DOI: 10.37190/abb/221220

Analysis of selected physiological, kinematic, strength and anthropometric indices influencing 200-m front crawl performance of young female swimmers

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Submitted: 27th January 2026

Accepted: 29th April 2026

Purpose: The swimming results of girls during puberty are determined by the level of physical development, general fitness and swimming skills modeled in the training process. The aim of this study is to examine the relationship between swimming speed at 200 m front crawl (v_{200}) and several of physiological (1minVO_2), strength (CMJ - counter movement jump, tethered swimming force), stroke kinematics (*SR* – stroke rate, *SL* – stroke length) considering biological age (*BA*). **Methods:** A total of forty-four female swimmers (mean age: 13.45 ± 0.85 years; height: 165 ± 6.16 cm; body mass: 53.2 ± 6.79 kg; biological age: 14.99 ± 2.27 years) participated in the study. All participants went through: *BA* assessment, 1 minute tethered swimming test with pulling force and oxygen uptake (breath-by-breath) measurements. Each participant performed *CMJ* test on force plate. On the basis of 200 m front crawl race was recorded and kinematic variables were calculated (v_{200}, *SR*, *SL*). **Results:** Stepwise multiple regression revealed that stroke kinematics (*SR*, *SL*), height of *CMJ* (*CMJh*) and biological maturation level (*BA*) are key factors, with strongest correlation to 200 m front crawl swimming speed explaining 95% of all results. Nevertheless, factors modeled in swimming training, such as swimming stroke kinematics (*SR*, *SL*), explained 93% of the results. **Conclusions:** Performance is determined by technical ability to apply force in the water represented by stroke kinematics, which is indirectly influenced by overall strength abilities and aerobic conditioning. Young swimmers, especially early mature should benefit from higher in- water strength (60F_{max}), *SL* and oxygen uptake (1minVO_2).

Key words: multiple regression models , female adolescents, oxygen uptake, stroke kinematics, tethered swimming

Introduction

Swimming performance at young age is a multifactorial construct influenced by psychological, anthropometric, genetic, motor control, and environmental factors [6], [16], [20], [23], [26]. Santos et al. [30] reported that the top swimmers at age-group level presented better stroke mechanics (technique) and applied greater amount of force, resulting in better propulsion in comparison to less experienced/ trained swimmers. Meanwhile, Abbott et al. [1] concluded that youth swimming is determined by technique and anthropometrics (body dimensions). Hogan et al. [12] analyzing data collected over 600 of youth female swimmers at age 10-15 observed that performance advantages associated with maturation are widely observed up to 13 years of calendar age.

In front crawl races, the 200 m event is the one in which a balance between well-developed aerobic and anaerobic metabolism provides the best results [5], [10]. Geithner et al. [11] study that aerobic power is closely associated with pubertal development and growth in adolescent swimmers, and that the highest velocity of peak $\dot{V}O_2$ development was observed at 12.3 ± 1.2 years of age among female swimmers. During a swimming race, aerobic metabolism contributes approximately 30–45% of total energy production within the first minute and accounts for over 70% of all energy sources in the 200 m front crawl among females [3]. Sousa et al. [35] observed that during a 200 m front crawl race, oxygen uptake values reached very high levels after the first 50 m lap. These high oxygen uptake values were then maintained for almost the entire race by many subjects. They also stated that, during extreme efforts such as the 200 m front crawl, the $\dot{V}O_2$ slow component did not occur. Unnithan et al. [39] showed no significant correlation between peak $\dot{V}O_2$ ($L \cdot min^{-1}$) and swimming time but there were relationship between relative $\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$) and 200-m front crawl race.

Somatic growth and biological maturation in adolescent swimmers lead to substantial anthropometric changes, which in turn influence technical characteristics and overall swimming performance [21], [31]. Swimming technique and efficiency commonly quantified using stroke rate (*SR*), stroke length (*SL*), and stroke index (*SI*) is widely recognized as a key determinant of performance during adolescence [16], [37]. Advancements in swimming technique are predominantly driven by long-term, structured training programs that incorporate systematic technical drills performed under varying conditions [34].

Tethered swimming is a reliable and commonly used method for assessing in-water strength capabilities in young swimmers, despite the fact it presents some limitations e.g. a lack of horizontal displacement during the propulsive movements [38]. Tethered swimming strength is associated with anaerobic capacity and performance in short- and middle-distance swimming events [28]. The pubescent period, encompassing ages 12–14 years in girls and 14–16 years in boys, is characterized by intensive development of muscular strength and the anaerobic energy system [40]. Some researchers [22], [25] suggest that tethered swimming strength testing is a measurable and relatively easy-to-use tool in developing swimmers. This can be attributed to swimmers' strength capabilities, as the force generated in water constitutes a key factor underlying improvements in swimming performance [4].

The aim of this study was to identify, among a range of anthropological, physiological, and biomechanical indices, those that most strongly explain 200 m front crawl performance of young female swimmers. Additionally, the study examined whether including biological age (*BA*) changes the explanatory power of the proposed models.

Material and methods

Participants

Forty-four female swimmers (mean age: 13.45 ± 0.85 years; height: 165 ± 6.16 cm; body mass: 53.2 ± 6.79 kg; biological age: 14.99 ± 2.27 years) participated in the study. Participants were recruited from the highest-performing swimmers within their age category in the Cracow region, Poland. Their competitive level was reflected by a mean performance of 412 ± 22 FINA points in the 200 m front crawl event, corresponding to the fifth performance threshold according to the Ruiz-Navarro swimming level classification [29].

The study was approved by the Bioethics Committee of the Regional Medical Chamber (approval No. 94/KBL/OIL/2020). All participants were clinically healthy and held valid licenses issued by the Polish Swimming Federation. The swimmers included in the study had completed 5–6 years of systematic training, currently engaging in at least eight training sessions per week, and regularly participated in national-level competitions and national age-group swimming championships. Written informed consent was obtained from all participants and their parents, who were informed about the study protocol and testing procedures. The tests were conducted in the following order:

Day 1: 1) anthropometric measurements, 2) counter movement jump, 3) A 1 minute tethered swimming test with pulling force and oxygen uptake assesement

Day 2: 200 m front crawl race with subsequent video analysis

Biological age

Biological age (*BA*) was assessed by an experienced anthropologist and calculated as:

$$\mathrm{BA} = \frac{(BHage + BMage)}{2}$$

where *BHage* represents the age corresponding to body height percentiles and *BMage* represents the age corresponding to body mass percentiles. Standardized and validated growth charts developed by The Children's Memorial Health Institute for the Polish population were used, with the 50th percentile applied to align height and body mass with chronological age.

200 m front crawl race

The 200 m front crawl race was performed in a 25 m swimming pool compliant with World Aquatics regulations. The standardized warm-up consisted of dry-land exercises followed by a 1000 m in-water component. Races were conducted with groups of three to five swimmers simultaneously to replicate competitive conditions.

Final race times and split times were recorded using an automatic timing system (Omega, Switzerland; OCP5, StartTime V). Swimmers started from the starting blocks in response to an acoustic signal. All trials were video recorded using a JVC GC-PX100BE camera (Japan) operating at a frame rate of 50 Hz. The camera was mounted on a tripod positioned 7 m above the water surface, on an extension aligned with the midpoint of the pool. Markers were placed along the side of the pool to indicate the 7 m distance from each wall, resulting in 11 m surface swimming zone. Kinematic indices related to technique and efficiency (*v*, *SR*, *SL*, *SI*) were calculated on the basis of video recording for each 50 m lap and then averaged across the 200 m race. The mean *SR* (cycles·min^{-1}) was determined from 12 stroke cycles, including 3 cycles from four 50 m laps measured within the surface swimming zone. *SL* was calculated for the 11 m surface swimming zone during each of the 4 laps. $V_{surface}$ was defined as velocity recorded in the 11 m surface swimming zone. The stroke index (*SI*; m^2·cycle·s^{-1}) was calculated as follows: $SI = V_{surface} \times SL$. Swimming velocity over 200 m ($\boldsymbol{v_{200}}$, m·s^{-1}) was calculated by dividing the final race time. The times for each surface swimming zone were determined when the swimmer's head crossed the imaginary line connecting the markers positioned on both sides of the pool, using Kinovea software (version 2024.1) [34].

Counter movement jump

A force plate (BP400600, AMTI, Watertown, MA, USA) was mounted on the laboratory floor, and each participant performed three vertical jumps. A 30 s rest interval was provided between jumps to ensure maximal effort. Prior to each jump, participants stood upright on the force plate with body weight evenly distributed between both feet, and hands were kept on the hips throughout all trials. The countermovement jump work - *CMJw* (J) was defined as the mechanical work generated during a single jump and was calculated from the best trial, serving as an absolute indicator of anaerobic muscular power. The mean vertical displacement of the centre of mass (h, cm) was used as an indicator of motor performance relative to body mass - *CMJh* (cm) [19].

1 minute tethered swimming test

Participants performed the test in a 25 m swimming pool in accordance with the procedure previously described by Sokołowski et al. [33]. Prior to the test, participants completed a 1000-m swimming warm-up and a familiarization session with the test procedures and conditions. During the 1 minute tethered swimming test, the participants were fitted with a waist belt and connected to a steel pole via a 5.65 m steel cable linked to a dynamometer (ZPS5-BTU-1kN, Staniak, Poland) sampling at 100 Hz; the fixing point was positioned 0.49 m above the water surface [34]. During the 1-minute tethered swimming test, the swimmers breathed through a valve system fixed to the mounting arm positioned above a swimmer. Respiratory parameters were recorded (breath-by-breath) simultaneously using an ergospirometer (Start 2000 MES, Poland) and subsequently analyzed using dedicated software (Ergo 2000M, MES, Poland). Maximum pulling force 60F_{max} (N) and mean oxygen uptake during the 60 s test - 1minVO_2 (l·min^{-1}) were recorded.

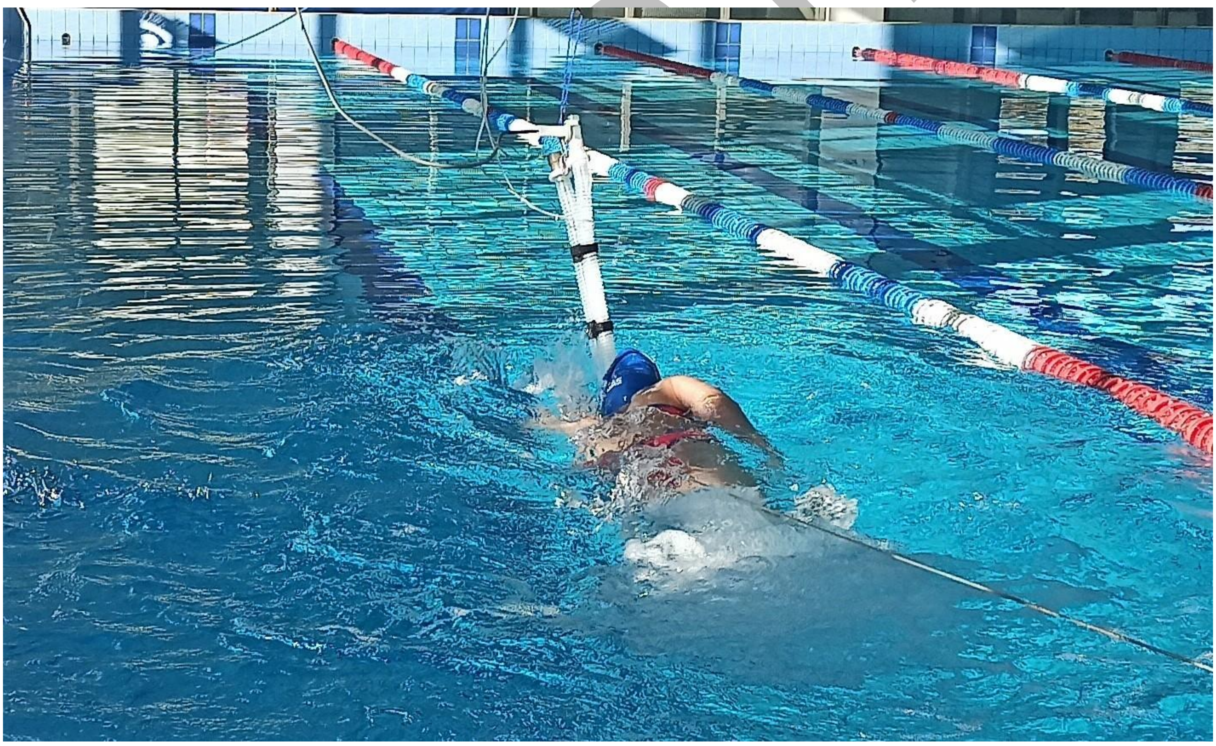

Figure 1. One of the participants during 1 minute tethered swimming test.

Statistical analysis

The distributional assumptions for regression analysis, including residual normality, homogeneity of variance, and the absence of multicollinearity, were verified using the Shapiro–Wilk and Levene procedures and were deemed acceptable. Descriptive statistics were reported as mean values with accompanying standard deviations, together with observed minimum and maximum ranges. Relationships between performance (v_{200}) and the other study variables were explored using Pearson's correlation analysis.

Performance-related regression models were then established using selected predictors. Subsequently, a multiple linear regression approach with backward elimination was applied, initially incorporating all candidate variables. In addition, predictors entered into the regression models were screened for potential redundancy (all values > 0.2) and evaluated for autocorrelation by means of the Durbin–Watson statistic (all values ≤ 2.0).

Results

Selected indicators that will be analyzed in further procedures (Table 1.).

Table 1. Mean, standard deviation and minimum-maximum values of the analyzed indices.

	mean	SD	min	max
BA	14.99	2.27	11.5	18
60F_{max}	208.6	45.87	51	297.3
1minVO_2	2.24	0.41	1.23	3.1
CMJh	0.28	0.03	0.20	0.34
SR	40.21	4.0	29.24	46.88
SL	1.91	0.18	1.64	2.42
v_{200}	1.35	0.08	1.08	1.5

Pearson correlation calculated between all the measured indices revealed that the highest correlation were noted between a) *BA* and 60F_{max}, 1minVO_2, *SL*, b) 60F_{max} and 1minVO_2, *SL*, v_{200}, c) *CMJh* and v_{200}, d) *SL* and *SR*, e) SR and v_{200} (Figure 2.).

* p < 0.05, ** p < 0.01

Figure 2. Heatmap of Pearson's correlation coefficients between all measured indices.

Four calculated multiple linear regression models explain the variance of the 200 m front crawl speed results as follows: Model 1 – 43%, Model 2 – 39%, Model 3 – 95%, Model 4 – 94%. Model 3 included indices of BA, 60F_{max}, *CMJh*, *SR*, *SL*. Excluding *BA* form the regression (Model 2, Model 4) caused decrease in the % value of the explained variance (from 43 to 39, from 95 to 94) (Table 2.).

Table 2. Multiple linear regression models explaining 200 m front crawl swimming speed.

Model 1	**Variables**	***B***	***Beta***	r_{semi}	**% of variance**	***t***	***p***
R^2 = .48	***BA***	0.001	0.272	0.232	5.37	2.01	0.051
adjusted R^2 = .43	**60F_{max}**	0.0004	0.226	0.192	3.7	1.67	0.103
F = 9.12; p < .001	***CMJh***	0.893	0.336	0.329	10.84	2.86	0.007
	SR	0.011	0.518	0.501	25.13	4.35	<0.0001
Model 2	**Variables**	***B***	***Beta***	r_{semi}	**% of variance**	***t***	***p***
R^2 = .43	**SR**	.01	.47	.47	21.81	3.91	.0003
adjusted R^2 = .39	**60F_{max}**	.00	.36	.34	11.83	2.88	.006

F = 10.04; p = .00005	CMJh	.89	.33	.32	10.30	2.68	.01
Model 3	**Variables**	***B***	***Beta***	r_{semi}	**% of variance**	t	p
R^2 = .96	***BA***	0.004	0.099	0.083	0.68	2.44	0.02
adjusted R^2 = .95	$60F_{max}$	0.0002	0.089	0.075	0.56	2.21	0.03
F = 166.81; p < .0001	***CMJh***	0.207	0.078	0.071	0.51	2.11	0.04
	SR	0.031	1.487	0.851	72.44	25.14	<0.00001
	SL	0.611	1.312	0.688	47.32	20.31	<0.00001
Model 4	**Variables**	***B***	***Beta***	r_{semi}	**% of variance**	t	p
R^2 = .95	$60F_{max}$	.00	.13	.12	1.46	3.37	.002
adjusted R^2 = .94	***CMJh***	.18	.07	.06	.40	1.75	.088
F = 183.7; p < .0001	**SR**	.03	1.50	.86	73.62	23.38	<.00001
	SL	.63	1.35	.72	51.98	20.06	<.00001

Stepwise multiple regression calculation selected four indices for the model: *SR*, *SL*, *BA* and *CMJh*. Regression model explained 95% of the results for the 200 m front crawl swimming speed. *SR* and *SL* explained 74.42 and 50.46% of the mentioned variance respectively (Table 3.)

Table 3. Stepwise multiple regression model explaining 200 m front crawl swimming speed.

	Variables	***B***	***Beta***	r_{semi}	**% of variance**	t	p
R^2 = .95	***SR***	.03	1.50	.86	74.42	24.30	<.001
adjusted R^2 = .95	***SL***	.62	1.34	.71	50.46	20.01	<.001
F = 188.57; p < .001	***BA***	.01	.14	.13	1.59	3.56	.001
	CMJh	.23	.09	.08	.64	2.26	.030

Multiple linear regression (Table 4.) showed that *SR* and *SL* itself explain 93% of 200 m front crawl speed from the study.

Table 4. Multiple linear regression of technique kinematics only (*SR*, *SL*) explaining 200 m front crawl swimming speed.

Variables	***B***	***Beta***	r_{semi}	**% of variance**	t	p

R^2 **= .93**	***SR***	.03	1.56	.94	88.44	22.72	<.000001
adjusted R^2 **= .93**							
F **= 271.24;** p **< .0001**	***SL***	.68	1.46	.88	77.23	21.23	<.000001

Discussion

Our goal was to determine the role of swimming kinematics, oxygen consumption and somatic attributes influencing the 200-m front crawl performance among young female swimmers. We discovered that inserting: *SR*, *SL*, *CMJh*, $60F_{max}$, *BA*, into the linear regression model allows to explain 94% of the variance for the 200 m front crawl swimming speed. Stepwise regression analysis selected indices *SR*, *SL*, *BA* and *CMJh* (from: *SR*, *SL*, *BA*, *CMJh*, $60F_{max}$ and $1minVO_2$) as that significant and created model explained 95% of the 200 m front crawl results. Moderate Pearson correlation was revealed between v_{200} and *SR*, *CMJh* and $60F_{max}$.

To our knowledge multivariate analysis of 200-m adolescent female front crawl performance was never performed. Results of our study suggest that swimming technique kinematics (*SR*, *SL*), lower and upper body strength (*CMJh*, $60F_{max}$) are the determinant factors of the 200-m front crawl performance in adolescent females. Simultaneously, peakVO_2 ($L \cdot min^{-1}$) and *SL* did not significantly correlate with performance. It should be noted that physiological response cannot be fully characterized by peak VO_2 alone, as this parameter primarily reflects the capacity for rapid activation of aerobic energy production. Including *SL* in the regression models, the percentage of the results explained by them increased. Unnitham et al. [39] came with the similar findings about lack of correlation between peakVO_2 and 200 m adolescent female front crawl performance. Nasirzade et al. [23] performed multivariate analysis for 200-m adolescent male front crawl performance but physiological indices (peakVO_2) were not included. They concluded that biomechanical indices of swimming technique (*SL*, *SR*, *SI* – stroke index) were the strongest predictors of 200-m front crawl performance explaining 87% of the results. In our study *SR* and *SL* only explained 93% of the 200-m front crawl performance.

Latt et al. [15] performed stepwise regression analysis, which revealed that 400-m adolescent female front crawl results are significantly related to factors: biomechanical (SI), physiological (VO_2 – $L \cdot min^{-1}$). In our study lack of significant correlation between $1minVO_2$ (0.26, p=0.09) might be due to shorter distance (in comparison with 400 m). Sokołowski et al. [33] revealed correlation between peakVO_2 from 20, 10 seconds intervals and 200-m front crawl among young male swimmers, but there was not significant relationship with 1minVO_2 (0.31, p=0.08). In our current study peakVO_2 values from 20 and 10 seconds intervals were calculated but due to lack of significant relationship with the performance were not presented and not included in the regression.

200-m front crawl was presented by the Seifert et al. [32] as the boundary swimming pace when the arm coordination switches from sprint to long distance. It was early discovered by Craig and Pendeegast [8] that 200 m is a distance when swimmers in the training process should increase the *SR* while trying to maintain *SL* or avoid the significant decrease of *SL*. We could assume that often observed decrease in *SL* could be due to severe muscle acidosis caused by lactate production. Mezzaroba & Machado [18] analyzing stroke kinematics in various front crawl distances (100, 200 and 400 m) among young boys (10-17 years old) concluded that *SR* decrease significantly with the longer swimming distance, but it is not related to maintaining/ increasing *SL*. In the current study we also observed significant correlation between *SL* and *BA*. We could state that less mature swimmers are less likely to maintain *SL*. In the previous study Sokolowski et al. [33] tried to check for the potential relationship between aerobic/energetic indices from 1 minute tethered maximum swimming and 200 m front crawl performance of the adolescent. Significant moderate relationship between *SL* and peakVO_2 values from 10 seconds (0.393; $p \leq .05$), as well as between peakVO_2 values from 10, 20, 30 seconds and tethered swimming force indices (maximum, average force and average impulse for one cycle) were found. In the current study 60F_{max} values were correlated with 1minVO_2 (0.4325; $p<.01$) and *SL* (0.3386; $p<.01$) confirming potential relationship between aerobic conditioning level, stroke kinematics and specific in-water strength. Nevertheless, the *SR* was the strongest predictor (Pearson correlation/ stepwise regression) of swimming speed in this set of selected indices. This may suggest that SR is an important factor in explaining performance; however, the influence of other indices, particularly SL, cannot be excluded. Linear regression analysis of biomechanical indices explaining 200 m front crawl performance, reported in [7], showed that neither SR (adjusted $R^2 = 0.10$, $p = 0.23$) nor SL was a significant predictor in the model. In turn, Nasirzade et al. [24] found that 200 m front crawl performance in young swimmers was significantly correlated with SR ($r = -0.42$, $p < 0.05$), although *SL* and *SI* showed stronger relationships with v200 ($r = -0.79$ and $r = -0.72$, respectively; $p < 0.01$) and *SR* did not enter the stepwise regression model.

In the current study *BA* values were close to significant (0.282; p=.064) correlated to v_{200}. It might be (considering low, close to significant correlation) that early mature swimmers, with higher *BA* in comparison to their pears, were more likely to develop higher: stroke force, stroke length, *CMJ* height. It is interesting that including *BA* in the regression from Model 4 (Table 2.) in comparison regression in Model 3 (Table 3.) does not increase significantly the explanatory potential of the model (adjusted R^2 = .94 vs. adjusted R^2 = .95) but make it lower. Possible explanation is the moderate correlation between $60F_{max}$ and *BA*. It is well documented [16], [17] that swimmers with higher maturation status (connected with higher anthropometric dimensions, stroke kinematics, strength and physiological capacity) perform better than their late-maturers contemporaries. Since the studies of Eriksson [9] maturation influence on anaerobic energy production has been investigated leading to the conclusion that anaerobic energy production is higher among adults than in children. A high stroke rate (*SR*) alone does not result in superior swimming performance and younger swimmers present different strategies to overcome fatigue during race than older ones. Appropriate balance between stroke rate (SR) and stroke length (SL) is strongly related to mechanical efficiency often expressed by stroke index (SI). Younger swimmers are often unable to maintain high stroke rate throughout the race, and at the same time they cannot compensate for this effect by increasing the SL[18].

Our study revealed a significant but moderate relationship between *CMJh* and swimming performance (0.37; $p \leq .05$). Keiner et al. [13] said that there may be connection between maximum strength level in turning and swimming performance. In their opinion strength training programs (mainly vertical jump) present high correlation with start performance. They concluded that greater leg power would improve starts and turns and by that lead to better performance. It is also the case that *CMJ* reflects greater overall motor system abilities, which may result in higher swimming speeds [36]. Tethered swimming is a reliable method for evaluating adolescent performance [2], [14]. In our study maximum tethered force was correlated with swimming performance (0.33; $p \leq .05$). But it was not selected as significant factor in a stepwise regression analysis. It could be due to including *CMJh* in the analysis, which presents slightly higher Pearson correlation with swimming speed. In the study of Ruiz-Navarro et al. [27] tethered swimming F_{max} presented higher correlation with performance. This difference between our and the above-mentioned study may be partly explained by shorter duration of the test and race which they referred to (30 s in Ruiz Navarro, 100 m front crawl).

Conclusions

According to executed multiple and stepwise regression analysis 200 m front crawl performance of adolescent females is connected to stroke kinematics (*SR*, *SL*), height of CMJ (*CMJh*) and biological maturation level (*BA*). Stroke kinematics itself is dominant in performance explanation. We cannot ignore the fact that *SL* and 60F_{max} were moderate correlated to *BA*. We could state that higher values of stroke kinematics indices (*SR*, *SL*), which is connected to ability to produce force (60F_{max}, *CMJh* and indirectly 1minVO_2) increase the potential to perform successfully in the 200 m front crawl performance among adolescent females. Cluster analysis of indices influencing the adolescent female swimming performance could be an interesting direction of the future research.

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