EXPERIMENTAL INVESTIGATIONS

Longitudinal Predictors of Aerobic Performance in Adolescent Soccer Players

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Summary. *Background. The importance of aerobic performance in youth soccer is well established. The aim of the present study was to evaluate the contributions of chronological age (CA), skeletal age (SA), body size, and training to the longitudinal development of aerobic performance in youth male soccer players aged 10 to 18 years.*

Material and Methods. Players (n=83) were annually followed up during 5 years, resulting in an average of 4.4 observations per player. Decimal CA was calculated, and SA, stature, body weight, and aerobic performance were measured once per year. Fat-free mass (FFM) was estimated from age- and gender-specific anthropometric formulas, and annual volume training was recorded. After testing for multicollinearity, multilevel regression modeling was used to analyze the longitudinal data aligned by CA and SA (Model 1 and 2, respectively) and to develop aerobic performance scores.

Results. The following equations provide estimations of the aerobic performance for young soccer players: $\hat{y}$(Model 1 [deviance from the null model =388.50; P<0.01]) =57.75+9.06×centered CA−0.57×centered CA^2+0.03×annual volume training and $\hat{y}$(Model 2 [deviance from the null model=327.98; P<0.01])=13.03+4.04×centered SA−0.12×centered SA^2+0.99×FFM+0.03×annual volume training.

Conclusions. The development of aerobic performance in young soccer players was found to be significantly related to CA, biological development, and volume of training.

Introduction

Match analysis of elite soccer has indicated that high-intensity actions are important in soccer (1), but with players covering an average of approximately 8–12 km during a single match (2), soccer is largely dependent upon a high level of aerobic capacity (3). Increases in absolute maximal oxygen uptake in adolescents are strongly correlated with increases in body weight, which, among other factors, are connected to changes in the lungs, heart, and skeletal muscle during puberty (4). Variation in size and performance associated with interindividual differences in biological maturation are especially important during the transition into and during adolescence in male soccer players. Players advanced in skeletal age (SA) relative to chronological age (CA) (higher SA/CA ratio) tend to be taller, heavier, stronger, more powerful, and faster than players somewhat "delayed" in skeletal maturation (5).

Relationships between biological (i.e., sexual) maturity and maximal O$_2$ uptake in youth soccer players (12–19 years) have been previously addressed (6). Results suggested that biological maturity did not exert an effect on aerobic fitness. Previous studies were cross-sectional (3, 5, 7–9) and consequently did not permit a clear distinction between the effects of growth, maturation and the effects of training on functional capacities. Longitudinal studies that simultaneously explore the effects of changes and relative contribution of body size and composition, biological maturation, and training and competition on aerobic capacity development in youth soccer players are needed.

It has been shown that the measured maximal O$_2$ uptake of professional soccer players do not change before and after a 5-week aerobic training period; however, time to exhaustion on the maximal O$_2$ uptake test on the treadmill increased significantly by 12% (10). These findings suggested that the measured maximal O$_2$ uptake was not a sensitive indicator of developmental changes in mid- and

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long-term maximal efforts in soccer players. Performance in a 20-m multistage continuous shuttle run is a motor task that also combines coordination, lower limb strength, and motivation, and it has been reported to be strongly correlated with the directly measured maximal O_2 uptake ($r=0.80$) suggesting that it could be used as a surrogate measure of aerobic capacity in children (11).

Longitudinal observations in soccer players suggested that maximal gains in aerobic performance occurred, on average, close to the time of peak height velocity, the interval of maximal growth rate in height during the adolescent growth spurt (12). The corresponding cross-sectional data of adolescent soccer players showed that Portuguese players 11–12 and 13–14 years of contrasting skeletal maturity status did not differ in speed, agility, power and four soccer skills (i.e., ball control, dribbling, speed, shooting accuracy, wall pass), but did differ in aerobic performance assessed by a 20-m intermittent shuttle run protocol, with "early" maturing athletes performing better than "on time" and "late" maturers (7). Our knowledge of the longitudinal relationships among aerobic performance, growth, maturation, and training is limited. Therefore, the purpose of this study was to evaluate the longitudinal development of the aerobic performance of youth soccer players aged 10 to 18 years, with a specific emphasis on the contributions of CA, SA, body size, and training as the potential explanatory variables.

Material and Methods

Subjects and Procedures. The research proposal was approved by the Scientific Committee of the University of Coimbra and the Portuguese Foundation for Science and Technology (PTDC/DES/112781). The Portuguese Soccer Federation and clubs were contacted, and institutional agreements were signed between the University of Coimbra and the sport organizations to assure the 5-year data collection. The guardians of the young athletes provided informed consent, and players provided their assent. Goalkeepers were not included since they complete different tasks during the game compared to outfield players.

The sample included 83 players aged 11–13 years at baseline from 5 local clubs in the Midlands of Portugal who were followed on an annual basis over 3 to 5 years (mixed-longitudinal). An average of 4.4 observations per player (min, 3; max, 5) were available. Each year data were collected within a 2-week period separated by 1 year under standard conditions at an indoor facility at the University of Coimbra. Assessments, including radiographs of the left hand–wrist, were performed at the same time of day (6:00 PM to 7:00 PM) during April.

Training History. The clubs were involved in a 9-month competitive season (September–May) reg-ulated by the Portuguese Soccer Federation. Teams had 3–5 training sessions per week (90–120 minutes per session) and one game, usually on Saturday. The players also participated in competitions at the national level, and it can be described as a developmental pool for a potential talent identification. Years of formal participation in soccer for each player were obtained through the publicly available Portuguese Soccer Federation records and were verified by club records. The annual volume of training (number of sessions and minutes) was recorded for each player by a research assistant. Playing time (minutes and games) were also collected, but not considered in the current study.

Age and Skeletal Maturity. Decimal CA was calculated as the difference between date of birth and date of the hand-wrist radiograph, which was used to assess SA. The posterior-anterior radiographs of the left wrist were taken, and the films were rated using the Fels method for the assessment (13). The protocol assigns grades to specific maturity indicators for the radius, ulna, carpals, metacarpals plus phalanges of the first, third, and fifth rays and utilizes the ratios of linear measurements of the widths of the epiphysis and metaphysis of the long bones. The presence (ossification) or absence of the pisiform and adductor sesamoid bones is also noted. The grades and the ratios were entered into a program (Felshw 1.0 Software, Lifespan Health Research Center, Departments of Community Health and Pediatrics, Boonshoft School of Medicine, Wright State University, Dayton, Ohio) to derive each subject's SA. The statistical protocol weighted the contributions of specific indicators, depending on CA and sex, in calculating SA and its standard error of estimate (a confidence interval for the assessment) (14, 15).

Anthropometry. A single anthropometrist measured stature, body weight, and 2 skinfolds (i.e., triceps and subscapular) following the standard procedures (16). Stature was measured to the nearest 0.1 m using a Harpenden stadiometer (model 98.603, Holtain Ltd, Crosswell, UK), and body weight was measured to the nearest 0.1 kg using SECA scales (model 770, Hanover, MD, USA). Skinfolds were measured to the nearest mm using a Lange caliper (Beta Technology, Ann Arbor, MI, USA). The technical errors of a measurement for stature (0.27 cm), body weight (0.47 kg), and skinfolds (0.47–0.72 mm) were well within the range of several health surveys in the United States and a variety of field surveys (17). Body fat was estimated from triceps and subscapular skinfold thicknesses using the protocol of Slaughter et al. (18). Fat-free mass (FFM) was derived in kg.

Aerobic Performance. Aerobic performance was measured using the 20-m multistage continuous

shuttle endurance test (19), a standard field test included in the European fitness test battery (20) and in the Portuguese physical education curriculum. In brief, 5–10 athletes performed a series of runs across a 20-m track, changing direction at the end of each run to coincide with an audio signal that was getting progressively faster. Subjects started running at a speed of 8.5 km/h, and the speed increased at various stages (0.5 km/h every minute). Each stage was made up of several shuttle runs, and players were instructed to keep pace with the signals as long as possible. The results were recorded as laps taken to complete the 20-m shuttle run test. Aerobic performance was expressed as the number of completed laps achieved in the shuttle run test. The test-retest (average 7 days apart) reliability (21) in 32 players was high ($R=0.86$).

Statistical Analysis. Means and standard deviations were calculated for the repeated measures of CA, SA, training history, anthropometrics, and aerobic performance.

Multicolinearity was examined using a correlation matrix and diagnostic statistics. Variables with small tolerance ($\leqslant 0.10$) and a variance inflation factor of >10 (corresponding to an R^2 of 0.90) are generally considered indicative of harmful multicolinearity (22). The incidence of a nearly perfect bivariate correlation between body weight and FFM ($r=0.96$) and a very large bivariate correlation between CA and SA ($r=0.83$) suggested an unacceptable multicolinearity occurrence. To avoid harmful multicolinearity, body weight was discarded by the auxiliary regression, and 2 multilevel models of predictors were considered. The Model 1 adopted CA as a level 2 variance component, and the Model 2 considered SA. Additionally, Pearson product moment correlation coefficients were used to determine the relationship between the dependent variable and the possible explanatory variables, establishing the order of entrance in the multilevel analysis (CA, $r=0.64$; SA, $r=0.53$; FFM, $r=0.49$; stature, $r=0.47$; annual volume training, $r=0.36$). Correlations were considered as trivial ($r<0.1$), small ($0.1<r<0.3$), moderate ($0.3<r<0.5$), large ($0.5<r<0.7$), very large ($0.7<r<0.9$), and nearly perfect ($r>0.9$) (23).

For the longitudinal analyses, a hierarchical random-effects model was constructed using a multilevel modeling approach (MLwiN 2.02). Multilevel modeling effectively captures the feature that the variance of the observations increases with time, and because each individual has his or her own slope and intercept, it provides the opportunity to determine the effects on the slope and intercept of each predictor variable and its significance by relating the observed effects to the respective standard errors (24). Thus, group effects larger than within-individual variation can be identified.

Moreover, it is common in longitudinal studies for some individuals to miss an observation and for some to drop out. The multilevel model has an advantage since the number of observations and temporal spacing between measurements can vary among subjects; all available data can thus be incorporated into the analysis. The multilevel models assume that the probability of missing data is independent of any of the random variables in the model. As long as a full information estimation procedure is used, such as maximum likelihood in MLwiN for normally distributed data, the actual missing mechanism can be ignored (25).

The repeated measurements of aerobic performance development were assessed within an individual (Level 1 of the hierarchy) and between individuals (Level 2 of the hierarchy). A detailed description of multilevel modeling and complete details of this approach are presented elsewhere (26). An additive polynomial random-effect multilevel regression model (25) was adopted to describe the developmental changes in aerobic performance. In a first attempt, the constant and CA (Model 1, CA as Level 2 predictor) and the constant and SA (Model 2, SA as Level 2 predictor) were allowed to vary randomly between individuals (Level 2). However, CA or SA as our time-dependent variables dramatically increased the parameter estimate of variance at Level 2, around the between-individuals intercept. This is because all individuals have different developmental performance trajectories. To overcome this problem, it was decided to shift the origin of the explanatory random variables (CA and SA) by centering to their mean values (i.e., CA 14.21 years and SA 14.56 years) (26).

Subsequently, predictor variables were accepted as significant if the estimated mean coefficient was greater than twice the standard error of the estimate ($P<0.05$). The final model included only variables that were significant independent predictors. To allow the nonlinearity of the aerobic performance development, age power functions (i.e., centered CA^2 and centered SA^2) were introduced into the linear model (24). The alpha level was set at 0.05.

Results

During the 5-year testing period, 366 observations on the outcome variable and all potential predictors were performed (Table 1). As expected, the mean values increased with age. The mean SA always exceeded the mean CA within each age cohort, and SDs ranged from 1.0 to 1.3 years in players aged 11 and 16 years.

Tables 2 and 3 summarize the results from the multilevel models. The random-effects coefficients describe the 2 levels of variance (within individuals [Level 1 of the hierarchy] and between individuals

Table 1. Mixed-Longitudinal Data Set for Age, Anthropometrics, Training History, and Aerobic Performance by Age Groups
(83 Players; 366 Complete Measurements)

Variable	Cohort						
	11 Years (n=40)	12 Years (n=57)	13 Years (n=83)	14 Years (n=80)	15 Years (n=66)	16 Years (n=30)	17 Years (n=10)
Chronological age, years	11.6 (0.3)	12.6 (0.3)	13.7 (0.3)	14.7 (0.3)	15.7 (0.3)	16.7 (0.3)	17.6 (0.3)
Skeletal age, years	11.8 (1.0)	12.7 (1.2)	14.0 (1.1)	15.0 (1.1)	16.3 (0.7)	17.1 (0.3)	17.7 (0.2)
Years in training, years	2.5 (0.9)	3.5 (1.2)	4.5 (1.1)	5.5 (1.1)	6.6 (1.1)	7.3 (1.4)	8.2 (1.1)
Annual volume training, h	111.7 (25.8)	141.7 (33.2)	147.7 (52.5)	167.1 (49.2)	168.9 (48.7)	185.2 (46.8)	187.9 (40.8)
Stature, cm	143.1 (6.0)	149.3 (7.1)	158.0 (8.1)	164.9 (7.6)	169.9 (6.4)	172.5 (5.2)	173.7 (4.2)
Body weight, kg	36.4 (5.3)	40.5 (6.4)	47.4 (8.6)	53.7 (8.5)	59.9 (8.6)	64.4 (9.6)	68.0 (9.4)
Fat-free mass, kg	32.2 (3.8)	35.6 (4.9)	41.4 (6.5)	46.7 (6.4)	51.4 (5.4)	54.2 (5.6)	56.8 (6.1)
20-m shuttle run, m	680 (360)	960 (360)	1140 (320)	1320 (380)	1520 (320)	1620 (220)	1720 (120)

Values are mean (standard deviation).

Table 2. Multilevel Regression Analysis of the Aerobic Performance for the Mixed-Longitudinal Data Set Aligned
by Chronological Age

Random Effect		Constant	Centered Chronological Age
Level 1 (within individuals)			
Constant		78.63 (7.71)	
Level 2 (between individuals)			
Constant		181.82 (32.13)	
Centered chronological age		−11.76 (8.17)	15.55 (4.20)
Step	Log Likelihood	Explanatory Variables	At Final Step
1	3296.20	Constant	<0.01	57.75 (2.90)
2	2918.95	Centered chronological age	<0.01	9.06 (0.59)
3	2911.60	Centered chronological age^2	<0.01	−0.57 (0.22)
4	2910.48	Fat-free mass	NS	NA
5	2911.24	Stature	NS	NA
6	2907.70	Annual volume training	<0.05	0.03 (0.02)
	388.50	Deviance from the null model	<0.01	

Random-effects values are estimated mean variance (standard error); fixed-effect values are estimated mean coefficients (standard error). NS, not significant; the variable was removed from the final model; NA, not applicable.

Table 3. Multilevel Regression Analysis of the Aerobic Performance for the Mixed-Longitudinal Data Set Aligned
by Skeletal Age

Random Effect		Constant	Centered Skeletal Age
Level 1 (within individuals)			
Constant		92.12 (8.87)	
Level 2 (between individuals)			
Constant		261.97 (45.87)	
Centered skeletal age		−15.83 (8.95)	11.56 (3.45)
Step	Log Likelihood	Explanatory Variables	At Final Step
1	3296.20	Constant	<0.01	13.03 (8.79)
2	2999.80	Centered skeletal age	<0.01	4.04 (0.90)
3	2995.78	Centered skeletal age^2	<0.05	−0.12 (0.15)
4	2972.12	Fat-free mass	<0.01	0.99 (0.19)
5	2969.40	Stature	NS	NA
6	2968.22	Annual volume training	<0.05	0.03 (0.01)
	327.98	Deviance from the null model	<0.01	

Random-effects values are estimated mean variance (standard error); fixed-effect values are estimated mean coefficients (standard error). NS, not significant; the variable was removed from the final model; NA, not applicable.

[Level 2 of the hierarchy]). The significant variances at Level 1 indicated that the aerobic performance increased significantly at each measurement occasion within individuals (estimate, >2×SE; $P<0.01$). The between-individuals variance matrix (Level 2) indicated that individuals had significantly different aerobic performance growth curves in terms of both their intercepts (constant/constant, $P<0.01$) and slopes of their lines (age/age, $P<0.01$). The variances of these intercepts and slopes were negatively and nonsignificantly correlated (constant/age, $P>0.05$) in the multilevel model. The negative sign of the covariance between intercepts and slopes means that at older age, the improvement of the aerobic performance occurs at a lower rate, and the lack of correlation suggests that individuals with higher intercepts do not necessarily have steeper slopes.

After each explanatory variable was adjusted for covariables, it can be seen that in the multilevel Model 1 (CA as Level 2 predictor, Table 2), centered CA ($P<0.01$), centered CA^2 ($P<0.01$), and annual volume training ($P<0.05$) had significant effects on the aerobic performance of these soccer players. The multilevel Model 2 (SA as Level 2 predictor, Table 3) included centered SA ($P<0.01$), centered SA^2 ($P<0.05$), FFM ($P<0.01$), and annual volume training ($P<0.05$). The power function of centered CA (i.e., centered CA^2) allowed shaping individual curves and then making the model nonlinear. It was also possible to develop equations to obtain estimates of the aerobic performance of young soccer players through the use of the multilevel models considering chronological or biological age: Model 1=57.75+9.06×centered CA−0.57×centered CA^2+0.03×annual volume training; Model 2=13.03+4.04×centered SA−0.12× centered SA^2+0.99×FFM+0.03×annual volume training. For example, in both models, one additional hour of annual training predicts, approximately, a 0.6-m improvement in the aerobic performance test (0.03×20 m).

The predicted mean aerobic performance scores aligned by CA (AE_{CA}) and SA (AE_{SA}) were plotted (Fig.). The predicted values improved with age. Nevertheless, after 15 years of age, small improvements were noted in AE_{CA}. Despite the lower annual gains after the age of 12, the APSA improved continuously until the age of 18.

Discussion

This study developed a multilevel model that better predicts the aerobic performance of adolescent male soccer players taking into account the athlete's chronological age, biological age (i.e., SA), physique, and training. To our knowledge, this is a novel approach. Through the use of multilevel modeling, we were able to model not only the within-subject variation of the aerobic performance with time, but also the variation between subjects while

Fig. Estimated aerobic performance scores aligned by chronological age and skeletal age in young soccer players

simultaneously accounting for other explanatory variables, such as CA, biological age, and training, of which have been shown to contribute to within-subject variation. The multilevel modeling procedure enabled us to separate out the effects of biological maturation while avoiding the errors inherent when using ratio standards and provided the means to study to what extent each factor influenced the pattern of development of the aerobic performance.

A recent longitudinal study (27) investigated the development of the intermittent endurance capacity in a sample of 130 talented Dutch soccer players aged 14–18 years who became professional and nonprofessional in adulthood. Even though the interactions with growth and maturation were not considered, players who reached the professional league showed a differential development pattern compared to their counterparts, and similarly to our results, reported a direct relationship between intermittent endurance capacity and time spent in soccer activities (training plus independent practice). It is known that with growth and training, players can improve their performance by increasing aerobic output during a particular movement (28). Young adults typically show a 15%–20% increase in maximal O_2 uptake with training, although there may be a large intraindividual variation due to genetic factors (29). Despite the arguments and research suggesting that prepubescent children are not capable of improving their endurance performance with training (9), there is much evidence to suggest otherwise (30).

Although the effects of exercise training on prepubescent children remain debatable (31), the prospective part of this study revealed that 1 extra hour of soccer-specific training represented an 0.6-m improvement in the aerobic performance of our athletes. This means that if these players have a regular training season of about 36 weeks (~9-month competitive season) and spend 1 hour extra per week training, a 22-m improvement would be expected. Although Williams and Reilly (32) noted that physiological measurements could not be used reliably on their own for the purposes of talent identification and selection, they also argued that physiological characteristics (such as aerobic performance) might be more influential in successful performance in the future, since contemporary professional soccer will be played at a higher tempo.

Longitudinal data on boys from the Leuven Longitudinal Twin Study suggested a simultaneous regulation of the timing of maximum growth in body dimensions and aerobic fitness during adolescence (33). The results from the Training of Young Athletes (TOYA) study indicated that the maximal O_2 consumption, adjusted for age and body dimensions, increased with a pubertal status in male ath-
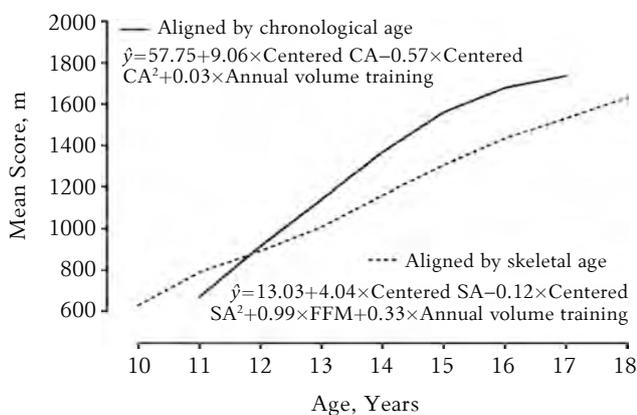
letes (24). In general, the available data indicate that age-related increases in the maximal O_2 consumption are mostly mediated by changes in size dimensions, as the hematological components of oxygen delivery and the oxidative mechanisms of the exercise muscle are related to body dimensions and muscle mass (34, 35). However, the individuality of timing and the tempo of maturation and year-to-year changes in body weight and the maximal O_2 consumption may be masked by maturity effects (17).

Several studies concluded that physical performance is related to anthropometric characteristics, partly because of growth and maturation (5, 8, 35). However, anthropometric characteristics are also related to CA, and FFM and the percentage of body fat can be influenced by training (17). A recent investigation using multilevel modeling showed that within the age range of 11–18 years, both CA and the stage of maturity were explanatory variables of maximal O_2 uptake, independent of body size and fatness (36). In the present study independent of the influence of the anthropometric characteristics, CA and SA had a significant contribution to the improvement of the aerobic performance. Additionally, the importance of variability associated with the biological age on the aerobic performance should be highlighted, even in the latter period of adolescence.

Adolescent male athletes tend to be advanced in skeletal maturation (5, 7, 17). In support of this, the boys in the present sample were advanced in SA relative to CA (Table 1). Changes in aerobic performance when aligned by CA and SA showed 2 distinct patterns (Fig.). The model aligned by CA suggested an initial linear development in aerobic performance toward the end of puberty. After the age of 15 years, the relationship with CA develops in a curvilinear fashion with a lower rate of improvement. This is consistent with the average age of end of peak growth velocity in aerobic endurance (12). The considerable interindividual variation in the SA of athletes of the same CA suggests a more complex relation between biological age and aerobic performance. Specifically, the development of the aerobic performance proceeds nearly linearly between 10 and 18 years of age. Whether this development proceeds linearly after the SA of 18 years is unknown. Future research could examine the development of the aerobic performance of soccer players after age 18 to clarify this issue.

From a practical point of view, routine testing of aerobic performance is easier when it is based on CA. Unavoidably, players who are older have higher endurance than younger individuals; however, the differences in athletic performance should be analyzed carefully because individuals of the same age may show large variations in biological age. This can largely confound the process of talent identification during the adolescent years. Although this study reports an important biological explanation of the aerobic performance, SA assessments are costly and require specialized equipment and interpretation, which may hinder its use in some field situations. Despite the limitation of noninvasive maturity estimates, methods like the prediction of percentage of adult height attained (without SA in the equation) (37) and the prediction of age at peak height velocity using anthropometric measurements (38) may be potentially useful tools in the practical context of sport. It is uncertain if our results can be generalized to other soccer populations, but it should be noted that there was only a slight selection bias as we had a good response rate.

Conclusions

The present study provided relevant developmental models to interpret intra- and interindividual variability in aerobic performance among adolescent soccer players. Aerobic performance was substantially related to chronological age, its power function (i.e., CA^2), and annual volume of training. In parallel, when considering skeletal age, the influence of fat-free mass and annual volume of training on aerobic performance was also apparent. In summary, our models can be used by coaches and physical conditioners to interpret the magnitude of annual gains in aerobic performance of adolescent soccer players.

Statement of Conflict of Interest
The authors state no conflict of interest.

References

1. Di Salvo V, Baron R, Gonzalez-Haro C, Gormasz C, Pigozzi F, Bachl N. Sprinting analysis of elite soccer players during European Champions League and UEFA Cup matches. J Sports Sci 2010;28:1489-94.
2. Stolen T, Chamari K, Castagna C, Wisloff U. Physiology of soccer: an update. Sports Med 2005;35:501-36.
3. Meckel Y, Machnai O, Eliakim A. Relationship among repeated sprint tests, aerobic fitness, and anaerobic fitness in elite adolescent soccer players. J Strength Cond Res 2009; 23:163-9.
4. Rowland TW. Children's exercise physiology. 2nd ed. Champaign, IL: Human Kinetics; 2005.
5. Coelho e Silva MJ, Figueiredo AJ, Simoes F, Seabra A, Natal A, Vaeyens R, et al. Discrimination of u-14 soccer play-

ers by level and position. Int J Sports Med 2010;31:790-6.

6. Cunha G, Lorenzi T, Sapata K, Lopes AL, Gaya AC, Oliveira A. Effect of biological maturation on maximal oxygen uptake and ventilatory thresholds in soccer players: an allometric approach. J Sports Sci 2011;29:1029-39.

7. Figueiredo AJ, Goncalves CE, Coelho e Silva MJ, Malina RM. Youth soccer players, 11-14 years: maturity, size, function, skill and goal orientation. Ann Hum Biol 2009;36:60-73.

8. Malina RM, Eisenmann JC, Cumming SP, Ribeiro B, Aroso J. Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13-15 years. Eur J Appl Physiol 2004;91:555-62.

9. Welsman JR, Armstrong N, Withers S. Responses of young girls to two modes of aerobic training. Br J Sports Med 1997;31:139-42.

10. Edwards AM, Clark N, Macfadyen AM. Lactate and ventilatory thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. J Sports Sci Med 2003;2:23-9.

11. Ahmaidi S, Collomp K, Prefaut C. The effect of shuttle test protocol and the resulting lactacidaemia on maximal velocity and maximal oxygen uptake during the shuttle exercise test. Eur J Appl Physiol Occup Physiol 1992;65:475-9.

12. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, et al. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci 2006;24:221-30.

13. Roche AF, Chumlea CW, Thissen D. Assessing the skeletal maturity of the hand-wrist: Fels method. Springfield, IL: CC Thomas; 1988.

14. Malina RM. Skeletal age and age verification in youth sport. Sports Med 2011;41:925-47.

15. Malina RM, Pena Reyes ME, Figueiredo AJ, Coelho-e-Silva MJ, Horta L, Miller R, et al. Skeletal age in youth soccer players: implication for age verification. Clin J Sport Med 2010;20:469-74.

16. Lohman TG, Roche AF, Martorell R. Anthropometric standardization reference manual. Champaign, IL: Human Kinetics; 1988.

17. Malina R, Bouchard C, Bar-Or O. Growth, maturation, and physical activity. 2nd ed. Champaign, IL: Human Kinetics; 2004.

18. Slaughter MH, Lohman TG, Boileau RA, Horswill CA, Stillman RJ, Van Loan MD, et al. Skinfold equations for estimation of body fatness in children and youth. Hum Biol 1988;60:709-23.

19. Leger LA, Mercier D, Gadoury C, Lambert J. The multistage 20 metre shuttle run test for aerobic fitness. J Sports Sci 1988;6:93-101.

20. EUROFIT. Handbook for the European Test of Physical Fitness. Rome: Council of European Committee for Development in Sports; 1988.

21. Mueller WH, Martorell R. Reliability and accuracy of measurement. In: Lohman TG, Roche AF, Martorell R, editors. Anthropometric standardization reference manual. Champaign, IL: Human Kinetics; 1988. p. 83-6.

22. Slinker BK, Glantz SA. Multiple regression for physiological data analysis: the problem of multicollinearity. Am J Physiol 1985;249:R1-12.

23. Hopkins WG. A scale of magnitudes for effect statistics. A new view of statistics. 2002. Available from: URL: http://www.sportsci.org/resource/stats/index.html. Accessed December 25, 2011.

24. Baxter-Jones A, Goldstein H, Helms P. The development of aerobic power in young athletes. J Appl Physiol 1993;75:1160-7.

25. Rasbash J, Browne W, Goldstein H, Yang M, Plewis I, Draper D, et al. A user's guide to MLwiN. London: Institute of Education; 1999.

26. Baxter-Jones A, Mirwald R. Multilevel modeling. In: Hauspie RC, Cameron N, Molinari L, editors. Methods in human growth research. Cambridge, UK: Cambridge University Press; 2004. p. 306-30.

27. Roescher CR, Elferink-Gemser MT, Huijgen BC, Visscher C. Soccer endurance development in professionals. Int J Sports Med 2010;31:174-9.

28. Elferink-Gemser MT, Visscher C, van Duijn MA, Lemmink KA. Development of the interval endurance capacity in elite and sub-elite youth field hockey players. Br J Sports Med 2006;40:340-5.

29. Bouchard C, Dionne FT, Simoneau JA, Boulay MR. Genetics of aerobic and anaerobic performances. Exerc Sport Sci Rev 1992;20:27-58.

30. Rowland TW, Boyajian A. Aerobic response to endurance exercise training in children. Pediatrics 1995;96:654-8.

31. Rowland TW. Exerciser and children's health. Champaign, IL: Human Kinetics; 1990.

32. Williams AM, Reilly T. Talent identification and development in soccer. J Sports Sci 2000;18:657-67.

33. Geithner CA, Thomis MA, Vanden Eynde B, Maes HH, Loos RJ, Peeters M, et al. Growth in peak aerobic power during adolescence. Med Sci Sports Exerc 2004;36:1616-24.

34. Armstrong N, Welsman JR. Assessment and interpretation of aerobic fitness in children and adolescents. Exerc Sport Sci Rev 1994;22:435-76.

35. Eisenmann JC, Pivarnik JM, Malina RM. Scaling peak VO2 to body mass in young male and female distance runners. J Appl Physiol 2001;90:2172-80.

36. Armstrong N, Welsman JR. Peak oxygen uptake in relation to growth and maturation in 11- to 17-year-old humans. Eur J Appl Physiol 2001;85:546-51.

37. Khamis HJ, Roche AF. Predicting adult stature without using skeletal age: the Khamis-Roche method. Pediatrics 1994;94:504-7.

38. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc 2002;34:689-94.