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# The relative power output and relative lean body mass of World and Olympic male and female champions with implications for gender equity

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**Abstract**
A uniform measure of the gender-related differential performance of female and male Olympic and World champions is proposed: relative power output applied to the environment. Laws of physics are employed to derive equations for estimating relative power output. In previous controlled laboratory studies, equally trained male and female athletes were shown to have a relative power output not significantly different from relative lean body mass. As to the estimated power output for 32 Olympic and World championship events contested between 1976 and 2004, eight in running, four in speed skating, three in jumping, twelve in swimming and five in rowing: 100% of the 32 event mean percentage differences in power output and 96% of the 411 event percentage differences in power output are within one standard deviation of the appropriate lean body mass percentage difference, consistent with equality of training. For 1952–1972, significantly higher percentage differences in power output are estimated in running and swimming compared with 1976–2004, consistent with women being less well trained than men during that earlier period. It is noted that efforts in recent years to provide equality of opportunity for female athletes coincide with equalization of estimated relative power output in competition with the relative lean body mass.

**Keywords:** *Lean body mass, power output, Olympics, World championships, gender equity, athletics, swimming*

## Introduction

Although women and men have competed in high-level athletic competition at least since the time of the ancient Olympic Games, the literature does not contain a procedure for uniformly evaluating gender-related differential performance across a spectrum of events together with compatible physiological explanations for those differences.

Men competed in the ancient Olympic Games from 776 B.C. until 393 A.D. (Miller, 2004). The length of the men's running track was 600 Greek feet (192 m), referred to as a *stadion*. Running events for men were contested over one stadion, two stadions (called the *diaulos*) and between 20 and 24 stadions (called the *dolichus*). Women could not compete in the Olympic Games since these were dedicated to a male god, Zeus; however, custom allowed unmarried women to attend. Unmarried women did compete at Olympia in the Heraea Games, dedicated to Hera, Zeus's mythological wife. Married women served as coaches, organizers and judges. For women's competition, the stadion was reduced by one-sixth to 500 Greek feet. It appears that women were deemed to be 17% slower than men over one length and to have less endurance than men since there were no races for women longer than one reduced stadion. Questions about the endurance of female athletes have persisted throughout the development of the modern Games. Female athletes in the modern Games have competed in running at 800 m or longer only since 1960 (after one 800-m run in 1928) and at the marathon only since 1984. The 800-m swim was not added until 1968 and rowing did not begin for women until 1976.

Gender differential performance is generally studied from two perspectives: observed athletic performance in competition and laboratory measurements taken in a controlled environment. The focus of this paper is on comparing the former with the latter via a common measure of performance. Previous studies of the former type use either world record performances or performances taken at some standard of competition where women and men compete at the same venue. World records for men and women are seldom set at the same time and

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therefore do not occur under the similar competitive conditions needed for meaningful gender-based comparisons. It is more consistent to use data drawn from the same competition; for example, using a World or Olympic winning performance. The differential performance for men and women competing in a timed event could be evaluated in terms of elapsed time difference. That difference varies widely, however. Without a uniform measure, one cannot determine how women compare at progressively longer distances for timed events so as to evaluate endurance effects. For example, some winning performances at the 2004 Athens Olympics were: men's 100-m run (9.85 s), women's 100-m run (10.93 s), men's marathon (2:10:55) and women's marathon (2:26:20). The time differences are 1.08 s and 925 s respectively, obviously scaled differently making a meaningful comparison difficult. Percentage difference in elapsed time is dimensionless, varies much less widely and is therefore more useful for comparing various timed events in a uniform manner. In this paper, percentage difference is found by taking the larger of two quantities as the base. For the 100-m run, the percentage difference is 100 (1 − 9.85/10.93) or 9.9%. For the marathon, the percentage difference is 100 (1 − 7855/8780) or 10.5%. The scale is comparable and there is less than a 1% difference moving from the 100-m run to the 42,195-m marathon, confirming the endurance of women versus distance for that sample. However, for an event such as the long jump measured by distance cleared, percentage difference, although dimensionless, is scaled differently from percentage difference in time. The winning man cleared 8.59 m at Athens compared with 7.07 m for the winning woman. The percentage difference is 100 (1 − 7.07/8.59) or 17.7%. Time difference and percentage difference do not provide a uniform measure.

Is there a more useful metric of differential performance, one that is scaled the same over a spectrum of events and one that, at the same time, permits comparison to values measured under laboratory conditions? Those are questions that this paper attempts to answer. To delimit the data and to select meaningful performances, attention is focused on World and Olympic winning performances, which represent the state-of-the art for the male and female champion at the time of each competition. Those performances occur at regular intervals and under similar competitive conditions. The rest of this paper is organized as follows. First, the laws of physics are used to derive the relative power output of each female Olympic and World champion, compared with her male counterpart for certain classes of events. Using those equations, the relative power output is estimated for gold medal performances as a uniform (similarly scaled) measure of differential performance. Then, the power developed by a female athlete is compared with that of her male counterpart based on previously-reported controlled laboratory studies that show that differences in power developed by equally trained female and male athletes diminish when corrected for lean body mass, suggesting that the relative power output of equally trained female and male athletes should be in proportion to lean body mass. Finally, it is noted that efforts in recent years to provide equality of opportunity for female athletes coincide with equalization of estimated relative power output in competition with the relative lean body mass.

## Relative power output estimated for winning performances

According to the laws of physics, power is defined (Lerner, 1996) as the rate of change of energy and, equivalently, as the product of force times the component of velocity in the direction to which force is applied. If $P$ represents power in watts, $E$ is energy in joules and $v_F$ is velocity in metres per second in the direction of the applied force in Newtons, then

$$P = Fv_F = dE/dt \tag{1}$$

Here $P$ is taken to be the mechanical output power applied by the athlete to the appropriate environment, so as to move the athlete's centre of gravity. Metabolic power, the rate of internal metabolic energy consumption, is about four times the mechanical output power applied to the environment, since the human body is a somewhat inefficient machine. Metabolic power is not calculated here. For the events to be considered, there are two different mechanisms for developing force. Ground reaction force, equal and opposite to the force of gravity, moves the athlete's centre of gravity in the events of athletics (running and jumping) and speed skating where the velocity in (1) is the vertical component. Hydrodynamic force, equal and opposite to drag force, moves the athlete's centre of gravity in swimming and rowing events where the velocity in (1) is taken to be in the forward direction of motion.

### *Ground reaction events*

While technique varies widely for running, speed skating, high jumping, long jumping and pole vaulting, the same physical laws govern the motion of the athlete's centre of gravity. Each of these events is mediated by the response of the athlete's centre of gravity to a ground reaction force working against gravity. As the athlete's foot pushes against the

ground, an equal and opposite ground reaction force pushes against the athlete's foot, moving the centre of gravity upwards.

*Running*

A runner achieves increased horizontal velocity by creating increased ground reaction force (Weyand, Sternlight, Bellizzi, & Wright, 2000) and not by faster leg movement. The sweep time for an athlete's non-contact leg is about the same for athletes at differing velocities. An increase in ground reaction force causes the leg to sweep farther forward during the same sweep time, generating a longer stride and greater velocity. Measurements of the power applied to a treadmill pressure plate at various velocities reveal a linear power–velocity relationship (Arampatzis, Knicker, Metzler, & Bruggermann, 2000). The mean mechanical power (that viewable by an outside observer looking at the centre of gravity) is given by the rate of change in potential energy $mgd$ as the centre of gravity rises $d$ units against gravity, divided by the time required to reach the peak of $d$ units. Here $m$ is the mass in kilograms, $g$ is the acceleration of gravity ($9.8\ \mathrm{m \cdot s^{-2}}$), $d$ is the vertical movement in metres and $v_{yo}$ is the initial upward velocity as the runner leaves the ground. Applying standard methods for a ballistic trajectory (Lerner, 1996) and ignoring air resistance, the vertical velocity while airborne is given by $v_{yo} - gt$. Zero vertical velocity occurs at the peak height, when $d$ units have been achieved against gravity; thus, the time-to-peak is $v_{yo}/g$. To find $d$, kinetic energy $mv_{yo}^2/2$ may be equated to potential energy $mgd$, resulting in $d$ equal to $v_{yo}^2/2g$. The mean power applied by the athlete is the mechanical power divided by efficiency $e$, where $0 < e \leq 1$. That is, some applied power does not result in useful mechanical power, as when running on a soft surface or using poor form. Accordingly, applied power exceeds useful mechanical power. The athlete's mean power is

$$P = mg\, v_{yo}/2e \tag{2}$$

Compared with (1), $mg$ is the ground reaction force pushing the athlete upward, $v_{yo}/2$ is the mean vertical velocity and $e$ accounts for inefficiency. It is more useful to express power in terms of the mean forward velocity $v$ (distance/race time), since the race time is available for the winning athlete. Assuming that the resultant velocity at the time of take-off makes an angle $\theta$ with the forward direction and assuming that $v$ is a constant, then $v_{yo}$ is $v \tan\theta$ and (2) becomes

$$P = mg\, v \tan\theta/2e \tag{3}$$

The linear $P$–$v$ relationship based on physics thus agrees with the experimental results outlined above. If an athlete with $m = 80$ kg wants to achieve $v = 10\ \mathrm{m \cdot s^{-1}}$ with $\tan\theta = 0.14$ and $e = 1$, then 549 W of power are required. If men and women have the same efficiency and take-off angle, then the ratio of applied power is

$$P_w/P_m = (m_w/m_m)(v_w/v_m) \tag{4}$$

The inverse of the mass ratio in (4) for men/women ($m_m/m_w$) was calculated using four data sets covering 36 years and a wide range of sports. The four values varied little. The ratios are 1.249 for 354 male and 181 female runners and jumpers who competed in the 1964 and 1968 Olympics (McArdle, Katch, & Katch, 1981), 1.254 for 516 male and 300 female swimmers who competed in the 1964 and 1968 Olympics from (McArdle *et al.*, 1981), 1.262 for Australian Olympic swimmers who competed from 1988 to 1994 (Pyne, Maw, & Goldsmith, 2000) and 1.261 for the 2000 USA Olympic rowing team whose body masses were posted on the usrowing.org website. The mean ratio of ($m_m/m_w$) for those four data sets is $1.26 \pm 0.11$. Since the standard deviation is small and the coverage of events so broad, $1.26 \pm 0.11$ is used henceforth for the various events to be analysed.

The percentage difference in power ($\%DP$) is

$$\%DP = 100(1 - P_w/P_m) \tag{5}$$

Table I contains mean $\%DP$ values found by applying (4) and (5) to the winning performances in eight running events contested during eight Olympic Games (1976–2004) and eight IAAF World Championships (1983–2001).

*Speed skating*

A detailed analysis of the biomechanics of speed skating (De Boer, Cari, Vaes, Clarijs, Hollander, De Groot & Van Ingen Schenau, 1987a, De Boer, Ettema, Van Gorkum, De Groot, & Van Ingen Schenau 1987b; De Koning, De Groot, & Van Ingen Schenau, 1989, 1991; Van Ingen Schenau, De Groot, & De Boer, 1985) reveals that the athlete begins a race with an acceleration sprint phase after which it is not possible to push directly backward due to the high forward velocity, typically more than $10\ \mathrm{m \cdot s^{-1}}$. The athlete then alternates between gliding and pushing off to maintain forward velocity. During the glide, the body is positioned to reduce drag. Following the glide, the athlete pushes off in a direction that is predominantly sideways (at an angle $\phi$ close to 90° from the forward direction) and at an additional upward push off angle $\theta$, causing the centre of gravity to move with a resultant velocity $v_r$ with vertical movement $d$.

The joint rotations, translations, forces and torques are similar to those employed in a vertical jump. The clap skate allows the use of strong

Table I. Percent difference in power by event, 1976–2004.

| Ground reaction events | | Hydrodynamic events | |
|---|---|---|---|
| Type of event | Percent difference in power | Type of event | Percent difference in power |
| Running events | | Swimming events | |
| 100 m | 27.5 ± 0.9% | 50 m | 31.5 ± 2.8% |
| 200 m | 28.0 ± 1.1% | 100 m | 29.8 ± 2.1% |
| 400 m | 28.9 ± 1.3% | 200 m | 27.4 ± 3.9% |
| 800 m | 29.0 ± 1.1% | 400 m | 25.1 ± 3.9% |
| 1500 m | 29.0 ± 1.7% | 100 m backstroke | 29.0 ± 2.8% |
| 5000 m | 29.5 ± 1.6% | 200 m backstroke | 25.6 ± 3.3% |
| 10,000 m | 29.5 ± 1.1% | 100 m breaststroke | 29.3 ± 2.4% |
| Marathon | 28.7 ± 0.8% | 200 m breaststroke | 29.0 ± 3.0% |
| | | 100 m butterfly | 29.2 ± 2.4% |
| Speed-skating events | | 200 m butterfly | 26.9 ± 2.2% |
| 500 m | 26.9 ± 0.9% | 200 m individual medley | 27.3 ± 3.5% |
| 1000 m | 27.4 ± 1.2% | 400 m individual medley | 24.5 ± 3.6% |
| 1500 m | 27.6 ± 1.8% | | |
| 5000 m | 27.1 ± 1.4% | Rowing events | |
| | | Single skulls | 34.2 ± 4.2% |
| Jumping events | | Double sculls | 30.8 ± 2.3% |
| High jump | 28.5 ± 0.9% | Quad sculls | 28.8 ± 2.9% |
| Pole vault | 30.8 ± 1.4% | Pairs w/o | 33.5 ± 2.7% |
| Long jump | 28.9 ± 0.8% | Eights | 30.9 ± 2.3% |
| All ground reaction events | 28.5 ± 1.2% | All hydrodynamic events | 29.0 ± 3.0% |

Running and jumping (8 Olympics 1976–2004, 8 IAAF World Championships 1983–2001).
Speed skating (8 Olympics 1976–2002, 8 ISU World Championships 1977–2003).
Swimming (8 Olympics 1976–2004, 9 FINA World Championships 1975–2003).
Rowing (3 Olympics 1988–1996).

extensor muscles generating more power than with the former rigid skate, where certain muscle movements had to be suppressed. To keep the forward velocity constant after each stroke, the small forward velocity component during the push-off, $v_r \cos\theta \cos\phi$, is equal and opposite to the reduction in speed due to friction and aerodynamic drag. The analysis of Van Ingen Schenau *et al.* (1985) indicates that an elite speed skater achieves increased velocity with the same amount of energy per stroke but with increased stroke frequency, the inverse of elapsed time per stroke. It follows that the product of energy per stroke and frequency per stroke is $dE/dt$, which by (1) equals power output. Power output is proportional to velocity as per Van Ingen Schenau *et al.* (1985), as in running, so that the analysis leading up to (2) is now valid. Here $v_{yo}$ is given by $v_r \sin\theta$, which replaces $v \tan\theta$ in (3). Given that $P$ is proportional to $v$, it follows that $v_r$ is proportional to $v$ for fixed $\theta$. Letting $v_r = kv$ for $0 < k < 1$, the output power becomes

$$P = mg\ kv \sin\theta / 2e \tag{6}$$

A push-off angle of about 50° is suggested in the references above. If $e = 1$, a forward velocity of $10\ \mathrm{m \cdot s^{-1}}$ can be maintained by an 80-kg speed skater with $\theta = 50°$ and $kv = 1.6\ \mathrm{m \cdot s^{-1}}$, requiring an applied power of 480 W. Assuming that men and women are equally efficient, that each use the same angle and that each use the same $k$, then (4) may be used for the power ratio in speed skating.

Table I contains mean $\%DP$ values found by applying (4) and (5) to the winning performances in four speed-skating events contested during eight Olympic Games (1976–2002) and eight ISU World Championships (1977–2003). The $\%DP$ values are consistent at the various distances because velocity is nearly the same at all distances due to the low friction environment.

### *Jumping*

High jump and pole vault performance is measured by the vertical height cleared. It is now necessary to derive power in terms of height cleared and not velocity to use winning performance results. A successful athlete must realize that there is a relationship between velocity and the height cleared. An athlete cannot achieve a given take-off velocity at any take-off angle as with a cannon or rifle. Analyses of the high jump by Jacoby and Fraley (1995) and Linthorne (1999) provide advice that if an athlete reduces horizontal velocity somewhat for a given take-off angle, then the athlete can achieve a higher vertical velocity component, $v_{yo}$, which results in a higher height being cleared. Thus, horizontal velocity, take-off angle and

take-off velocity must be tuned. Tuning those factors is a complicated task. The above authors suggest that the take-off angle should be about 50°. It is interesting that the Fosbury Flop technique, which improved high jump performance, and the clap skate, which improved speed-skating performance, both employ about the same take-off angle and both innovate by allowing greater use of extensor biomechanics.

In the pole vault (McGinnis 1991, 1997), the flexibility of the pole limits the velocity that can be directed vertically when the pole is flexed so as to rebound. A pole vault athlete attempts to convert as much as possible of $v$ into $v_{yo}$, by timing the placement of the pole, hand locations and body positioning. A fibre glass pole allows conversion of a greater $v$ (and higher resulting $d$) than the stiffer steel and bamboo poles of the past. From the above, it follows for either event that $v_{yo} = (2gd)^{1/2}$. Thus, (2) becomes

$$P = mg^{3/2}d^{1/2}/2^{1/2}e \tag{7}$$

By definition, $d$ is measured from the centre of gravity upward to the height cleared, while the height cleared is measured from the ground. Thus, $d$ is the height cleared minus the starting height of the centre of gravity above the ground. In two classical studies, Croskey, Dawson, Leussen, Marohn, & Wright (1922) and Hellebrandt and Franssen (1943) reported that the centre of gravity of a typical man is located at 56% of height and the centre of gravity of a typical woman is located at 55% of height. Using those values and height data in McArdle *et al.* (1981), a male jumper has a centre of gravity that is 1 m above the ground when upright and women one of 0.93 m above the ground when upright. In the pole vault, the athlete plants the pole while in a fairly upright stance; hence $d$ would be the height cleared −1 m for men and the height cleared −0.93 m for women. Video analyses of some world-class high jumpers suggest that an elite high jumper should dip somewhat at take-off (Jacoby & Fraley, 1955; Linthorne, 1999) so that the centre of gravity is above ground by 46% of the athlete's height. It follows that $d$ would be the height cleared −0.84 m for men and the height cleared −0.78 m for women. Although the centre of gravity passes under the high jump bar and pole vault bar (Jacoby & Fraley, 1955; Linthorne, 1999; McGinnis, 1991, 1997), that small correction is ignored here. If an 80-kg male athlete clears 2.1 m in the high jump with $e = 1$, the required power is 1948 W. For a similar 6-m clearance in the pole vault, $P = 3880$ W. In terms of initial upward velocity, the analysis predicts that a male pole vault athlete should clear $(v_{yo}^2/2g) + 1$ m. If a forward velocity of 10 $m \cdot s^{-1}$ is directed upward, the height cleared would be 6.1 m, agreeing with current world-class performance and approach speed.

If men and women are equally efficient, the power ratio of the high jump and pole vault is

$$P_w/P_m = (m_w/m_m)(d_w/d_m)^{1/2} \tag{8}$$

The long jump take-off angle (Linthorne, 1999; Wakai & Linthorne, 2000) is about 20° to provide good distance achieved for a given $v$, given biomechanical demands. As to physics, let $L$ represent the horizontal distance travelled in twice the time for $d$ to be achieved – that is, for the centre of gravity to return to the same height as on take-off. If $v$ is constant, then the product of the time-to-peak and the forward velocity gives $L$, resulting in $2(v_{yo}/g)v$. One can relate $v$ to $v_{yo}$ and then relate $v_{yo}$ to $L$, where (2) becomes

$$P = mg^{3/2}\tan\theta^{1/2}L^{1/2}/2^{3/2}e \tag{9}$$

It is desirable to relate $L$ in (9) to the long jump distance, measured from the take-off point to the ground at the landing point. After travelling $L$ units horizontally, the athlete's centre of gravity is the same distance above the ground as at the starting point; hence, some additional horizontal distance is to be travelled until the athlete touches the ground. An analysis was made of several typical $v$ values, each with a take-off angle of 20° and typical centre of gravity heights above the ground for men and women. The results suggest that for a man $L$ is approximately the long jump distance −2.1 m, and for a women $L$ is approximately the long jump distance −1.9 m.

For an 80-kg man with $e = 1$ to achieve a long jump of 8.6 m, the required power would be 1334 W. If men and women are equally efficient and take off at the same angle, then (8) may be used for the long jump, by replacing $d$ with $L$.

Table I contains mean %*DP* values found by applying (5) and (8) to the winning performances in the high jump, pole vault and long jump contested during eight Olympic Games (1976–2004) and eight IAAF World Championships (1983–2001). The %*DP* values are consistent for the high jump and long jump. The mean for the pole vault is the highest of all ground reaction events. The women's pole vault is a relatively new event, having been contested in only two Olympic Games and two World Championships. By 2004, %*DP* for the pole vault had dropped to 28.83%, a value close to that of the other jumping events.

## Hydrodynamic events

Work is done against gravity in the ground reaction events described above. In swimming and rowing, the downward gravitational force (weight) $mg$ is

balanced by the upward buoyancy force, where the weight of the volume of water displaced equals the weight of the swimmer or boat. Vertical forces are in balance and need not be considered further. In water, an athlete generates a forward hydrodynamic thrust force that is the equal but opposite to the drag force imposed on the athlete by the water. According to the laws of hydrodynamics (Lerner, 1996), power may be calculated in terms of the hydrodynamic drag force $F$, mean forward velocity $v$ and efficiency $e$:

$$P = Fv/e = (\rho v^2 S C_d/2)v/e \qquad (10)$$

where $\rho$ is the density of water (1000 kg · m$^{-3}$), $S$ is the surface area (m$^2$) in contact with the water, $C_d$ is the dimensionless drag coefficient that accounts for the effect of the shape of the swimmer or boat upon drag force, $v$ is the forward velocity and $e$ is efficiency. Note that power depends on the third power of velocity. The hydrodynamics of swimming have been studied extensively (Toussaint & Beck, 1992; Toussaint *et al.*, 1988; Toussaint, Janssen, & Kluft, 1991; Toussaint, Knops, De Groot, & Hollander, 1990; Jang, Flynn, Costill, Kirwin, Houmard, Mitchell, & D'Acquisto, 1987). A swimmer can be tethered in a moving flume of water of known velocity. The applied force upon the tether can be measured and $C_d$ can be found by dividing the measured force by $(\rho v^2 S/2)$. For boats, a computer simulation can be used (Tuck & Lazauskas, 1996) to estimate the drag coefficient. One convenient approach is to obtain the *volumetric* drag coefficient at a given velocity, which does not require measuring the surface area in contact with water. By assuming a slender cylinder for the shape of the swimmer or boat, $S$ is taken to be the 2/3 power of the volume of displaced water: $(m/\rho)^{2/3}$. Some effort might result in adding kinetic energy to water but not in providing useful thrust. This lost power can be treated as a value of $e$ less than 1. The power ratio for a hydrodynamic event using the volumetric drag coefficient is

$$P_w/P_m = (v_w/v_m)^3 (m_w/m_m)^{2/3} (C_{dw}/C_{dm})(e_w/e_m)^{-1} \qquad (11)$$

*Swimming*

For swimming (Toussaint *et al.*, 1988), the drag coefficient ratio $(C_{dw}/C_{dm})$ is about 0.9 at Olympic winning velocities. Elite female and male swimmers apply 450–1100 W of power to the surrounding water, but efficiency is low (Toussaint & Beck, 1992; Toussaint *et al.*, 1990). Less than 10% of the applied power moves the swimmer forward. Efficiency depends on the swimmer's size, in much the same way that a large propeller is more efficient than a small one (Toussaint *et al.*, 1990). A reasonable model for a swimmer's efficiency is $(e_w/e_m) = (m_w/m_m)$, so that (11) becomes

$$P_w/P_m = (v_w/v_m)^3 (C_{dw}/C_{dm})(m_w/m_m)^{-1/3} \qquad (12)$$

Table I contains mean %*DP* values found by applying (5) and (12) to the winning performances in 12 swimming events contested during eight Olympic Games (1976–2004) and nine FIFA World Championships (1975–2003). The %*DP* value drops as distance increases for each stroke. This is probably an artifact of using one drag coefficient ratio at all distances. As distance increases, velocity drops. The studies referenced above indicate that women have a relatively lower drag coefficient ratio than men at lower velocities. If the drag coefficient ratio is reduced versus distance, the women's applied power would drop and the %*DP* value would become larger, equalizing %*DP* as distance increases for each stroke.

*Rowing*

Stefani and Stefani (2000) estimate the power applied per rower for all Olympic winning performances contested from 1908 through 1996. Power is estimated directly from (10), using drag coefficient values from Tuck and Lazauskas (1996), athlete body masses estimated from team rosters and boat weights provided by manufacturers. The masses in (10) include the athletes, boat and oars.

Applied power per rower increases slowly between 1908 and 1976, increases significantly from 1976 to 1980 and then increases slowly from 1980 to 1996. The rowing machine or ergometer was introduced just before 1976, significantly increasing off-water muscle-specific training time. The ergometer joins the clap skate, Fosbury Flop and fibre glass pole, all mentioned above, as significant sports innovations.

Women began to compete over the same 2000-m course as the men in 1988; hence, Olympic winning performances in 1988, 1992 and 1996 can be compared. From 1988 to 1996, power per winning rower in Olympic competition varied from 200 to 400 W, generally agreeing with ergometer values measured directly for elite athletes.

Table I contains mean %*DP* values, found by applying (5) to the power output of winning performances in five rowing events contested during those three Olympics.

## Relative power output from laboratory studies (importance of lean body mass)

Several studies have documented and analysed measurements of the power generated by male

and female athletes under laboratory conditions. Typically, two types of power measurements can be taken: aerobic measurements of maximal oxygen consumption ($\dot{V}O_{2max}$) and anaerobic measurements using a force–velocity measuring device such as an ergometer to record power output. Maud and Schultz (1986) tested the anaerobic power of 52 male and 50 female physically active college students using a cycle ergometer. They found "no significant differences in men and women in either anaerobic power or anaerobic capacity when values were given relative to fat free body mass". Lutoslawska, Klusiewics, Sitkowsi and Krawczyk (1996) assessed ten male and nine female rowers using a rowing ergometer to measure power for a simulated all-out 2000-m rowing race. They concluded that "Mean power output was significantly lower in female than male rowers, but that difference disappeared when power output was related to lean body mass (LBM)" and that "training status rather than gender determines the substrate selection during muscular work". Iwaoki, Hatta, Atomi and Miyashita (1988) assessed ten male and eight female trained college distance runners using a treadmill. The 18 runners were matched as closely as possible in terms of power output per kilogram of lean body mass. Iwaoki *et al.* reported that "These results suggest that there are no remarkable gender differences in lactate threshold and respiratory compensation threshold when compared in relative terms". Varol, Agkun and Turkoglu (1991) measured $\dot{V}O_{2max}$ in five trained sprint runners, five trained middle-distance runners, five trained long-distance runners and 11 students not participating in sport. The authors compared $\dot{V}O_{2max}$ per kilogram of body mass and concluded that "No significant differences were found among athletes regarding this parameter, but the mean values for athletes were statistically different from that of the non-athletes".

These four studies arrive at two conclusions. First, training can increase power output per kilogram of lean body mass. Second, equally trained athletes of both genders have no significant difference in power output per kilogram of lean body mass. These studies suggest that power output ($P$) follows an allometric scaling in terms of lean body mass ($LBM$) raised to exponent one. That is, $P$ is given by $C \cdot LBM$, where $C$ varies with training but not with gender. In principle, $C$ could be parameterized in terms of lactate threshold, fast-twitch and slow-twitch muscle assay, and so on, where the relative importance of the independent variables could differ for men and women but the aggregated value of $C$ is not significantly different for equally trained men and women.

A corollary of these two conclusions is that the relative power output of equally trained Olympic and World champion men and women would not be significantly different from the relative lean body mass ratio. The mass ratio $m_w/m_m$ was estimated earlier in this paper to be $1.26 \pm 0.11$ based on four sets of data taken from 1964 to 2000. To complete an estimate of the ratio $LBM_w/LBM_m$, one needs the lean fraction of body mass $l$ given by $l = LBM/m$. Lean body mass is the product of total body mass $m$ times the lean fraction $l$. An athlete with a lean body mass of 80 kg and a total body mass of 100 kg has a lean ratio $l$ of 80/100 or 0.8 (20% body fat). Note that $l$ is one minus the fraction of body mass that is fat. Thus,

$$LBM_w/LBM_m = (m_w/m_m)(l_w/l_m) \qquad (13)$$

Using (13), the percentage difference in lean body mass is

$$\%DLBM = 100(1 - LBM_w/LBM_m) \qquad (14)$$

Here (5) and (14) would not be significantly different if male and female athletes were equally trained.

Fleck (1983) analysed the body fat composition of 826 American Olympians (528 men and 298 women) using hydrostatic weighing and anthropometric methods. The sample size is large and includes some of the world's most elite athletes; hence, the values can be considered representative of those elite athletes who become Olympic and World champions. Fleck notes similar body fat compositions for athletes in events performed against gravity, such as running and jumping, and similar body fat compositions for athletes in events where the athlete is supported, as in swimming and canoe/kayak. Therefore, Fleck's (1983) data for runners is used here for running, jumping and speed-skating events (ground reaction events), while the mean of his swimming and canoe/kayak athletes is used for swimming and rowing events (hydrodynamic events). Female and male Olympic runners have $13.7 \pm 3.6\%$ and $6.5 \pm 1.2\%$ body fat respectively. The mean value of (13) becomes (1/1.26) (0.863/0.935) or 0.732. Including the standard deviations for body fat, typical elite female and male ground reaction event participants can be expected to have a percentage difference using (14) of $26.8 \pm 5.3\%$ for lean body mass. Values of fat percentage for females and males in canoe/kayak are $22.2 \pm 4.6\%$ and $13.0 \pm 2.5\%$ and in swimming are $19.5 \pm 2.8\%$ and $12.4 \pm 3.7\%$ respectively. The mean for the two sets is $20.9 \pm 3.7\%$ and $12.7 \pm 3.1\%$ respectively. Including standard deviations, typical elite female and male participants in a hydrodynamic event can be expected to have a percentage difference using (14) of $28.1 \pm 6.2\%$ for lean body mass.

*Comparison of percent difference in power output with percent difference in lean body mass*

An estimated *%DP* for a ground reaction event in the range 21.5 to 32.1% is within ± one standard deviation of the *%DLBM*, and an estimated *%DP* for a hydrodynamic event in the range 21.9 to 34.3% is within ± one standard deviation of the *%DLBM* value. Table II provides a comparison of event means and event values for *%DP* with *%DLBM*.

For running events, all eight event means and all of the 112 event values are within one standard deviation of the *%DLBM* value. For speed-skating events, all four event means and all 51 event values are within one standard deviation of the *%DLBM* value. Note that if (4) is equal to (13), then the velocity ratio is equal to the lean ratio ($l_w/l_m$). Each 1% of body fat reduces the lean fraction by 1% and thus reduces velocity by 1%.

For jumping events, all three event means and 97% of the 37 event values are within one standard deviation of the *%DLBM* value. Note that if (8) is equal to (13), the ratio ($d_w/d_m$) is equal to $(l_w/l_m)^2$. Each 1% of body fat degrades height or distance by 2%, so that body fat is twice as important in a jumping event as in a running event. The mean *%DP* for all ground reaction events is 28.5 ± 1.2% compared with a *%DLBM* of 26.8 ± 5.3%. The difference between the means is 0.32% *DLBM* standard deviation.

For swimming events, all 12 event means and 93% of the 196 event values are within one standard deviation of the *%DLBM* value. If (12) is equal to (13) for swimming, given also that the drag coefficient ratio is about equal to the lean ratio, then the velocity ratio is equal to $(m_w/m_m)^{4/9}$. For women/men, $(1/1.26)^{4/9}$ suggests a velocity ratio of 9.8%, consistent with the average velocity difference for the 12 events of 9.5 ± 0.9%.

For rowing events, all five event means and 80% of the 15 event values are within one standard deviation of the *%DLBM* value. If rowers of the same gender compete in boats of similar design, letting (12) equal (13) results in the velocity ratio for those two boats, ($v_2/v_1$), being equal to $(m_2/m_1)^{1/9}$, the mass ratio of rowers, boat and oars. When the mass doubles for rowers of the same gender, velocity should increase by a factor of $2^{1/9}$ or 1.08. For example, in the 1996 Olympics, the winning women's quad sculls velocity/double sculls velocity was 5.16/4.80 = 1.08, while for women's double sculls velocity/single sculls velocity the ratio was 4.80/4.42 = 1.09, both agreeing with theory. Note also that *%DP* is higher for decreased numbers of rowers for sculls events (two oars per rower) and for the pairs without coxswain and eights events (one oar per rower). It is likely that women are at an increased anaerobic strength disadvantage relative to men where there are fewer rowers per boat, in that stronger rowers usually are seated in the smaller boats. The *%DP* mean for all 17 hydrodynamic events is 29.0 ± 3.0% compared with the *%DLBM* of 28.1 ± 6.2%. The difference between the means is 0.14% *DLBM* standard deviation.

In Table II, no significant difference (less than ± one standard deviation) is observed between percentage difference in power output and percentage difference in lean body mass, consistent with equality of training for the two genders. Has the percentage difference in power output been higher in the past, which would be consistent with inequity of training opportunity for women?

Table II. Event means and event values within one standard deviation of the lean body mass value.

| Type of event | Event means | Within one standard deviation | Event values | Within one standard deviation |
|---|---|---|---|---|
| Running | 8 | 8 (100%) | 112 | 112 (100%) |
| Speed skating | 4 | 4 (100%) | 51 | 51 (100%) |
| Jumping | 3 | 3 (100%) | 37 | 36 (97%) |
| Swimming | 12 | 12 (100%) | 196 | 182 (93%) |
| Rowing | 5 | 5 (100%) | 15 | 12 (80%) |
| All | 32 | 32 (100%) | 411 | 393 (96%) |

*Percentage difference of power output in the past*

Table III shows mean *%DP* per Olympic year for the gold medal performances in running and swimming through 1972, from the first women's running event in 1928 and from the first women's swimming event in 1912.

Table III. Percent difference in power for swimming (1912–1972) and running (1928–1972).

| | Running | | Swimming | |
|---|---|---|---|---|
| Olympics | Events | Percent difference in power | Events | Percent difference in power |
| 1912 | | | 1 | 55.4 |
| 1920 | | | 1 | 46.3 |
| 1924 | | | 4 | 42.1 ± 5.9 |
| 1928 | 1 | 29.7 | 4 | 39.4 ± 6.1 |
| 1932 | 1 | 31.3 | 4 | 34.8 ± 2.3 |
| 1936 | 1 | 28.9 | 4 | 37.0 ± 4.3 |
| 1948 | 2 | 31.3 ± 0.1 | 4 | 32.6 ± 3.4 |
| 1952 | 2 | 29.4 ± 1.7 | 4 | 34.5 ± 3.9 |
| 1956 | 2 | 28.8 ± 1.8 | 4 | 32.1 ± 5.3 |
| 1960 | 3 | 30.2 ± 3.3 | 4 | 28.3 ± 4.3 |
| 1964 | 4 | 30.7 ± 0.6 | 4 | 31.1 ± 0.9 |
| 1968 | 4 | 31.0 ± 1.7 | 5 | 29.6 ± 4.5 |
| 1972 | 5 | 29.0 ± 1.2 | 11 | 32.2 ± 4.9 |

The numbers of women's events are significantly less in Table III than today. All 10 %*DP* running values and 12 of 13 %*DP* swimming values are above the comparable means from Table I. For the period beginning with the second Games after the Second World War – that is, 1952–1972 – wherein the mass ratio which changed little from 1964–2000 should be applicable, the mean %*DP* per Olympiad in running events is 29.9%, 1.4% higher than the ground reaction %*DP* mean in Table I. The mean %*DP* in swimming events per Olympiad for 1952–1972 is 31.3%, 2.3% higher than the %*DP* hydrodynamic mean in Table I. Significantly higher %*DP* than %*DLBM* is consistent with women being less well trained than their male counterparts over that period.

Stefani (1977), Whipp and Ward (1992) and many others noted the higher rate of improvement of women compared with men in running and swimming from the 1950s to the 1970s. That higher rate of improvement is consistent with a "catch up" of %*DP* from above %*DLBM* to near %*DLBM*.

## Efforts at improving gender equity

Several Olympic events in existing sports and a number of new sports have been added for female Olympians (Hawkes & Vickers, 1989). Wallechinsky (2004) gives the following percentages of Olympians who were women: 1900 (1.9%), 1920 (2.9%), 1960 (11.4%), 1980 (21.5%) and 2000 (38.5%). Clearly those percentages are moving towards equal representation.

In the United States, legislation referred to as Title IX was passed in 1972, empowering the US Department of Education to ensure equality of opportunity for men and women in education and in athletic participation provided by those educational institutions. A Commission met in 2003 to review 30 years of gender equity progress under Title IX and to recommend changes (Leland & Cooper, 2003). The Proportional Athletic Opportunity provision requires that the fraction of female participants in sport be within 5% of the fraction of females in the general school population. The Commission noted that from 1981 to 1999, the number of women's college teams increased by 66% and the number of female high school athletes increased by 847%, as institutions increased female participation from what had been a position of significant under-representation. Title IX also requires balancing relative expenditures for women and men for both equipment and staffing. That is, Title IX is intended to equalize quantitative and qualitative opportunities for women.

One Commission recommendation would allow the counting of unfilled slots for female athletes towards the Proportional Athletic Opportunity requirement, while another would allow the use of a questionnaire to determine the fraction of women interested in sport to replace the fraction of women in the general school population. Two Commission members, both former Olympic gold medallists, issued a minority report, suggesting that weakening the tests of compliance might allow educational institutions to reduce opportunities for female athletes (De Varona & Foudy, 2003).

Although the number of Olympic events is now reasonably balanced, media coverage is not necessarily balanced (Higgs, Weiller, & Martin, 2003 and Lopiano, 2000). Balancing quantitative opportunity does not necessarily confer equality of social acceptance. The European Commission of the European Union is seeking a more comprehensive version of gender equity referred to as gender mainstreaming (Rees, 2003).

Although it is true that simply increasing the number of female competitors does not necessarily improve performance, a quantitative increase might also induce quantitative improvement in coaching and equipment. Some Olympic attendance and improvement data are illustrative. Wallechinsky (2004) provides a table showing that the largest relative increase of competitors occurred from 1896 (245 male competitors) to 1900 (1097 male competitors). Data in Stefani (1998) show that the largest improvement in athletics performances in modern Olympic history also occurred from 1896 to 1900, when all competitors were male, a 10.9% improvement in timed and measured events. Wallechinsky (2004) shows a 15% increase of total competitors from the first Games after the First World War in 1920 to the second in 1924, and a 20% increase from the first Games after the Second World War in 1948 to the second in 1952. Stefani (1998) shows higher rates of improvements for men and women in athletics and swimming in 1924 and 1952 compared with 1920 and 1948 respectively. It is thus noteworthy that efforts in recent years to provide equality of opportunity for female athletes coincide with equalization of estimated relative power output in competition with the relative lean body mass, consistent with equality of training.

## Conclusions

Relative percentage difference in power applied to the environment by a female compared with her male counterpart Olympic and World champion can serve as a uniform measure of relative gender-based performance. The laws of physics may be used to estimate that relative power output, based on the winning performances of Olympic and World champions competing in athletics (running and jumping), speed skating, swimming and rowing from 1976 to 2004. One hundred percent of the 32 event mean

percent differences and 96% of the 411 event percent differences are within one standard deviation of the appropriate lean body mass difference, consistent with equality of training.

From 1952 to 1972, percent differences in power output are significantly higher in running and swimming than for the period 1976 to 2004, consistent with women being less well trained than men during that earlier period. It was noted that efforts in recent years to provide equality of opportunity for female athletes coincided with equalization of estimated relative power output in competition with the relative lean body mass.

It is also interesting to note that women have achieved a symbolic form of recognition since the time of the ancient Olympic Games mentioned at the beginning of this paper. The Olympic Flame is lit in Olympia at Hera's shrine. Thus, a female of mythology now serves as the inspiration for today's Games, in which both genders may compete.

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