# **New records in human power**

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# **Abstract**

Maximal aerobic and anaerobic power are crucial performance determinants in most sports disciplines. Numerous studies have published power data from elite athletes over the years, particularly in runners, cyclists, rowers and cross-country skiers. In this invited review, we define the current “world records” in human upper limits of aerobic and anaerobic power. Currently, O2max values of ~7.5 and 7.0 L.min-1 in male cross-country (XC) skiers and rowers, respectively, and/or ~90 ml.kg-1.min-1 in XC skiers, cyclists and runners can be described as upper human limits for aerobic power. Corresponding values for women are slightly below 5.0 L.min-1 in rowers and XC skiers and ~80 ml.kg.min-1 obtained in XC skiers and runners. Extremely powerful male athletes may reach ~85 W∙kg-1 in countermovement jump (CMJ) (peak vertical power) and ~36 W∙kg-1 in sprint running (peak horizontal power), cycling (instantaneous power during force-velocity testing from a standing position) and rowing (instantaneous power). Similarly, their female counterparts may reach ~70 W∙kg-1 in CMJ and ~30 W∙kg-1 in sprint running, cycling and rowing. The presented values can serve as reference values for practitioners and scientists working with elite athletes. However, several methodological considerations should be taken into account when interpreting the results. For example, calibrated apparatus and strict procedures are required to ensure high measurement validity and reliability, and the sampling rate for anaerobic power assessments must be strictly predetermined and carefully measured. Doping is also a potential confounding factor when interpreting the human upper limits of aerobic and anaerobic power.

# **Introduction**

Higher, faster, stronger: what are the upper limits of human performance? In a published study from January 2008, Berthelot et al.1 estimated that world records had reached 99% of their asymptotic values and that human upper performance limits in sport would be reached within one generation. Only months later, Usain Bolt improved the 100-m world record to 9.69 s in the Beijing Summer Olympics, followed by an even more astonishing 9.58 s world record one year later, a world record improvement equivalent to that achieved from 1968 to 1999. This is one of numerous examples throughout sports history of unanticipated “quantum leaps” in performance due to physiological, biomechanical and technological advances.

Alongside the progression of world records, the physiological capacity of the world´s best athletes has developed substantially. Metabolic energy turnover and efficient transfer to external power output underlies successful performance in sports. Accordingly, regular assessment of aerobic and anaerobic power informs the overall training strategy of most of today’s elite athletes. Numerous groups have reported contemporary power data from elite athletes, particularly runners, cyclists, rowers and cross-country (XC) skiers, providing the opportunity to re-analyze human upper limits, historical trends and sex differences. In this invited review, we define the current “world records” in physiological capacity: human upper limits of aerobic and anaerobic power. Unpublished observations from national sports science centers are added to the manuscript in cases where the scientific literature is scarce. We believe combining these data sources provides a valid picture of the current limits of human power output.

Maximal aerobic and anaerobic *power* are herein defined as the highest values reached per time unit, denominated in watts (J∙s-1). However, an important distinction is the difference between *metabolic power* (i.e., the rate of ATP consumed by the body, which aerobically is estimated by the O2 uptake per min) and *external power output* (i.e., the product of metabolic power and the efficiency of locomotion).

# **Maximal aerobic power**

## **Assessing maximal oxygen uptake**

Maximal oxygen uptake (O2max) has been established as a valid and reliable measure of the maximal ability to produce metabolic power aerobically. While O2max integrates cardiac output, total body hemoglobin, muscle blood flow and muscle oxygen extraction, the primary limiting factor for O2max in athletes is the ability of the cardiorespiratory system to deliver oxygen to the exercising muscles.2 A.V. Hill introduced the O2max concept in the 1920s, and already in the 1930s high values for O2max were observed in athletes and identified as a marker of elite performance.3 These early findings were followed by seminal methodological studies in the 1950s and 60s by Taylor, Åstrand and Saltin, establishing applicable protocols and physiological indicators for its measurement.4 To reach O2max, the test protocol necessitates employment of relatively large muscle mass while exercising in a dynamic movement (e.g. running and cycling) and typically consists of a progressive increase in intensity timed to induce voluntary exhaustion after approximately 4-6 minutes of work. The main criterion used to confirm that an athlete has reached O2max is a levelling off or decrease in O2 despite increasing workload and ventilation.5

O2max is strongly correlated with endurance performance in heterogeneous groups of performers. However, the strength of this relationship generally deteriorates in homogenous subsets of elite endurance athletes, consistent with the contributing role of other factors such as fractional utilization of O2max and work economy/efficiency.6 High O2max is necessary but not sufficient for elite endurance performance.

Today’s best endurance performers have body sizes and compositions that closely match the specific constraints of their disciplines. Based on publically available biographical information, the three male and three female medalists at the 2014 rowing WC single sculling rowing event averaged 198 cm/98 kg and 185 cm/77 kg, respectively. In contrast, the medal winning males and females for the 5000-m running event at the London 2012 Olympics averaged 170 cm/57 kg and 160 cm/43 kg, respectively. Elite cross-country (XC) skiers fall squarely between these extremes with gold medalist men and women averaging 182 cm/75 kg and 170 cm/60 kg, respectively.7,8 This also means that different *absolute* versus body mass normalized (*relative*) O2max values are reached among the best performing athletes in these sports.

It is well established that in weight supported events such as rowing and track cycling, successful athletes tend to be larger, with high O2max expressed in *absolute* units (L.min-1).9 However, for most endurance disciplines, maximal oxygen uptake *relative* to body mass (ml.kg-1.min-1), is a stronger predictor of performance, under “gravity resisted” conditions where a relatively low body mass is beneficial (e.g. XC running, mountain biking, and road cycling).6 These differences across sports are mainly due to variation in biomechanical constraints, which explains why different scaling components of body mass are used when expressing O2max in different sport contexts.

## **Upper limits**

In the 1960s, Saltin & Åstrand10 reported three male athletes, out of all Swedish national team level athletes tested, with *absolute* O2max values between 6.0 and 6.2 L.min-1, leading them to speculate that 6 L.min-1 approached an upper range for O2max. They speculated further that 6 L.min-1 encroached on limits for pulmonary diffusion capacity and cardiac output. However, already in 1979, Hagerman et al.11 reported absolute O2max nearing 7 L.min-1 in two elite oarsmen, and in 1987, Berg12 reported data from a 96 kg XC skier with a O2max of 7.2 L.min-1. Later, Saltin13 reported an absolute O2max of 7.48 L.min-1 in a Swedish XC skier. Among Norwegian XC skiers, five male athletes have exceeded 6.95 L.min-1 O2max, with four of those being gold medalists in World Championships or Olympic Games.7 Recently, Miculic & Bralic reported that two Olympic champion rowers yielded 7.1 L.min-1 O2max on average.14

To put these exceptionally high O2max values in a physiological context, it is worthwhile to contextualize them within the three components of the Fick equation. A large male endurance athlete (approximately 100 kg) who achieves the improbable combination of a heart rate of 200 b.min-1, 200 mlO2.dl-1 a-v O2 difference and 200 ml.beat-1 maximal stroke volume would reach an *absolute* O2max of 8.0 L.min-1 (but a *relative* O2max of “only” 80 mL·min-1·kg-1).15 Each of these Fick equation components represents extremes rarely observed, or essentially theoretical maximums in highly trained athletes. For example, a-vO2 difference of 200 mlO2.dl-1 would require a blood hemoglobin concentration of 17.0 g.dl-1 combined with venous blood oxygen concentrations as low as those seen on high mountain expeditions.15,16 Therefore, it is tempting to revise the speculation of Åstrand & Saltin from 1967 to say that 7.0-7.5 L.min-1 O2max in male athletes of 80-100 kg likely encroaches on the upper limits of human aerobic power.

While the *absolute* O2max values reported above are generally reached in rowers or relatively large XC skiers, the highest *relative* O2max values are reached in XC skiers (distance specialists), distance runners and road/mountain bike cyclists (Figure 1). Most medal-winning male XC skiers reach *relative* O2max values of 80–85 mL·min-1·kg-1, with the highest values reported so far being ~90 mL·min-1·kg-1.7,8 For male distance runners and cyclists, values in the range of 75–85 mL·min-1·kg-1 are frequently seen, but absolute values are normally below 6 L·min-1 due to their low body mass.17,18 Santalla et al.18 reported values of ~80 mL·min-1·kg-1 in Tour de France climbers, whereas Tour de France winners are reported in the range 79-86 mL·min-1·kg-1. A recent study showed that a two-time Tour de France champion had 5.91 L·min-1 and 85 mL·min-1·kg-1 O2max,19 and a doped Lance Armstrong had O2max of 84 mL·min-1·kg-1.20 Collectively, these values suggest a minimum threshold of 80 mL·min-1·kg-1 to win the Tour. Some other exceptionally high *relative* O2max values have been reported in cyclists. For example, > 90 mL·min-1·kg-1 was measured in two male world champion and world record holding pursuit cyclists.21 Among world class distance runners, O2max 80 mL·min-1·kg-1 represents a reasonable mean based on observations of both European and Kenyan runners.22 However, tests of gold medal winning athletes both from Kenya and European countries indicate that some of the very best runners reach *relative* O2max values of 85 mL·min-1·kg-1 .23 Somewhat surprisingly, we are not aware of valid reports of ≥ 90 mL·min-1·kg-1 O2max among elite male distance runners.

\*\*\*Figure 1 about here\*\*\*

{Joyner, 2008 #18095}

In women, the highest *absolute* O2max values observed among XC skiers are slightly below 5.0 L.min-1.7,24 Personal communication with other laboratories testing elite rowers and XC skiers also suggests that 5.0 L.min-1 approximates the upper limit of what contemporary world-class female performers in XC skiing (60-72 kg body mass) and rowing (70-85 kg body mass) have achieved. Returning to the Fick equation, 5.0-5.2 L.min-1 O2 max in a female endurance athlete would require an upper limit blood hemoglobin (15 g.dl-1), a maximal heart rate of 200 combined with a maximal stroke volume of 150 ml.beat-1 and a-v O2 diff of 170 ml.dl-1. This combination is unlikely, so we propose that 5.0 L.min-1 O2max in female athletes of 65-80 kg is the upper limit of aerobic power in women.

The highest reported *relative* O2max values in women are found in XC skiers, with world cup and medal winning performers achieving 70-80 mL.kg-1.min-1.7,24 Similarly ~70 mL·min-1·kg-1 appears to be a prerequisite for internationally elite performance in cross-country mountain biking, as exemplified with a world leading female mountain biker obtaining 70.1 mL·min-1·kg-1.25 Wilber et al.26 reported average values of 68.0 mL·min-1·kg-1 in a sample of elite mountain bikers and road cyclists. These values are comparable to those found in elite female middle- and long-distance runners, where both Billat et al.27 and Lacour et al.28 have also reported an average of just below 70 mL·min-1·kg-1.However, compared to the comprehensive data now available on O2max values in the world’s best male endurance athletes, we still lack corresponding data for women. Among thousands of O2max tests performed on female endurance athletes at the Norwegian Olympic Training Center the last 25 years, the three highest relative values (~80 mL·min-1·kg-1) were achieved by a long-distance runner (Olympic finalist), an orienteerer (jr. World Championship medalist) and a XC distance skier (World Champion).

Peak oxygen uptake is clearly lower during modes of exercise where muscle mass involvement is constrained. For example, male and female XC skiers attain 76% versus 67% of their O2max with isolated upper-body poling.29 This implies peak “upper body” O2 values of > 60 and close to 50 mL·min-1·kg-1 in men and women, respectively. Kayakers, however, show peak O2 values above 85% of their VO2max in upper-body exercise,30 and although they have lower O2max than skiers, this means that some of the best male and female kayakers exhibit the same upper body O2peak values. In addition, Paralympic sitting sports such as wheelchair, or Nordic sit skiing are completely constrained to upper body muscle work, both in their sport and when testing in arm cranking, arm cycling or upper-body poling. Systematic reports of O2peak data from contemporary high-level performers in these Paralympic events is lacking, but Couttsreported 67 mL·min-1·kg-1 in an elite paraplegic distance track competitor.31

## **Sex differences**

Cultural factors played a major role in the rapid improvement of women’s performance compared to men until the 1990’s. However, sex differences in performance time over standard distances among the world’s best endurance athletes in most events have thereafter remained relatively stable at approximately 8-12%.8 In this connection, O2max is considered the primary factor explaining the sex difference in endurance performance. In comparison to Saltin & Åstrand’s10 evaluation of O2max in athletes of both sexes from numerous disciplines in the 1960’s, the gap between men and women has decreased substantially, consistent with greater improvements in women’s performances during this same period. In the light of the equivalent training loads of male and female XC skiers and lack of any change in the sex difference during the past two decades, a 15-20% difference in *relative* O2max appears to be physiologically determined among equally talented and well-trained men and women.32 Among elite distance runners and cyclists, O2max values are typically ∼15% higher in men than in women.32 Differences in body size contribute greatly to sex differences in absolute O2max, while sex differences in relative O2max are attributed to a higher percentage of body fat and lower hemoglobin concentration in women.32

# **Maximal anaerobic power**

## **Assessing maximal anaerobic power**

Anaerobic power refers to metabolic energy turnover and/or the external work per time unit produced independent of oxygen consumption. Anaerobic metabolic reactions drive a 4-fold faster peak rate of energy transfer than the aerobic system.33 From a practical perspective, peak anaerobic power signifies the greatest instantaneous power during a single movement with the aim of producing maximal velocity at take-off, release or impact.34 Anaerobic power is typically expressed as absolute (W) or relative (W·kg-1) external power output, since the upper limit of metabolic power is difficult to measure non-invasively with today’s methods.

Margaria et al.35 were pioneers in measuring maximal/peak anaerobic power for athletes. These Italian researchers developed a simple stair-running test and showed that peak power was reached after 1.5-2 seconds and could be sustained for 4-5 seconds. Later, scientists have purposed and applied specific tests for varying modalities. The test specificities for determination of anaerobic peak power are crucial for outcomes and interpretations. Firstly, anaerobic power can only be validly expressed as external power output, which is in contrast to aerobic power where oxygen uptake can be used as a highly reliable proxy for aerobic metabolic power. It is currently impossible to accurately assess the mechanical efficiency of anaerobic power conversion, which in turn makes it difficult to interpret whether performance changes or differences between athletes are due to higher muscle metabolism or better mechanical efficiency. Secondly, with the proviso that the muscles pull in the same direction, the amount of muscle mass activated at the same time is almost linearly related to peak/maximal anaerobic power.36,37 It has hence been demonstrated at an inter-individual level that the anaerobic power is nearly directly proportional to muscle mass involved.37-39 For example, the peak power measured in unilateral movements (running and cycling) is about half of bilateral movements such as a vertical jump.38,40,41 Finally, the time-power curve is hyperbolic.36,37 The steep left part of the curve shows that peak power drops substantially with only small increases in time (Figure 3). Indeed, a tenth of a second will have a considerable impact on the calculations of power, and thus, the time for anaerobic power assessments must be strictly predetermined and carefully measured. Based on these considerations, it is not possible to assess a generic anaerobic maximal power. Comparisons of power values across modalities (e.g., cycling, jumping and running) are meaningless, and each anaerobic power test must be treated separately.

## **Upper limits**

### *Cycling*

The Wingate test was developed in 1970s and has been widely used over the years to assess anaerobic power and capacity.38,41,42 The test protocol consists of 30 s cycling at absolute maximal effort (without any attempt at “pacing” to maximize mean power) on a stationary ergometer. Peak power has typically been reported as the highest average over 5 s, and values exceeding 11 W∙kg-1 for women and 14 W∙kg-1 for men have been are considered “elite” level when summarizing data from a broad range of athletes.42-44 The most powerful female and male individuals have been reported to exceed 12 and 17 W∙kg-1.42-44 Nowadays it is more typical to report peak power from 1-s periods or one revolution,42,45 logically leading to higher output values. Hofman et al.46 reported peak power of 18 and 24 W∙kg-1 for female and male world-class speed skaters, when performed from a standstill start in a seated position.

A limitation associated with the Wingate test is that the load (frictional resistance) is predetermined and therefore not necessarily optimal for each individual.38 Hence, the Wingate test has been shown to underestimate peak power compared to force-velocity anaerobic tests.43 The force-velocity test consists of repeated short sprints of ~5-6 sec with increasing loads, allowing a better estimation of peak power at an individual level.41,43,45 To circumvent these limitations, Martin et al.40 developed a flywheel ergometer, which allowed instantaneous power measurements and a force-velocity profiling based on one 3-4 s all-out cycle-sprint acceleration only. The same authors have reported that male elite track cyclists can reach 31-33 W∙kg-1 (~ 2600 W).40,47 Unpublished observations by Jonvik et al. (Maastricht University) have shown that four female Dutch elite cyclists reached peak power in the range 20-23 W∙kg-1 when assessed over 1 s. When measured over one pedal revolution, the power values are ~ 10 W∙kg-1 lower than the instantaneous recordings,40 and the highest individual one pedal revolution values observed in males are ~ 20-25 W∙kg-1.40,48-50 These values are comparable to what cyclists managed during a field test (SRM power meter). 49,50 Noteworthy, in the studies of Martin et al.,49,50 the participants were seated during the sprints. This means that peak power is underestimated, as a standing position allows activation of more muscle mass and higher peak power (~ 10%) compared to the seated position.51,52 Based on these considerations, it is reasonable to assume that extremely powerful males may reach an instantaneous power of 36-37 W∙kg-1 in the standing position. This is in accordance with unpublished observations from the University of Lillehammer (Norway), where a BMX rider (82 kg, quarterfinalist from the Rio 2016 Olympics) reached 3020 W and 36.9 W∙kg-1 when the sampling rate was 200 Hz. Similarly, female elite cyclists may approach 30 W∙kg-1.

\*\*\* Figure 2 about here\*\*\*

### *Sprint running*

Computation models have been developed the last decade to calculate mechanical outputs and horizontal profiles of accelerated sprinting in the world’s fastest 100-m sprinters.53-55 These models are based on inputs such as i) the athlete’s body mass and height, ii) either distance-time or speed-time running data, and iii) wind speed, ambient temperature and pressure. Individual power-force-velocity profiles can be calculated from the modeling by derivation of the speed-time curve that leads to horizontal acceleration data. Based on this approach, Slawinski et al.56 calculated that absolute and relative peak acceleration power in male (79 ±7 kg) and female (60 ±5 kg) world-class sprinters were 2392 ±271 and 1494 ±186 W and 30.3±2.5 and 24.5 ±4.2 W·kg-1, respectively, typically attained after ~1 s of sprinting. Horizontal power production is strongly correlated with accelerated sprinting performance in heterogeneous groups of performers,57 but the strength of this relationship deteriorates in homogenous subsets of elite sprinters.56 The highest individual values observed (based on personal communication with the first author) were ~3000 W/36.1 W·kg-1 and 2050 W/29.3 W·kg-1, obtained by Dwain Chambers and Marion Jones in the World Championships in Seville in 1999. However, it should be noted that both these athletes were involved in the Balco doping scandal disclosed three years later. Other exceptional power output values are 2800 W/35 W·kg-1 by Maureece Greene and 1364 W/27 W·kg-1 by Shelly-Ann Fraser. Usain Bolt achieved ~2750 W during his world-record race in 2009.56 If we assume that his body mass was 94 kg, as stated on his personal web-site (http://usainbolt.com/bio), his relative power output was 29.3 W·kg-1. Rabita et al.57 reported 29.3 ±2.3 W·kg-1 in four elite sprinters with 100-m personal best times in the range 9.95-10.29 s.

Logically, there will be variation in mechanical outputs as a function of timing checkpoints. The longer time splits (e.g., 20-m vs. 5-m splits), the more smoothening of the speed-time curve that leads to horizontal acceleration data. Distance-time data for each 5th or 10th meter during the acceleration phase is likely required to ensure valid mechanical outputs, but such short acceleration splits are challenging to assess accurately.58

### *Vertical jumping*

Bilateral vertical jump seems to be the exercise modality where the highest anaerobic power output values are reached.45 Elite weightlifters generate similar or higher power during vertical jumps than during weightlifting, and athletic sprinters achieve two-to-three times higher W·kg-1 during countermovement jump (CMJ) compared to sprinting.59 A force plate or optical kinematic system with sampling rate ≥ 200 Hz is needed to calculate instantaneous peak power during vertical jump.60 The power level increases rapidly during the propulsion/concentric phase of a vertical jump (200-300 ms) and peaks shortly before take-off (Figure 3). The peak power phase (> 95% of peak power) lasts 20-30 ms. Since vertical jump height can be determined by the velocity of the center of mass (CoM) at take-off , there is a very strong relationship between peak power (W·kg-1) and jump height. In research literature, mean CMJ height with no arm swing (akimbo) in subsets of male elite power athletes have been reported in the range 45-55 cm, 59,61,62 translating to mean peak power in the range 50-65 W·kg-1. Individual values are rarely reported, but if we add three standard deviations (1SD ≅5 cm), we come close to 70 cm and 80 W·kg-1. This is in accordance with unpublished data from the Norwegian Olympic Training Center, where the highest observed CMJ (akimbo) heights out of ~30000 measurements since 1995 are 72 cm and 58 cm for men and women, corresponding to ~ 85 and ~ 70 W·kg-1, respectively. McGilvery63 hypothesized a theoretical human upper limit of 64 W·kg-1, based on the required high-energy phosphate utilization that can be sustained from maximal creatine kinease enzyme activity. Compared to the above-mentioned values, McGilvery’s assumption seems too low.

\*\*\*Figure 3 about here\*\*\*

If we add arm swing, peak power and jump height can reach considerably higher values than akimbo CMJ. A well-coordinated arm swing can add as much as 18-38% increased jump height.64-66 Harman et al.64 reported ~ 21% increased power output when arm swing was allowed. The effect of the arm swing on a CMJ can be explained by an increased work done by the legs due to an increased propulsion phase time, and CoM elevation at toe off/take off. Hence, arm swing increases both the kinetic and potential energy levels during the jump.65 Unfortunately, scientific information of vertical jumps with run-up and arm swing performed by elite athletes is lacking. However, anecdotal observations indicate that the human upper limit for such jumps is ~ 110 cm (CoM elevation). To illustrate, the basketball player Kadour Ziani has repeatedly been captured on video having the top of his head above the basketball rim (305 cm). Ziani is about 180 cm tall, and if we assume that CoM is elevated 15-20 cm at the end of take-off, his CoM elevation is 105-110 cm at the point where the top of his head is aligned with the rim (thus, an underestimation). Interestingly, this CoM elevation is similar to the former high jumper Hollis Conway. According to Dapena,67 Conway cleared 2.34 m in the Olympics in 1992, but his CoM reached 2.41 m. Assuming that CoM was 1.29 m above ground level (70% of 1.84 m body height) at take-off, Conway elevated his CoM by approximately 112 cm. Based on a vertical take-off speed of 4.65 m∙s-1, his CoM was elevated by 110 cm.67 Similarly, Emilia Dragieva (body height 1.69 m) elevated her CoM by 86 cm, based on a vertical take-off velocity of 4.1 m/s when clearing 2.00 m during a high jump.67 The higher jump heights and power outputs obtained in run-up jumps compared to jumping from standstill are mainly explained by an increased muscle force during the propulsion/concentric phase and storage and release of elastic energy.68,69 Indeed, more research on power output during vertical jumps with run-up and arm swing in elite athletes is warranted.

### *Other modalities*

The challenges associated with on-water power testing during rowing have led to the widespread use of the Concept II rowing ergometer and similar devices. Power output is typically expressed as mean values for the entire distance or work period during intermittent laboratory tests (e.g., 2000 m), but some studies have published power outputs obtained by elite athletes during much briefer working periods. Averaged over 10 maximal strokes, 24 elite Spanish rowers (body mass 84 ± 5 kg) obtained 630 ± 45 W, or 7.5 W·kg-1.70 Unpublished test data from the Norwegian Olympic Training Center have shown that two heavyweight oarsmen, one Olympic Champion and another World Champion, were able to exceed 11 W·kg-1 during an all-out 10-s ergometer test. Similarly, two world-class heavyweight kayakers have reached 6.3 W·kg-1. As for the previously discussed exercise modalities, the pre-defined time window and working period is crucial for power output interpretation. Metikos et al.71 reported that 24 trained male and female junior rowers could reach an instantaneous peak power of 23.8 ±5 W∙kg-1. Correspondence with one of the authors (prof. Goran Markovic, University of Zagreb) revealed that the highest individual male and female values were 31.6 and 24.8 W∙kg-1. It is reasonable to assume that world-class rowers can reach considerably higher values, perhaps on par with those obtained by the very best athletic sprinters and BMX cyclists.

In double poling XC skiing, average cycle values of approximately 550 W (7.5-8 W∙kg-1) has been obtained during treadmill roller skiing in male elite skiers.72 Like rowing, half of the ski double poling cycle does not produce propulsion. The propulsive phase is likely well above 1000 W (>15 W∙kg-1) and the instantaneous power as high or higher than reported by Swarén & Eriksson73 (i.e., 1350 W) using the classical style in a 1500 m sprint race. Even higher values are most likely possible to reach for elite skiers during a 100-m maximal sprint with the skating technique, but this has not yet been examined.

## **Sex differences**

More contractile tissue can produce greater amounts of metabolic power anaerobically and the larger muscle mass of men explains their advantage in this respect.74 However, because it is more challenging to assess anaerobic than aerobic energy production validly and reliably, few studies on the sex gap in anaerobic power have yet appeared. The sex difference for peak acceleration power normalized to body mass in world-class sprinters seems to be 16-17%,56 with similar sex differences typically being observed for countermovement tests. The corresponding sex difference (W∙kg-1) in cycling is ~25%.38,43,44,46 This difference which remains after body mass normalization can be explained by the fact that muscle mass comprises a higher percentage of total body mass in males.

## **Methodological considerations**

Several methodological considerations must be taken into account when interpreting the results presented in this study. Regarding O2max measurements, it is crucial that the O2 analyzers are specifically validated and calibrated for measuring the extremely high ventilatory minute volumes achieved by elite endurance athletes. It should be noted that most commercially available metabolic carts are purpose-built for testing patients with capacity limitations, not elite athletes with 7 L.min-1 O2max. Moreover, varying exercise modalities (running vs. cycling or rowing) can also impact measurements due to variations in total muscle mass devoted to each exercise. For example, an elite cyclist or oarsman may reach an even higher O2max during uphill treadmill running than from testing with their specifically trained modality.

Strict procedures are also required to ensure high validity and reliability for anaerobic power quantification. For example, handlebar and saddle positions, crank arm length, pedals and shoes, riding position (standing or seated), resistance (% of body weight), and starting procedures (starting from standstill or pedaling) should all be standardized for a cycling test of anaerobic power. Additionally, the measuring device needs to be validated, and the sampling frequency or periods must be defined.38

Historically doping is a major confounding factor when interpreting human upper limits and sex differences.74 Various types of doping enhance performance, androgens/testosterone markedly enhancing anaerobic power. On the aerobic end, EPO or traditional blood doping augments total red cell mass and thereby aerobic power through expansion of a-v O2 difference. We must acknowledge that individual or mean measurements reported in this review could have been influenced by doping. Doping tainted measurements would tend to narrow the sex difference reported here due to the greater scope for doping enhancement in females, particularly in measurements related to strength and power performance. The misuse of anabolic androgenic steroids was clearly widespread in the 1980’s and is considered to explain many of the women’s world records established then, which have remained unchallenged. Whether there are differences between sexes in the effects of increasing red cell mas is yet unknown, but the lower hemoglobin concentration in women indicate that they might have a greater potential for improvements.75

## **Perspectives**

Currently, O2max values of ~7.5 and ~7.0 L.min-1 in XC skiers and rowers, respectively, and/or ~90 ml.kg-1.min-1 in male XC skiers, cyclists and runners can be described as upper human limits in aerobic power. Corresponding values for women are slightly below 5.0 L.min-1 in rowers and XC skiers and ~80 ml.kg.min-1 obtained in XC skiers and runners. Extremely powerful male athletes may reach ~85 W∙kg-1 in CMJ (peak vertical power) and ~36 W∙kg-1 in sprint running (peak horizontal power), cycling (instantaneous power during force-velocity testing from a standing position) and rowing (instantaneous power). Similarly, their female counterparts may reach ~70 W∙kg-1 in CMJ and ~30 W∙kg-1 in sprint running, cycling and rowing. The presented values can serve as reference values for practitioners and scientists working with elite athletes. Compared to the comprehensive data published on aerobic and anaerobic power values in world-leading male athletes, there is a lack of corresponding data for women. Future studies should aim to fill this gap, in addition to outline and establish common procedures for power output assessments in typical anaerobic sports disciplines.

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# **References**

1. Berthelot G, Thibault V, Tafflet M, Escolano S, El Helou N, Jouven X, Hermine O, Toussaint JF. The citius end: world records progression announces the completion of a brief ultra-physiological quest. *PLoS One*. 2008;3:e1552.
2. Bassett DR Jr, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc*. 2000;32:70-84.
3. Robinson S, Edwards HT, Dill DB. New records in human power. *Science* 1937;85:409-410.
4. Seiler S. A brief history of endurance testing in athletes. *Sportscience* 2011;15:40-86.
5. Poole DC, Jones AM. Measurement of the maximum oxygen uptake O2max: O2 peak is no longer acceptable. *J Appl Physiol.* 2017;122:997-1002.
6. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol*. 2008;586:35-44.
7. Tønnessen E, Haugen TA, Hem E, Leirstein S, Seiler S. Maximal aerobic capacity in the winter-Olympics endurance disciplines: Olympic-medal benchmarks for the time period 1990-2013. *Int J Sports Physiol Perform*. 2015;10:835-839.
8. Sandbakk Ø, Holmberg HC. Physiological capacity and training routines of elite cross-country ckiers: Approaching the upper limits of human endurance. *Int J Sports Physiol Perform*. 2017 [Epub ahead of print]
9. Volianitis S, Secher NH. Rowing, the ultimate challenge to the human body - implications for physiological variables. *Clin Physiol Funct Imaging*. 2009;29:241-244.
10. Saltin B, Åstrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol*. 1967;23:353-358.
11. Hagerman FC, Hagerman GR, Mickelson TC. Physiological profiles of elite rowers. *Phys Sportsmed*. 1979;7:74-83.
12. Bergh U. The influence of body mass in cross-country skiing. *Med Sci Sports Exerc.* 1987:19:324-331.
13. Saltin B. The physiology of competitive cross-country skiing across a four decade perspective; with a note on training induced adaptations and role of training at medium altitude. In Science and Skiing, eds. Mueller E, Schwameder H, Kornxl E, Raschner C. E & FN Spon, London 1996:435–469.
14. Mikulic P, Bralic N. Elite status maintained: a 12-year physiological and performance follow-up of two Olympic champion rowers. J Sports Sci. 2017;23:1-6.
15. Levine BD. VO2max: what do we know, and what do we still need to know? *J Physiol.* 2008;586:25-34.
16. Sutton JR, Reeves JT, Wagner PD, Groves BM, Cymerman A, Malconian MK, Rock PB, Young PM, Walter SD, Houston CS. Operation Everest II: oxygen transport during exercise at extreme simulated altitude. *J Appl Physiol*. 1988;64:1309-1321.
17. Faria EW, Parker DL, Faria IE. The science of cycling: physiology and training - part 1. *Sports Med*. 2005;35:285-312.
18. Santalla A, Earnest CP, Marroyo JA, Lucia A. The Tour de France: an updated physiological review. *Int J Sports Physiol Perform*. 2012;7:200-209.
19. Bell PG, Furber MJ, Van Someren KA, Antón-Solanas A, Swart J. The physiological profile of a multiple Tour de France winning cyclist. *Med Sci Sports Exerc*. 2017;49:115-123.
20. Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. *J Appl Physiol*. 2005;98: 2191-2196.
21. Craig NP, Norton KI. Characteristics of track cycling. *Sports Med*. 2001;31:457-468.
22. Saltin B, Larsen H, Terrados N, Bangsbo J, Bak T, Kim CK, Svedenhag J, Rolf CJ. Aerobic exercise capacity at sea level and at altitude in Kenyan boys, junior and senior runners compared with Scandinavian runners. *Scand J Med Sci Sports*. 1995;5:209-221.
23. Larsen HB, Sheel AW. The Kenyan runners. *Scand J Med Sci Sports*. 2015;25:110-8.
24. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg HC. The physiological capacity of the world's highest ranked female cross-country skiers. *Med Sci Sports Exerc.* 2016;48:1091-1100.
25. Impellizzeri FM, Ebert T, Sassi A, Menaspà P, Rampinini E, Martin DT. Level ground and uphill cycling ability in elite female mountain bikers and road cyclists. *Eur J Appl Physiol.* 2008;102:335-341.
26. Wilber RL, Zawadzki KM, Kearney JT, Shannon MP, Disalvo D. Physiological profiles of elite off-road and road cyclists. *Med Sci Sports Exerc.* 1997;29:1090-1094.
27. Billat V, Lepretre PM, Heugas AM, Laurence MH, Salim D, Koralsztein JP. Training and bioenergetic characteristics in elite male and female Kenyan runners. *Med Sci Sports Exerc*. 2003;35:297-306.
28. Lacour JR, Padilla-Magunacelaya S, Barthélémy JC, Dormois D. The energetics of middle-distance running. *Eur J Appl Physiol Occup Physiol*. 1990;60:38-43.
29. Hegge AM, Myhre K, Welde B, Holmberg HC, Sandbakk O. Are gender differences in upper-body power generated by elite cross-country skiers augmented by increasing the intensity of exercise? *PLoS One* 2015;10:e0127509.
30. Michael JS, Smith R, Rooney KB. Determinants of kayak paddling performance. *Sports Biomech*. 2009;8:167-179.
31. Coutts KD. Peak oxygen uptake of elite wheelchair athletes. *Adapt Phys Activ Quart*. 1990;7:62-66.
32. Sandbakk Ø, Solli GS, Holmberg HC. Sex differences in world record performance: The influence of sport discipline and competition duration. *Int J Sports Physiol Perform*. 2017. [Epub ahead of print]
33. Barclay CJ, Woledge RC, Curtin NA. Energy turnover for Ca2+ cycling in skeletal muscle. *J Muscle Res Cell Motil*. 2007;28:259-274.
34. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Med*. 2011;41:17-38.
35. Margaria R, Aghemo P, Rovelli E. Measurement of muscular power (anaerobic) in man. *J Appl Physiol*. 1966;21:1662-1664.
36. Wilkie DR. The relation between force and velocity in human muscle. *J Physiol*. 1950;110:249-280.
37. Wilkie DR. Man as a source of mechanical power. *Ergonomics* 1960;3:1-8.
38. Driss T, Vandewalle H. The measurement of maximal (anaerobic) power output on a cycle ergometer: a critical review. *Biomed Res Int*. 2013;2013:589361.
39. Perez-Gomez J, Rodriguez GV, Ara I, Olmedillas H, Chavarren J, Gonzalez-Henriquez JJ, Dorado C, Calbet JA. Role of muscle mass on sprint performance: gender differences? *Eur J Appl Physiol*. 2008;102:685-694.
40. Martin JC, Wagner BM, Coyle EF. Inertial-load method determines maximal cycling power in a single exercise bout. *Med Sci Sports Exerc*. 1997;29:1505-1512.
41. Vandewalle H, Peres G, Heller J, Panel J, Monod H. Force-velocity relationship and maximal power on a cycle ergometer. Correlation with the height of a vertical jump. *Eur J Appl Physiol Occup Physiol.* 1987;56:650-656.
42. Bar-Or O. The Wingate anaerobic test. An update on methodology, reliability and validity. *Sports Med*. 1987;4:381-394.
43. Jaafar H, Rouis M, Attiogbe E, Vandewalle H, Driss T. A comparative study between the Wingate and force-velocity anaerobic cycling tests: Effect of physical fitness. *Int J Sports Physiol Perform.* 2016;11:48-54.
44. Zupan MF, Arata AW, Dawson LH, Wile AL, Payn TL, Hannon ME. Wingate anaerobic test peak power and anaerobic capacity classifications for men and women intercollegiate athletes. *J Strength Cond Res.* 2009;23:2598-2604.
45. Vandewalle H, Peres G, Monod H. Standard anaerobic exercise tests. *Sports Med*. 1987;4:268-289.
46. Hofman N, Orie J, Hoozemans MJ, Foster C, de Koning JJ. Wingate test is a strong predictor of 1500m performance in elite speed skaters. *Int J Sports Physiol Perform*. 2017. [E-pub ahead of print]
47. Martin JC, Gardner AS, Barras M, Martin DT. Modeling sprint cycling using field-derived parameters and forward integration. *Med Sci Sports Exerc*. 2006;38:592-597.
48. Dorel S, Hautier CA, Rambaud O, Rouffet D, Van PE, Lacour JR, Bourdin M. Torque and power-velocity relationships in cycling: relevance to track sprint performance in world-class cyclists. *Int J Sports Med*. 2005;26:739-746.
49. Gardner AS, Martin DT, Barras M, Jenkins DG, Hahn AG. Power output demands of elite track sprint cycling. *Int J Perf Anal Sport*. 2005;5:149-154.
50. Gardner AS, Martin JC, Martin DT, Barras M, Jenkins DG. Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests. *Eur J Appl Physiol*. 2007;101:287-292.
51. Martin JC, Davidson CJ, Pardyjak ER. Understanding sprint-cycling performance: the integration of muscle power, resistance, and modeling. *Int J Sports Physiol Perform.* 2007;2:5-21.
52. Simenz CJ, Garceau LR, Lutsch BN, Suchomel TJ, Ebben WP. Electromyographical analysis of lower extremity muscle activation during variations of the loaded step-up exercise. *J Strength Cond Res*. 2012;26:3398-3405.
53. Morin JB, Edouard P, Samozino P. Technical ability of force application as a determinant factor of sprint performance. *Med Sci Sports Exerc*. 2011;43:1680-1688.
54. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol.* 2012;112:3921-3930.
55. Samozino P, Rabita G, Dorel S, Slawinski J, Peyrot N, Saez de Villarreal E, Morin JB. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Sports*. 2016;26:648-658.
56. Slawinski J, Termoz N, Rabita G, Guilhem G, Dorel S, Morin JB, Samozino P. How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scand J Med Sci Sports*. 2017;27:45-54.
57. Rabita G, Dorel S, Slawinski J, Sàez-de-Villarreal E, Couturier A, Samozino P, Morin JB. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Sports*. 2015;25:583-594.
58. Haugen T, Buchheit M. Sprint running performance monitoring: methodological and practical considerations. *Sports Med*. 2016;46:641-56.
59. McBride JM, Triplett-McBride T, Davie A, Newton RU. A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *J Strength Cond Res*. 1999;13:58-66.
60. Davies CT, Rennie R. Human power output. *Nature* 1968;217:770-771.
61. Carlock JM, Smith SL, Hartman MJ, Morris RT, Ciroslan DA, Pierce KC, Newton RU, Harman EA, Sands WA, Stone MH. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *J Strength Cond Res.* 2004;18:534-539.
62. Komi PV, Bosco C. Utilization of stored elastic energy in leg extensor muscles by men and women. *Med Sci Sports*. 1978;10:261-265.
63. McGilvery RW. The use of fuels for muscular work. In Metabolic adaptation to prolonged physical exercise, eds. Howald H & Poortmans JR, Birkhauser Verlag, Basel. 1975:12-30.
64. Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM. The effects of arms and countermovement on vertical jumping. *Med Sci Sports Exerc*. 1990;22:825-833.
65. Lees A, Vanrenterghem J, De CD. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech*. 2004;37:1929-1940.
66. Vaverka F, Jandacka D, Zahradnik D, Uchytil J, Farana R, Supej M, Vodicar J. Effect of an arm swing on countermovement vertical jump performance in elite volleyball players. *J Hum Kinet*. 2016;53:41-50.
67. Dapena J. The high jump. In Biomechanics in sport: Performance enhancement and injury prevention, ed. Zatsiorsky VM, Blackwell Science 2000:284-311.
68. Bobbert MF, Casius LJ. Is the effect of a countermovement on jump height due to active state development? *Med Sci Sports Exerc*. 2005;37:440-446.
69. Bobbert MF, Gerritsen KG, Litjens MC, Van Soest AJ. Why is countermovement jump height greater than squat jump height? *Med Sci Sports Exerc*. 1996;28:1402-1412.
70. Izquierdo-Gabarren M, Expósito RG, de Villarreal ES, Izquierdo M. Physiological factors to predict on traditional rowing performance. *Eur J Appl Physiol*. 2010;108: 83-89
71. Metikos B, Mikulic P, Sarabon N, Markovic G. Peak power output test on a rowing ergometer: A methodological study. *J Strength Cond Res*. 2015;29:2919-2925.
72. Stöggl TL, Holmberg HC. Double-poling biomechanics of elite cross-country skiers: Flat versus uphill terrain. *Med Sci Sports Exerc*. 2016;48:1580-1589.
73. Swarén M, Eriksson A. Power and pacing calculations based on real-time locating data from a cross country skiing sprint race. In: Objective analysis methods in the mechanics of Sports (Thesis) by Swarén M, Royal Institute of Technology, Stockholm, Sweden 2016.
74. Seiler S, De Konig JJ, Foster C. The fall and rise of the gender difference in elite anaerobic performance 1952–2006. *Med Sci Sports Exerc.* 2006;39:534-540.
75. Schmidt W, Prommer N. Impact of alterations in total hemoglobin mass on VO2max. *Exerc Sport Sci Rev*. 2010;38:68-75.

# **Figure legends**

**Figure 1.** The highest reported values of maximal oxygen uptake (O2max) in different endurance sports among men (A and C) and women (B and D). \*\*\* are previously unpublished data from our laboratory.

**Figure 2.** Relative anaerobic power output in male (Panel A) and female (Panel B) elite athletes across cycling settings. FV indicates that data are obtained from force-velocity tests. Inst. = instantaneous. Grey bars denote that the values are estimated.

**Figure 3.** The development of force (Panel A), velocity (Panel B) and power (Panel C) during a countermovement jump.  In this example, a male sprinter (65 kg) jumped 66 cm and achieved 5024 W and 77 W∙kg-1. Power > 95% of peak = 35 ms, while power > 99% of peak = 15 ms.

Figure 1.



Figure 2.



Figure 3.

