Collins.[49](#_ENREF_49) Do women who naturally produce more testosterone and have no intention of cheating also have a naturally occurring performance advantage over other women? Definitive answers to such questions remain elusive. However, while such conditions are present in a very small proportion of the population, many of these exceptions may be elite athletes since the hormone profiles of athletes are shown to differ from those of normal subjects and thus from established reference ranges. Overall, this indicate that an individual's profile may contribute to his/her proficiency in a particular sport.50

In this connection, several types of doping may enhance performance to a greater extent in women than men, which may have influenced the findings summarized here. A woman who exposes herself to high levels of androgen may gain a significant performance advantage that is likely to be more pronounced than the analogous advantage to be gained from such doping by men. This practice was widespread in the 1980’s and is considered to explain many of the women’s world records established then, which have remained unchallenged since then.

***Perspectives***

The cultural acceptance for women in sport and a more equal distribution of economic resources has led to more extensive participation of women, both in terms of training and competing. This has been a key to the more rapid improvement in women’s than men’s athletic performance up until the 1990’s, after which the difference in performance by the world’s best male and female athletes has remained relatively stable at around 8-12%. The exceptions are events involving relatively large contributions of upper-body power, where this difference is larger (>12%), and ultra-endurance swimming, where, in contrast, the gap is now less than 5%. In the longest swimming events, women may even outperform men.

The physiological advantages that men possess include a larger body size with a higher proportion of skeletal muscle, a lower percentage body fat, and greater capacities for delivering anaerobic and aerobic energy. The greater strength and anaerobic capacity in men normally disappears when normalized for fat-free body mass, whereas the higher hemoglobin concentrations leads to 5-10% greater maximal oxygen uptakes in men also with such normalization. The higher percentage of muscle mass in the upper-body of men results in a particularly large sex difference in power production during upper-body exercise.

While the exercise efficiency of men and women is usually similar, women metabolize fat more effectively and demonstrate better hydrodynamics, better ability to float on water and enhanced tolerance for cold water. Moreover, women tend to pace themselves differently, choosing a more constant speed throughout long races. Together, these factors help explain why the sex gap in performance is smallest (or even non-existent) in connection with long-distance swimming.

Future performance will not progress indefinitely, and whether and when sport performance reaches its natural limits is a subject of continuous debate. Regression equations based on past results indicate that performance in many sport disciplines is approaching a plateau, at least for men. However, predicting future sex differences requires a deeper integrative understanding of the physiological, psychological, social, behavioral and environmental factors involved. For example, more effective training methods, technological innovations and/or improvements in rules and regulations may help improve performance to a greater extent than presently thought be possible.

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**Figure legends**

**Figure 1.** Sex differences in connection with the male and female world records in A) running, B) speed skating and C) swimming for various distances. Women’s performance was defined as 100%.

**Figure 2.** Sex differences in connection with the male and female world records in speed skating (500 m to 10,000 m), running (100 m to marathon), freestyle swimming (50 m to 1500 m), single sculler rowing (2000 m), K1 kayaking (200 m to 2000 m) and canoeing (200 m and 500 m). Each bar represents the average percentage difference (and standard deviations) across all of the distances indicated, with women’s performance defined as 100%.

 **Figure 3.** Sex differences in power output, body composition and physiological variables in connection with various sports. The values given are the increase in men’s average (and ranges in dotted boxes) relative to the corresponding values in women (defined as 100%). These values are based on the author’s overall interpretation of the scientific literature with relevance for world record performances.

Fat met. = fat metabolism, LB = lower body, UB = upper body, VO2peak = peak oxygen uptake.