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Physical Development and Swimming Performance During Biological Maturation in Young Female Swimmers

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A B S T R A C T

The present study analyzed the development of physiological, biomechanical and anthropometrical parameters in young female swimmers and assessed the effect of these parameters on swimming performance during biological maturation. In total, 26 female swimmers participated in the study in which data were annually collected for two consecutive years. Body composition, basic anthropometrical parameters and biological age were measured. During the 400-m front-crawl swimming, the energy cost of swimming and stroking parameters were assessed. Peak oxygen consumption (VO_{2peak}) was assessed by means of the backward-extrapolation technique recording VO_2 during the first 20 sec of the recovery period after a maximal trial of 400-m distance. During the 2-year follow-up study period, age, height, body mass, body fat %, fat free mass, bone mineral mass, total bone mineral density, arm span and biological maturation values significantly increased during each year ($p<0.05$). The tracking of the physical characteristics measured over the 2-year study period was relatively high ($r>0.694$), except for the body fat% ($r>0.554$). The tracking of the Tanner stages was also high ($r=0.759$–0.780). Stepwise regression analyses showed that biomechanical factors ($R^2>0.322$; $p<0.05$) best characterized the 400-metre swimming performance in young female swimmers, followed by bioenergetical ($R^2>0.311$; $p<0.05$) and physical ($R^2>0.203$; $p<0.05$) factors during all three measurement times.

***Key words**: swimming performance, anthropometrics, biomechanics, energy cost*

Introduction

Competitive swimming is a cyclic sport activity performed with the aim of travelling a given distance as fast as possible[1]. In swimming, the performance is influenced by the capacity of generating propelling power and minimizing the resistance to advance in the liquid environment[2]. This occurs with the improvement of the technique, the biomechanical standard and the physical conditioning of the swimmer, including body composition[2].

The maximal performance during front crawl swimming depends on the swimming economy and the maximal metabolic power[3]. Traditionally, energy cost of swimming (Cs) is defined as the total energy expenditure required for displacing the body over a given unit of distance[4–6]. It might be expected that the Cs would change as a young swimmer develops from a child into adulthood, as a consequence of growth, that is changing drag and buoyancy and due to the improvement of the swimming technique[3]. The technical ability of the swimmer and the overall efficiency strongly affect the Cs at a given swimming speed[1]. The energy cost of swimming has usually been assessed by using the ratio of oxygen consumption (VO_2) and the corresponding speed of progression[4,7,8]. Oxygen-consumption values measured during the recovery have been used to extrapolate backward to determine the peak oxygen consumption (VO_{2peak}) during the maximal swimming bout in adults[9] and also in children[10]. There is limited information available about the swimming economy of children[3,10].

In addition, the relationship between the somatic traits, physical capacity, and performance has been a source of interest to scientists[11]. To be successful at the international level of swimming competition, it is be-

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lieved that intensive training must begin before puberty[12]. Participating in a competitive sport at a young age has been associated with a specific body composition and body proportions[13,14]. The processes of growth and maturation are related, and both exert an influence on the physical performance[15]. Several investigations have studied the anthropometric characteristics of successful swimmers[16,17], whereas a number of studies have examined the relationship between these characteristics and the swimming performance[17,18]. An association between body form and stroke length have been found and it was also concluded that parameters such as height, and the cross sectional and surface area may be important to success in swimming[11]. Data on the relationship among physical traits, physical capacity and swimming performance during the pubertal development are extremely limited in young swimmers[11].

Different biomechanical parameters should also be considered as determinants of the swimming performance[19]. Most of the biomechanical studies[20–22] carried out concerned the relationship between the stoke rate (SR), stroke length (SL) and swimming performance. Another parameter often used is the stroke index (SI), considered a valid indicator for swimming efficiency in adults[9] and even in children[10].

The goals of the present investigation were to determine: 1) the development of physiological, biomechanical and anthropometrical parameters in young female swimmers during the biological maturation; and 2) how these parameters affect swimming performance in young female swimmers during the biological maturation.

Methods

Participants

In total, 26 female swimmers participated in the study (Table 1). At the beginning of the study, all subjects had a training background of 3.7 ± 1.8 years and had been training for 6.2 ± 1.9 hrs/week for at least the last 2 years. All children and parents were thoroughly informed of the purposes and contents of the study and a written informed consent was obtained from the parents before participation. This study was approved by the Medical Ethics Committee of the University of Tartu.

Study design

The study was initiated in September 2005 and data were annually measured for two consecutive years. Measurements were taken on three different occasions during the testing period. All children participated at all three measurement time points. At the first visit, the main anthropometrical parameters and biological age were measured[10,23]. The body height was measured using Martin metal anthropometer in cm (±0.1 cm) according to the standard technique and the body mass was measured with minimal clothing with medical electronic scale (A&D Instruments, UK) in kg (±0.05 kg). The body mass index (BMI) was calculated as body mass (in kg) divided by height (in m^2). In addition, arm span was measured to the nearest 0.1 cm[10]. The biological age of the participants was assessed according to the self-assessment using an illustrated questionnaire of the pubertal stage according to the Tanner classification method[24]. The pubertal development assessment according to Tanner method, which uses the self-assessment of breasts and the pubic hair stage in girls, has been previously validated[25]. The participants were given photographs, figures and descriptions, and asked to choose the one that most accurately reflected their appearance. In case of discrepancies between the two variables (breast development and pubic hair stage), a greater emphasis for the determination of the Tanner stage was placed on the degree of the breast development. The second measurement session consisted of maximal 400-m front-crawl swimming test in the swimming pool[10]. During the third measurement session, the body composition parameters were measured using dual-energy X-ray absorptiometry (DXA). Whole-body fat (FM), fat free (FFM), and bone mineral (BM) mass were measured using the DPX-IQ densitometer (Lunar Corp., Madison, WI, USA). The bone-mineral density (BMD) was determined as the total body BMD and at the site of the posterior-anterior spine[10]. The first and second measurement sessions were separated by at least 48 hrs, and the third measurement session depended on the participants' schedules and DXA availability at the hospital.

The maximal 400-m front-crawl swimming test was performed in a 25-m swimming pool, with the start of the trial taking place in the water[10]. In addition, subjects did not perform regular turning motions at the end of the lane but instead resumed swimming immediately without gliding underwater after the turn[3]. Each swimmer performed 400-m swimming at a maximal evenly paced effort[23]. During the test, the Cs and stroking parameters were assessed[3,10]. To exclude the influence of turning and start, the average swimming speed (v; m/s) maintained by each swimmer during the trail was measured over 15 m within two points 5.0 m distance from each end of the pool ($v = D/t_{15}$, where D = 15 m and t_{15} = time for the 15 m)[19,22]. Stroke rate (SR) was measured with the help of the video analysis[20]. Average stroke rate (cycles/min) was the average number of strokes completed by the swimmers during the 15-m distance[21]. Stroke length (SL; m/cycle) value was calculated from the ratio between the average speed and the corresponding stroke rate[21,22]. Stroke index (SI; m^2/s/cycles) was calculated by multiplying the swimming speed by the stroke length[9]. Blood samples for the measurement of blood lactate concentration (La) were obtained from capillary blood samples taken from the finger-tip and analysed using Dr. Lange's enzymatic photometric method (Berlin, Germany) at the third, fifth, and seventh minute during the recovery period to obtain the peak value[26]. The net increase of blood lactate (ΔLa) was obtained by subtracting the pretrial value (equal to 1 mmol/L) from the peak value attained during the recovery phase[3]. The peak oxygen consumption was assessed by means of the backward-extrapolation technique recording VO_2 during the first 20 s of recovery period after the maximal over the 400-m distance[3,7] using a portable open-circuit system (MedGraphics VO200, St. Paul, MN, USA)[10].

Statistical analysis

Data analysis was performed using SPSS 13.0 for Windows (Chicago, IL, USA). Standard statistical methods were used to calculate means and standard deviations (mean ± SD). One-way analyses of variance were used to examine changes over time. Where appropriate, post-hoc analysis was completed with Student's t-test to determine where differences existed. Partial correlation coefficients were used to evaluate associations between different variables of interest after adjustment for the age and pubertal status[23]. Multivariate linear regression analyses were performed to determine the potential associations of swimming performance with different variables of interest[10,27]. The interperiod Spearman correlation coefficients were also used as tracking coefficients[15,28]. All time points were correlated with the baseline measure and additionally, between the second and third measurements[28]. Significance was set at $p<0.05$.

Results

During the 2-year follow-up study period, the age, height, body mass, body fat%, FFM, BM, total BMD, arm span, and biological maturation values significantly increased during each year ($p<0.05$) (Table 1). However, the increases in the FM and spine BMD values between the second and third measurements, and that in the BMI value between the first and second measurement, were not significant ($p>0.05$). Performance time of the 400-metre front crawl swim significantly improved during each year (Table 2). Mean v, SL, SI, and Cs values of the swimming test were significantly improved only at the third measurement, whereas ΔLa was significantly increased after the first measurement and no changes occurred between the second and third measurements. In addition, VO_2 was significantly increased after the second measurement.

A partial correlation analysis revealed that the 400 m performance time was related to the v ($r>-0.873$) and SI ($r>-0.522$) values at all three measurement times. At the same time, the performance time was related to the SL ($r>-0.478$) at the second and third measurement points and to the Cs ($r=0.490$) and VO_2 ($r = -0.551$) values only at the third measurement time after controlling for the age and pubertal status. However, the Cs of the 400-metre swimming performance was significantly related ($p<0.05$) to the body mass ($r>0.411$), BMI ($r>0.412$), and spine BMD ($r>0.500$) values at all three measurement points. In addition, the VO_2 was related to the body mass ($r=0.426$) and BM ($r=0.504$) and the Cs was related to the total BMD ($r=0.584$) at the second measurement. The arm span ($r>0.433$) was related to the SL and the VO_2 ($r>0.406$) was related to the FFM at all three measurement times. The SL was related to height ($r>0.411$), the Cs was related to the FFM ($r> 0.406$) and BM ($r>0.423$), the SI was related to the height ($r>0.460$) and the arm span ($r>0.413$), the VO_2 was related to the total BMD ($r>0.452$) and the spine BMD ($r>0.439$) at the second and third measurements. At the third measurement time, the Cs was related to the v ($r=0.468$), body fat% ($r=0.550$) and FM ($r=-0.463$) values, the SI was related to the total BMD ($r=0.406$) and BM ($r=0.407$) values and the SR was related to the BMI ($r=0.407$) value. All the other relationships assessed at three different time points were not significant ($r<0.398$; $p>0.05$).

The stepwise regression analyses revealed that SI ($R^2>0.449$; $p<0.05$), FFM ($R^2>0.318$; $p<0.05$) and VO_2 ($R^2>0.311$; $p<0.05$) were the best predictors of the 400-m front-crawl swimming performance from the measured biomechanical, physical and bioenergetical parameters at the first and second measurement times, respec-

TABLE 1
MEAN (±SD) ANTHROPOMETRCAL AND BODY COMPOSITION PARAMETERS IN FEMALE SWIMMERS (n=26) OVER THREE YEARS

Variable	First measurement	Second measurement	Third measurement
Age (yrs)	12.7 ± 2.2	13.6 ± 1.9*	14.6 ± 1.9*#
Height (cm)	160.9 ± 9.3	163.0 ± 8.6*	164.7 ± 7.3*#
Body mass (kg)	50.3 ± 9.2	52.8 ± 8.7*	55.8 ± 8.8*#
BMI ($kg.m^{-2}$)	19.5 ± 2.9	19.8 ± 2.6	20.5 ± 2.9*#
Body fat%	20.7 ± 5.7	22.1 ± 5.7*	23.2 ± 6.4*#
FM (kg)	10.0 ± 3.8	10.9 ± 3.5*	12.0 ± 4.4*
FFM (kg)	37.2 ± 6.0	38.9 ± 6.1*	40.1 ± 5.3*#
BM (kg)	2.0 ± 0.4	2.1 ± 0.4*	2.1 ± 0.3*#
Total BMD ($g.cm^{-2}$)	1.03 ± 0.08	1.04 ± 0.08*	1.06 ± 0.06*#
Spine BMD ($g.cm^{-2}$)	0.97 ± 0.15	0.99 ± 0.14*	1.02 ± 0.13*
Arm span (cm)	163.9 ± 9.4	166.4 ± 7.8*	167.7 ± 7.3*#
Tanner stage	2.3 ± 0.8 (1–4)	3.0 ± 0.8* (2–5)	3.5 ± 0.6*# (3–5)

* Significantly different from the first measurement; P<0.05.
# Significantly different from the second measurement; P<0.05.

TABLE 2
MEAN (±SD) BIOMECHANIC AND BIOENERGETIC VALUES OBTAINED FROM THE MAXIMAL 400 METRE FRONT CRAWL SWIM IN FEMALE SWIMMERS (n=26) OVER THREE YEARS

Variable	First measurement	Second measurement	Third measurement
Time (s)	373.9 ± 39.2	366.8 ± 41.6*	354.2 ± 34.4*#
v ($m.s^{-1}$)	1.04 ± 0.10	1.05 ± 0.11	1.09 ± 0.10*#
SL ($m.cycle^{-1}$)	0.94 ± 0.12	0.94 ± 0.13	0.99 ± 0.11*#
SR ($cycle.min^{-1}$)	67.8 ± 5.3	67.9 ± 4.9	66.7 ± 3.9
SI ($m.^2s.^{-1}cycles^{-1}$)	0.99 ± 0.22	1.00 ± 0.24	1.09 ± 0.20*#
Cs ($kJ.m^{-1}$)	1.55 ± 0.46	1.66 ± 0.42	1.72 ± 0.43*#
VO_2 ($L.min^{-1}$)	2.61 ± 0.54	2.68 ± 0.57	2.98 ± 0.58*
ΔLa ($mmol.L^{-1}$)	4.2 ± 2.0	4.8 ± 1.9*	4.8 ± 2.4*

* Significantly different from first measurement; p<0.05.
# Significantly different from the second measurement; p<0.05.

TABLE 3
INTERPERIOD SPEARMAN CORRELATION COEFFICIENTS OF ANTHROPOMETRIC, BODY COMPOSITION, BIOMECHANIC AND BIOENERGETIC VALUES MEASURED IN FEMALE SWIMMERS (n=26) AT THREE TIME POINTS

Variable	First measurement vs Second measurement	Second measurement vs Third measurement	First measurement vs Third measurement
Height (cm)	0.784	0.694	0.715
Body mass (kg)	0.978	0.944	0.927
BMI ($kg.m^{-2}$)	0.937	0.835	0.772
Body fat%	0.800	0.781	0.554
FM (kg)	0.954	0.789	0.760
FFM (kg)	0.962	0.957	0.923
BM (kg)	0.986	0.953	0.932
Total BMD ($g.cm^{-2}$)	0.969	0.884	0.868
Spine BMD ($g.cm^{-2}$)	0.981	0.930	0.884
Arm span (cm)	0.940	0.970	0.900
Time (s)	0.858	0.843	0.809
v ($m.s^{-1}$)	0.941	0.902	0.903
SL ($m.cycle^{-1}$)	0.915	0.861	0.896
SR ($cycle.min^{-1}$)	0.855	0.684	0.687
SI ($m.^2s.^{-1}cycles^{-1}$)	0.878	0.885	0.830
Cs ($kJ.m^{-1}$)	0.644	0.588	0.434
VO_2 ($L.min^{-1}$)	0.645	0.615	0.600
ΔLa ($mmol.L^{-1}$)	0.705	0.530	0.455

tively. At the third measurement point, the SI (R^2=0.322; p<0.05) from the biomechanical parameters measured, the BM (R^2=0.203; p<0.05) from the physical values measured, and the VO_2 (R^2=0.346; p<0.05) from the bioenergetical values measured were the best predictors of 400-metre front crawl swimming performance. According to the stepwise regression analyses, the biomechanical factors (R^2>0.322; p<0.05) characterised best the 400-metre swimming performance in young swimmers, followed by the bioenergetical (R^2>0.311; p<0.05) and physical (R^2>0.203; p<0.05) factors at all three measurement times.

The tracking of the measured physical characteristics over the three-year study period was relatively high (r>0.694), except for the body fat% (r>0.554) (Table 3). The interperiod Spearman correlation coefficients for the 400-metre front crawl swim biomechanical values measured were also relatively high: time (r=0.809–0.858), v (r=0.902–0.941), SL (r=0.861–0.915), SR (r=0.684–0.855) and SI (r=0.830–0.885). In contrast, the tracking of the bioenergetical values was slightly lower: Cs (r=0.434–0.644), VO_2 (r=0.600–0.645) and ΔLa (r=0.455–0.705). Furthermore, in contrast to the measured physical and biomechanical characteristics, the tracking coefficients of the bioenergetical values also decreased increasing with the time interval between the measurements (Table 3).

Discussion

The purpose of the present investigation was to analyse the influence of specific physical, bioenergetical and biomechanical parameters on the swimming performance in biologically maturing young female swimmers. To our knowledge, there are no other studies that have investigated the swimming performance improvement longitudinally taking into account all these parameters in complex. The present results demonstrated that biomechanical parameters best characterised the 400-metre swimming performance in our young female swimmers, followed by the bioenergetical and physical factors at all three measurement times. This demonstrates that the development of sport-specific technical skills is the most important part during the early years of swimming training in young female swimmers. In addition, SI and VO_2 were the best predictors of the swimming performance from the biomechanical and bioenergetical values measured at the three measurement points, respectively. While FFM at the first two and BM at the third measurements points were the most important parameters to characterize swimming performance from the physical parameters measured. The tracking coefficients of the swimming performance time together with the swimming biomechanical characteristics and the physical parameters of swimmers were relatively high, while the tracking of the sport-specific bioenergetical values was lower.

The most important of the present findings was that biomechanical parameters best characterised the 400-metre swimming performance, while the SI was the best predictor characterising swimming performance in young female swimmers. The SI is an indicator of swimming economy since it describes the swimmers ability to move at a given velocity with the fewest number of strokes[9]. In addition, the tracking coefficients of the biomechanical characteristics were relatively high (see Table 3). This indicates that it is important to aim the improving the biomechanical skills during the early years of swimming training in girls. Consistent with this the most rapid growth of the swimming speed occurs from 11 to 13 years of age in boys[27]. A slow increase of the swimming speed at 13–14 years is followed by the second acceleration from 14 to 16 years of age[27]. This was the case also in our girls, where biomechanical characteristics of stroke parameters significantly improved at the third (age: 14.6 ± 1.9 yrs) but not at the second (age: 13.6 ± 1.9 yrs) measurement point. The knowledge of the age particulars and the year-by-year dynamics of stroke parameters may allow us to control and correct the process of the technical preparation of young swimmers[23].

Swimmers usually start serious training at a very early age, and anthropometrical parameters affect swimming performance[10]. Our study, also found that swimmers with good anthropometrical characteristics also have a better swimming time, swimming speed and stroking parameters. The tracking coefficients of the physical parameters were high; hence it is important to pay attention to the selection process of young female swimmers. Anthropometric parameters track highly during puberty[28] and the early biological maturation of swimmers has been attributed to sport-specific selection[26]. In addition, training does not appear to affect young swimmers physical growth and biological maturation[26]. However, young swimmers learn to control the structure and efficiency of movement while they grow up and mature in the process of a 5–7-year training program; during this time they pass through prepubertal stages of ontogenesis when rapid physical growth and motor development take place[27].

It is interesting to note that the Cs was not steadily increased throughout the three measurement points (see Table 2). No differences in Cs was found between the first (age: 12.7 ± 2.2 yrs) and second (age: 13.6 ± 1.9 yrs) measurement points. This indicates that a slow increase in Cs at 12–14 years is followed by the acceleration from 14 to 16 years of age. Accordingly, differences in the Cs could be for the differences in the level of the biological maturation and in the specific stroke parameters of the swimming test in young female swimmers (see Table 2). To date, only a small number of studies[9,22,29] have investigated the relationship between the energetics of swimming and the stroke parameters. It has been suggested that the lower Cs in younger swimmers could be related to specific anthropometric parameters[29]. However, this was not the case in our young female swimmers, which is in accordance with the results of Poujade et al.[22]. In our study, the Cs of the 400-metre swimming performance was significantly related ($p<0.05$) to the body mass ($r> 0.411$), BMI ($r>0.412$), and spine BMD ($r>0.500$) values at all three measurement points. This indicates that the Cs is related to the parameters of the overall growth in the girls.

In contrast to the physical and biomechanical characteristics measured, the tracking coefficients of the bioenergetical values were relatively lower and decreased with the increasing time interval between the measurements (see Table 3). In accordance with our results, it has been suggested that it is rather difficult to predict how the aerobic power may develop throughout the puberty[26]. The growth in the aerobic power is significantly related to the physical growth (i.e., height and body mass) and to the pubertal development[26]. Accordingly, the VO_2 during the 400-m swimming distance was related to the FFM ($r>0.406$; $p<0.05$) at all three measurements time points in young female swimmers. Furthermore, it has been found that at 12 years of age, postpubertal children have greater levels of aerobic power compared to that of prepubertal children, which indicates that the biological age together with the chronological age is an important factor in the development of the aerobic power[31]. Baxter-Jones et al.[26] suggested that specific training effectively increases the aerobic power above the increases normally attributed to the age and to the corresponding physical growth and maturation. This was also the case in our study (see Table 2), where an increase in aerobic power toward the end of puberty was more noticeable.

In conclusion, our results demonstrate that the improvement of swimming performance during the growth and biological maturation was mainly related to the improvement in the biomechanical factors followed by the bioenergetical and physical factors during the 2-year study period in young female swimmers.

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TJELESNI RAZVOJ I PLIVANJE TIJEKOM BIOLOŠKOG SAZRIJEVANJA MLADIH PLIVAČICA

SAŽETAK

Ova longitudinalna analiza proučava razvoj fizioloških, biomehaničkih i antropometrijskih parametara kod mladih plivačica te se fokusira na utjecaj ovih parametara na uspješnost u plivanju tijekom biološkog sazrijevanja. Prikupljani su podaci od 26 mladih plivačica tijekom 2 godine. Mjerena je građa tijela, osnovni antropometrijski parametri i biološka dob. Tijekom isplivavanja kraul tehnikom na 400 metara mjerena je potrošnja energije te parametri zamaha rukom. Najviša točka potrošnje kisika mjerena obrnutom ekstrapolacijom zbila se u prvih 20 sekundi perioda oporavka nakon isplivanih 400 m kraul. Tijekom dvije godine longitudinalnog istraživanja vrijednosti dobi, visine, tjelesne mase, postotka tjelesne masti, bezmasne mase, mineralne mase kosti, sveukupne mineralne gustoće kostiju, raspona ruku i biološkog sazrijevanja značajno su se povećavale svake godine ($p<0,05$). Tjelesne karakteristike bile su relativno visoke ($r>0,694$), izuzev postotka tjelesne masti ($r>0,554$). Vrijednosti Tannerovih stadija također su bile visoke ($r=0,759$–$0,780$). Analiza postupnom regresijom pokazuje da biomehanički faktori ($R^2>0,322$; $p<0,05$) najbolje karakteriziraju uspješnost plivanja na 400 m kod mladih plivačica, zatim bioenergetski ($R^2>0,311$; $p<0,05$) i fizički ($R^2>0,203$; $p<0,05$) faktori tijekom sva tri vremena mjerenja.