Original Article

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Determinants of swimming performance and the physiological development of girls aged 10–12 during three years of swimming training

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Authors' Contribution: A – Study Design, B – Data Collection, C – Statistical Analysis, D – Manuscript Preparation, E – Funds Collection

Abstract: *Introduction:* To achieve success in international sports competition, swimming training must begin prior to the onset of puberty. Scientific studies exploring the relationship between biological traits and athletic performance in children are most often based on cross-sectional designs, which may limit their ability to account for individual developmental variation. *Aims:* (1) To analyze the effects of a three-year swimming training programme on selected characteristics of prepubescent girls who began training without prior selection; (2) to identify which examined variables most strongly influence performance in 50m and 400m front crawl. *Methods:* The experimental group consisted of 14 female swimmers (mean chronological age: 10.48 ± 0.30 years; body mass: 34.99 ± 2.77kg; height: 146.00 ± 3.05cm at baseline) and the control group consisted of 14 girls who participated only in compulsory physical education classes (mean chronological age: 10.52 ± 0.29 years; body mass: 37.93 ± 6.02kg; height: 145.55 ± 3.88cm). Measurements were conducted over three consecutive years. In both groups, body mass and height, maximal oxygen uptake ($\dot{V}O_2max$), vital capacity (VC), forced expiratory volume in one second (FEV_1), and breath-hold time (BHT) were assessed. Additionally, tests of speed and coordination, lower-limb explosive strength, and abdominal muscle strength were performed. The experimental group also completed timed swimming tests of 50m and 400m front crawl. *Results:* The most important determinants of 400m performance were explosive strength and body mass. For the 50m distance, maximal anaerobic power was an additional significant factor. *Conclusions:* Swimming training during the prepubertal period can serve as an effective means of supporting the harmonious physical and functional development of girls, without posing a risk to normal biological maturation.

Keywords: Performance female swimming, swimming performance, prepubertal period, longitudinal study

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INTRODUCTION

Swimming is becoming an increasingly demanding sport every year. Following the ban on cloth swimsuits, coaches began searching for new training methods that would allow athletes to compete at the highest level [1]. It is also worth emphasizing that to achieve success in international sports competitions, swimming training must begin before the onset of puberty [2]. Scientific reports clearly indicate that participating in sports benefits the developing bodies of young people [3–5]. Many corrective exercises aimed at improving posture are performed in the water, and weight management interventions in the aquatic environment can be performed without excessive strain and risk of injury [6]. Most swimming coaches look for children with a specific anthropometric profile (tall, long upper and lower limbs, narrow hips), although these characteristics do not always translate into swimming performance later in development [7–9]. The authors emphasize that well-developed muscular strength and power play a significant role in achieving high swimming performance, especially in sprint events (i.e., 50, a100, and 200 meters) [10]. It should be emphasized that these correlations correlate well with swimming performance in adult (competitive) swimmers, but do not always translate into swimming efficiency in children. This may be due to differences in biological development and initial swimming skills [11].

Very often, the relationship between biological variables and athletic performance is derived from cross-sectional studies, leading to inconsistencies due to individual variability in developmental patterns [3]. Researchers in this field often select young swimmers who have already been selected for the sport, complicating the interpretation of results. This early selection favors tall children with long limbs, a long trunk, large feet, and good aerobic capacity [12]. In the present study, participants began swimming voluntarily, without prior selection based on anthropometric or physiological parameters. Therefore, the results may provide a more accurate picture of the influence of training and natural biological development on performance, regardless of initial selection. This fills an important research gap and highlights the need for longitudinal studies of these processes. To complement traditional statistical approaches, a multivariate model—possibly global—is necessary to provide new insights into changes in swimming performance and the impact of swimming participation on developing organisms, especially during the prepubertal period [13]. Longitudinal studies provide important insights, but few have examined swimming in girls aged 10–12 [9,14–16].

Interventions and phenomena within a specific system can trigger responses in another, seemingly unrelated system [13]. According to the literature, there is a lack of research examining the changes in the correlation between biological characteristics and athletic performance over several years—as well as the influence of individual determinants on specific swimming distances and styles during the prepubertal period. Therefore, the following objectives are justified: (1) to evaluate the effects of a three-year swimming training program on selected variables in prepubertal girls who began swimming without prior selection; and (2) to identify which of the examined variables exert the greatest influence on performance in the 50- and 400-meter front crawl. This knowledge will enhance understanding of the selection process during the prepubertal period and support swimming instructors and coaches in developing long-term training programs that align with natural biological growth and maturation.

MATERIAL AND METHODS

Participants

The study involved a sample of 28 female volunteers. The experimental group consisted of 14 girls (mean chronological age: 10.48 ± 0.30 years; mean body mass: 34.99 ± 2.77kg; mean height: 146.00 ± 3.05cm at the beginning of the study) who trained in swimming at School Sports Clubs in the city of Czestochowa. Recruitment to the sports clubs took place without any form of preliminary selection. At the start of the study (Grade 4 of Primary School), the girls began their swimming training; however, they already possessed basic swimming skills, having participated in swimming lessons twice a week from Grades 1 to 3. The control group consisted of 14 girls (mean chronological age: 10.52 ± 0.29 years; body mass: 37.93 ± 6.02kg; height: 145.55 ± 3.88cm) who attended only compulsory physical education classes. In accordance with the requirements of the Declaration of Helsinki, all participants and their parents were informed about the purpose and methodology of the research. Written consent to participate was obtained, and the study protocol was approved by the Bioethics Committee for Scientific Research at Jan Dlugosz University in Czestochowa (approval number KB-2/2012).

Study Protocol

The research project had an experimental and longitudinal design. The study was conducted over three consecutive years—from autumn 2011 to spring 2014—with measurements taken every six months between 8:00 and 12:00 (a total of six measurements). Each year, the experimental group completed a 35-week training program (Figure 1).

In both groups, body mass and body height were measured using a scale with a stadiometer (WPT 150.0; RadWag; Poland) with an accuracy of 0.1kg and 0.5cm, respectively. To assess the biological maturity index—Maturity Offset (MO)—the simplified formula proposed by Moore for the female population was used [19].

$$MO = -7.709133 + 0.0042232 \times (\text{age} \times \text{height})$$

Respiratory volumes were measured using a Spirobank II spirometer, including vital capacity (VC), forced vital capacity (FVC), and forced expiratory volume in the first second (FEV_1). For VC, participants sat and breathed calmly for several minutes before standing up, taking the deepest possible inhalation, and then exhaling maximally into the spirometer for at least six seconds while wearing a nose clip. The test was repeated three times at 5-minute intervals, and the best result was recorded. FEV_1 was measured using a similar procedure, but participants performed a rapid, forceful exhalation, expelling as much air as possible within one second after assuming a standing position. FVC—representing the total volume of air forcefully exhaled after a maximal inspiration—was measured by instructing participants to take a deep breath while standing and then exhale into the mouthpiece as quickly and completely as possible. Breath-hold time (BHT) was measured at peak inspiratory flow following 10 seconds of hyperventilation.

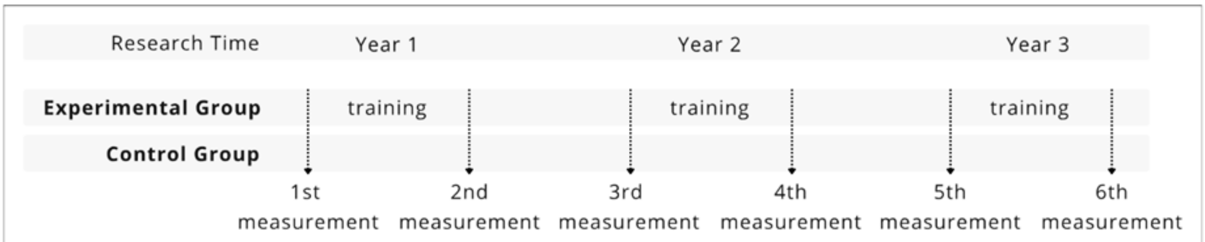

Figure 1. Diagram of the study measurements.

Anaerobic performance was assessed using a standing vertical jump test. The participant stood sideways to a wall (with the dominant hand closest), with the arm fully extended upward, and this standing reach height was marked. She then performed a vertical jump with the knees flexed at 90° and an arm swing, marking the highest point reached. The test was conducted three times without shoes, and the best result was used. Maximal anaerobic power (MAP) was calculated based on jump height (h), body mass (m), and gravitational acceleration ($g = 9.81\ m/s^2$) according to the following formula [20]: $MAP = m \times g \times h$.

The maximal multistage 20-meter shuttle run test (commonly known as the beep test) was used to assess aerobic capacity. This test involved running back and forth over a distance of 20 meters at a pace controlled by audio signals. Participants were required to complete each run within the time dictated by the sound, which became shorter with each successive stage. The initial running speed was 8.5 km/h and increased by 0.5 km/h at every stage. The number of shuttle runs also increased at each level: the first stage required seven runs at a constant pace, the second stage required eight runs, and so on, up to the fourth stage. From stages five to eight, participants completed 10 runs, and from stages nine to thirteen, they were required to complete 12 runs of 20 meters. If a participant failed to reach the line before the next signal, the test was terminated. The total number of successful shuttle runs was recorded.

Based on the speed achieved at the final completed stage and the participant's chronological age, maximal oxygen uptake ($\dot{V}O_2max$)—an indicator of aerobic fitness—was calculated using the equation developed by Léger et al. [21]:

$$\dot{V}O_2max = 31.025 + 3.238 \times P - 3.248 \times W + 0.1536 \times P \times W$$

where
P represents the maximal running speed (km/h) from the last completed stage, and *W* represents chronological age, rounded down to the nearest whole number.

The following motor performance tests were also administered to assess: Lower-limb power (standing long jump). Starting behind a marked take-off line with feet parallel, participants bent their knees, swung their arms backward, and performed a maximal forward jump. The distance from the take-off line to the back edge of the heel at landing was measured in centimetres [22]. Speed and coordination (knee-clap sprint). From a stationary start, participants ran in place for 10 seconds, lifting their knees high and clapping their hands under each raised knee. The total number of claps was recorded as the score[23]. Abdominal muscle strength (horizontal scissors). In a supine position with arms alongside the body, participants lifted both legs just above the ground and performed alternating horizontal "scissor" movements for as long as possible. The duration of the trial was recorded in seconds [24]. The order of the motor tests (standing long jump, standing long jump, knee-clap sprint, horizontal scissors, and the 20-meter multistage shuttle run test) was randomly assigned among the participants. Only one test was performed per day, with a minimum one-day interval between consecutive tests.

The experimental group also performed swimming tests: timed 50m and 400m front crawl. The tests were conducted after approximately 10 minutes of land-based warm-up and 200 meters of front-crawl swimming in the water as part of the familiarization ("warm-up") phase. The order of the swimming assessments was randomized, with only one exertion test performed on any given day, and the rest interval between tests was at least one day. The swimming test results and statistical analyses are presented in Table 3.

The training macrocycle was planned in accordance with the guidelines of the British Swimming Federation for girls aged 9–12 years [25] and consisted of four morning training sessions (Figure 2).

Research Time	Year 1	Year 2	Year 3
Training frequency	35 weeks' 4 sesions / per week	35 weeks' 4 sesions / per week	35 weeks' 4 sesions / per week
Training unit diagram	Warm up: 200-300m Main part: 5x50m only arms 5x50m only legs 5x50m coordination arms/legs 2x100m full style Cool down: 200-300m	Warm up: 300-400m Main part: 6x50m only arms 6x50m only legs 6x50m coordination arms/legs 5x100m full style Cool down: 200-300m	Warm up: 300-400m Main part: 5x100m only arms 5x100m only legs 5x100m coordination arms/legs 4x100m full style Cool down: 200-300m
Total meters covered	1500m / per session	2000m / per session	2500m / per session

Figure 2. Training macrocycle of female swimmers (aged 9–12 years) according to the guidelines of the British Swimming Federation.

Statistical Analysis

The collected data were examined for normality of distribution using the Shapiro–Wilk test. In cases where the test indicated a lack of normal distribution for a given variable, the results were log10 transformed for further statistical analysis. Statistical assessment of differences between the study groups was performed using a two-way ANOVA with repeated measures for the time factor. Swimming test results were evaluated using a one-way repeated measures ANOVA. To assess differences between individual measurements, the Newman–Keuls post-hoc test was applied. The effect sizes of the main effects were evaluated using partial eta squared. Correlations between variables were assessed using Pearson correlation coefficients (r), with a Bonferroni correction applied to avoid Type I error arising from multiple comparisons, thereby reducing the significance level to $p < 0.0006$. The contribution of individual variables to swimming performance was estimated using stepwise multiple regression analysis with backward elimination. Only variables that significantly correlated with the dependent variable were included in the analysis. All calculations were performed using Statistica 12.0 (Statsoft, Poland). Measurement results are presented as arithmetic means and standard deviations (±SD) or, when distributions were not normal, as medians (M) and interquartile ranges (IQR). In all cases, except for multiple comparisons, the level of statistical significance was set at $p < 0.05$.

RESULTS

At the start of the study, girls in both the experimental and control groups did not differ in terms of biological maturity (BM). Throughout the study period, no differences were observed in the increase of this index between the groups (Table 1). At the beginning of the experiment, the group of swimmers did not differ statistically from the control group in chronological age, body mass, or height. After the three-year study period, the experimental group exhibited a higher body mass ($p<0.05$) than the swimming-trained group, with this difference becoming significant from the third measurement onwards (Table 1). At the start of the study, no differences between the groups were observed for forced expiratory volume in the first second (FEV1) or vital lung capacity (VC). From the second year of the study, the vital capacity of swimmers began to increase significantly– by the end of the study, swimmers had a markedly higher VC than the non-training group ($p<0.001$). The results also showed an increasing difference between swimmers and non-swimmers in terms of breath-hold time (BHT), from $p<0.01$ to $p<0.001$ (Table 1). The three-year observation revealed no differences between the groups in maximal anaerobic power (MAP) or maximal oxygen uptake ($\dot{V}O2max$), although the swimming group already exhibited a significantly higher $\dot{V}O2max$ at the beginning of the study ($p<0.001$). This difference remained unchanged throughout the experiment (Table 1). At the start of the study, the swimmer group demonstrated significantly greater speed and coordination than the control group ($p<0.005$). In the second, third, and fourth measurements, no significant differences were observed between the groups; however, in the final year of the study, swimmers again displayed significantly greater speed and coordination ($p <0.05$ and $p <0.005$, respectively). The largest differences were observed in the standing long jump results– swimmers achieved significantly greater distances than the non-swimming group starting from the second measurement (measurement 2 – $p<0.05$; measurements 3, 4, 5, and 6 – $p<0.01$). Differences between groups in abdominal muscle strength ("cross scissors" test) were significant only in the first measurement, favouring the swimmers ($p <0.05$) (Table 1).

Repeated measures ANOVA revealed that significant variability over time (main effect of the Time factor) was observed for all measured variables except BHT and $\dot{V}O2max$. Group membership (main effect of the GROUP factor) significantly influenced the outcomes for body mass, VC, BHT, $\dot{V}O_2max$, running in place with clapping, standing long jump, and the "cross scissors" test. Significant dynamics of variability (interaction effect) were observed for eight variables: body mass, height, FEV1, VC, MAP, $\dot{V}O_2max$, standing long jump, and chronological age (Table 1). Figure 3 illustrates the trajectories of changes in all measured variables between the first, third, and final measurements over the three-year study period.

The results of the swimming tests at both distances improved with each measurement (main effect of the Time factor). However, post-hoc analysis showed significantly greater differences between consecutive results of swimmers only for the short-distance test – 50m crawl (Table 2).

The correlation analysis showed that, over the three-year study period, there was a negative correlation between the mean results in the 50m crawl and seven measured variables: body mass, body height, biological maturity offset (MO), maximal anaerobic power (MAP), maximal oxygen uptake ($\dot{V}O_2max$), lower-limb explosive strength (standing long jump distance), and chronological age. This indicates that, as the values of the above variables increased, performance in the short-distance swimming test improved significantly. For the 400m crawl, the correlation analysis demonstrated that performance improved with increases in five variables: body mass, body height, biological maturity offset (MO), lower-limb explosive strength, and chronological age (Figure 4).

According to the results of the multiple regression analysis performed using the stepwise backward method, the most important factors determining 50m crawl performance in 12-year-old girls were standing long jump distance ($p< 0.001$), body mass ($p< 0.05$), and maximal anaerobic power (MAP) ($p< 0.05$). In contrast, the most important determinants of 400m crawl performance were body mass ($p< 0.001$) and standing long jump distance ($p< 0.005$) (Table 4).

Table 1. Summary of six consecutive measurements of the studied variables in the experimental group (N= 14) and the control group (N= 14). Values are presented as x ± SD for normally distributed variables or as M (IQR) for variables with non-normal distribution.

Variable	Group	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	G	T	G x T
Body mass (kg)	S	34.986 ± 2.772	36.579 ** ± 2.608	37.900 ± 2.723	40.136 *** 2.723	42.793 *** 3.750	44.650 *** ± 4.000	F=9.87 p=0.040 n^2_p=0.275	F=189.46 p=0.001 n^2_p =0.879	F=3.38 p=0.007 n^2_p =0.115
	C	37.929 ± 6.020	41.229 *** ± 6.335	43.893 *** ± 7.037	46.943 *** ±6.293	50.100 *** ± 5.740	54.800 *** ± 9.200			
	p	>0.05	>0.05	<0.05	<0.05	<0.01	<0.05			
Body height (cm)	S	146.000 ± 3.045	149.429 *** ± 3.333	151.929 *** ± 3.902	155.964 *** ± 4.601	159.714 *** ± 5.395	163.571 *** ± 5.306	F=0.44 p=0.512 n^2_p=0.017	F=578.57 p=0.001 n^2_p=0.957	F=3.08 p=0.012 n^2_p=0.106
	C	145.536 ± 3.875	149.107 *** ± 3.928	151.214 *** ± 4.223	155.286 *** ± 4.246	158.250 *** ± 4.835	160.857 *** ± 5.304			
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05			
MO (years)	S	-1.242 ± 0.253	-0.792 *** ± 0.262	-0.449 *** ± 0.284	-0.141 *** ± 0.336	0.594 **** ± 0.398	1.200 *** ± 0.987	F=0.124 p=0.728 n^2_p =0.005	F=3059.67 p= 0.001 n^2_p=0.992	F=2.059 p= 0.075 n^2_p =0.073
	C	-1.241 ± 0.254	-0.801 *** ± 0.280	-0.488 *** ± 0.275	0.095 *** ± 0.288	0.571 *** ± 0.343	1.073 *** ± 0.352			
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05			
Chronological age (years)	S	10.487 ± 0.296	10.960 *** ± 0.290	11.314 *** ± 0.283	11.916 *** ± 0.286	12.306 *** ± 0.301	12.973 *** ± 0.473	F=0.0 p=0.839 n^2_p=0.002	F=10303.8 p=0.001 n^2_p=0.997	F=3.8 p=0.003 n^2_p=0.126
	C	10.524 ± 0.292	10.970 *** ± 0.303	11.307 *** ± 0.286	11.901 *** ± 0.295	12.389 *** ± 0.302	12.927 *** ± 0.296			
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05			
FEV1 (l)	S	1.658 ± 0.402	1.743 ± 0.458	1.670 ± 1.280	1.715 ± 0.536	1.765 ± 0.524	1.797 ± 0.467	F=3.017 p=0.094 n^2_p=0.104	F=2.288 p=0.050 n^2_p=0.081	F=4.399 p=0.001 n^2_p=0.145
	C	1.647 ± 0.287	1.536 ± 0.296	1.464 ± 0.460	1.392 ± 0.445	1.235 ± 0.410	1.235 ± 0.350			
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05			
VC (l)	S	2.245 (0.300)	2.341 ± 0.294	2.484 * ± 0.349	2.651 * ± 0.378	2.774 ± 0.354	2.830 ± 0.321	F=14.121 p=0.001 n^2_p=0.352	F=12.213 p=0.001 n^2_p=0.320	F=8.878 p=0.001 n^2_p=0.255
	C	2.049 ± 0.396	2.065 ± 0.376	2.069 ± 0.388	2.082 ± 0.400	2.092 ± 0.401	2.086 ± 0.398			
	p	>0.05	>0.05	>0.05	<0.05	<0.001	<0.001			
BHT (s)	S	54.132 ± 14.038	56.695 ± 12.785	54.302 ± 13.775	56.200 ± 10.857	61.355 ± 9.412	65.411 ± 7.482	F=34.137 p=0.001 n^2_p=0.568	F=1.854 p=0.107 n^2_p=0.067	F=1.889 p=0.101 n^2_p=0.068
	C	36.474 ± 9.820	35.015 (6.840)	36.941 ± 10.965	37.319 ± 12.720	38.021 ± 11.864	36.992 ± 11.455			
	p	<0.01	<0.001	<0.01	<0.001	<0.001	<0.001			
MPA (J)	S	96.091 ± 19.053	107.206 * ± 18.824	105.516 ** ± 19.661	120.562 * ± 18.450	133.191 * ± 25.056	148.142 * ± 22.710	F=0.354 p=0.557 n^2_p=0.013	F=58.745 p=0.001 n^2_p=0.693	F=2.961 p=0.015 n^2_p=0.102
	C	94.070 ± 20.423	109.218 ± 22.748	123.654 ± 32.593	132.483 ± 31.625	137.622 ± 33.430	144.487 ± 35.126			
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05			
VO2max (ml*kg*min)	S	47.479 ± 3.479	47.897 ± 3.575	49.179 ± 4.359	49.491 ± 4.789	51.315 * ± 3.574	51.300 ± 3.386	F=108.1 p=0.001 n^2_p=0.806	F=1.4 p=0.220 n^2_p=0.052	F=13.2 p=0.001 n^2_p=0.337
	C	39.124 (2.387)	39.124 (4.329)	39.385 (4.329)	39.033 ± 2.249	38.767 ± 2.667	37.530 * ± 2.518			
	p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001			
Running in place with claps (no of claps)	S	24.714 ± 3.024	25.857 ± 2.282	26.357 ± 2.205	27.571 ± 2.472	28.643 ± 2.373	29.857 ± 1.657	F=13.19 p=0.001 n^2_p=0.337	F=28.75 p=0.001 n^2_p=0.525	F=1.22 p=0.301 n^2_p=0.045
	C	21.429 ± 3.956	22.500 ** (4.000)	24.286 * ± 24.571	25.571 ± 2.623	25.143 ± 2.445	25.286 ± 2.400			
	p	<0.01	>0.05	>0.05	>0.05	<0.05	<0.05			
Standing long jump (m)	S	1.394 ± 0.143	1.482 * ± 1.482 (a)	1.566 * ± 0.146	1.636 ± 0.147	1.664 ± 0.139	1.688 ± 0.120	F=25.451 p=0.001 n^2_p=0.495	F=12.737 p=0.001 n^2_p=0.329	F=8.631 p=0.001 n^2_p=0.249
	C	1.300 ± 0.143	1.287 ± 0.113	1.251 ± 0.135	1.291 ± 0.243	1.320 ± 0.253	1.334 ± 0.238			
	p	>0.05	>0.05	<0.001	<0.001	<0.001	<0.001			
Cross scissors (s)	S	44.091 ± 24.671	42.434 (24.560)	45.715 (24.730)	57.854 ± 30.629	63.117 ± 30.509	64.691 ± 28.544	F=11.205 p=0.002 n^2_p=0.301	F=15.524 p=0.001 n^2_p=0.374	F=0.171 p=0.973 n^2_p=0.007
	C	17.610 (14.910)	25.444 * ± 12.175	27.618 ± 11.841	31.051 ± 15.297	33.394 ± 14.305	35.484 ± 14.171			
	p	<0.05	>0.05	>0.05	>0.05	>0.05	>0.05			

G - Main effect of Group , T - Main effect of Time ; G x T – Interaction Group x Time; S – Swimmers group, C – Control group; * – comparison with the previous measurement (* – p<0.05; ** – p<0.01; *** – p<0.001); p – statistical significance; n^2_p – effece size

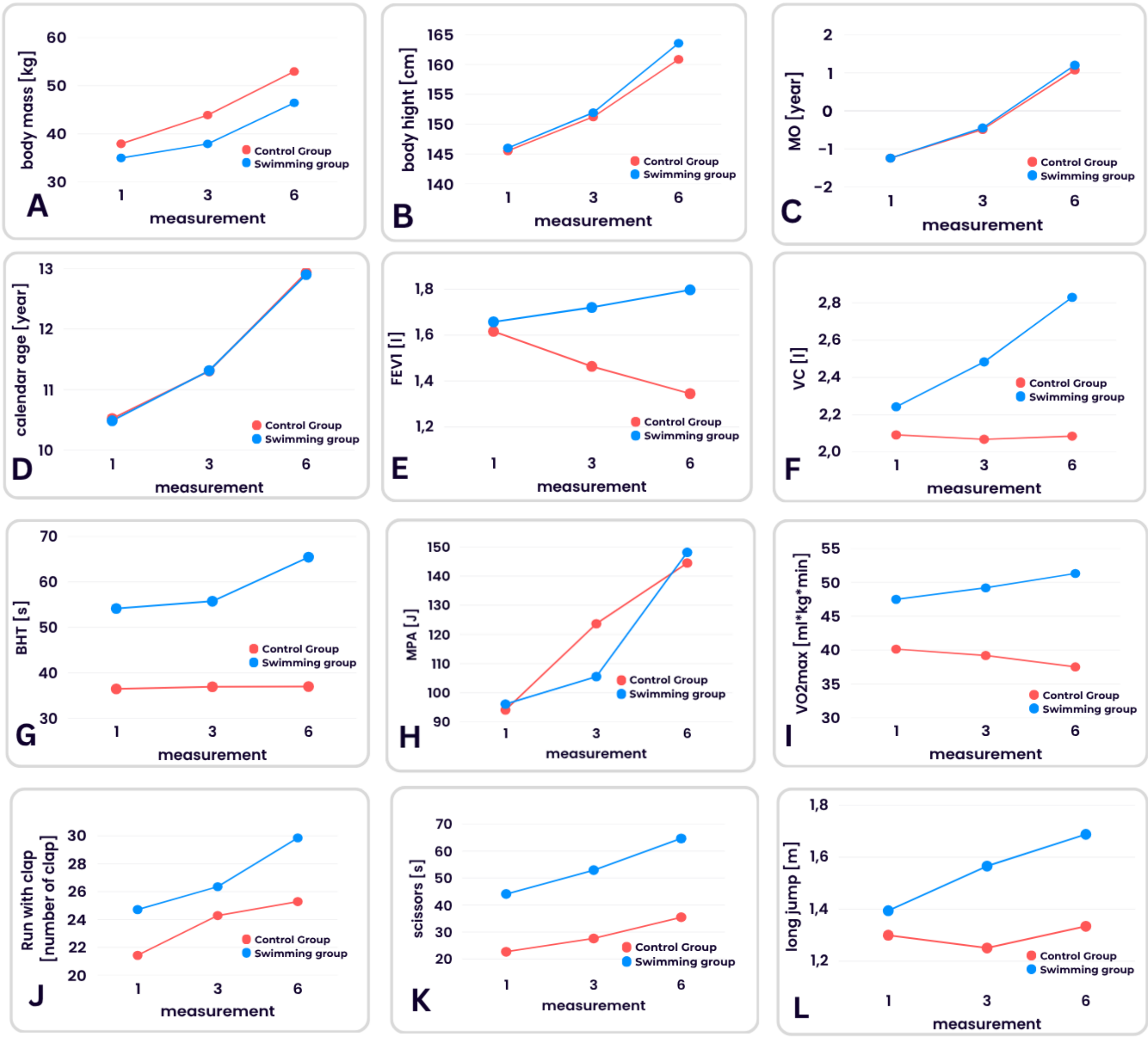

Figure 3. Mean trajectories of measured parameters over the 3-year study period. (A) Body mass [kg]; (B) Body height [cm]; (C) MO [years]; (D) Chronological age [years]; (E) FEV1 [L]; (F) VC [L]; (G) BHT [s]; (H) MAP [J]; (I) $\dot{V}O_2max$ [ml·kg^{-1}·min^{-1}]; (J) Running in place with claps [number of claps]; (K) Scissors test [s]; (L) Standing long jump [m].

Table 2. Summary of swimming test results in the experimental group (N= 14). Values are presented as x ± SD for normally distributed variables or as M (IQR) for variables with non-normal distribution

Variable	Time 1	Time 2	Time 3	Time 4	Time 5	Time 6	Main effect of Time
50m (s)	46.110 (12.980)	46.680 ** ± 9.469	43.478 * ± 8.545	38.830 * (8.510)	37.618 ** (3.594)	36.321 3.368	F= 40.437 p=0.001 n^2_p = 0.757
400m (s)	484.220 (165.320)	501.451 ± 124.641	464.040 ± 66.553	441.401 ± 49.683	422.900 ± 38.854	414.332 ± 46.025	F=10.76 p=0.001 n^2_p = 0.453

* – comparison with the previous measurement (* – p< 0.05; ** – p< 0.01; *** – p< 0.001)

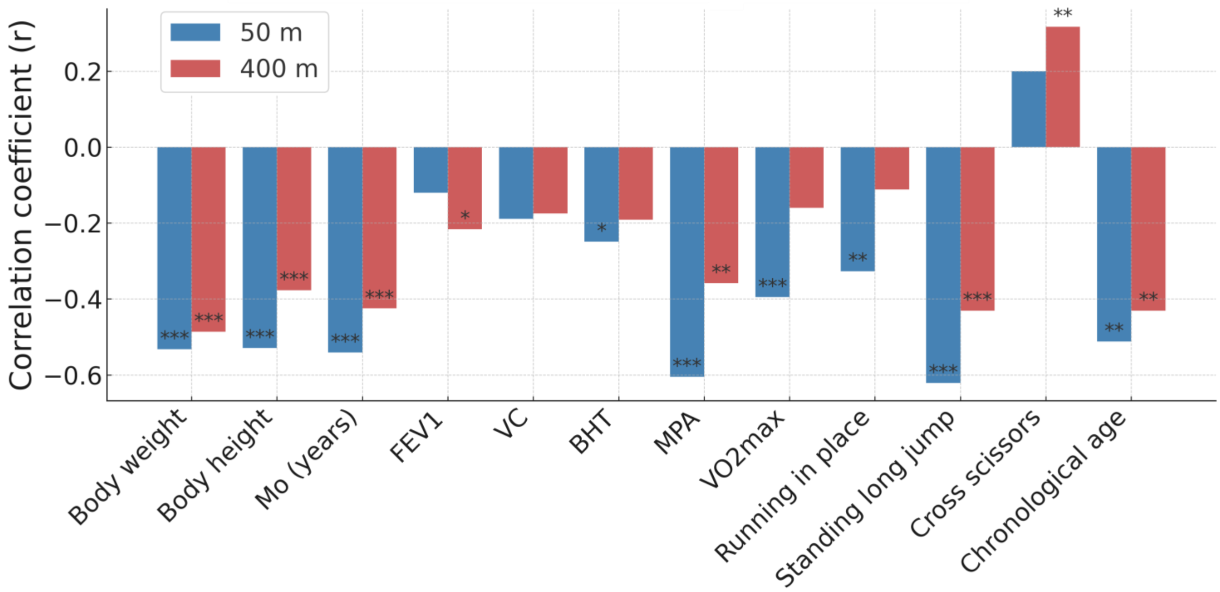

Figure 4. Summary of Pearson correlation analysis between the measured variables and swimming test results.

Table 4. Results of multiple regression analysis for swimming test outcomes as dependent variables

Dependent variable	R^2	SE	Independent variable	β ± SE	B ± SE	p
50m (s)	0.531	0.059	Standing long jump (m)	-0.366 ± 0.097	-0.654 ± 0.174	p<0.001
			Body mass	-2.278 ± 0.103	-0.233 ± 0.086	p<0.05
			MPA	-0.237 ± 0.091	-0.383 ± -0.146	p<0.05
400m (s)	0.308	0.073	Body mass	-0.364 ±0.102	-0.601 ±0.168	p<0.001
			Standing long jump	-0.295 ±0.102	-0.540 ± 0.186	p<0.005

DISCUSSION

The effect of physical activity on aerobic capacity has been extensively studied in adults; however, there is limited evidence in healthy children, particularly girls [7]. Studies examining the effects of endurance training in children estimate that VO_2max increases by a maximum of 5–6%. Considering only studies demonstrating a significant training effect, the average improvement in VO2max increases to 8–10%. These findings suggest that an intensity greater than 80% of maximum heart rate is required to achieve a significant increase in peak VO_2max [26].

In this three-year study, no differences were observed between the experimental and control groups in maximal oxygen uptake. This lack of change may be attributed to the low intensity and duration of the training sessions, consistent with previous reports [9]. Furthermore, genetic factors may contribute to the lack of change in VO_2max during prepuberty. According to the literature, exercise training accounts for only about 30% of the variability in $\dot{V}O_2max$, while 70% is influenced by other factors [26]. In this study, the lack of between-group differences in $\dot{V}O2max$ did not correspond to the results of the breath-hold test (BHT). It is known that breath-hold time is significantly associated with aerobic capacity. Long-term follow-up in the present study showed an increasing difference in BHT between the swimming group and the control group. This is related to the characteristics of aquatic sports, as swimmers frequently hold their breath during training sessions, which causes transient hypoxia [27]. No significant differences were observed in measures of anaerobic capacity between the swimming and non-swimming groups. This suggests that during prepuberty, the development and improvement of anaerobic capacity may be limited due to the underdeveloped energy pathways for anaerobic metabolism. Studies conducted on older swimmers indicate an increase in anaerobic capacity compared with non-swimmers [28]. Using the 30-second Wingate test [29], no differences in anaerobic capacity were found between 11-year-old boys who were trained in swimming and a control group. Limited research is available for prepubertal girls, suggesting that changes in anaerobic capacity compared with their non-swimming peers require further investigation. The swimming group demonstrated improved strength, speed, and coordination compared with their non-swimming peers. This is consistent with reports indicating a strong relationship between muscular strength and power and swimming performance [11]. Lower limb and hip muscle function is a key driver of swimming performance, meaning these muscle groups are more stimulated to develop in children who practice swimming [30]. Explosive lower limb strength (measured by the standing long jump) increased significantly in the experimental group compared to the control group. Although the swimming program was primarily aimed at improving endurance, strength gains were still observed in the swimming group. In adults, simultaneous training for endurance, strength, and power can lead to molecular signaling conflicts in muscle cells, preventing simultaneous improvement [31]. However, in prepubertal children, simultaneous training for strength, power, and endurance leads to simultaneous improvement in these abilities [32]. This may be attributed to neurological mechanisms, including increased motor neuron recruitment, which allows for strength gains without significant muscle hypertrophy [33]. Moreover, during training tasks – especially aerobic ones – swimmers perform powerful leg kicks during starts and turns, movements similar to a standing long jump, which can increase explosive lower limb strength even during endurance training.

The three-year swimming training program did not affect the rate of biological maturation in girls. Biological maturity (BMP) refers to the number of years before or after reaching peak height velocity (PHV), considered the maximum growth spurt during puberty [19]. According to the results, both girls in the experimental and control groups were prepubertal at the beginning of the study and showed no differences in the rate of biological maturation throughout the study. The main factor determining whether to perform the 50-meter front crawl was The girls' greatest achievement was the standing long jump. Studies conducted on 12- to 14-year-old boys showed that sprint performance was primarily influenced by upper limb length, horizontal jump, and grip strength, whereas in girls of the same age, the key factors were body height, hand length, and horizontal jump [17]. In this study, the effect of the standing long jump (explosive lower limb strength) could be explained by the dynamic starts and turns performed over 25 m, which account for approximately 30% of the total race time in the final result [34,35]. Another factor determining performance in the 50 m freestyle was body mass. The literature indicates that swimming does not significantly change body mass compared to non-swimmers, but it helps prevent excessive weight gain, which is desirable in swimming because lower body mass reduces water resistance, especially frontal drag [36]. In the present study, increased body mass in the experimental group improved performance in the 50-meter front crawl, likely due to greater muscle mass and, consequently, stronger upper limb pull during underwater phases, starts, and turns [37]. A third important factor was maximal anaerobic power. Short-duration efforts rely heavily on anaerobic energy systems, which contribute several times more to metabolic output than aerobic metabolism [38,39]. In the 400-meter freestyle race, body mass was the most important determinant, consistent with other studies highlighting anthropometric characteristics such as body mass, height, and upper limb length as key factors influencing swimming performance [40]. However, the literature on the influence of body mass on endurance performance in prepubertal girls is limited, warranting in-depth analysis. The second determinant of 400-meter performance was the standing long jump distance. The influence of lower limb explosive power on 400-meter performance may be related to the nature of swimming training. Lower limb and hip muscles are crucial for propulsion, and prepubertal swimmers experience greater stimulation of these muscles [30].

The results of this study should be interpreted with several methodological limitations in mind. The relatively small sample size limits the generalizability of the results to a broader population of prepubertal girls. Environmental factors such as diet, sleep, and physical activity outside of training were not controlled and may have influenced biological maturation and physiological adaptations. Spontaneous physical activity levels were not assessed in the control group, which may have hampered comparisons between groups.

LIMITATIONS

Several limitations of this study should be acknowledged. First, the sample size was relatively small (N = 14). Although post hoc analysis using G*Power software (version 3.1.9.2; University of Cologne, Germany) indicated that a minimum of 12 measurements would be sufficient for $\alpha = 0.05$. No confounding factors were found in the coordination results: socioeconomic status of the participants, genetic predisposition, participation in other physical activities, and coordination testing in land conditions, which may be relevant to the variables studied. Factors such as diet, motivation, and environmental conditions were not taken into account in the participants' cases. Pubertal control was determined based on biological age calculations.

CONCLUSION

A three-year swimming training program in girls aged 10–12 years positively influences the development of morphological traits, respiratory function, and selected motor abilities, particularly lower-limb power, coordination, and abdominal muscle endurance. The strongest determinants of 50m crawl were lower-limb power, body mass, and maximal anaerobic power. For endurance performance (400m crawl), the key determinants were body mass and lower-limb power. Biological maturity (MO) did not differ significantly between groups and was not influenced by participation in swimming training, suggesting that swimming at this age neither accelerates nor delays biological maturation. Swimming training in the prepubertal period can be an effective tool for supporting harmonious physical and functional development in girls without risk of disrupting biological development. From a coaching perspective, the findings indicate that training young swimmers should emphasize the development of lower-limb power and appropriate loading to enhance anaerobic power, while maintaining balance with technical and endurance training.

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