

Modeling Maximum Oxygen Uptake of Elite Endurance Athletes

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ABSTRACT

NEVILL, A. M., D. BROWN, R. GODFREY, P. J. JOHNSON, L. ROMER, A. D. STEWART, and E. M. WINTER. Modeling Maximum Oxygen Uptake of Elite Endurance Athletes. *Med. Sci. Sports Exerc.*, Vol. 35, No. 3, pp. 488–494, 2003. **Purpose:** To compare the maximum oxygen uptake ($\dot{V}O_{2max}$) of elite endurance athletes and to explain why the body mass exponent, necessary to render $\dot{V}O_{2max}$ independent of body mass, appears to be greater than 0.67. **Methods:** Study 1: $\dot{V}O_{2max}$ of 174 international sportsmen and women was assessed. Athletes were recruited from seven sports (middle- and long-distance runners, heavyweight and lightweight rowers, triathletes, and squash and badminton players). Study 2: calf and thigh leg muscle masses were estimated in 106 male and 30 female athletes from 11 sports. Differences in $\dot{V}O_{2max}$ and leg muscle masses between “sports” and “sex” were analyzed independent of body mass by using allometric log-linear ANCOVA. **Results:** Heavyweight rowers had the greatest $\dot{V}O_{2max}$ when expressed in $L \cdot min^{-1}$ but long-distance runners had the highest $\dot{V}O_{2max}$ in $mL \cdot kg^{-1} \cdot min^{-1}$. However, the ANCOVA identified no difference in “mass independent” $\dot{V}O_{2max}$ between the five “pure” endurance sports (runners, rowers, and triathletes) ($P > 0.05$) with the two racket sports being significantly lower. The body mass covariate exponent was inflated, estimated as 0.94. The results from study 2 estimated calf and thigh leg muscle masses to increase in proportion to body mass, $m^{1.11}$ and $m^{1.38}$, respectively. **Conclusions:** After having controlled for differences in body mass, $\dot{V}O_{2max}$ did not differ between pure endurance sports ($P > 0.05$). Assuming that athletes’ thigh muscle mass increases in proportion to body mass $m^{1.38}$ as observed in study 2, a similar disproportional increase in $\dot{V}O_{2max}$ would be anticipated, providing a plausible explanation for the inflated mass exponent associated with $\dot{V}O_{2max}$ identified in this and other studies. **Key Words:** ALLOMETRIC MODELING, ANCOVA, CALF MUSCLE GIRTH, THIGH MUSCLE GIRTH

Since the early 19th century, the maximum rate at which an athlete can take up, transport, and use oxygen ($\dot{V}O_{2max}$) has been a focus of interest (3,7). In spite of reservations about the sensitivity of $\dot{V}O_{2max}$ to reflect training-induced improvements in endurance performance, it is still used to characterize cardiopulmonary function of athletes, and there are extensive guidelines on recommended protocols to produce this measure (4,26,29).

Attempts have been made to compare the $\dot{V}O_{2max}$ of elite athletes from a variety of sports to establish which mode of exercise elicits the greatest ability to take up, transport, and use oxygen (3,10). However, such comparisons have always been confounded by the known association between maximum oxygen uptake and body size.

It is well known that larger subjects have greater maximum oxygen uptake when $\dot{V}O_{2max}$ is expressed in the absolute units, liters ($L \cdot min^{-1}$). However, the most commonly reported measure of maximum oxygen uptake is a ratio standard in which mass-related $\dot{V}O_{2max}$ is expressed in the units ($mL \cdot kg^{-1} \cdot min^{-1}$). It is known that such ratio standards can mislead (16,24) and “over-scale” by converting the positive correlation between maximum oxygen uptake and body mass into a negative one (15). Thus, by comparing the maximum oxygen uptake of athletes expressed in either $L \cdot min^{-1}$ or $mL \cdot kg^{-1} \cdot min^{-1}$, heavier athletes are being either advantaged or penalized, depending on units in which $\dot{V}O_{2max}$ is expressed, compared with their lighter counterparts. Clearly, a fairer comparison of maximum oxygen uptake needs to remove the effect of body mass before valid inference can be made as to which sport and/or mode of exercise requires its athletes to have the greatest maximum oxygen uptake.

There is a long history of demonstrations to show that physiological and performance variables are not linearly related to dimensions of the body (17,18,20,25); relationships tend to be nonlinear (13) and are said to be allometric (19). Allometric modeling expresses a physiological or performance variable y as a function of an anthropometric variable x by the equation $y = ax^b$ where a is the common multiplier and b the exponent. The constants a and b can be

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TABLE 1. Physical characteristics (mean \pm SD) of the men and women participants from study 1 by the various sports.

	<i>N</i>	Age (yr)	\pm SD	Body Mass (kg)	\pm SD	Stature (m)	\pm SD	%Fat	\pm SD
Men									
Badminton players	17	22.7	3.9	77.5	6.4	1.79	0.05	12.8	1.8
Heavyweight rowers	28	24.4	3.2	93.3	6.0	1.93	0.04	11.4	2.4
Lightweight rowers	12	28.5	4.4	73.9	1.3	1.82	0.03	10.8	3.1
Long-distance runners	10	26.6	5.4	62.2	5.4	1.74	0.03	8.5	2.2
Middle-distance runners	18	21.2	2.0	67.1	4.7	1.80	0.06	9.4	1.1
Squash players	7	24.0	1.8	73.9	7.4	1.81	0.06	9.7	1.9
Triathletes	6	21.8	4.9	69.4	8.8	1.78	0.07	9.0	3.0
Totals/means	98	24.2		73.9		1.81		10.5	
Women									
Badminton players	12	22.6	4.0	62.0	6.6	1.64	0.07	24.2	4.0
Heavyweight rowers	16	26.0	5.0	75.9	7.2	1.79	0.05	23.5	3.8
Lightweight rowers	13	26.8	4.4	60.3	3.1	1.68	0.05	19.9	2.8
Long-distance runners	10	24.9	6.7	49.6	5.2	1.62	0.06	16.8	2.2
Middle-distance runners	11	24.3	5.3	55.6	5.0	1.66	0.05	17.7	1.7
Squash players	6	25.6	4.4	64.2	3.4	1.68	0.04	24.7	3.1
Triathletes	8	21.0	5.4	63.6	6.6	1.68	0.02	23.2	4.2
Totals/means	76	24.5		61.6		1.68		21.5	

estimated by taking natural logarithms (\ln) of x and y and then performing linear regression to produce an expression: $\ln(x) = \ln(a) + b \cdot \ln(x)$ (13,19,28). It has been suggested that $\dot{V}O_2$ and $\dot{V}O_{2\max}$ should be expressed as power function ratios where, from the surface law, body mass should be raised to the power 0.67 (15,19) or, with acknowledgment of elasticity in body structures, 0.75 (11). Moreover, a sample-specific exponent identified by appropriate log-log transformations can be used. Groups can be compared by means of these power function ratios or, alternatively, by log-linear ANCOVA (15). Such approaches assume that growth and development are accompanied by isometric changes in the size of the body and its segments. Alexander et al. (1) demonstrated clearly that in animals, such changes do not occur and that disproportionately large growth occurs for instance in the lower limb, especially the thigh.

Opportunities to explore allometric relationships in elite athletes are rare because of the difficulties in securing groups large enough to make such investigations meaningful. In this study, two large groups of elite sportsmen and women have been recruited as participants, and thus no such limitation was imposed. Hence, the purpose of the present study was to compare the maximum oxygen uptake ($\dot{V}O_{2\max}$) of elite endurance athletes from a range of endurance sports and to identify and interpret the most appropriate methods to express $\dot{V}O_{2\max}$ independent of body size.

METHODS

Participants (Study 1)

With local ethics committee and institutional procedures' approval, 174 international-standard men and women athletes from seven sports in which endurance was an important component provided written informed consent and participated. The physical characteristics of participants (mean \pm SD) are described in Table 1.

The athletes were part of either United Kingdom government funded sport science support program or the British Olympic Association's similar scheme. Participants in-

cluded world champions, world record holders, and Olympic gold medallists.

Procedures

Laboratory assessments were undertaken at the British Olympic Medical Center, Northwick Park Hospital, Harrow, UK, and De Montfort University Bedford, Bedford, UK. The athletes were fully accustomed to the procedures. Body mass was assessed to the nearest 0.05 kg by using beam balance scales (Avery Berkel, Dublin, Ireland; Herbert and Sons, Edmonton, UK) with the athletes wearing minimal clothing. By using British Association of Sport and Exercise Sciences criteria (4), $\dot{V}O_{2\max}$ was determined during either continuous or discontinuous incremental tests to volitional exhaustion on motorized treadmills or rowing ergometers. Expired air was collected and analyzed by online breath-by-breath systems (CoVox Microlab, Exeter, UK; Jaeger EOS-Sprint, Market Harborough, UK; Mijnhardt Oxycon Champion, Bunnik, The Netherlands), which were calibrated immediately before and verified immediately after testing using gases of known concentration and syringes of known volume. Test-retest coefficients of variation (17) for $\dot{V}O_{2\max}$ in the groups were less than 4%. The percentage of body fat was estimated using the techniques proposed by Durnin and Womersley (6).

Participants (Study 2)

With local ethics committee and institutional procedures' approval, 106 men and 30 women from 11 sports or activities provided written informed consent and participated. Male subjects were part of a study designed to predict % fat in athletes (22). The physical characteristics of the participants (mean \pm SD) are described in Table 2. The men comprised runners, cyclists, swimmers, triathletes, racket players, upper-body athletes (rock climbers and kayakers), rugby players, rowers, strength athletes (power-lifters and bodybuilders), and noncompetitive "keep-fit" exercisers who undertook advanced circuit training. The women com-

TABLE 2. Physical characteristics and corrected calf and thigh muscle girths (mean ± SD) of the men and women participants from study 2 by the various sports and activities.

Sports	N	Age (yr)	SD	Body Mass (kg)	SD	Stature (m)	SD	Calf (cm)	SD	Thigh (cm)	SD
Men											
Cycling	16	28.6	6.0	74.2	8.0	1.81	0.07	34.9	2.3	50.9	2.2
Keep fit	9	32.2	4.8	76.8	7.9	1.81	0.06	35.1	3.5	50.0	4.3
Racket	12	30.6	8.5	75.7	5.3	1.79	0.07	34.7	2.0	50.3	3.8
Rowing	15	21.6	2.8	79.5	6.0	1.84	0.07	35.1	1.6	51.9	3.2
Rugby	11	25.3	5.8	91.4	10.0	1.84	0.07	37.7	1.9	56.2	3.9
Running	12	26.6	6.5	70.7	5.6	1.79	0.06	35.2	1.7	50.7	2.7
Strength	6	25.7	7.9	85.2	11.9	1.76	0.09	36.7	4.3	54.8	3.3
Swimming	2	19.0	0.0	81.9	2.8	1.88	0.02	36.8	1.6	52.7	2.1
Triathlon	15	32.6	7.7	72.5	8.1	1.77	0.06	34.6	1.9	49.9	4.0
Upper body	8	35.0	5.8	76.7	10.6	1.79	0.09	36.9	2.9	52.0	3.7
Total/mean	106	28.3		77.5		1.80		35.5		51.6	
Women											
Cycling	3	29.0	3.6	58.8	4.8	1.65	0.04	30.5	1.4	47.5	2.5
Dancing	4	29.0	7.6	53.8	1.1	1.70	0.05	30.4	2.7	43.0	2.4
Keep fit	5	25.6	3.4	55.7	2.9	1.62	0.02	30.8	3.0	44.7	2.6
Racket	2	20.0	0.0	62.8	3.5	1.64	0.05	29.7	1.1	43.2	2.8
Rowing	5	25.0	4.1	65.8	9.0	1.75	0.04	32.4	3.1	46.1	2.4
Running	11	24.8	5.3	52.2	6.0	1.67	0.07	31.2	2.3	42.8	3.0
Total/mean	30	25.6		56.6		1.68		31		44.2	

prised cyclists, racket players, runners, rowers, noncompetitive exercisers, and dancers. All (except the keep-fit group and dancers) had competed at university or higher level and had trained for a minimum of 4 h·wk⁻¹, for a minimum of 3 yr. Of the entire group, 26 men and four women were international athletes, and of these, two men were Olympic athletes.

Procedures

Anthropometric measures were made according to procedures recommended by the International Society for the Advancement of Kinanthropometry. Circumferences were measured using an anthropometric tape (Rockton, IL) to 0.1 cm at the thigh (midway between the inguinal crease and the proximal border of the patella) and the maximum calf on the right side of the body, or left if this was the preferred limb. Skinfolds were measured to 0.1 mm on the right side of the body using Harpenden calipers (British Indicators, Luton, UK) along these circumferences at anterior thigh and medial calf.

The calculation of corrected girths applies to upper and lower limbs, and used the principal assumptions outlined in Stewart et al. (23). The tissue boundaries were assumed to be circular and concentric. If the skin plus adipose tissue thickness is *d*, and the thigh girth is *G*_{thigh}, then the thigh muscle girth *G*_{TM} is given by $G_{TM} = G_{thigh} - 2\pi \cdot d$ (skinfold values are converted to cm for this calculation). If it is further assumed that the skinfold caliper reading *S* is twice the adipose tissue thickness, then $G_{TM} = G_{thigh} - \pi \cdot S$. Physical characteristics and corrected calf and thigh muscle girths (mean ± SD) by the various sports and activities of the men and women participants from study 2 are described in Table 2.

Statistical Methods

Study 1. Differences in maximum oxygen uptake between “sport” and “sex” were compared using a two-way ANOVA. Maximum oxygen uptake was expressed in the

absolute units, liters (L·min⁻¹), as well as the ratio standard mass-related units (mL·kg⁻¹·min⁻¹). Comparisons of maximum oxygen uptake independent of body mass, age and body fat, were made using the ANCOVA, based on the proportional allometric model originally proposed by Nevill and Holder (13) and subsequently developed by Nevill and Holder (14). The adopted model for maximum oxygen uptake ($\dot{V}O_2$) is given by

$$\dot{V}O_{2max} = \text{mass}^{k_1} \cdot \exp(b_0 + b_1 \cdot \text{age} + b_2 \cdot \text{age}^2 + b_3 \cdot \% \text{fat}). \quad (1)$$

The model can be linearized with a log-transformation, and ANCOVA can then be used to estimate the effects of sport and sex having controlled for differences in these confounding covariates of mass, age, age², and %fat. The transformed ANCOVA model becomes

$$\log_e(\dot{V}O_{2max}) = k_1 \cdot \log_e(\text{mass}) + b_0 + b_1 \cdot \text{age} + b_2 \cdot \text{age}^2 + b_3 \cdot \% \text{fat}, \quad (2)$$

where the constant *b*₀ is allowed to vary for each level of sport and sex. If either the ANOVA or ANCOVA main effect difference between sports was detected, pairwise comparisons were made using the Bonferroni adjustment for multiple comparisons.

To confirm the appropriateness of the allometric model (Equation 1), the maximum log-likelihood criterion, originally recommended by Cox (5) to compare models with different structural forms, was used to assess and compare the quality of fit of the log-transformed allometric ANCOVA model (Equation 2) with the equivalent additive ANCOVA model using untransformed data.

Study 2

To establish whether calf and thigh muscle girth (MG) increased in proportion to body mass (kg), the following allometric model was fitted:

$$MG = a_i \cdot \text{mass}^{k_2}. \quad (3)$$

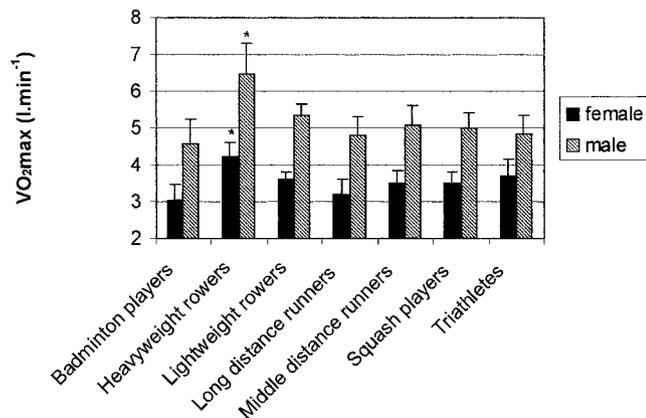


FIGURE 1—Differences in maximum oxygen uptake ($L \cdot \text{min}^{-1}$) between sport and sex from study 1 (mean \pm SD). * Heavyweight rowers' mean $\dot{V}O_{2\text{max}}$ ($L \cdot \text{min}^{-1}$) was greater than all the other sports ($P < 0.001$).

As with study 1, the model can be linearized with a log-transformation and ANCOVA used to compare leg muscle girths by sport and sex having controlled for differences in body mass, i.e., by allowing a_1 to vary for each level of sport and sex using body mass as the covariate. Based on the principal of geometric similarity (19) (assuming participants' bodies are the same shape but their body size dimensions vary/increase proportionally), both the calf and thigh muscle girths [linear dimensions (L) of body size] should increase in proportion to $m^{0.33}$, where m denotes the participants' body mass [a volumetric dimension (L^3) of body size]. Hence, we anticipated that the mass exponents associated with the calf and thigh muscle girths, estimated using Equation 3, should be approximately $k_2 = 0.33$. Also based on the principle of geometric similarity, we could estimate that calf and thigh leg muscle volumes should increase in proportion to muscle girth (MG)³, or from Equation 3, (mass^{k_2})³.

$$\dot{V}O_{2\text{max}} \sim (m^{2/3})^{1.38} = m^{0.92} \quad (4)$$

RESULTS

Study 1. Differences in maximum oxygen uptake, expressed in absolute units ($L \cdot \text{min}^{-1}$) and mass-related units ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) between the main effects sport and sex can be seen in Figures 1 and 2, respectively.

As anticipated by Nevill and Holder (13), the residuals from the ANOVA of maximum oxygen uptake ($L \cdot \text{min}^{-1}$) were not normally distributed, and a logarithmic transformation was required to correct this nonnormality. The two-way ANOVA of $\log_e(\dot{V}O_2)$ confirmed significant sport and sex main effects but no interaction. The Bonferroni pairwise comparisons between sports identified heavyweight rowers as having the greatest $\dot{V}O_{2\text{max}}$ [men = 6.5; (SD = 0.82) $L \cdot \text{min}^{-1}$ and women = 4.2 (SD = 0.40) $L \cdot \text{min}^{-1}$] that was greater than all the other sports ($P < 0.001$).

In contrast, the residuals from the two-way ANOVA of mass-related maximum oxygen uptake ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) were found to be acceptably normally distributed. The two-

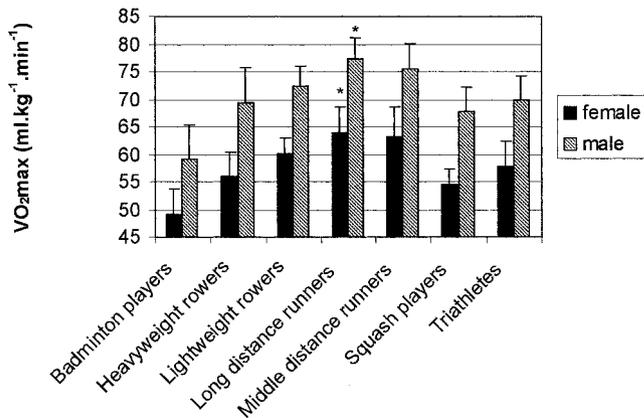


FIGURE 2—Differences in maximum oxygen uptake ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) between sport and sex from study 1 (mean \pm SD). * Long-distance runners' mean $\dot{V}O_{2\text{max}}$ ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) was greater than all other sports except middle-distance runners ($P < 0.01$).

way ANOVA of $\dot{V}O_{2\text{max}}$ ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) also confirmed significant sport and sex main effects again with no interaction. However, on this occasion, the Bonferroni pairwise comparisons between sports identified the long-distance runners as having the greatest $\dot{V}O_{2\text{max}}$ [men = 77.4 (SD = 3.7) $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ and women = 64.1 (SD = 4.6) $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$] that was significantly greater than all other sports except middle-distance runners whose mean $\dot{V}O_{2\text{max}}$ was only 1.44 (SEE = 1.39) $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ below that of the long-distance runners.

The two-way ANCOVA of $\log_e(\dot{V}O_2)$ (Equation 2) confirmed significant sport and sex main effects but no interaction (Fig. 3).

The Bonferroni pairwise comparisons of the adjusted $\dot{V}O_{2\text{max}}$ between sports now identified the middle-distance runners as having the greatest adjusted $\dot{V}O_{2\text{max}}$ [men = 4.9 (SD = 0.58) $L \cdot \text{min}^{-1}$ and women = 4.3 (SD = 0.34) $L \cdot \text{min}^{-1}$] that was only significantly greater than badminton and squash players, i.e., there was no significant difference in adjusted $\dot{V}O_{2\text{max}}$ between the five groups middle-distance runners, long-distance runners, heavyweight rowers, light-

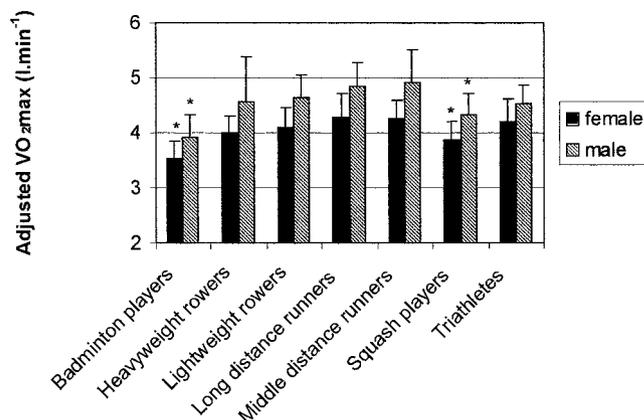


FIGURE 3—Differences in adjusted maximum oxygen uptake ($L \cdot \text{min}^{-1}$) between sport and sex from study 1 (mean \pm SD), adjustments made for the mean age (24.6 yr), body mass (67.8 kg), and body fat (16.7%). * Badminton and squash players' mean adjusted $\dot{V}O_{2\text{max}}$ were less than all other sports ($P < 0.05$).

TABLE 3. Mean and standard deviation (mean \pm SD) $\dot{V}O_{2\max}$ ($\text{mL}\cdot\text{kg}^{-0.67}\cdot\text{min}^{-1}$) and ($\text{mL}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$) from study 1 by sport and sex.

	N	$\dot{V}O_{2\max}$ ($\text{mL}\cdot\text{kg}^{-0.67}\cdot\text{min}^{-1}$)	SD	$\dot{V}O_{2\max}$ ($\text{mL}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$)	SD
Male					
Badminton players	17	248	28	175	19
Heavyweight rowers	28	310	31	216	21
Lightweight rowers	12	300	15	213	11
Long-distance runners	10	302	18	217	12
Middle-distance runners	18	304	22	217	15
Squash players	7	280	17	198	12
Triathletes	6	282	15	201	11
Total/mean	98	291	30	206	21
Female					
Badminton players	12	192	19	138	14
Heavyweight rowers	16	233	17	165	12
Lightweight rowers	13	232	10	167	7
Long-distance runners	10	232	19	170	14
Middle-distance runners	11	238	19	172	14
Squash players	6	215	13	154	9
Triathletes	8	228	19	163	13
Total/mean	76	225	23	162	17

weight rowers, and triathletes ($P > 0.05$). The ANCOVA of log-transformed $\dot{V}O_{2\max}$ identified $\log_e(\text{mass})$, age, and age² as significant covariates. The body mass exponent was estimated as $k = 0.94$ (95% confidence interval from 0.79 to 1.08). The age and age² slope parameters were $b_1 = 0.029$ and $b_2 = -0.00048$, respectively. Elementary differential calculus estimated $\dot{V}O_{2\max}$ to peak at age = $-b_1/(2\cdot b_2) = 0.029/0.00096 = 30.2$ yr. The %body fat slope parameter was estimated as $b_3 = -0.0079$.

The superiority of the allometric ANCOVA model was confirmed using the maximum log-likelihood quality-of-fit criterion. The maximum log-likelihood criterion for the log-transformed $\dot{V}O_{2\max}$ model (Equation 2) described above was -28.34 , much greater than the maximum log-likelihood criterion based on the equivalent additive linear model given by -59.89 . Note that in these comparisons, the same number of predictor variables was used in both the log-transformed and nontransformed models.

Note that the fitted body mass exponent, $k_1 = 0.94$, had a 95% confidence interval from 0.79 to 1.08. This interval precludes the two theoretical exponents of 0.67 and 0.75, but does include the ratio-standard mass exponent 1.0. To facilitate comparisons with other studies only, Table 3 describes mean $\dot{V}O_{2\max}$ and SD, expressed as power function ratios in the units ($\text{mL}\cdot\text{kg}^{-0.67}\cdot\text{min}^{-1}$) and ($\text{mL}\cdot\text{kg}^{-0.75}\cdot\text{min}^{-1}$), by sport and sex.

Study 2. To explain the unexpectedly high body mass exponent identified in study 1 ($k_1 = 0.94$), we investigated whether the calf muscle girth and thigh muscle girth increased in proportion to body mass (kg) by using the allometric model (Equation 3). As described earlier in the Methods section, based on the assumption of geometric similarity, the body mass exponents should be approximately $k_2 = 0.33$.

The ANCOVA failed to identify any significant differences between either sport or sex in calf or thigh muscle girths after having controlled for differences in body mass. The fitted body mass exponents (Equation 2) for the calf were $k_2 = 0.37$ (95% confidence interval from 0.29 to 0.45) and for the thigh were $k_2 = 0.46$ (95% confidence interval

from 0.38 to 0.54). Note that the mass exponent for the calf muscle girth encompasses the theoretical value 0.33, but the mass exponent for the thigh muscle girth exceeds this theoretical value 0.33, predicted by geometric similarity. Based on these exponents and assuming geometric similarity, we can estimate that the calf and thigh muscle volume exponents (given by $m^{k_2\cdot 3}$) will be proportional to $m^{1.11}$ and $m^{1.38}$, respectively.

DISCUSSION

The men and women heavyweight rowers demonstrated the greatest $\dot{V}O_{2\max}$ when expressed in the absolute units ($\text{L}\cdot\text{min}^{-1}$). Of course, this finding simply reflects the rowers' greater body mass [men = 93.3 (SD = 6.0) women = 75.9 (SD = 7.2) kg] as seen in Table 1. In contrast, when $\dot{V}O_{2\max}$ was expressed as the traditional ratio standard ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), the lighter long-distance and, to a lesser extent, the middle-distance runners were found to have the greatest mass-related $\dot{V}O_{2\max}$. This result was anticipated by Nevill et al. (15), who demonstrated using log-linear multiple regression, that 5-k running speed was best predicted by speed ($\text{m}\cdot\text{s}^{-1}$) = $84.3\cdot(\dot{V}O_{2\max})^{1.01}\cdot\text{mass}^{-1.03}$, i.e., the best predictor of 5-k run times recorded as a running speed ($\text{m}\cdot\text{s}^{-1}$) is almost exactly proportional to the ratio standard maximum oxygen uptake ($\text{L}\cdot\text{min}^{-1}$) divided by body mass (kg) or ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).

However, in an attempt to identify the form of exercise or sporting activity that elicits the greatest $\dot{V}O_{2\max}$ independent of body mass (as well as other confounding variables), the ANCOVA of log transformed $\dot{V}O_{2\max}$ could not distinguish between the five endurance sports of middle-distance runners, long-distance runners, heavyweight rowers, lightweight rowers, and triathletes. Observed differences were not significant ($P > 0.05$). Only the mass-adjusted $\dot{V}O_{2\max}$ values of the two racket sports, badminton and squash, were less than the other five pure endurance sports ($P < 0.001$ and $P < 0.05$, respectively). The allometric ANCOVA model estimated the body mass exponent as 0.94 (95% confidence intervals from 0.79 to 1.08), which is significantly higher than either of the anticipated body mass exponents 0.67 or 0.75 previously reported (3,9,12,13,15,19), although not dissimilar to that (1.01) reported by Sjödin and Svedenahg (21) using young trained male runners. We acknowledge that the 95% confidence interval for mass in this study does indeed encompass the ratio-standard parameter 1.0, suggesting a possible linear association between $\dot{V}O_{2\max}$ ($\text{L}\cdot\text{min}^{-1}$) and body mass. However, a closer inspection of Figure 2 clearly demonstrates that the ratio standard favors the lighter long- and middle-distance runners and thus fails to render $\dot{V}O_{2\max}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) completely independent of body mass. The results from study 2 provide a plausible explanation for these inflated exponents.

Alexander et al. (1) observed that the proximal leg muscle mass of a wide range of mammals had a greater proportion of muscle mass to body mass in larger mammals, $m^{1.1}$. The results of study 2 suggest that the volume of calf muscle mass increases at approximately the same rate, $m^{1.11}$, but the

volume of thigh muscle mass of the sportsmen and women increases at an even greater rate, in proportion to $m^{1.38}$. If we assume that $\dot{V}O_{2\max}$ of nonathletes increases in proportion to body mass ($m^{2/3}$) and that the thigh leg muscles are making a major contribution to the participants' $\dot{V}O_{2\max}$ performance, then the larger athletes will consume a similar disproportionate increase in maximum oxygen uptake given by not dissimilar to the mass exponent 0.94, associated with $\dot{V}O_{2\max}$ of elite athletes identified by the ANCOVA in study 1. We recognize that drawing the above conclusions, based on data from two independent studies, is a limitation of the present work. Clearly, future research should attempt to collect measurements of maximum oxygen uptake and estimates of leg muscle mass on the same individuals to help confirm the above assumptions and associations between $\dot{V}O_{2\max}$ and leg muscle mass.

It is important to recognize the value of adopting the allometric ANCOVA model (Equation 1) compared with alternative additive/linear ANCOVA models (8,24,27). The superiority was confirmed when the maximum log-likelihood criteria for the log-transformed ANCOVA analyses were greater than the analyses based on the equivalent additive linear models (not log-transformed). Because the maximum likelihood criteria were greater, the error variance will automatically be less. Consequently, any inferences drawn from the results based on the log-transformed model (Equation 2) are more powerful with reduced probability of type II errors and hence more likely to lead to correct conclusions when comparing differences in $\dot{V}O_{2\max}$ between groups of sportsmen and women.

Although postural muscles of the upper and lower leg may be common to all activities, strength training triggers adaptations including hypertrophy and force-velocity char-

acteristics according to movement and activity type according to the principle of specificity (2). Despite this, no significant differences were found in calf and thigh corrected girths between sporting groups after adjustment for body size, reinforcing the validity of this methodology. In contrast, comparison of anthropometric relationships of upper-body morphology between sporting groups is more problematic due to differential contribution of specific muscle groups to performance. Thus, upper body modeling may be inappropriate using such a variety of sporting groups and has been omitted from the present analysis.

The ANCOVA also identified significant age and age² parameters as $b_1 = 0.029$ and $b_2 = -0.00048$, respectively, from which we can estimate that the $\dot{V}O_{2\max}$ of elite athletes will peak at approximately 30 yr. This is consistent with the training that is required to develop endurance capacity, whereas sprinters in general perhaps owe more to genetic endowment than subsequent training practices. Also noteworthy is the observation that $\dot{V}O_{2\max}$ declines at the rate of 0.79% for each additional percentage of body fat of elite endurance athletes.

In conclusion, the results of the present studies have identified a disproportionate increase in both calf and thigh leg muscle mass ($m^{1.11}$ and $m^{1.38}$, respectively) and a similar disproportionate increase in $\dot{V}O_{2\max}$ found to be in proportion to $m^{0.94}$. Having controlled for these differences in body mass, the ANCOVA of log transformed $\dot{V}O_{2\max}$ could not distinguish between the five sports, middle-distance runners, long-distance runners, heavyweight rowers, lightweight rowers, and triathletes. Only the $\dot{V}O_{2\max}$ of two racket sports, badminton and squash, were significantly below the other five pure endurance sports.

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