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Aerobic capacity in swimming, cycling and arm cranking in swimmers aged 11–13 years

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Abstract

Background This study aimed to compare the aerobic capacity in swimming, cycling and arm cranking in swimmers aged 11–13 years.

Methods Eleven swimmers (mean age, 12.1 ± 1.0 years) performed three incremental exercise tests. One of the tests was performed under specific conditions (front crawl swimming), and the other two were under non–specific conditions (cycling and arm cranking). Data on the pulmonary gas exchange were recorded using the portable analyser MetaMax 3B (Cortex, Leipzig, Germany). One-way analysis of variance for repeated measures was employed to test the null hypothesis and determine statistically significant differences between the indicators obtained under specific and non–specific testing conditions. Pearson's correlation coefficient was calculated to assess the relationships between the indicators of the pulmonary gas exchange.

Results The relative peak oxygen uptake ($\dot{V}O_2$peak) value during swimming was 49.3 ± 6.2 mL/kg/min, which was higher than that during arm cranking (39.6 ± 7.3 mL/kg/min; $P < 0.01$) but lower than that during cycling (54.3 ± 7.8 mL/kg/min; $P < 0.01$). The peak minute ventilation ($\dot{V}_E$peak) value during swimming (84.9 ± 12.6 L/min) was higher than that during arm cranking (69.4 ± 18.2 L/min; $P < 0.01$) but lower than that during cycling (98.4 ± 15.4 L/min; $P < 0.01$). Strong positive correlations were observed in the absolute and relative $\dot{V}O_2$peak values between swimming and cycling ($r = 0.857$, $P < 0.01$; $r = 0.657$, $P < 0.05$) and between swimming and arm cranking ($r = 0.899$, $P < 0.01$; $r = 0.863$, $P < 0.05$). A strong positive correlation was also observed in $\dot{V}_E$peak values between swimming and arm cranking ($r = 0.626$, $P < 0.05$).

Conclusion Swimmers aged 11–13 years showed $\dot{V}O_2$peak and $\dot{V}_E$peak values during the specific swimming test greater than those during arm cranking but lower than those during cycling. However, aerobic capacity parameters measured during specific swimming conditions correlated with those measured during non–specific arm cranking and cycling conditions.

Keywords $\dot{V}O_2$peak, Aerobic capacity, Swimmers, Youth

Background

Horizontal body position, water immersion, hydrostatic pressure in water and the specific nature of movement in swimming differ significantly from those in other sports. Swimming performance is significantly influenced by several domains, including biomechanics, physiology, anthropometrics, motor control, and muscle strength and conditioning [1, 2]. Research highlights the

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significant role of energetics in swimming performance, with key variables including total energy expenditure and energy cost [2]. Total energy expenditure includes energy from aerobic, anaerobic lactic, and anaerobic alactic pathways, with aerobic contribution measured through net oxygen uptake [3–5]. In competitive swimming, where most events last less than four minutes, athletes engage in demanding endurance training. Therefore, the aerobic capacity, particularly peak oxygen uptake (VO_2peak) of swimmers should be considered to achieve the best results [6].

Young swimmers' performance is influenced by a combination of anthropometric, physiological, and technical factors, competitive level, and maturational aspects with notable differences from adult swimmers [7–9]. The model based on biomechanical and energetic variables could explain up to 80% of young swimmers' performance. Aerobic capacity seems to be more developed in prepubertal and early pubertal stages rather than anaerobic capacity, thus it is a more important factor influencing physical performance during this period of growth and maturation [10]. Therefore, from the energetic factors aerobic capacity might be important in young swimmers aged 11–13 years involved in our study. As young swimmers undergo maturation, they experience increases in muscle mass [11] and enhanced activity of glycolytic enzymes [12, 13], leading to improved anaerobic fitness [12, 14]. These physiological changes contribute significantly to performance improvements while approaching adulthood.

Previous studies showed that indicators of the aerobic capacity of swimmers can differ depending on the selected testing methods, ergometers, and muscle groups involved [15–18]. Performing tests under specific conditions is crucial because it can most precisely reflect the specificity of adaptation in athletes. Many studies have been conducted with adult swimmers under specific conditions, including flume, tethered and free swimming [18–22]. Measuring VO_2peak while swimming also offers significant advantages as it ensures consistency in body position and muscle engagement, mirroring competition conditions. Continuous oxygen uptake measurements provide precise determination of VO_2peak during swimming, by also allowing for the detection of submaximal VO_2 values, ventilatory thresholds, and corresponding heart rate values [15, 18, 23]. However, such process is complex, expensive, and time–consuming, requiring the involvement of qualified personnel. Continuous measurement of oxygen consumption during swimming requires a specially designed snorkel for breath-by-breath analysis, which can be particularly challenging with younger participants as such equipment is not normally used during the training sessions or competitions. The snorkel must be connected to metabolic testing equipment, which is vulnerable to water damage. Consequently, the swimmer must be attached to either a rod held by someone on land or a physical structure suspended above the pool, both of which restrict the swimmer's ability to move freely [24, 25]. Performing tests under free swimming conditions can provide informative insight on young athletes' responses and adaptations to specific conditions. The assessment of biomechanical and energetics profile in young swimmers are not the same as for adult or elite swimmers. The ethical issues are raised and the procedures have to be less expensive, invasive, complex and time consuming [8]. To our knowledge, there is a lack of studies investigating young 11–13–year–old swimmers with several years of training experience, and their aerobic capacity during specific swimming conditions.

Pulmonary gas exchange indicators in adult swimmers differ between testing conditions as some swimmers reach higher [26] or similar [18] values during swimming than cycling tests, while others reach higher values during running or cycling tests [15]. How the aerobic capacity may differ between specific swimming and non-specific tests in young 11–13–year–old swimmers is unclear. There is also a lack of information about the pulmonary gas exchange indicator relationships between specific and non-specific testing conditions in young 11–13–year–old swimmers, while some information is available about these relationships in adults [23, 27, 28]. Cycling and tethered swimming tests demonstrated high validity with comparable VO_2peak estimates, explaining a large proportion of differences in endurance performance while arm cranking showed weaker relationship with competitive swimming performance [18]. This information may be important because it can show the validity of the non–specific testing conditions which could selectively assess the capacity of the upper and lower body muscles which are activated during front crawl swimming. The contraction regimen of the muscles during arm cranking and cycling is closer to swimming than that during running where lots of eccentric muscle contractions are present.

Therefore, we hypothesized that young 11–13–year–old swimmers' respiratory gas exchange values during swimming would be greater than during arm cranking but lower than during cycling. We also hypothesized that the relationships between testing conditions may be more pronounced in young 11–13–year–old swimmers, because they have not yet reached high levels of adaptation, as compared to adult athletes.

The aim of this study was to compare the aerobic capacity in swimming, cycling and arm cranking in swimmers aged 11–13 years.

Methods

Participants

Eleven swimmers participated in the study. The participants' World Aquatic points (WAP) ranged from 203 to 377 in the 50–meter freestyle swimming. This corresponds to the 5th swimmers' performance classification level according to the new model proposed by Ruiz-Navarro et al. [29]. The swimmers were included in the study if they were 11–13 years old, had a training experience of regular training (at least 3 times a week) for at least 3 years, regularly participated in national competitions and acquired at least 200 WAP. All swimmers did not have any medical contraindications to attend regular swimming training sessions at the sports schools. We included 6 girls and 6 boys in the study, although one of the girls did not complete all the necessary tests. Once the potential participants were identified, we provided them and their parents (or guardians) with detailed information about the study procedures and obtained informed consent. The study was conducted in accordance with the Declaration of Helsinki and approved by the Kaunas Regional Biomedical Research Ethics Committee. The characteristics of the participants are presented in Table 1.

Study design

Individual testing schedules were created after the participants and their parents provided consent. The participants had to visit the laboratory three times on separate days, during which they performed three incremental tests under specific (swimming test) and non–specific (cycle and arm crank ergometer tests) conditions. The three different incremental tests were completed in a randomized order and separated by at least 48 h.

Data collection and analysis

Anthropometry

Anthropometric data, such as body mass, body mass index and fat mass (%), were determined using the body composition analyser TBF–300 (TANITA, Tokyo, Japan), which employs the principles of bioelectrical impedance analysis.

Pulmonary gas exchange

The oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$), tidal volume (V_T), breathing frequency (BF) and respiratory exchange ratio (RER) were measured on a breath–by–breath basis and averaged every 5 s during the three incremental specific and non-specific exercises and recovery periods, using the portable pulmonary gas exchange analyser MetaMax 3B (Cortex, Leipzig, Germany). The portable gas exchange analyser was shown to provide reliable measurements of metabolic demand with adequate validity for field–based measurements [24]. Heart rate (HR) was also continuously measured and averaged every 5 s throughout the three tests and recovery periods. Gas exchange values during cycling and arm cranking were measured using the "Hans Rudolph" face mask. Gas exchange values during swimming were measured using "Cortex Swim Option for MetaMax 3B–R2" which is designed to be used in the flume, in the pool or in the open water. The practical considerations for using such equipment were analysed and published [25]. The gas exchange analyser included a specific snorkel with an integrated saliva suction device. The snorkel also had an integrated HR module with 5-kHz technology to improve underwater Bluetooth® connectivity and heart rate monitoring using the H10 heart rate monitor (Polar, Kempele, Finland). The pulmonary gas exchange analyser was calibrated according to manufacturer's recommendations before each test. Pulmonary gas exchange variables were measured on a breath-by-breath basis. Each peak value ($\dot{V}O_2$peak, $\dot{V}_E$peak, $V_T$peak, BFpeak and RERpeak) was the peak 20–second interval average value attained during the incremental exercise test.

Table 1 Characteristics of the participants

Age (years)	Height (cm)	Body mass (kg)	Body mass index	Fat mass (%)	WAP
12.1 ± 1.0	160.5 ± 7.7	45.3 ± 11.0	17.1 ± 2.8	14.6 ± 7.8	304.9 ± 59.1

Ergometry

Incremental swimming test (SW)

The initial testing procedures were conducted in a swimming pool, where the participants performed incremental front crawl swimming. The swimming was performed in a 25-m swimming pool, with water and air temperatures of approximately 26 °C and 28 °C, respectively. To ensure consistency in the increase of swimming speed, we used a light-emitting diode device called the Virtual Swim Trainer (Indico Technologies, Torino, Italy), which provided visual cues to swimmers regarding the desired velocity for each segment of their swim. The device was programmed to increase the speed by 0.05 $m \cdot s^{-1}$ every 50 m. Before the test, the participants warmed–up by swimming at a comfortable pace for approximately 4 min. During the test they swam at a predetermined speed of 0.80 $m \cdot s^{-1}$ for the first 50 m, followed by an increase to 0.85 $m \cdot s^{-1}$ for the subsequent 50 m segment, and so forth. The participants were instructed that when they could not maintain the pace set by the moving light-emitting diode lights they had to finish the remaining distance of the 50-m segment with all-out effort, the test was then terminated. The participants exited the pool and rested in a supine position for 5 min immediately after swimming. The protocol of the incremental swimming test is presented in Fig. 1.

Incremental cycle ergometer test (CE)

The participants then underwent a gradually increasing workload on the Corival cycle ergometer (Lode, Groningen, Netherlands). The participants were instructed to maintain a cadence of 70 per min while the workload remained constant at 40 W for 4 min (warm-up). The workload was subsequently increased by approximately 4.2 W every 10 s or 25 W every min. The exercise was terminated when the cadence was lower than 60 per min for 15 s. The protocol of the incremental cycle ergometer test is presented in Fig. 2. The air temperature in the laboratory during the non-specific testing was approximately 18–20 °C.

Incremental arm crank ergometer test (ACE)

The ACE was conducted using the Angio ergometric unit (Lode) following a methodology similar to that used during the incremental CE. The cadence of 70 per min was maintained both during constant and consistently increasing workloads. The constant workload for 4 min was 10 W; the workload then increased gradually by approximately 1.7 W every 10 s or 10 W every min. The exercise was terminated when the cadence was lower than 60 per min for 15 s. The protocol of the incremental arm crank ergometer test is presented in Fig. 3.

Blood lactate measurements

After performing each incremental test, the participants had to rest in the supine position for 5 min, after which a capillary blood sample was taken to measure blood lactate concentration [La5'] using the Lactate Pro 2 (Arkray, Kyoto, Japan) analyser.

Statistical analysis

Data provided in tables and graphs are presented as means and standard deviations. The Shapiro–Wilcoxon test was conducted to assess the normality of distribution. One-way analysis of variance for repeated measures was employed to test the null hypothesis and determine the differences between the indicators obtained under specific and non-specific testing conditions. The effect size was calculated using Cohen's d method by dividing the two population mean differences by the pooled standard deviation. Pearson's correlation coefficient was calculated to assess the relationships between the indicators of the pulmonary gas exchange. The correlation coefficients from 0.30 to 0.50 (or from –0.30 to –0.50) were considered low, from 0.50 to 0.70 (or from –0.50 to –0.70) – moderate, from 0.70 to 0.90 (or from – 0.70 to –0.90) – high and from 0.90 to 1.00 (or from –0.90 to

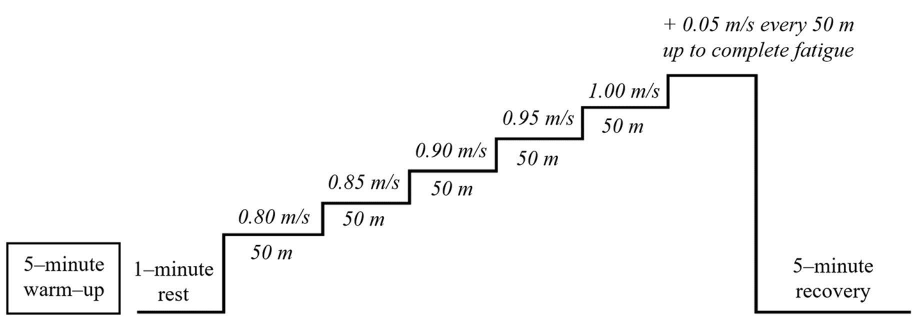

Fig. 1 Protocol of the incremental swimming test

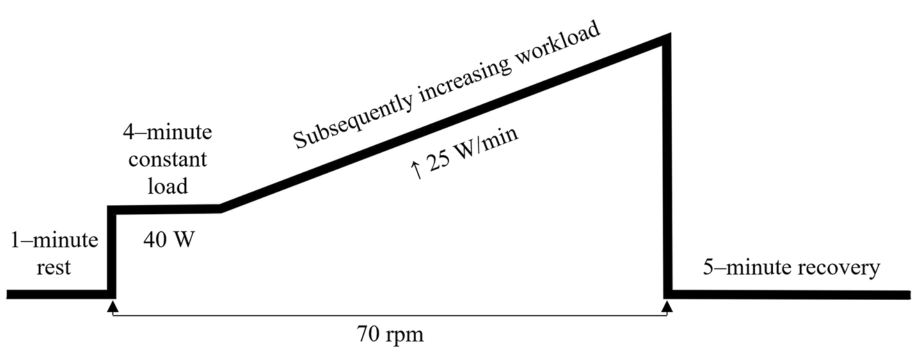

Fig. 2 Protocol of the incremental cycle ergometer test

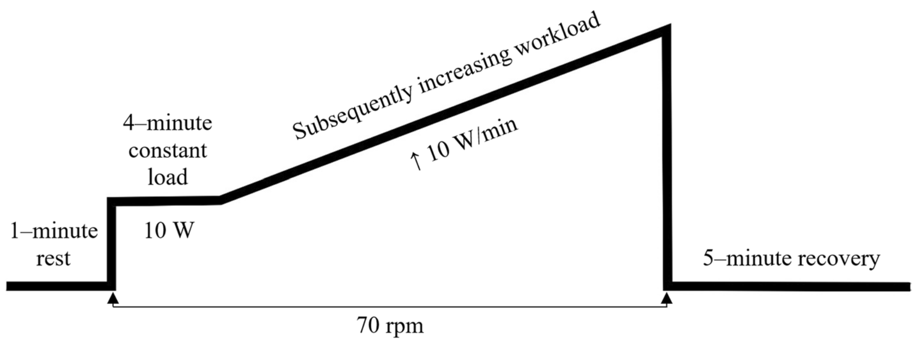

Fig. 3 Protocol of the incremental arm crank ergometer test

–1.00) – very high [30]. The differences and correlations were considered statistically significant at $P<0.05$. All calculations were performed using the Statistical Package for Social Sciences (SPSS v.27, SPSS Inc., Chicago, IL, USA).

Results

Peak values

The relative $\dot{V}O_2$peak value during the SW was approximately 9% lower and 20% higher than during the CE and ACE, respectively (Fig. 4). The effect size of the type of ergometry: SW vs CE – 0.420, SW vs ACE – 0.971, CE vs ACE – 1.562.

The mean values of other pulmonary gas exchange indicators are presented in Table 2. The absolute $\dot{V}O_2$peak, $V_E$peak and $V_T$peak values during the SW were lower than those during the CE but higher than those during the ACE.

HRpeak value after the SW was approximately 8% and 5% lower than after the CE and ACE, respectively (Fig. 5). [La5'] after the SW was approximately 49% and 10% lower than after the CE and ACE, respectively (Fig. 6).

Correlations between peak values under specific and non-specific testing conditions

Figure 7 shows positive correlations between the relative $\dot{V}O_2$peak values in the SW and CE ($r=0.657$) (A) and in the SW and ACE ($r=0.843$) (B). No statistically significant correlations were found between the relative $\dot{V}O_2$peak value in the SW and other pulmonary gas exchange indicators observed in the CE and ACE.

Correlations between the pulmonary gas exchange indicators obtained under specific and non-specific testing conditions are presented in Table 3. A positive correlation was observed between the absolute $\dot{V}O_2$peak value in the SW and the absolute $\dot{V}O_2$peak, $V_E$peak and $V_T$peak values in both CE and ACE. The $V_E$peak value in the SW correlated with the absolute $\dot{V}O_2$peak, $V_T$peak and BFpeak values in the CE. The $V_E$peak value in the SW also correlated with the absolute $\dot{V}O_2$peak, $V_E$peak and $V_T$peak values in the ACE. The $V_T$peak value in the SW

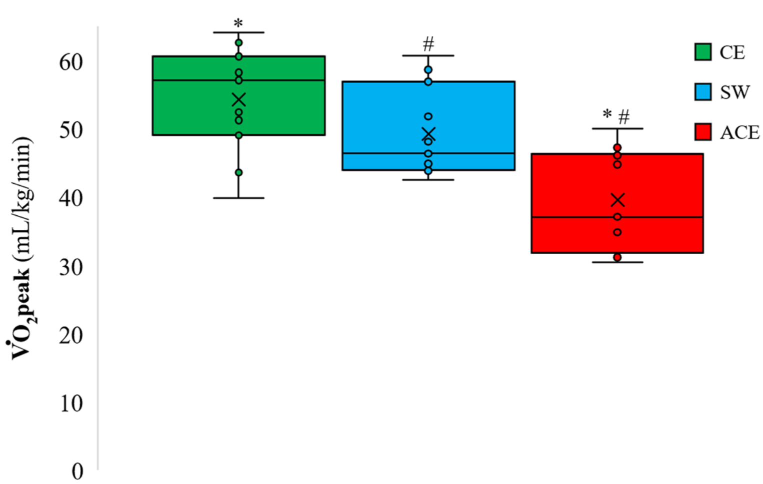

Fig. 4 The relative $\dot{V}O_2$peak values under different testing conditions. SW, swimming test; CE, cycle ergometer test; ACE, arm crank ergometer test. *$P<0.01$, the difference from SW; #$P<0.01$, the difference from CE

Table 2 Maximum pulmonary gas exchange indicators under specific and non-specific testing conditions

	SW	CE	ACE	%diff SW vs CE	%diff SW vs ACE	%diff CE vs ACE
$\dot{V}O_2$peak (L/min)	2.213 ± 0.508 ##	2.408 ± 0.415 **	1.766 ± 0.407 **##	− 8%	+ 20%	+ 27%
$\dot{V}_E$peak (L/min)	84.940 ± 12.629 ##	98.421 ± 15.406 **	69.412 ± 18.195 **##	− 14%	+ 18%	+ 29%
$V_T$peak (L)	1.776 ± 0.453 ##	1.969 ± 0.547 **	1.620 ± 0.455 *##	− 10%	+ 9%	+ 18%
BFpeak (bpm)	62.6 ± 8.1	61.2 ± 12.3	53.4 ± 10.5 **#	+ 2%	+ 15%	+ 13%
RERpeak	1.06 ± 0.03 ##	1.18 ± 0.05	1.08 ± 0.04 ##	−10%	−2%	+ 8%

%diff Percentage difference among different testing conditions, *SW* Swimming test, *CE* Cycle ergometer test, *ACE* Arm crank ergometer test, $\dot{V}O_2$ Oxygen uptake, $\dot{V}_E$ Min ventilation, V_T Tidal volume, *BF* Breathing frequency, *RER* Respiratory exchange ratio, *bpm* breaths per min

* $P < 0.05$, differences from SW

** $P < 0.01$, differences from SW

# $P < 0.05$, differences from CE

$P < 0.01$, differences from CE

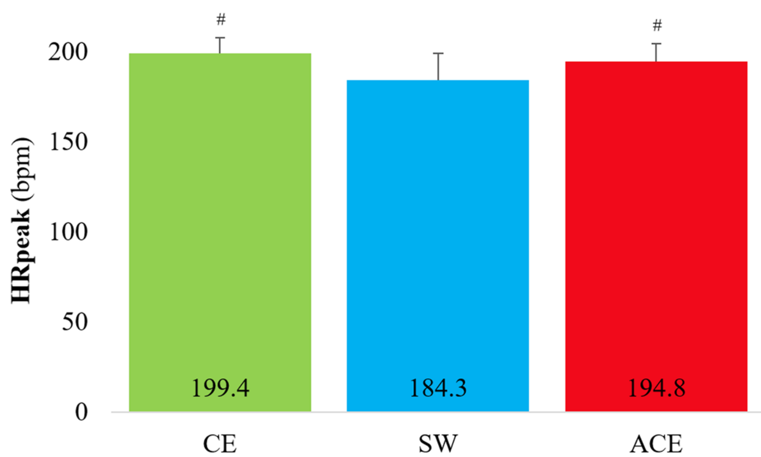

Fig. 5 Peak HR values under different testing conditions. SW, swimming test; CE, cycle ergometer test; ACE, arm crank ergometer test. #$P < 0.05$, the difference from SW

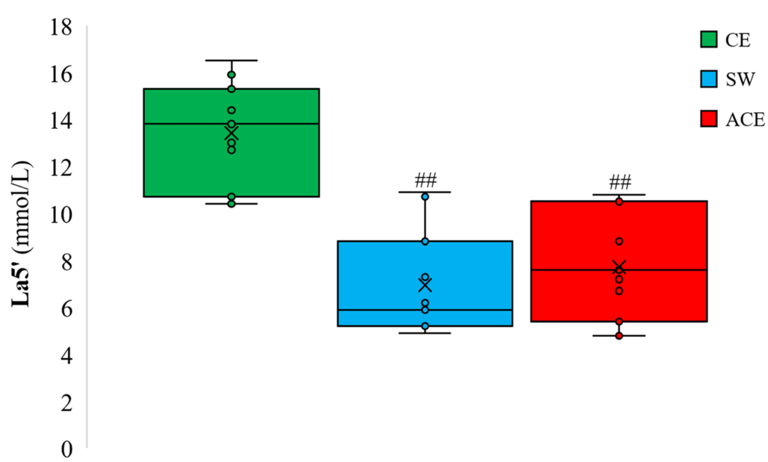

Fig. 6 [La5′] values after testing under different conditions. SW, swimming test; CE, cycle ergometer test; ACE, arm crank ergometer test. ##$P < 0.01$, the difference from CE

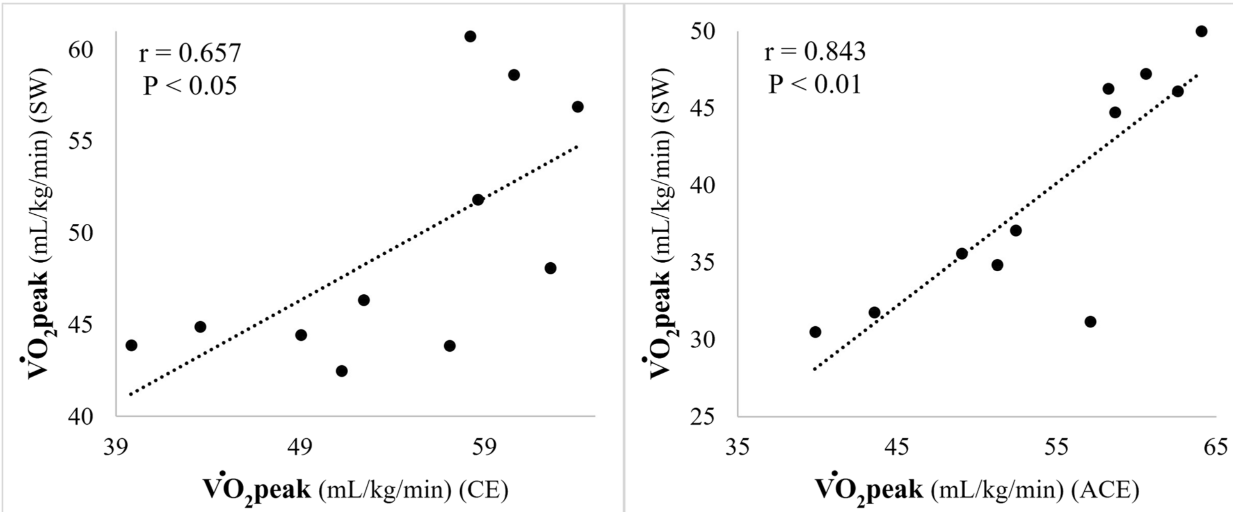

Fig. 7 Relationships of the relative $\dot{V}O_2$peak values during specific and non-specific testing conditions. SW, swimming test; CE, cycle ergometer test; ACE, arm crank ergometer test; $\dot{V}O_2$peak, peak oxygen uptake

correlated with the $\dot{V}O_2$peak, $V_E$peak and $V_T$peak values in the CE and with the $\dot{V}O_2$peak, $V_T$peak and BFpeak values in the ACE. The BFpeak value in the SW correlated with the $V_T$peak value in both CE and ACE.

Discussion

The present study is the first to measure the aerobic capacity under specific swimming conditions in young swimmers aged 11–13 years. In addition, we evaluated the differences and associations of the aerobic capacity of young swimmers under three different testing conditions (swimming, cycling and arm cranking). We observed that $\dot{V}O_2$peak and $V_E$peak values during swimming were lower than those during cycling but higher than those during arm cranking. We also found that the $\dot{V}O_2$peak value during swimming strongly correlated with those during both cycling and arm cranking, while the $V_E$peak value during swimming only correlated with that during arm cranking.

On comparing our findings with previous findings, we observed that adult swimmers had higher $\dot{V}O_2$peak values than the young swimmers aged 11–13 years in our study. The $\dot{V}O_2$peak values of highly trained adult swimmers range from 44.2 ± 7.7 mL/kg/min to 76.8 ± 6.5 mL/kg/min during swimming [15, 18–22, 26, 31–48]. The $\dot{V}O_2$peak values during swimming in the present study were within this range but closer to the lower values. Notably, the $\dot{V}O_2$peak values ranging from 53.5 ± 4.2 mL/kg/min to 57.2 ± 4.6 mL/kg/min were observed in young 13–14–year–old female swimmers [21, 49]. Lower $\dot{V}O_2$peak values observed in our study may be due to the age differences of the participants, because our study involved swimmers aged 11–13 years while other studies focused on adult athletes [15, 26, 31–33, 46, 48]. Adaptation of the physiological systems to aerobic training because of longer training experience leads to higher $\dot{V}O_2$peak values among adult swimmers and less expressed differences in $\dot{V}O_2$peak values among ergometers, as demonstrated by Pinna et al. [26].

Adult elite swimmers in other studies had $V_E$peak values ranging from 83.0 ± 9.2 L/min to 152.1 ± 21.9 L/min [15, 19, 25, 31, 35, 36, 42, 46, 47]. The $V_E$peak values during swimming in the present study were within this range but were closer to the lower values. Such outcome could be explained by the anthropometric differences between young and adult athletes. Previous research has observed positive correlations between age and maximal V_E [50], as well as between height and maximal V_E [51], while others found a direct relationship between the increase in lean body mass and maximal V_E [52]. The increase in V_E during the period of growth and maturation is more related to the increase of V_T rather than BF [51].

The HRpeak values of adult elite swimmers ranged from 174.8 ± 11.8 bpm to as high as 193.6 ± 7.5 bpm [19, 22, 26, 31, 32, 35–37, 40, 42, 44, 46, 47, 53]. The HRpeak values during swimming in the present study were in the middle of this range. Almeida et al., [22] observed similar to our HRpeak values in young swimmers. Kimura et al. [15], on comparing different testing conditions, found that the mean HRpeak values during swimming were 5% lower compared to cycling and 5% higher compared to arm cranking. Pinna et al. [26] found the opposite trends in HRpeak, where the highest HRpeak values were observed during arm cranking and they were 6% higher

Table 3 Correlations between pulmonary gas exchange indicators under specific and non-specific testing conditions

		SW			
		$\dot{V}O_2$peak (L/min)	$\dot{V}_E$peak (L/min)	$\dot{V}_T$peak (L)	BFpeak (bpm)
CE	$\dot{V}O_2$peak (L/min)	0.857**	0.808**	0.879**	−0.497
	$\dot{V}_E$peak (L/min)	0.715*	0.521	0.818**	−0.496
	$\dot{V}_T$peak (L)	0.759**	0.729*	0.939**	−0.702*
	BFpeak (bpm)	−0.560	−0.794**	−0.601	0.465
ACE	$\dot{V}O_2$peak (L/min)	0.899**	0.811**	0.729*	−0.494
	$\dot{V}_E$peak (L/min)	0.669*	0.626*	0.443	−0.283
	$\dot{V}_T$peak (L)	0.840**	0.741**	0.820**	−0.772**
	BFpeak (bpm)	−0.434	−0.526	−0.760**	0.585

SW Swimming test, *CE* Cycle ergometer test, *ACE* Arm crank ergometer test, *VO2* Oxygen uptake, *VE* Min ventilation, *VT* Tidal volume, *BF* Breathing frequency, *bpm* Breaths per min

*$P < 0.05$

**$P < 0.01$

compared to swimming and cycling, where identical values were observed. Our study showed 8% and 5% lower HRpeak values in swimming compared to cycling and arm cranking, respectively. Lower HRpeak values during swimming could be explained by the horizontal body position. Stroke volume and cardiac filling in the supine position are enhanced compared with sitting or standing positions [53]. Arms and the upper body are mainly responsible for generating power during swimming. Therefore, differences in the active muscle mass between swimming and cycling can affect the response of the cardiovascular system and lead to differences in the HRpeak values between them [54]. Enhanced vagal tone due to water immersion can lead to lower HRpeak values during swimming than during on-land exercises [55]. Another possible reason for differences in the HRpeak values between swimming and on-land exercises may be related to increased external pressure and heat conduction in water compared with those in on-land exercises [56].

La5’ values in adult swimmers after the maximal swimming tests ranged from 6.9 ± 2.5 mmol/L to 12.9 ± 3.0 mmol/L [22, 31–33, 35, 38, 39, 42–44, 47, 48]. The [La5’] values after the swimming test in the present study were towards the lower end of this range. Eriksson and Saltin [57] reported that muscle lactate production increased with age. Previous studies also found lower blood lactate levels in younger individuals compared to adults [58]. Age-related changes in muscle enzyme activity are evident, with muscle biopsies showing lower levels of the glycolytic enzyme phosphofructokinase in children aged 11–13 years compared to adults [59–61]. Cycling primarily involves the large lower body muscles, which have a greater capacity for lactate production, while arm cranking and swimming primarily rely on the upper body muscles that have less overall muscle mass. Therefore, lower lactate production is observed during swimming and arm cranking than cycling [62].

In comparisons involving cycling, swimming and arm cranking, a similar study has been conducted with adult swimmers, and a higher $\dot{V}O_2$peak value was obtained during tethered swimming than during cycling and arm cranking [21]. While de Haan et al., [18] observed almost identical $\dot{V}O_2$peak values between swimming and cycling, 21% lower $\dot{V}O_2$peak was also observed during arm cranking compared to swimming and cycling. Moreover, Kimura et al. [15] observed $\dot{V}O_2$peak differences similar to ours among testing conditions, where the $\dot{V}O_2$peak value during swimming was approximately 11% lower and 37% higher than that during cycling and arm cranking, respectively. In our study, the percentage differences between swimming and cycling $\dot{V}O_2$peak values were similar (8%) while the differences between swimming and arm cranking $\dot{V}O_2$peak value were almost twice as low (20%). Most studies observed lower $\dot{V}O_2$peak values during arm cranking compared to swimming, although differences between swimming and cycling can vary from 11% lower [15] to 11% higher [26] in swimming compared to cycling. Lower $\dot{V}O_2$peak differences in our study could be due to the lower level of adaptation and its specificity level. Kimura et al. [15] also found that the $V_E$peak values during swimming were approximately 24% lower and 26% higher than those during cycling and arm cranking, respectively. In our study, we observed similar trends in the $V_E$peak values, with the 14% difference between swimming and cycling and 18% difference between swimming and arm cranking. The lowest $\dot{V}O_2$peak and $V_E$peak values usually achieved during arm cranking compared with other modes of exercise, such as cycling, could be explained by the smaller muscle mass involved, as well as the muscle fibre ratio, because arm muscles consist of a higher percentage of type II fibres [16]. Moreover, arm muscles consume less oxygen and have a lower oxidative capacity than leg muscles [56]. The differences in $\dot{V}O_2$peak and $V_E$peak values between swimming and cycling could be due to different recruitment and activation levels of muscles. However, in front crawl swimming only about 15% of the propulsive force is generated by the legs [63]. Furthermore, leg muscles could possibly reach higher activation levels and working muscle mass could be higher during cycling. Both arm and leg muscles might be proportionally but less activated during swimming than cycling.

Associations found in our study suggest that the $\dot{V}O_2$peak value observed in the SW was closely related to that observed under non-specific testing conditions. This finding indicates that swimmers aged 11–13 years who had a higher aerobic capacity during swimming would also have higher $\dot{V}O_2$peak values in both CE and ACE. Similarly, previous studies also observed strong positive correlation coefficients (0.73 – 0.97) between the $\dot{V}O_2$peak value during swimming and that during arm cranking [23, 27, 28]. Despite these studies being more than two decades old, these correlations still provide valuable insight into the physiological relationships between swimming and arm-cranking activities. A more recent study by Sousa et al. [16] did not identify any significant $\dot{V}O_2$peak correlations between different testing conditions in triathletes. However, the $V_E$peak value during swimming showed a significant correlation only with the $V_E$peak value during arm cranking. This finding suggests that arm cranking is a more relevant exercise modality when assessing pulmonary function compared with other forms of exercise, such as cycling, which did not demonstrate a significant correlation with the swimming-related $V_E$peak value. Physiological adaptations to exercise training are highly specific to the nature of the training activity. Therefore, the $\dot{V}O_2$peak values attained by athletes (rowers, cyclists and cross-country skiers) were as high as, or higher than, those attained on the treadmill [64]. Despite the specificity, the adaptation has a general component. Some transfer-of-training effects have been reported, including increased $\dot{V}O_2$peak values and reduced submaximal HR with untrained limbs, thus providing evidence for central circulatory adaptations to chronic endurance exercise [65, 66]. Approximately half of the increase in trained limb performance has been suggested to result from a centralized training effect and half from the peripheral adaptations, specifically alterations in trained skeletal muscle [67]. According to Fick's equation, $\dot{V}O_2$peak depends on the peak cardiac output and maximal arteriovenous oxygen difference. Cardiac output is dependent on the performance of the cardiovascular system, while the difference in arteriovenous oxygen is dependent on the capacity of the working muscles to consume oxygen. Swimming training develops both the cardiorespiratory system and upper and lower body muscles. Therefore, swimmers who perform better during swimming may also perform better during cycling and arm cranking. In addition, young swimmers with shorter training experiences do not show as developed specificity of adaptation as that of adult swimmers.

Limitations

The equipment used in the present study somewhat limits certain aspects of swimming. For example, due to the snorkel position, swimmers could not perform the usual, more efficient turns and unilateral and bilateral breathing because all inhalations and exhalations are performed with the face directed towards the bottom of the pool. The biological age was not determined, which could also be one of the limitations because our study involved 11–13-year-old participants of both genders.

Conclusion

Swimmers aged 11–13 years showed $\dot{V}O_2$peak and $\dot{V}_E$peak values during the specific swimming test were greater than those during arm cranking but lower than those during cycling. However, aerobic capacity parameters measured during specific swimming conditions correlated with those measured during non-specific arm cranking and cycling conditions.

Abbreviations

%diff	Percentage difference among different testing conditions
[La5′]	Blood lactate concentration 5 min after the test
ACE	Arm crank ergometer test
BF	Breathing frequency
CE	Cycle ergometer test
HR	Heart rate
RER	Respiratory exchange ratio
SW	Swimming test
$\dot{V}CO_2$	Carbon dioxide output
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$peak	Peak oxygen uptake
$\dot{V}_T$	Tidal volume
WAP	World Aquatic points

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Authors' contributions
V.M., L.S. and A.S. were in charge of the conception and the design of the study. V.M., I.J.Z. and A.J. were in charge of data acquisition, analysis and interpretation of data. The manuscript was drafted by V.M., L.S. and A.S. All authors read and approved the final manuscript.

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Availability of data and materials
Selected data are available upon reasonable request from the corresponding author.

Data availability
The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at Lithuanian Sports University.

Declarations

Ethics approval and consent to participate
All subjects and their parents or legal guardians were provided with detailed information about the study procedures and written informed consent to participate was obtained. All experiments were performed in accordance with the Declaration of Helsinki and other relevant national guidelines and regulations. Ethical approval was obtained from The Lithuanian National Committee for Bioethics (date: 30.05.2018; Nr: BE–2–28).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Barbosa TM, Bragada JA, Reis VM, Marinho DA, Carvalho C, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sport. 2010;13(2):262–9. https://doi.org/10.1016/j.jsams.2009.01.003.
2. Barbosa TM, Costa MJ, Marinho DA. Proposal of a deterministic model to explain swimming performance. Int J Swimming Kinet. 2013;2(1):1–54.
3. di Prampero PE, Pendergast DR, Wilson DW, Rennie DW. Energetics of swimming in man. J Appl Physiol. 1974;37(1):1–5. https://doi.org/10.1152/jappl.1974.37.1.1.
4. Zamparo P, Capelli C, Pendergast D. Energetics of swimming: a historical perspective. Eur J Appl Physiol. 2011;111(3):367–78. https://doi.org/10.1007/s00421-010-1433-7.
5. Figueiredo P, Zamparo P, Sousa A, Vilas-Boas JP, Fernandes RJ. An energy balance of the 200m front crawl race. Eur J Appl Physiol. 2011;111:767–77. https://doi.org/10.1007/s00421-010-1696-z.
6. Costill D, Maglischo E, Richardson A. Swimming. Handbook of sports medicine and science. Oxford: Blackwell Scientific Publications; 1992.
7. Vitor Fde M, Böhme MT. Performance of young male swimmers in the 100-meters front crawl. Pediatr Exerc Sci. 2010;22(2):278–87. https://doi.org/10.1123/pes.22.2.278.
8. Barbosa TM, Costa M, Marinho DA, Coelho J, Moreira M, Silva AJ. Modeling the links between young swimmers' performance: energetic and biomechanic profiles. Pediatr Exerc Sci. 2010;22(3):379–91. https://doi.org/10.1123/pes.22.3.379.
9. Alves M, Carvalho DD, Fernandes RJ, Vilas-Boas JP. How anthropometrics of young and adolescent swimmers influence stroking parameters and performance? A systematic review. Int J Environ Res Public Health. 2022;19(5):2543. https://doi.org/10.3390/ijerph19052543.
10. Armstrong N, Welsman JR. Development of aerobic fitness during childhood and adolescence. Pediatr Exerc Sci. 2000;12(2):128–49. https://doi.org/10.1123/pes.12.2.128.
11. Boisseau N, Delamarche P. Metabolic and hormonal responses to exercise in children and adolescents. Sports Med. 2000;30(6):405–22. https://doi.org/10.2165/00007256-200030060-00003.
12. Inbar O, Bar-Or O. Anaerobic characteristics in male children and adolescents. Med Sci Sports Exerc. 1986;18(3):264–9. https://doi.org/10.1249/00005768-198606000-00002.
13. Kaczor JJ, Ziolkowski W, Popinigis J, Tarnopolsky MA. Anaerobic and aerobic enzyme activities in human skeletal muscle from children and adults. Pediatr Res. 2005;57(3):331–5. https://doi.org/10.1203/01.PDR.0000150799.77094.DE.
14. Falgairette G, Bedu M, Fellmann N, Van-Praagh E, Coudert J. Bio-energetic profile in 144 boys aged from 6 to 15 years with special reference to sexual maturation. Eur J Appl Physiol Occup Physiol. 1991;62(3):151–6. https://doi.org/10.1007/BF00643734.
15. Kimura Y, Yeater RA, Martin RB. Simulated swimming: a useful tool for evaluation the VO2 max of swimmers in the laboratory. Br J Sports Med. 1990;24:201–6. https://doi.org/10.1136/bjsm.24.3.201.
16. Sousa A, Borrani F, Rodríguez FA, Millet GP. Oxygen uptake kinetics is slower in swimming than arm cranking and cycling during heavy intensity. Front Physiol. 2017;8:639–48. https://doi.org/10.3389/fphys.2017.00639.
17. Marko D, Bahenský P, Snarr RL, Malátová R. VO2peak comparison of a treadmill vs. cycling protocol in elite teenage competitive runners.

cyclists. and swimmers. J Strength Cond Res. 2022;36:2875–82. https://doi.org/10.1519/JSC.0000000000004005.
18. de Haan M, van der Zwaard S, Schreven S, Beek PJ, Jaspers RT. Determining V̇O2max in competitive swimmers: comparing the validity and reliability of cycling, arm cranking, ergometer swimming, and tethered swimming. J Sci Med Sport. 2024;27(7):499–506. https://doi.org/10.1016/j.jsams.2024.03.015.
19. Nagle EF, Nagai T, Beethe A, Lovalekar M, Tuite MS, Beckner ME. Reliability and validity of a flume-based maximal oxygen uptake swimming test. Sports. 2023;11:42–53. https://doi.org/10.3390/sports11020042.
20. Espada MC, Ferreira CC, Gamonales JM, Hernández-Beltrán V, Massini DA, Macedo AG. Body composition relationship to performance, cardiorespiratory profile, and tether force in youth trained swimmers. Life. 2023;13:1806–18. https://doi.org/10.3390/life13091806.
21. Sokołowski K, Strzała M, Stanula A, Kryst Ł, Radecki-Pawlik A, Krężałek P. Biological age in relation to somatic, physiological, and swimming kinematic indices as predictors of 100 m front crawl performance in young female swimmers. Int J Environ Res Public Health. 2021;18:6062–72. https://doi.org/10.3390/ijerph18116062.
22. Almeida TA, Pessôa Filho DM, Espada MA, Reis JF, Simionato AR, Siqueira LO. VO2 kinetics and energy contribution in simulated maximal performance during short and middle distance–trials in swimming. Eur J Appl Physiol. 2020;120:1097–109. https://doi.org/10.1007/s00421-020-04348-y.
23. Bonen A, Wilson BA, Yarkony M, Belcastro AN. Maximal oxygen uptake during free, tethered, and flume swimming. J Appl Physiol. 1980;48:232–5. https://doi.org/10.1152/jappl.1980.48.2.232.
24. Vogler AJ, Rice AJ, Gore CJ. Validity and reliability of the Cortex MetaMax3B portable metabolic system. J Sports Sci. 2010;28(7):733–42. https://doi.org/10.1080/02640410903582776.
25. Lomax M, Mayger B, Saynor ZL, Vine C, Massey HC. Practical considerations for assessing pulmonary gas exchange and ventilation during flume swimming using the metaswim metabolic cart. J Strength Cond Res. 2019;33(7):1941–53. https://doi.org/10.1519/JSC.0000000000002801.
26. Pinna M, Milia R, Roberto S, Marongiu E, Olla S, Loi A. Assessment of the specificity of cardiopulmonary response during tethered swimming using a new snorkel device. J Physiol Sci. 2013;63:7–16. https://doi.org/10.1007/s12576-012-0226-7.
27. Gergley TJ, McArdle WD, DeJesus P, Toner MM, Jacobowitz S, Spina RJ. Specificity of arm training on aerobic power during swimming and running. Med Sci Sports Exerc. 1984;16:349–54.
28. Obert P, Falgairette G, Bedu M, Coudert J. Bioenergetic characteristics of swimmers determined during an arm-ergometer test and during swimming. Int J Sports Med. 1992;13:298–303. https://doi.org/10.1055/s-2007-1021270.
29. Ruiz-Navarro JJ, López-Belmonte Ó, Gay A, Cuenca Fernández F, Arellano R. A new model of performance classification to standardize the research results in swimming. Eur J Sport Sci. 2023;23(4):478–88. https://doi.org/10.1080/17461391.2022.2046174.
30. Hinkle DE, Wiersma W, Jurs SG. Applied statistics for the behavioural sciences. 5th ed. Boston: Houghton Mifflin; 2003.
31. Nagle EF, Nagai T, Beethe AZ, Lovalekar MT, Zera JN, Connaboy C. Reliability and validity of a pool-based maximal oxygen uptake test to examine high-intensity short-duration freestyle swimming performance. J Strength Cond Res. 2019;33:1208–15. https://doi.org/10.1519/JSC.0000000000003113.
32. de Jesus K, Sousa A, de Jesus K, Ribeiro J, Machado L, Rodríguez F. The effects of intensity on VO2 kinetics during incremental free swimming. Appl Physiol Nutr Metab. 2015;40:918–23. https://doi.org/10.1139/apnm-2015-0029.
33. de Matos CC, Marinho DA, Duarte-Mendes P, de Souza Castro FA. VO2 kinetics and bioenergetic responses to sets performed at 90%, 92.5%, and 95% of 400-m front crawl speed in male swimmers. Sport Sci Health. 2022;18:1321–9. https://doi.org/10.1007/s11332-022-00903-6.
34. Lomax M, Royal JT, Kapus J, Massey H, Saynor Z. Oxygen uptake kinetics and ventilatory and metabolic parameters do not differ between moderate-intensity front crawl and breaststroke swimming. Physiol Rep. 2022;10:1–9. https://doi.org/10.14814/phy2.15361.
35. Gay A, Zacca R, Abraldes JA, Morales-Ortíz E, López-Contreras G, Fernandes RJ, Arellano R. Swimming with swimsuit and wetsuit at typical vs. cold-water temperatures (26 vs. 18℃). Int J Sports Med. 2021;42:1305–12. https://doi.org/10.1055/a-1481-8473.
36. Pelarigo JG, Fernandes RJ, Ribeiro J, Denadai BS, Greco CC, Vilas-Boas JP. Comparison of different methods for the swimming aerobic capacity evaluation. J Strength Cond Res. 2018;32:3542–51. https://doi.org/10.1519/JSC.0000000000001873.
37. Rodríguez FA, Iglesias X, Feriche B, Calderón-Soto C, Chaverri D, Wachsmuth NB. Altitude training in elite swimmers for sea level performance (altitude project). Med Sci Sports Exerc. 2015;47:1965–78. https://doi.org/10.1249/MSS.0000000000000626.
38. Reis VM, Marinho DA, Policarpo FB, Carneiro AL, Baldari C, Silva AJ. Examining the accumulated oxygen deficit method in front crawl swimming. Int J Sports Med. 2010:421–7.https://doi.org/10.1055/s-0030-1248286.
39. Reis JF, Alves FB, Bruno PM, Vleck V, Millet GP. Effects of aerobic fitness on oxygen uptake kinetics in heavy intensity swimming. Eur J Appl Physiol. 2012;112:1689–97. https://doi.org/10.1007/s00421-011-2126-6.
40. Bentley DJ, Roels B, Hellard P, Fauquet C, Libicz S, Millet GP. Physiological responses during submaximal interval swimming training: effects of interval duration. J Sci Med Sport. 2005;8:392–402. https://doi.org/10.1016/s1440-2440(05)80054-4.
41. Roels B, Schmitt L, Libicz S, Bentley D, Richalet J, Millet G. Specificity of V˙o2max and the ventilatory threshold in free swimming and cycle ergometry: comparison between triathletes and swimmers. Br J Sports Med. 2005;39:965–8. https://doi.org/10.1136/bjsm.2005.020404.
42. Sousa AC, Vilas–Boas JP, Fernandes RJ. Kinetics and metabolic contributions whilst swimming at 95, 100, and 105% of the velocity at VO2 max. BioMed Res Int. 2014:1–9.https://doi.org/10.1155/2014/675363.
43. Sousa A, Figueiredo P, Keskinen KL, Rodríguez FA, Machado L, Vilas-Boas JP, Fernandes RJ. VO2 off transient kinetics in extreme intensity swimming. J Sports Sci Med. 2011;10:546–56.
44. Fernandes RJ, Keskinen KL, Colaço P, Querido AJ, Machado LJ, Morais PA. Time limit at V· O2max velocity in elite crawl swimmers. Int J Sports Med. 2008;29:145–50. https://doi.org/10.1055/s-2007-965113.
45. Fernandes RJ, Marinho DA, Barbosa TM, Vilas-Boas JP. Is time limit at the minimum swimming velocity of VO2 max influenced by stroking parameters? Percept Mot Skills. 2006;103:67–75. https://doi.org/10.2466/pms.103.1.67-75.
46. Fernandes RJ, Billat VL, Cruz AC, Colaço PJ, Cardoso CS, Vilas-Boas JP. Does net energy cost of swimming affect time to exhaustion at the individual's maximal oxygen consumption velocity? J Sports Med Phys Fitness. 2006;46:373–80.
47. Holmer I, Lundin A, Eriksson BO. Maximum oxygen uptake during swimming and running by elite swimmers. J Appl Physiol. 1974;36:711–4. https://doi.org/10.1152/jappl.1974.36.6.711.
48. Correia RA, Feitosa WG, Figueiredo P, Papoti M, de Souza Castro FA. The 400-m front crawl test: energetic and 3D kinematical analyses. Int J Sports Med. 2020;41:21–6. https://doi.org/10.1055/a-1023-4280.
49. Almeida TAF, Pessôa Filho DM, Espada MC, et al. Physiological responses during high-intensity interval training in young swimmers. Front Physiol. 2021;12.https://doi.org/10.3389/fphys.2021.662029.
50. Rowland TW, Cunningham LN. Development of ventilatory responses to exercise in normal white children. Chest. 1997;111(2):327–32. https://doi.org/10.1378/chest.111.2.327.
51. Rutenfranz J, Andersen KL, Seliger V, et al. Exercise ventilation during the growth spurt period: comparison between two European countries. Eur J Pediatr. 1981;136:135–42. https://doi.org/10.1007/BF00441915.
52. Prioux J, Ramonatxo M, Mercier J, Granier P, Mercier B, Prefaut C. Changes in maximal exercise ventilation and breathing pattern in boys during growth: a mixed cross-sectional longitudinal study. Acta Physiol Scand. 1997;161(4):447–5841. https://doi.org/10.1046/j.1365-201X.1997.00245.x.
53. Bundgaard-Nielsen M, Sørensen H, Dalsgaard M, Rasmussen P, Secher NH. Relationship between stroke volume, cardiac output and filling of the heart during tilt. Acta Anaesthesiol Scand. 2009;53:1324–8. https://doi.org/10.1111/j.1399-6576.2009.02062.x.
54. Olstad BH, Bjørlykke V, Olstad DS. Maximal heart rate for swimmers. Sports. 2019;7:235–47. https://doi.org/10.3390/sports7110235.
55. Schmid JP, Noveanu M, Morger C, Gaillet R, Capoferri M, Anderegg M, Saner H. Influence of water immersion, water gymnastics and swimming on cardiac output in patients with heart failure. Heart. 2007;93:722–7. https://doi.org/10.1136/hrt.2006.094870.
56. Ørtenblad N, Nielsen J, Boushel R, Söderlund K, Saltin B, Holmberg HC. The muscle fiber profiles, mitochondrial content, and enzyme activities of the exceptionally well-trained arm and leg muscles of elite cross-country

skiers. Front Physiol. 2018;9:1031–42. https://doi.org/10.3389/fphys.2018.01031.
57. Eriksson O, Saltin B. Muscle metabolism during exercise in boys aged 11 to 16 years compared to adults. Acta Paediatr Belg. 1974;28:257–65.
58. Rostein A, Dofan R, Bar-Or O, et al. Effect of training on anaerobic threshold, maximal aerobic power and anaerobic performance of preadolescent boys. Int J Sports Med. 1986;7(5):281–6. https://doi.org/10.1055/s-2008-1025775.
59. Eriksson B. Physical training, oxygen supply and muscle metabolism in 11–13 year old boys. Acta Physiol Scand. 1972;384:1–48.
60. Gollnick P, Armstrong R, Saubert C, Piekl K, Saltin B. Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. J Appl Physiol. 1972;33:312–9. https://doi.org/10.1152/jappl.1972.33.3.312.
61. Aucouturier J, Baker JS, Duche P. Fat and carbohydrate metabolism during submaximal exercise in children. Sports Med. 2008;38:213–38. https://doi.org/10.2165/00007256-200838030-00003.
62. Astorino TA, Emma D. Differences in physiological and perceptual responses to high intensity interval exercise between arm and leg cycling. Front Physiol. 2021;12.https://doi.org/10.3389/fphys.2021.700294.
63. Vorontsov A, Rumyantsev V. Propulsive forces in swimming, biomechanics in sport: performance enhancement and injury. Prevention. 2000;9:205–31. https://doi.org/10.1002/9780470693797.
64. Strømme SB, Ingjer F, Meen HD. Assessment of maximal aerobic power in specifically trained athletes. J Appl Physiol. 1977;42:833–7. https://doi.org/10.1152/jappl.1977.42.6.833.
65. Clausen JP, Klausen K, Rasmussen B, Trap-Jensen. Central and peripheral circulatory changes after training of the arms or legs. Am J Physiology-Legacy Content. 1973;225:675–682.https://doi.org/10.1152/ajplegacy.1973.225.3.675.
66. McKenzie DC, Fox EL, Cohen K. Specificity of metabolic and circulatory responses to arm or leg interval training. Eur J Appl Physiol. 1978;39:241–8. https://doi.org/10.1007/BF00421447.
67. Thompson PD, Cullinane E, Lazarus B, Carleton RA. Effect of exercise training on the untrained limb exercise performance of men with angina pectoris. Am J Cardiol. 1981;48:844–50. https://doi.org/10.1016/0002-9149(81)90348-9.

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