ORIGINAL ARTICLE

Appropriate interpretation of aerobic capacity: allometric scaling in adult and young soccer players

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Objective: To compare aerobic capacity of young and adult elite soccer players using appropriate scaling procedures.

Methods: Twenty four male adult (mean (SD) age 24 (2) years, weight 75.7 (7.2) kg, $V\textsc{o}_2\textsc{max}$ 66.6 (5.2) ml/lbm/min, where lbm is lean body mass in kg) and 21 youth (14 (0.4) years, 60.2 (7.3) kg, 66.5 (5.9) ml/lbm/min) elite soccer players took part in the study. Allometric equations were used to determine the relation between maximal and submaximal oxygen cost of running (running economy) and body mass.

Results: Maximal and submaximal oxygen uptake increased in proportion to body mass raised to the power of 0.72 (0.04) and 0.60 (0.06) respectively. The $V\textsc{o}_2\textsc{max}$ of adult players was similar to that of the youth players when expressed in direct proportion to body mass—that is, ml/kg/min—but 5% higher ($p<0.05$) when expressed using appropriate procedures for scaling. Conversely, compared with seniors, youth players had 13% higher ($p<0.001$) energy cost of running—that is, poorer running economy—when expressed as ml/kg/min but not when expressed according to the scaling procedures.

Conclusions: Compared with the youth soccer players, $V\textsc{o}_2\textsc{max}$ in the seniors was underestimated and running economy overestimated when expressed traditionally as ml/lbm/min. The study clearly shows the pitfalls in previous studies when aerobic capacity was evaluated in subjects with different body mass. It further shows that the use of scaling procedures can affect the evaluation of, and the resultant training programme to improve, aerobic capacity.

Aerobic energy production during a soccer game is substantial, and the average exercise intensity is ~75% and 85% of maximal oxygen uptake ($V\textsc{o}_2\textsc{max}$) and maximal heart rate respectively.[1–4] This corresponds to about 50 ml/kg/min for a 75 kg player with a $V\textsc{o}_2\textsc{max}$ of 65 ml/kg/min. Helgerud *et al*[2] showed that an improvement in $V\textsc{o}_2\textsc{max}$ of 18 ml/kg$^{0.75}$/min and 7% reduced energy cost of submaximal running—that is, improved running economy—increased both the distance covered in a game by 1800 m and the average exercise game intensity by 4%. Furthermore, increased aerobic capacity was associated with 24% more involvement with the ball and a doubling of the number of sprints performed.[2] Thus aerobic capacity certainly plays an important role in modern soccer and has a major influence on technical performance and tactical choices. For male elite junior and senior players, average $V\textsc{o}_2\textsc{max}$ is 160–190 ml/kg$^{0.75}$/min (or 55–65 ml/kg/min), with some players reaching values as high as 235 ml/kg$^{0.75}$/min (80 ml/kg/min) (personal observation).[5 6]

In addition to $V\textsc{o}_2\textsc{max}$, aerobic capacity consists of anaerobic threshold and running economy. Owing to the duration of the game, the average exercise intensity must be close to anaerobic threshold, but the players are either exercising above, accumulating lactate, or below for lactate clearance, thus only a small part of a game is spent at the actual intensity corresponding to anaerobic threshold. Hoff *et al*[3] estimated that an improvement in running economy of 5% would increase the distance covered in a game by about 1000 m.

Although the aerobic capacity of male senior players has been thoroughly described, there exist few data on (elite) youth soccer players. Bunc and Psotta[7] reported that 8 year old male soccer players had similar $V\textsc{o}_2\textsc{max}$ and anaerobic threshold values to elite adult players, but higher energy cost of running at intensities below anaerobic threshold. However, these data were expressed in direct proportion to body mass (ml/kg/min), which is the traditional but often a functionally imprecise method used to compare aerobic capacity of subjects with different body weight.[8] Dimensional scaling of geometrically similar individuals suggests that $V\textsc{o}_2\textsc{max}$, which is primarily limited by maximal cardiac output, should be proportional to body mass raised to the power of 0.67.[9] Empirical studies have shown that, depending on the group studied, oxygen uptake should be expressed in relation to body mass (ideally lean body mass) raised to the power of 0.75–0.94, over a wide range of body weights.[10 11 12 13 14] As senior players are probably consistently heavier than youth players, their $V\textsc{o}_2\textsc{max}$ might be underestimated and energy cost of running overestimated when expressed in the traditional way (ml/kg/min).

The purpose of this study was to determine the aerobic capacity of youth soccer players and to compare it with that of adult elite soccer players using appropriate procedures for comparison.

METHODS

Allometric scaling

To determine if we were allowed to calculate a common scaling exponent for the whole group, an initial test of homogeneity of regression slopes between the two groups (youth and seniors) was performed. This process included entering group (youth and seniors) and a group × log lbm interaction term as covariates in the analysis (where lbm is lean body mass in kg). The following model was used in SPSS (release 12.0 for Windows; SPSS, Chicago, Illinois, USA):

$$\log V\textsc{o}_2 = \log a + b \log \text{lbm} + c \times \text{group (coded 1 for youth and 2 for senior).}$$

The initial analysis showed that the interaction term had no significant effect on the variance in either submaximal ($p = 0.34$) or maximal ($p = 0.42$) oxygen uptake. Then the

Table 1 Physical and physiological characteristics of the players

	Youth players (n = 21)	Senior players (n = 24)
Age (years)	14 (0.4)	24 (2)
Height (cm)	170 (5.5)	178 (7.1)*
Body mass (kg)	60.2 (7.3)	75.7 (7.2)**
Body fat (%)	11.8 (3.2)	11.6 (1.8)
Maximal heart rate (beats/min)	198 (7)	190 (10)*
Maximal oxygen uptake		
litres/min	3.60 (0.6)	4.45 (0.5)**
ml/lbm/min	66.5 (5.9)	66.6 (5.2)
ml/lbm$^{0.72}$/min	206 (17)	216 (11)*
Running economy		
ml/lbm/min at 7 km/h	39.2 (2.9)	36.0 (3.1)**
ml/lbm/m	0.34 (0.02)	0.30 (0.02)**
ml/lbm$^{0.60}$/m	1.65 (0.04)	1.65 (0.08)
Anaerobic threshold (% $\mathrm{VO_2MAX}$)	88.8 (5.5)	89.3 (4.7)
Lowest treadmill speed at $\mathrm{VO_2MAX}$ (km/h)	13.9 (1.1)	15.3 (1.1)**
Maximal treadmill speed at $\mathrm{VO_2MAX}$ (km/h)	15.1 (1.2)	16.5 (1.0)**

Data are mean (SD).
*Significantly different from the youth players, $p<0.05$; **$p<0.001$.
lbm, lean body mass in kg.

following equations were used to determine a common exponent for the relation between maximal and submaximal oxygen uptake and body mass:

$$\mathrm{VO_2} = a \times \mathrm{lbm_b}^{b}$$

where a is the mass coefficient, $\mathrm{lbm_b}$ is the lean body mass in kg, and b is the reduced exponent, the numerical value of which can be obtained from the log-log plot of the experimental data, as the logarithmic expression is a straight line ($\log \mathrm{VO_2} = \log a + b \times \log m_b$).[9]

Subjects and laboratory environment

Twenty four adult and 21 young male soccer players volunteered to participate in the study and provided written informed consent in accordance with the Declaration of Helsinki. The university ethics committee approved the study protocol. The subjects could withdraw from the study at any time. They were informed about the test protocols, without being informed about the aim of the study. Table 1 presents the players' physical characteristics. Percentage of body fat was calculated using the formula of Siri[15] based on four skinfold measurements (biceps, triceps, subscapularis, and suprailiac) as follows:

$$\%\ \text{body fat} = 27.409 \times \log(\Sigma\ 4\ \text{skinfolds}) - 26.789$$

where each skinfold value is in mm.

The adult players were first choice members of the senior Tunisian national team which was preparing for the Nations' African Cup. They were all regular players in their respective teams and were training 7 to 8 times a week in addition to the weekly games usually held on Sundays. The youth players were living in a special "centre of excellence" belonging to the national Tunisian soccer federation. At the time of the experiment, their average weekly training programmes included six training sessions a week (each session lasting for about 90 minutes), mainly soccer training. They also participated in one official game a week. The cohorts studied were composed of nine and eight defenders, six and seven midfield players, and six and nine forwards for the youth and adult groups respectively.

The experiment was performed in the second half of the season—that is, five to eight months after the beginning of the competitive season. All tests were performed between 2 pm and 5 pm in a laboratory (temperature 19.8 (1)℃, atmospheric pressure 1018 (2) mm Hg, relative humidity 70.5 (4.6)%). The subjects wore shorts and running shoes. They abstained from exercise the day before the tests and did not consume caffeine on the day of the test.

Aerobic capacity

The subjects ran on a 5.5% slope motorised treadmill (Woodway: Ergo XELG 90, Weil, Germany) for four minutes at 7 km/h, followed by a 1 km/h increment every minute until exhaustion, which occurred within 10–15 minutes for all players. Running economy was measured as the average oxygen uptake during the last 30 seconds at 7 km/h. The oxygen uptake stabilised after two to three minutes for all subjects during the four minute run at 7 km/h. When the subject was running at 7 km/h, no-one in the testing room was allowed to speak or make a noise. Thereafter, each player was instructed and verbally encouraged to give maximal effort during the test. Cardiorespiratory variables were determined using a calibrated breath by breath system (ZAN 680, Oberthulba, Germany) allowing continuous measurement of heart rate, oxygen uptake, and lung ventilation. Heart rate was determined from a 12 lead electrocardiograph. Heart rate and the respiratory data were provided on a report once every 30 seconds with the values averaged over the last 10 respiratory cycles on a sliding technique basis as previously reported.[16] The lowest and highest running velocities associated with $\mathrm{VO_2MAX}$ were established as described by Billat and Koralsztein[17] and Paavolaïnen *et al*[18] respectively, and respiratory compensation threshold as described by Beaver *et al*.[19]

Blood sampling and determination of blood lactate concentration

Blood samples were collected 3.5 minutes after the $\mathrm{VO_2MAX}$ test. The 20 µl samples of capillary blood were withdrawn from an earlobe with Microzym micropipettes. They were stored in tubes containing 180 µl of a haemolytic solution to ensure good preservation of the samples at room temperature. Blood lactate concentration was subsequently measured using an enzymatic method (Microzym L; Setric Génie Industriel, Toulouse, France).

Statistical analysis

Data are expressed as mean (SD). After confirming normal distribution, a one way analysis of variance was used to evaluate differences between groups. $p<0.05$ was considered to be significant.

RESULTS

For all subjects, $\mathrm{VO_2MAX}$ was reached with the following variables: the oxygen uptake levelled off despite increased running speed, respiratory exchange ratio was 1.2 (0.3), heart rate less than 5 beats/min from the maximum, and blood lactate concentration 9.5 (1.3) mmol/l—that is, the true $\mathrm{VO_2MAX}$ was reached. There was no difference in aerobic capacity between playing positions, and therefore the averaged data for each group are presented.

Neither maximal nor submaximal oxygen uptake were directly proportional to body mass in the present population of subjects. The exponent b was found to be significantly lower than unity for the entire group, and the mean value was 0.72 (0.04) and 0.60 (0.06) for $\mathrm{VO_2MAX}$ and submaximal oxygen uptake (at 7 km/h) respectively. The exponents for submaximal oxygen uptake and $\mathrm{VO_2MAX}$ were significantly different ($p<0.01$).

Thus, classically expressed, $\mathrm{VO_2MAX}$ in senior players was underestimated. Indeed, it was similar to that of the youth

Table 2 Maximal oxygen uptake (VO$_2$MAX) and running economy normalised to lean body mass

	Present study		Bunc and Psotta[7]	Bunc *et al*[24]
	Youth (n = 21)	Senior (n = 24)	Youth (n = 22)	Senior (n = 15)
Age (years)	14 (0.4)	24 (2)	8 (0.1)	25 (3.4)
Lean body mass (kg)	53.9 (5.4)	66.9 (6.6)	22.7	70.4
VO$_2$MAX				
litres/min	3.60 (0.6)	4.45 (0.5)**	1.60 (0.14)	4.80 (0.41)
ml/lbm/min	66.5 (5.9)	66.6 (5.2)	70.5	68.2
ml/lbm$^{0.72}$/min	206 (17)	216 (11)*	168	224
Running economy				
ml/lbm/m	0.34 (0.02)	0.30 (0.02)**	0.26	0.21
ml/lbm$^{0.60}$/m	1.65 (0.04)	1.65 (0.08)	0.91	1.16

Data are calculated using lean body mass. Data presented without SD are calculated from mean values of oxygen uptake, lean body mass, and running speed when measuring running economy in the actual papers.
*Significantly different from the youth players, $p<0.05$; **$p<0.001$.
lbm, lean body mass in kg.

players when expressed in direct proportion to body mass—that is, ml/lbm/min—but 5% higher ($p<0.05$) when expressed using appropriate procedures for scaling (ml/lbm$^{0.72}$/min) (table 1). Conversely, youth players had 13% higher ($p<0.001$) energy cost of running—that is, poorer running economy—and thus running economy was underestimated when expressed as ml/lbm/m compared with senior players. As can be seen from table 1, there were no differences between groups in running economy expressed correctly as ml/lbm$^{0.60}$/min.

No difference in anaerobic threshold was observed between groups when expressed as ml/lbm$^{0.60}$/min or as a percentage of VO$_2$MAX.

Compared with the youth players, the senior players were 25% heavier ($p<0.001$) but no differences were observed in fat percentage (table 1). Maximal heart rate was 4% lower ($p<0.01$) in senior players.

DISCUSSION

This is the first study to show that VO$_2$MAX, but not running economy and anaerobic threshold, in youth soccer players is lower than that in senior elite soccer players when using appropriate scaling procedures.

VO$_2$MAX and submaximal oxygen uptake at 7 km/h were proportional to $m_b^{0.72}$ and $m_b^{0.60}$ respectively—that is, the oxygen uptake per kg body mass displayed an inverse relation to body mass. This is in agreement with previous studies[10 11] and supports the argument that dimensional scaling should be used in comparisons of subjects with different body mass. Thus it is reasonable to expect light subjects to have a higher oxygen uptake per kg body mass than their heavier counterparts.

The present scaling procedure is the classical scaling approach for comparing metabolic rate in subjects of different body weight. The approach is grounded in basic principles of geometry, physics, and biology, and offers a general unifying explanation for scaling which is used extensively in biology.[20 21] An alternative attractive multiple-cause model of allometry has been suggested by Darveau *et al*,[8] in which there are multiple contributors to control. For example, alveolar ventilation, pulmonary diffusion, cardiac output, capillary-mitochondria tissue diffusion, cytosolic and mitochondrial metabolism, actomyosin ATPase, and calcium pump among others all have their own characteristic b values, which, with their control contributions, determine the value of the b scaling coefficient for overall energy metabolism (global b). This approach is appealing because it recognises that metabolic rate is a complex feature that results from a combination of functions which may differ from basal and maximal aerobic metabolism. For example, at VO$_2$MAX oxygen delivery by the lung and heart are close to an upper ceiling. In contrast, actomyosin and the calcium pump still display a huge reserve capacity.[22] Because of these contrasting conditions in the energy supply versus energy demand processes as aerobic maximum fluxes are approached, it is not surprising that the control contributions for energy supply increase while those for energy-demand processes at VO$_2$MAX diminish toward zero.[22] Thus, at VO$_2$MAX, the oxygen delivery steps significantly increase the global b scaling coefficient. At basal metabolic rate, however, all the oxygen delivery steps display a huge excess capacity, and the control contributions for the oxygen delivery steps approach zero and contribute little to the global b exponent. In scaling of the basal metabolism, the oxygen delivery steps virtually do not contribute to the global b scaling exponent, which is therefore largely determined by energy demand processes, whereas at VO$_2$MAX the oxygen delivery steps significantly increase the global b scaling coefficient. In line with these data, we found a significantly lower b exponent for submaximal oxygen uptake compared with VO$_2$MAX. According to this model, the b exponent for basal and maximal aerobic metabolism should be within the limits of 0.76–0.79 and 0.82–0.92 respectively.[8] Calculating our data according to the model of Darveau *et al*[8] does not affect the conclusions of the present study. Although the model of Darveau *et al*[8] is appealing, more scientific data are necessary to determine the accurate effect of both the supply and demand steps on the global b. Recently, a large empirical study of adult male subjects by Batterham and Jackson[23] supports the model of Darveau *et al*,[8] which seems to form the basis of modern scaling.

Table 3 Maximal oxygen uptake (VO$_2$MAX) and running economy in two subjects (A and B) differing in body weight

	A (80 kg)	B (50 kg)
Running economy, VO$_2$SUBMAX at 7 km/h		
ml/lbm/min	34.5	39.0
ml/lbm$^{0.60}$/min	199	186
VO$_2$MAX		
ml/lbm/min	55	60
ml/lbm$^{0.72}$/min	188	179

Table 2 illustrates how it is possible to make wrong conclusions when evaluating aerobic capacity of subjects with different body mass. Bunc and Psotta[7] concluded that the VO$_2$MAX of 8 year old soccer players was similar to, and running economy poorer than, that of senior players.[24] As seen from table 2, this seems to be correct when VO$_2$MAX is expressed in direct proportion to body mass (ml/lbm/min). However, if their average data is reanalysed using appropriate scaling procedures, as in the present study, the VO$_2$MAX of senior players is found to be higher than that of the youth players. Furthermore, in direct contrast with their conclusion,[7] but similar to the present study, there is no difference in running economy between the senior and 8 year old soccer players, and, if anything, running economy is better in the younger players—that is, lower oxygen cost when expressed as ml/lbm$^{0.60}$/min. Calculating the data using the commonly used scaling component 0.75 gave identical conclusions.

In line with Svedenhag,[25] expressing oxygen uptake in relation to m_b^1 or according to appropriate scaling procedures may influence evaluation and the design of an exercise regimen. Subjects A and B from this study (table 3) illustrate this. If oxygen uptake is expressed traditionally as ml/lbm/min, subject A has a better running economy but a lower VO$_2$MAX than subject B. The natural conclusion from this would be to design an exercise training programme to improve the poorer functional capacity. However, if appropriate scaling procedures are used, the subjects have comparable values, or if anything the opposite result to the initial analysis is found. Thus appropriate scaling may well affect the evaluation and the resultant training programme devised to improve capacity.

What is often mixed up in the discussion of how to express oxygen uptake in relation to body mass is the relation between aerobic performance and aerobic capacity. As we know that aerobic capacity certainly influences on-field performance,[2] it is reasonable to give some priority to this when devising a training schedule for a season. From table 3, it is obvious that a knowledge of appropriate scaling procedures is needed when evaluating players' aerobic capacity—that is, VO$_2$MAX, running economy, and anaerobic threshold—to design an appropriate individual training programme. However, even though VO$_2$MAX, for example, may be improved, which improves the player's ability to run longer and faster and be more involved in "duels" in each game, it is not a guarantee, as aerobic performance is influenced by a myriad of factors such as team tactics, opponents, energy intake, etc. Thus aerobic performance per se should not be governed by the statistical adjustments of allometry, whereas aerobic capacity, which is an important basis for aerobic performance, should.

The mean VO$_2$MAX values for youth players presented here (180 (21) ml/lbm$^{0.75}$/min) are the highest ever reported for a youth soccer team and of the order of that observed in national under 16 teams.[26 27] Furthermore, VO$_2$MAX was substantially higher than that reported for 8 year old soccer players[7] (table 2), but in the normal range reported for senior elite players.[28] However, the values are not all that impressive considering the advantages of a high VO$_2$MAX in modern soccer. A very effective interval training programme, increasing VO$_2$MAX by about 0.5% each training session, has been described.[2 3] Furthermore, as shown by Helgerud *et al*,[2] improving VO$_2$MAX and running economy by ~11% and 7% respectively had the consequence that the team ran a total of 18 000 m more at a higher intensity, which also influenced the on-field performance as well as the running. For more details, see Helgerud *et al*.[2]

CONCLUSION

This study shows the importance of using appropriate scaling procedures when comparing the aerobic capacity of subjects who differ in body weight. VO$_2$MAX and submaximal oxygen uptake should be expressed in relation to the body mass raised to the power of 0.72 and 0.60 respectively. The data show that only VO$_2$MAX, and not the energy cost of running or anaerobic threshold, was lower in youth players than seniors. Knowing the advantages of a high aerobic capacity in modern soccer should lead to more effective training regimens, which may involve increasing the number of sessions a week to achieve higher values than reported in youth and senior soccer today.

What is already known on this topic

It is generally believed that young and adult elite soccer players have the same aerobic capacity.

What this study adds

This study shows that interpreting aerobic capacity data can lead to errors if VO$_2$ is expressed classically—that is, in ml/kg/min. When appropriately expressed according to allometric scaling, the data allow aerobic capacity to be correctly interpreted. This study shows that young soccer players have lower VO$_2$MAX than adults but a similar running economy.

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ELECTRONIC PAGES

Online original articles

The following electronic only articles are published in conjunction with this issue of *BJSM* (see also pages 69 and 110)

Effects of training period on haemorheological variables in regularly trained footballers

Y Karakoc, H Duzova, A Polat, *et al*

Objective: To investigate the effects of one football training period on haemorheological variables in regularly trained footballers.

Method: Ten subjects were randomly selected from the reserve team of a football club in the Turkish Premier League. During the last week of the football season, one day before a standard training session and two days after the previous league match, venous blood samples were taken (pre-exercise). After 90 minutes of standard training, further blood samples were taken (post-exercise). Blood lactate, blood viscosity, plasma fibrinogen, blood clotting time, acid-base variables, and plasma Na$^+$, K$^+$, and Ca^{2+} were determined.

Results: Haemoglobin, packed cell volume, and mean corpuscular volume were all significantly decreased, whereas white blood cells and platelets were both increased after training. Blood viscosity decreased but the reduction was not significant. Blood lactate, plasma glucose, and Na$^+$ content were significantly increased, but standard bicarbonate, actual bicarbonate, and Ca^{2+} were significantly decreased. Blood clotting time had shortened significantly after training. Blood viscosity was inversely correlated with plasma glucose concentration ($r = -0.48$ and $p = 0.032$).

Conclusions: The results show that blood viscosity tends to decrease as the result of this type of training. This is due to a reduction in packed cell volume and mean corpuscular volume. The increased blood lactate does not have an adverse effect on the blood viscosity of these subjects because protective mechanisms develop with regular training throughout the season.

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Differences in sole arch indices in various sports

S T Aydog, O Tetik, H A Demirel, *et al*

Background: There are controversial data about the relation between foot morphology and athletic injuries of the lower extremity. Studies in soldiers have shown some relationship, whereas those involving athletes have not shown any significant relationship. The reason for these differences is not clear.

Objective: To determine the effect of various sports on sole arch indices (AIs).

Method: A total of 116 elite male athletes (24 soccer players, 23 wrestlers, 19 weightlifters, 30 handball players, and 20 gymnasts) and 30 non-athletic men were included in this cross sectional study. Images of both soles were taken in a podoscope and transferred to a computer using a digital still camera. AIs were calculated from the stored images.

Results: The AI of the right sole of the gymnasts was significantly lower than that of the soccer players, wrestlers, and non-athletic controls ($p<0.01$). The AI of the right sole of the wrestlers was significantly higher than that of the soccer players, handball players, weightlifters, gymnasts, and non-athletic controls ($p<0.03$). The AI of the left sole of the gymnasts was significantly lower than that of the wrestlers and nonathletic controls ($p<0.001$). The AI of the left sole of the wrestlers was significantly higher than that of the soccer players, handball players, and gymnasts ($p<0.007$). The AI of both soles in handball players was significantly lower than those of the non-athletic subjects ($p = 0.049$). The correlation between the AI of the left and right foot was poor in the soccer players, handball players, and wrestlers ($r = 0.31$, 0.69, and 0.56 respectively), but was high in the gymnasts, weightlifters, and non-athletic controls ($r = 0.96$, 0.88, and 0.80 respectively).

Conclusion: The AIs of the gymnasts and wrestlers were significantly different from those of other sportsmen studied, and those of the gymnasts and handball players were significantly different from those of non-athletic controls.

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