Physiological, Biomechanical and Energetic Parameters changes during Descending Front Crawl Swimming in Young Athletes

Tomasz Gabryś[1], Katarzyna Kucia[2], Urszula Szmaltan–Gabryś[3], Mariusz Ozimek[4], Arkadiusz Stanula[5], Marcelina Nowakowska[6]

[1.] Institute of Physical Education and Sport, State School of Higher Education in Oswiecim, Poland
[2.] Department of Water Sports, Institute of Sport, University School of Physical Education in Cracow, Poland
[3.] Department of Anatomy, University School of Physical Education Cracow, Poland
[4.] Department of Track end Fields Sports, Institute of Sport, University School of Physical Education in Cracow, Poland
[5.] Department of Sports Training, The Jerzy Kukuczka Academy of Physical Education in Katowice, Poland
[6.] Department of Sport's Theory and Kinesiology, Institute of Sport, University School of Physical Education in Cracow, Poland
tomaszek1960@o2.pl

Abstract: The purpose of this research was to determine the relationships in relevant biomechanical, energetic and physiological parameters between 200m front crawl incremental swimming performance in male and female adolescent swimmers. The study involved 6 girls (aged 14.5±0.54 years, height 169.00±4.14 cm and body mass 57.83±5.77 kg) and 7 boys (aged 14.7±0.42 years, height 174.71±3.81 cm, body mass 59.71±8.86 kg). Measurements enabling the biomechanical assessment of swimming velocity (V), stroke rate (SR) and stroke length (SL) were performed. Blood lactate concentrations were established with the enzymatic-amperometric method. Swimming economy was assessed as described in Capelli et al. and was expressed as a ratio between end-exercise VO2 at 80% volume total (VT) and velocity. Values of minute ventilation (VE), end-tidal partial pressure of oxygen, end-tidal partial pressure of carbon dioxide, carbon dioxide output (VCO2), respiratory-exchange ratio (RER), and oxygen uptake (VO2) were continuously measured by a breath-by-breath gas-exchange using the measurement system Cosmed K4b2 Aquatrainer. Results show that at all test levels and in both genders, swimming velocity was determined by the energetic parameter – stroke index SI. The performance of 15-year-old boys and girls swimming 200 m front crawl at intensities ranging from 60 to 100% VO_{2max}, depends on the interaction of biomechanical (SL, SR), energetic (SI) and relative carbon dioxide output parameters, as well as on relative oxygen uptake and respiratory exchange ratio. Comprehensive research into the parameters could help explain the interaction nature and individual differences in swimming performance, thus contributing to the enhancement of long-term athlete development (LTAD).

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1. Introduction

The recording of pulmonary VO2 (pVO2) in the initial exercise phase, provides important information on the growth dynamics of muscle VO2 (mVO2). With the onset of physical exercise metabolite concentration starts to change, activating mitochondrial oxidative phosphorylation and causing mVO2 to increase (Rossiter et al.,1999). Studies using the breath-by-breath method to analyze pVO2 kinetics utilize electronic gas analyzers that allow changes in respiratory pressure to be analyzed quickly and efficiently (Whipp et al., 1972). An exponential function used to process pVO2 values shows in detail how they change in a unit of time. The three phases of pVO2 kinetics are characterized by their specific time constants τ (tau) that represent the time it takes to reach 63% of primary response. Phases I, II and III are called, respectively, a cardio-dynamic component, a primary component, and a slow component. Studies on pVO2 kinetics usually omit phase I that goes on for 15-20 seconds, concentrating on phase II whose duration is expressed by the time constant τp. The available studies indicate that pVO2 kinetics in phase II can be precisely expressed by mVO2 increase (Fawkner et al., 2003). Faster oxygen uptake in phase II (shorter τp) means a lower oxygen deficit and enhanced muscle metabolic stability (Hagberg et al., 1978). Reis et al. (2012) studying adult freestyle swimmers have proved that phase II is a square-wave transition from rest to high and extremely high swimming intensity and that athletes reaching phase III (the slow component) perform better during middle-distance swimming (400m freestyle).

Moderate-intensity exercise (below lactate threshold) does not lead to phase III, because after 2-3 minutes of phase II a steady state is achieved. With high-intensity exercise (above lactate threshold - LT) the situation is different. In this case, the slow component of oxygen uptake (phase III) appears between 2nd and 6th minute of exercise.

Depending on its intensity, exercise may lead to a steady state or VO2max (Wilkerson et al., 2004). Interestingly, the slow component amplitude (As) is smaller in children than in adults (Poole et al., 2005). Although the debate over the physiological origin of the slow component has not found its conclusion yet, studies point to the interaction of many muscular factors, mainly the recruitment of type II muscle fibers, rising body temperature and catecholamine concentrations, less efficient ATP hydrolysis in tired muscle fibers, lower pH and greater engagement of respiratory muscles (Rodriguez et al., 2008, Barbosa et al., 2006, Stanula et al., 2013).

Both gas analyzer technology and the methodology of their use have significantly developed in recent years, particularly as a solution supporting the breath-by-breath method of analyzing physiological parameters and VO2 in the aquatic environment. The state-of-the-art generation of miniature gas analyzers coupled with sophisticated snorkels allow direct, precise and reliable measurements of cardio respiratory parameters to be made (Rodriguez et al., 2008, Reis et al., 2012).

Gas analyzers are applied to determine oxygen uptake kinetics during swimming (Dekerle et al., 2010); but the authors of this article have not found any studies where they are used to assess oxygen uptake kinetics and biomechanical and energetic parameters of the front-crawl swimming technique in adolescent male and female swimmers. Most studies of this type focus on adult swimmers (Barbosa et al., 2010a, Lätt et al., 2010); or young male swimmers (Barbosa et al., 2010b).

Nor have the authors identified comprehensive studies where different physiological, biomechanical and energetic parameters are analyzed in order to establish the swimming efficiency of young boys and girls. An exception is the still limited number of studies where the breath-by-breath method was employed to assess oxygen uptake kinetics in adolescent swimmers during swimming. Because of the present state of knowledge, this study was designed to find relationships between changes in the physiological, biomechanical and energetic parameters of the swimming technique that occur in 15-year-old boys and girls with gradually rising exercise intensity. The research results were analyzed in order to find: relationships between the biomechanical and energetic parameter values during swimming at different intensities and the dynamics of the respiratory (physiological) parameters and variations in oxygen consumption kinetics following from changing swimming velocity.

2. Material and Methods

The study involved 6 girls (aged 14.5±0.54 years, body height 169.00±4.14 cm, body mass 57.83±5.77 kg) and 7 boys (aged 14.7±0.42 years, body height 174.71±3.81 cm, body mass 59.71±8.86 kg) representing a high level of swimming skills in their age group (record holders and medal winners at the swimming championships). In the 2-year-period before the test, all subjects had trained regularly 8-10 times a week and had participated in Championships.

The subjects and their legal guardians were informed in writing about the test's rules, methods and aims. The guardians granted their consent for the subjects to participate in the research. The test protocol followed the guidelines of the Declaration of Helsinki of 1975. The research project was approved by The Bioethics Commission at Regional Medical Chamber, Cracow, no. 118/KBL/OIL/2012.

Subjects' anthropometric parameters were established with instruments manufactured by Sieber Hegner Maschinen AG, Switzerland, in accordance with the International Standards for Anthropometric Assessment .

The ambient parameters were 25.13±1.41 C and 1010.33±0.81 mbar for girls and 25.70±2.08 C and 1010.28±0.95mbar for boys. The test was performed at the onset of the preparatory period for Polish Winter Championships in the second macrocycle, 6 weeks before the main event. The test parameters were the same for all subjects.

The subjects were tested in a 25 m long indoor swimming pool after a standard warm-up of 20 minutes. During the warm-up, subjects were provided with freestyle snorkels and were asked to swim 4 x 100m front crawl drill and 2 x 100m front crawl with progressively increasing intensity, so that they could swim at the speed set for the first phase of the test. The test protocol basically assumed that the swimmers would perform a discontinuous incremental test (5x200 m with 60s rest intervals), with the speed being individually adjusted to account for 60% of the swimmer's personal best speed at the first level, and then increasing by 10% at each subsequent level. According to the protocol, the test was to be stopped for 1 hour of rest and then resumed, if the difference between the assumed and actual speed exceeded 0.1 m s^{-1}, but this option was never exercised. The test was structured as follows: in-water starts, open turns without underwater gliding alternately to the right and left hand side to prevent the wires of the measuring device from getting tangled, one minute breaks between particular levels during which capillary blood was sampled from the swimmers.

2.1. Biomechanics data collection

Measurements enabling the biomechanical assessment of swimming velocity (V), stroke rate (SR) and stroke length (SL) were performed in the middle 15m of each lap**.**

Swimming velocity (V) was measured by a specialist provided with a chronometer with accuracy of 0.01s. It was expressed by the following formula:

$$\bar{V} = \frac{d}{t} \qquad \text{Equation 1.}$$

where V – swimming velocity, d – distance, t – swimming time.

The stroke rate (SR) was measured by another specialist with a crono-frequency metre from 3 consecutive strokes cycles.

The stroke length (SL) was calculated from the formula:

$$SL = \frac{\bar{V}}{SR} \qquad \text{Equation 2.}$$

2.2 Data collection

According to the reviewed literature, high stroke index (SI) values in front crawl are strongly determined by low energy cost (C) and total energy expenditure (E_{tot})(Barbosa et al., 2010b) This means that swimming efficiency can be assessed with the swimming index (SI) given by the following equation:

$$SI = SL \cdot V \qquad \text{Equation 3.}$$

In this study, blood lactate concentrations in the subjects were established with the enzymatic-amperometric method (EKF Diagnostics, Germany) using the BIOSEN C-line analyser (EKF Diagnostic, Germany). Earlobe capillary blood (20 µL) was sampled in the last 20 seconds of each work stage during the incremental test. Before blood analysis, the analyzer was calibrated with standard 12-mmol L–1 solution. After each exercise level, the subjects were informed how they performed.

Swimming economy was assessed as described in Capelli et al. (Barbosa et al., 2010 a,b)and was expressed as a ratio between end-exercise VO2 at 80% volume total (VT) and velocity. Values of minute ventilation (VE), end-tidal partial pressure of oxygen, end-tidal partial pressure of carbon dioxide, carbon dioxide output (VCO2), respiratory-exchange ratio (RER), and oxygen uptake (VO2) were continuously measured by a breath-by-breath gas-exchange using the measurement system Cosmed K4b2 Aquatrainer (Gayda et al., 2010, Maglischo 2011) Gas analyzers were calibrated before each test with ambient air (O2 20.93% and CO2 0.03%) and a gas mixture of known composition (O2 16.04% and CO2 5.00%). An O2 analyzer with a polarographic electrode and a CO2 analyzer with an infrared electrode sampled expired and inspired gases at the mouth. The face mask had a low dead space and was equipped with a low-resistance, bidirectional digital turbine (28-mm diameter). This turbine was calibrated before each test with a 3-L syringe (Cosmed, Rome, Italy). Face masks allowed participants to breathe simultaneously through mouth and nose. Heart rate was continuously measured via Polar heart-rate monitor (Polar Electro Oy, Kempele, Finland) and acquired by the Cosmed system.

2.3 Statistical analysis

All statistical computations were performed with the STATISTICA 10 package from StatSoft. The data were checked for normal distribution using the Shapiro-Wilk W test. The paired Student's t-test was employed to determine differences between the values of the considered parameters. For the purpose of selecting statistically significant biomechanical and energetic and physiological parameters explaining swimming velocity at particular levels of the 5 x 200 m front crawl incremental test, a reverse stepwise regression was used. As the subjects were found not to be statistically significantly regarding their morphometric characteristics, the regression analysis was performed jointly for both genders. Statistical significance was set at $p < 0.05$.

3. Results

Table 1 shows that the biomechanical and energetic parameters characterising the male and female swimmers at particular levels of the test are not statistically significantly different, unlike the parameters of VO_2 kinetics.

Table1. Front-crawl biomechanical and energetic parameters at particular levels of a test involving 15-year-old swimmers of both genders (mean ±SD).

Variable	Gender	I step 60%	II step 70%	III step 80%	IV step 90%	V step 100%
V (m/s^{-1})	F-15	1,14±0,04	1,17±0,04	1,21±0,05	1,26±0,06	1,28±0,07
	M-15	1,14±0,04	1,20±0,03	1,27±0,05	1,31±0,05	1,33±0,05
SR ($cycle/min^{-1}$)	F-15	29,10±3,36	30,66±3,79	33,41±4,27	34,51±3,72	36,77±4,54
	M-15	27,35±1,90	30,52±3,59	32,75±3,59	33,90±4,73	34,78±4,61
SL (m)	F-15	2,37±0,27	2,32±0,31	2,22±0,33	2,22±0,26	2,11±0,25
	M-15	2,52±0,18	2,39±0,26	2,36±0,31	2,35±0,30	2,34±0,36
SI	F-15	2,70±0,36	2,71±0,42	2,70±0,48	2,80±0,43	2,70±0,40
	M-15	2,87±0,25	2,89±0,33	3,00±0,45	3,07±0,41	3,13±0,55

Definition of abbreviations: F-15 – 15 years old female swimmers; M-15 –15 years old male swimmers; SL – Stroke Length; SI – Stroke Index; SR – Stroke Rate; V – Velocity;

Table 2. The parameters of VO_2 kinetics for 15-year-old swimmers of both genders by test level (mean ±SD; statistically significant results at *p<0.05 are in boldface)

Variable	Gender	I step 60%	II step 70%	III step 80%	IV step 90%	V step 100%
BF ($1/min^{-1}$)	F-15	33,66±11,05	35,27±11,07	39,25±11,25	43,23±11,13	46,21±11,59
	M-15	31,80±7,07	33,85±6,19	42,11±9,97	48,03±11,13	52,23±11,53
VE (l/min)	F-15	62,01±11,74	62,96±9,90	72,21±14,58	81,87±15,16	84,00±15,13
	M-15	71,21±19,46	74,79±13,26	90,58±18,34	97,66±28,52	103,15±28,70
VO_2 (l/min)	F-15	2,57±0,29	2,53±0,18*	2,89±0,37*	3,13±0,41	3,28±0,42
	M-15	2,61±0,86	3,17±0,53*	3,69±0,81*	3,79±1,07	3,97±0,95
$V'CO_2$ (l/min)	F-15	2,12±0,31	2,15±0,20*	2,54±0,40*	2,96±0,42*	2,35±1,34
	M-15	2,24±0,73	2,79±0,49*	3,51±0,85*	3,75±1,00*	3,85±0,90
RER	F-15	0,82±0,05*	0,85±0,02*	0,88±0,04*	0,95±0,05	0,96±0,23
	M-15	0,90±0,08*	0,90±0,04*	0,95±0,04*	1,22±0,42	0,96±0,61
VO_2/kg ($ml/min^{-1}/kg^{1}$)	F-15	44,64±6,26	44,05±5,14*	50,04±6,97*	54,12±5,80*	55,62±4,35
	M-15	49,27±2,60	54,87±1,71*	61,77±6,11*	66,12±5,91*	59,39±5,22
$V'CO_2$/kg ($ml/min^{-1}/kg^{1}$)	F-15	36,90±6,61	37,60±5,43*	44,23±8,34*	51,26±6,77*	49,54±5,19*
	M-15	38,66±9,21	48,15±1,88*	60,50±6,31*	65,31±7,06*	64,02±7,08*
La($mmol l^{-1}$)	F-15	2,76±1,40	2,54±1,62	3,08±1,68	4,40±2,39	6,87±3,39
	M-15	2,67±0,62	2,74±0,67	3,95±1,53	6,35±2,20	7,38±2,59

Definition of abbreviations: F-15 – 15 years old female swimmers; M-15 –15 years old male swimmers;BF – Breathing Frequency; V'CO2 – Carbon Dioxide Output; La – Lactate; VE – Minute Ventilation; VO2 – Oxygen uptake; RER – Respiratory Exchange Ratio; VO2/kg – Relative Oxygen Uptake; V'CO2/kg – Relative Carbon Dioxide Output

According to the data (table 2), most statistically significant differences in the analysed parameters occurred between 15-year-old boys and girls at levels 2, 3 and 4 of the test. The differences are the greatest for VO_2 (oxygen uptake), VCO_2 (carbon dioxide output), RER (respiratory exchange ratio), VO_2/kg (relative oxygen uptake), and $V'CO_2$/kg (relative carbon dioxide output).

Table 3 shows regression equations with parameter values recorded at particular levels of the test. The analysis of the coefficients of determination (R^2) indicates that the parameters in the equations explain from 98 to 99% of variation in 200m front-crawl velocity that the swimmers achieved at particular levels of the test.

The regression equations in table 3 and 4 allowed statistically significant determinants of swimming velocities at particular levels of the test to be identified. The level 1 velocity (V1) was determined by SL1 (-2.879±0.055, P<0.01), SI1 (3.312±0.056, P<0.01), LA1 (0.050±0.015, P<0.01). At level 2 (V2), SI2 (3.952±0.168, P<0.01) SL2 (-3.482±0.166, P<0.01) were the most important. At level 3, the strongest and statistically significant determinants of velocity (V3) proved to be, again, SL3 (-3.976 ±0.142, P<0.01) SI3 (3.589±0.141, P<0.01), but also (BF3). The level 4 velocity (V4) was determined by SI4 (2.951±0.038, P<0.01) and SL4 (-2.447 ±0.037, P<0.01), but also by V'O2/kg 4 (0.134±0.031, P<0.008) ;V'CO2/kg 4 (-0.114 ±0.031, P<0.014), and RER 4 (0.033±0.012, P<0.047). The parameters that were found to have the greatest effect on front-crawl velocity at level 5 (V5) were mainly SL5 (-3.537 ±0.177, P<0.01) and SR5 (-0.385±0.080, P<0.01), as well as SI 5 (3.837±0.111, P<0.01).

Table 3. Reverse stepwise regression for predicting 200 m front crawl incremental performance (p<0.05).

V 1 - I step 60 %						
Parameter	b*	St. error b*	b	St. error b	t value (8)	p level
Intercept			1,133	0,006	191,696	0,001
SI1	3,312	0,056	0,412	0,007	59,616	0,001
SL1	-2,879	0,055	-0,467	0,009	-51,872	0,001
Del-LA1	0,050	0,015	0,002	0,001	3,241	0,012
V'CO2/kg 1	-0,016	0,014	0,000	0,000	-1,170	0,276
R=0.9993; R^2=0.9986; Adj.R^2= 0.9979; F(4,8)=1454,4; p<0.001; SEE=0.0017						
V 2 – II step 70 %						
Intercept			1,168	0,014	83,035	0,001
SI2	3,952	0,168	0,389	0,017	23,509	0,001
SL2	-3,482	0,166	-0,461	0,022	-21,033	0,001
V'CO2/kg 2	0,064	0,042	0,000	0,000	1,536	0,163
Del-LA2	-0,051	0,041	-0,002	0,001	-1,224	0,256
R=0.9951; R^2=0.9902; Adj.R^2=0.9853; F(4,8)=201,75; p<0.001; SEE=0.044						
V 3 – III step 80 %						
Intercept			1,219	0,019	65,506	0,001
SI3	3,589	0,141	0,419	0,016	25,518	0,001
SL3	-2,976	0,142	-0,517	0,025	-20,933	0,001
BF 3	0,041	0,033	0,000	0,000	1,229	0,050
R=0.9959; R^2=0.9919; Adj.R^2=0.9891; F(3,9)=365,34; p<0.001; SEE=0.057						
V 4 – IV step 90 %						
Intercept			1,239	0,008	159,037	0,001
SI4	2,951	0,038	0,411	0,005	77,011	0,001
SL4	-2,447	0,037	-0,519	0,008	-66,933	0,001
V'O2/kg 4	0,134	0,031	0,001	0,000	4,247	0,008
V'CO2/kg 4	-0,114	0,031	-0,001	0,000	-3,677	0,014
RER 4	0,033	0,012	0,006	0,002	2,625	0,047
BF 4	-0,024	0,015	0,000	0,000	-1,663	0,157
V'E 4	0,021	0,018	0,000	0,000	1,186	0,289
R=0.9998; R^2=0.9995; Adj.R^2=0.9988; F(7,5)=1446,5; p<0.001; SEE=0.020						
V 5 – V step 100 %						
Intercept			1,691	0,082	20,717	0,001
SI5	3,837	0,111	0,484	0,014	34,560	0,001
SL5	-3,537	0,177	-0,716	0,036	-19,963	0,001
SR5	-0,385	0,080	-0,006	0,001	-4,834	0,001
V'O2/kg 5	-0,021	0,013	0,000	0,000	-1,551	0,160
R=0.9993; R^2=0.9986; Adj.R^2=0.9980; F(4,8)=1472,2; p<0.001; SEE=0.029						

Table 4. The determinants of 200m front-crawl velocity in 15-year-old boys and girls.

Parameter		V1	V2	V3	V4	V5
Speed		Low 60%	Low-Medium 70%	Medium–High 80%	Very High 90%	Maximum 100%
Energy Source		Aerobic Fatty Acid	Aerobic Threshold	Aerobic Overload	Anaerobic Lactate Production	Anaerobic Lactate Tolerance
Intensity		31-50% VO_{2max}	51-69% VO_{2max}	70-85% VO_{2max}	86-100% VO_{2max}	86-100% VO_{2max}
Lactate	F-15	2,76±1,40	2,54±1,62	3,08±1,68	4,40±2,39	6,87±3,39
	M15	2,67±0,62	2,74±0,67	3,95±1,53	6,35±2,20	7,38±2,59
VO_2/kg	F-15	44,64±6,26	44,05±5,14	50,04±6,97	54,12±5,80	55,62±4,35
	M-15	49,27±2,60	54,87±1,71	61,77±6,11	66,12±5,91	59,39±5,22
Hypothetical Determining Factors						
Biomechanics		SL	SL	SL	SL	SL; SR
Energetic		SI	SI	SI	SI	SI
Physiological		x	x	BF	VO_2/kg, VCO_2/kg RER	x

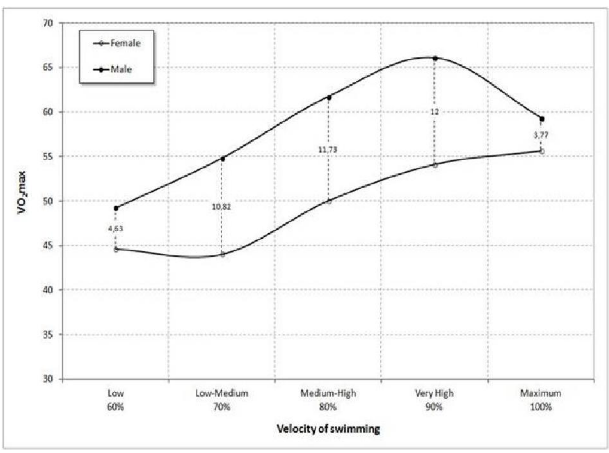

Figure 1. VO_{2max} of 15-year-old male and female swimmers against increasing swimming velocity.

4. Discussions

A detailed analysis of the data did not find the 15-year-old male and female swimmers to be statistically significantly different with respect to biomechanical and energetic parameters, as well as most physiological parameters. This finding is consistent with the conclusions of authors such as (Olfert et al., 2004) and Barbosa et al. (2010 b), according to whom both genders have androgynous body build at this age. The literature review has showed that the data specific to particular genders and their chronological and biological ages (Barbosa 2010a, Latt et al., 2010, Barker et al., 2008) and the data showing the use of energy generated by aerobic metabolism (Barker et al., 2008), but particularly their means, are similar. The similarity between the results of this research and the findings reported by the above authors indicates that the decision to make a joint regression analysis of swimmers of both genders was correct.

As shown by the research results, swimming velocity at level 1 (V1) was determined by the swimming index (SI1), stroke length (SL1) and blood lactate concentration (LA1). The direction of LT changes (lactate threshold) with respect to VO2max implies that the level of LA1 can be used as a predictor of V1. In their studies with children, (Barker et al., 2008) Barker et.al have found that the lactate threshold is already exceeded at exercise intensities of 63% and 75%% of VO2max. Another factor rendering LA1 useful as a predictor of V1 is changes in muscle metabolic profile, i.e. in the glycolytic enzyme activity, that occur with aging (Wilkerson et al., 2004).

Exercise intensity at level 2 of the test was moderate. The only determinants of swimming velocity were the energetic parameter SI2 and the biomechanical parameter SL2. Constant, considerable stroke length over the whole distance was found to be crucial for maximum velocity to be maintained. This relationship has been confirmed by other researchers (Alberty et al. 2006, Keskinen,Komi 1989). That swimming velocity V2 and the parameters of oxygen uptake kinetics were not correlated seems to imply that pulmonary ventilation changes were harmonised with the rate of oxygen uptake. According to some authors (Dempsey et al., 2003, 2004, West 2004); the level of pulmonary ventilation can be expressed through a so-called ventilatory equivalent of oxygen uptake VO2(RCP)/V'CO2max.

At level 3 of the test, the biomechanical parameter (SI3), the energetic parameter (SL3), and the physiological parameter 'breathing frequency' (BF3) proved to be, as before, the strongest and statistically significant determinants of swimming velocity. Higher BF3 at level 3 of the test suggests that the physiological response to excess CO2 generated by lactic acid metabolism in active muscle tissue was hyperventilation. These results too are similar to the other authors' findings (Poole et al. 2005, Barbosa et al., 2010b).

At level 4 of the test VO2 kinetics parameters reached their maximum values. Swimming velocity was determined by SI4 and SL4 as well as by physiological determinants V'O2/kg 4 V'CO2/kg 4 and RER 4. The biomechanical and energetic parameters changed as follows: the stroke length (SL4) slightly decreased causing the swimming index (SI) to increase fast. Swimmers' fatigue and their tendency to reduce energetic cost (Keskinen,Komi 1989, Toussaint et al., 2006) is probably the reason this happens. Another determinant of swimming velocity at this level of the test was the respiratory exchange rate RER4, because its value resulted from much higher breathing frequency and greater respiratory volume. The literature explains that such a significant increase in pulmonary ventilation against its rest level is enabled by breathing frequency rising to almost 50 cycles per minute and the respiratory volume increasing by approximately 2,5l. The presence of high V'CO2/kg (Relative Carbon Dioxide Output) may be an indication that hyperventilation that appeared at level 3 continued (Wilkerson et al., 2004, Poole et al., 2005)

At this level of the test, the subjects probably exercised at maximum intensity. There is evidence that maximal aerobic exercise has a major effect on physiological parameters, such as V'CO2, V'O2/kg, BF and VE. Maximum exercise considerably increases RER4, V'CO2 4 and V'O2 4, as well as one-minute oxygen uptake (Olfert et al., 2004, Dempsey et al., 2003. The changes are caused by a higher breathing frequency and increased respiratory volume being physiological responses to excess CO2 generated by lactate metabolism. This relationship confirms that the determinants of swimming velocity established for this level of the test were correct. According to Assist (2013) high intensity exercise like swimming lactate threshold test leads to increase in free radicals which measured through vanillylmandelic acid in urine. The diet supplementations include vitamin C, and E enhanced gene expression RNA, and superoxide dismutase SOD2, 3 that led to decrease VMA level. Also, improved 200m, 400m record, and swimming lactate threshold record.

The most distinct determinants of front-crawl velocity at level 5 were biomechanical parameters SL5 and SR5 and the energetic parameter SI5. Results imply that the symptoms of growing fatigue started to recede at this level (Toussaint et al., 2006, Dekerle et al., 2005). The role of the biomechanical parameters as established in this study and by other authors is similar (Touberkis et al., 2006).

The authors predict that competitive swimming will increasingly use strategies involving individually adjusted proportions of stroke length and frequency to ensure optimal stroke parameters and thereby maximum swimming velocity. According to Barbosa (2010) both energy cost (C) and stroke index (SI) are determined by swimming velocity (V). This type of a relationship is described in statistics as co linearity, so SI values must be interpreted with much caution.

It is known that greater swimming velocity can be achieved by increasing the stroke length (SL) (14); (Touberkis et al., 2006) and that the higher swimming performance, the higher SI (Sanchez, Arellano 2002, Jesus et al., 2010). From the biomechanical perspective, swimming velocity (V) can be expected to rise when the stroke rate (SR) increases and the stroke length (SL) is consistently high.

The conclusion that can be drawn from the above findings is that swimming performance depends on the interaction of biomechanical, energetic and physiological factors. This means that comprehensive investigations on young and adult swimmers have greater potential for forecasting their future achievements and for explaining why particular swimmers differ in swimming performance than studies targeted at particular parameters (Kjendle et al., 2004).

6. Conclusions

The research has not found 15-year-old male and female swimmers to be statistically significantly different with respect to biomechanical and energetic parameters and VO2 values obtained during a graded exercise test with exercise intensities rising from 60 to 100%. Results also show that the swimmers have similar morphometric characteristics.

The biomechanical parameter determining the swimming velocity of 15-year-old boys and girls in 200m front crawl with intensities between 60% and 100% was the stroke length (SL). At swimming intensity of 100% the only other biomechanical parameter to have effect was the stroke rate (SR); its value was consistently rising between the subsequent levels of the test in both male and female groups while optimal stroke length was maintained.

At all levels of the test and in both groups of subjects, swimming velocity was determined by the energetic parameter (the stroke index SI). This explains swimmers' growing fatigue as well as the increasing energy cost of exercise.

The following physiological parameters were found to have the strongest effect on the velocity of 15-year-old athletes swimming 200m front crawl: breathing frequency (BF) at exercise intensity of 80% and V'CO2/kg; V'O2/kg and RER 4 at exercise intensity of 90%.

An analysis of the research findings identifies the incremental swimming test as a sensitive tool for measuring the anaerobic endurance in young athletes involved in speed-endurance disciplines.

Further research should concentrate on seeking relationships between the character of the applied training means and their outcomes as revealed by the specific test (Szmatlan-Gabryś et al., 2014)

Practical implications

The performance of 15-year-old boys and girls swimming 200 m front crawl at exercise intensities ranging from 60 to 100% of VO_{2max}, depends on the interaction of biomechanical (SL, SR), energetic (SI) and physiological (V'CO2/kg) parameters, as well as on V'O2/kg and RER 4. Comprehensive research into the parameters could help explain the nature of the interaction and of individual differences in swimming performance, thus contributing to the enhancement of long-term athlete development (LTAD).

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Corresponding Author:
Prof. Tomasz Gabryś Ph.D
Institute of Physical Education and Sport, State School of Higher Education in Oswiecim, Poland
E-mail: tomaszek1960@o2.pl

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