SELECTED ANTROPOMETRIC CHARACTERISTIC OF SWIMMERS VS. KINEMATICS OF THE SWIMMING START

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ABSTRACT

We researched for relationships between selected anthropometric parameters of the elite swimmers and their performance considering the biomechanical structure of the swimming start as well as preferred back plate position. The study group consisted of 13 female and 14 male swimmers. First, anthropometric measures were obtained with a 3D scanner (Mephisto EX-PRO, 4D Dynamics Bvba, Belg). Subsequently, participants performed a kick-start. An instrumented starting block and four video cameras were used to collect kinematic data of the starts. The footage was analyzed using SIMI Motion software. Then Pearson's correlation coefficient was calculated. Athletes of both sexes with greater body height and longer upper limbs preferred to position the back plate further from the front of the starting block (r > 0.5). The duration of the push-off phase decreased with increasing body height and lower limb length (r = 0.64; r = 0.68). Males with higher body mass and longer upper limbs covered a longer distance during the flight phase (r = 0.75; r = 0.58). In the female group, a positive correlation was shown for torso length and flight time and distance (r = 0.67; r = 0.74). Males with higher body mass had shorter total start time (r = -0.67). Conscious individual choice of the starting position can result in an improvement in the quality of the swimming start. The obtained results allow for monitoring and evaluation of the individual technique of the swimming start and thus improve the training process.
Keywords: kick-start, body dimension, sex, biomechanics, performance.

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INTRODUCTION

In a swimming race, the final result depends not only on the swimming technique performed on distance but also on the start, turns, and finish [1]. This result is the sum of all the elements mentioned and is primarily a consequence of the multidirectional training process. Therefore, researchers most often look for cause-and-effect correlations between swimming performance and its biomechanical, physiological, motor, or psychological determinants [2-5]. An important role in the broader spectrum of research in the field of optimizing the training process in the direction of increasing performance plays analyses based on the athlete's somatic potential. This is reasoned by the genetic factor of the human body morphology, which is minor susceptible to adaptation to training stimuli [3,5,6]. In swimming, due to the specific properties of water, resulting in hydrodynamic resistive/propulsive forces, studies searching for the influence of somatic characteristics on the elements of swimming technique and their performance have a long tradition [2,7,8].

The swimming start (Figure 1) is the only element of the swimming race that includes the swimmer's actions on land (block phase), in the air (flight phase), and in the water (glide phase, underwater leg propulsion phase, and swim phase) [9,10]. The cited peculiarities of the swimming start result in a high complexity of the executed movement structures and their coordination in time and space. Thus, it seems to be an obvious justification for undertaking separate analyses of this element of the swimming race.

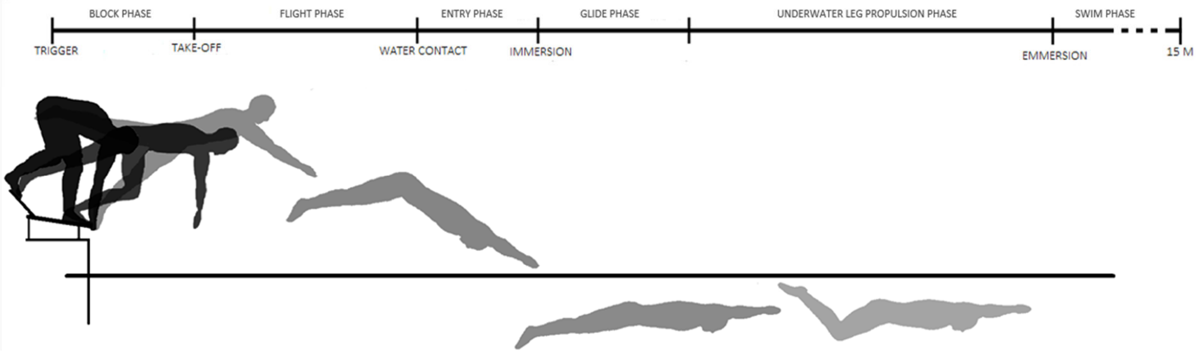

Fig. 1 Phases of the swimming start.

Improving the swimming start performance can occur through changes in starting conditions, the swimmers' individual motor capabilities, changes in the starting technique, or through modifications to the starting block setup permitted by the swimming rules [9]. Despite the fact that studies on the somatic characteristics of swimmers are numerous [7], we can find only a few scientific reports considering the correlation between swimmers' anthropometric parameters and the performance characteristics of the swimming start [11-14]. The available analyses have more often focused on analyzing the swimmers' body composition rather than looking for correlations between the somatic characteristics of the swimmers and their starting performance. Among the available scientific papers, one can find a description of the correlation between the length of the shin (as an anatomical measure to position the back plate of the starting block) and the spatial positioning of other body segments during the swimming start [15,16]. The aforementioned authors also showed that the positioning of the back plate of the starting block according to shin length significantly determines the duration of the block phase [16] and reaction time [15]. On the other hand, Wędrzyk et al. [13] showed that in a group of young swimmers, limb length had no significant effect on starting position. Another research stream in this area, arising from the similarities that exist between the swimming track-start and the sprint start [17,18], pays attention to, the role of the anthropometric parameters of swimmers in their preferences in the positioning of the feet relative to the back plate of starting block.

The aforementioned analysis of the current state of knowledge demonstrates the need to explore the factors objectively determining the interrelation between swimmers' somatic potential and successful performance of the swimming start. Therefore this study is an attempt to research for relationships between selected anthropometric parameters of the elite swimmers and their starting performance in terms of biomechanics. There is reason to believe that a comparison of the spatio-temporal parameters describing various phases of the swimming start with the set of easy-to-measure anthropometric parameters will reveal practical outcomes useful for individualization and rationalization of the technical training of this element of the swimming race, leading to improve the performance.

METHODS

The study group consisted of 25 swimmers representing international sports level (12 females aged 16 ± 1.7 years and 13 males aged 19.7 ± 3.9 years, with at least 750 FINA points). The study was conducted in the laboratory (anthropometric variables) and in a 25m indoor swimming pool (swimming start). Prior to the investigations, the participants were informed about the aim and the design of the study. All of them expressed voluntary consent to participate in the research. All procedures were performed in accordance with the Declaration of Helsinki regarding human research and were approved by the University's Ethics Committee.

ANTHROPOMETRIC MEASURMENTS

In the first part of the research protocol, the acquisition of anthropometric data took place (Figure 2). During the measurement, each participant was dressed in a standard swimsuit. It was performed in stillness, in two - anatomical and in streamline positions. Using four 3D scanners (Mephisto EX-PRO, 4D Dynamics Bvba, Belgium) aligned in the frontal, backward, and sagittal (right side and left side) planes, 3D models of each swimmer's body were constructed. Selected anthropometric points were then estimated for each person. Based on these, the variables shown in Table 1 and Figure 2 were calculated. Additionally, body mass was measured using the Inbody 230 device (Biospace Co. Ltd., Seoul, Korea).

Tab. 1

Anthropometric variables were selected for the analyses.

No.	Variable
1	Body height (B-v)[cm]
2	Shoulder breadth (a-a) [cm]
3	Pelvic breadth (ic-ic) [cm]
4	Shoulder breadth in the streamline position (widest part) [cm]
5	Length of the upper limb (a-sty) [cm]
6	Body height in the streamline position (B-da) [cm]
7	Length of upper limbs in the streamline position (a-da) [cm]
8	Torso length in the streamline position (a-tro) [cm]
9	Lower limb length (tro- mlf) [cm]
10	Foot length (ap-mlf) [cm]

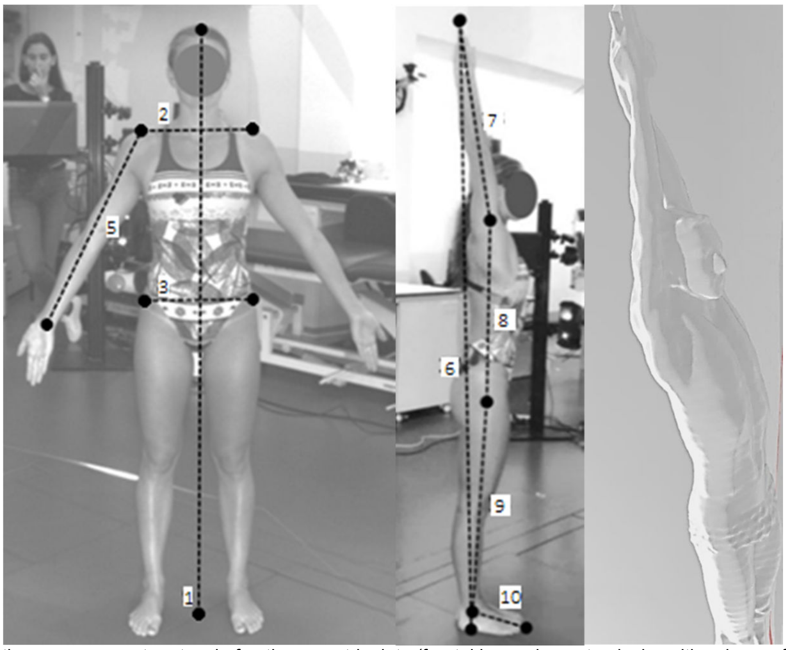

Fig. 2 Graphic presentation of the measurement protocol of anthropometric data (frontal image in anatomical position, image from the side in the streamline position, three-dimensional model obtained with the scanner).

SWIMMING START

The subjects' task was to perform a swimming start with the "kick-start" technique (known and preferred by all subjects) along with swimming a 20-m distance at maximum possible velocity. Sound and visual starting signals were provided. To collect data describing the phase on the block, an instrumented starting block (compliant with FINA regulations for OMEGA OSB 14) was used [19]. It is equipped with independent dynamometer platforms allowing measurement of ground reaction forces generated independently by each limb during the block phase. The temporal variables of the sub-phases of the block phase (hands take-off, rear foot take-off, front foot stand, and movement time) were also estimated from the data obtained in this way through analysis in MatLab (MathWorks Inc., Natick, MA, USA).

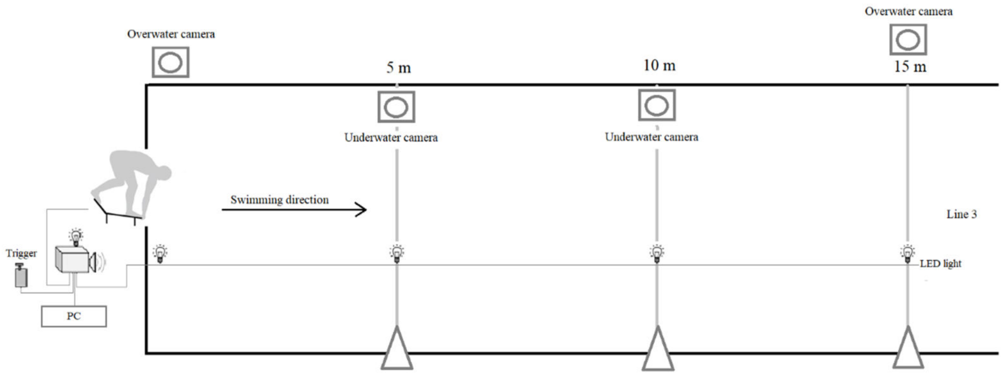

Fig. 3 A set of measuring devices used for data acquisition, based on which the values of the spatio-temporal variables describing the structure of the swimming start were determined.

Four video cameras (GoPro Hero 5, GoPro, San Mateo, CA, USA) working at 120 fps were located along the side wall of the swimming pool, parallel to the swimmers' path of movement. They were dedicated to recording participants' actions from the start signal until their head reached the point marking a distance of 15 m from the edge of the starting platform line (Figure 3). Along the measurement track, markers were placed in the field of view of each camera, as well as LEDs that transmitted a light signal to notify of the start of a given test and allow synchronization of the measurement devices.

SIMI Motion System (SIMI Reality Motion Systems GmbH, Germany) was used to analyze the collected video footage. The first frame with visible LED light was used to determine the starting signal for a given trial. This way the values of selected spatio-temporal variables describing the kinematic structure of swimming start were obtained. The selection of variables and the measurement protocol were determined based on available scientific reports involving analyses of the performance of the swimming start [9,20,21,22]. The scientifically confirmed definitions of the kinematic variables describing swimming start are presented in Table 2.

Tab. 2

Definitions of kinematic variables describing the execution of the swimming start.

Variable	Definition
Hands take-off (s)	The time interval between the starting signal and the last contact of the hands with the starting block
Rear foot take-off (s)	The time interval between the starting signal and the last contact of the rear foot with the starting block
Front foot stand (s)	The time interval between the last contact of the rear foot with the starting block and the moment when total vertical force fell to zero
Movement time (s)	The time interval from the first visible change in the starting block reaction force curve and the instant when total vertical force fell to zero
Flight time (s)	The time interval between the last contact of the toes with the block and the moment of the first contact of the hands with the water
Flight distance (m)	The horizontal distance measured between the point where fingertips entered the water and the starting wall
5 time (s)	The time interval between the starting signal and the moment when the head crossed the 5 m mark
5-10 time (s)	The time interval between the moment when the head crossed the 5-m mark and the moment when the head reached the 10 m mark
10 time (s)	The time interval between the starting signal and the moment when the head crossed the 10 m mark
10-15 time (s)	The time interval between the moment when the head crossed the 10-m mark and the moment when the head reached the 15 m mark
15 time (s)	The time interval between the starting signal and the moment when the head crossed the 15 m mark

The data of each variable were evaluated with descriptive statistics, the Shapiro-Wilk test, and the Levene's test, to ensure that they met the assumptions of parametric statistical procedures. To describe the group with representative values of the obtained data means and standard deviations of all variables were calculated. Next, the Student's t-test was performed for two independent groups, which was used to determine whether the sex of the study participants differentiates the studied variables of the kinematic structure of the swimming start and whether the sex criterion differentiates the selected anthropometric variables of the subjects. Pearson's correlation analysis was used to determine the relationships between the anthropometric variables considered and the variables describing the spatio-temporal structure of the swimming start. Statistical analyses were performed using Statistica 13.1 software (StatSoft, Tulsa, OK, USA). The level of statistical significance was established at α = 0.05.

RESULTS

Sex-stratified descriptive statistics for anthropometric variables of the swimmers researched are presented in Table 3. As expected, the results of the t-test revealed the sex effect on the anthropometric characteristics of the swimmers. Therefore, the outcomes were analyzed and interpreted separately for males and females. Males had a higher body mass than females (p = 0.001). Considering measurements taken in the anatomical position, males were characterized by higher values of body height (p = 0.002), torso length (p = 0.020), shoulder breadth height (p < 0.001), and foot length (p = 0.046). None of the anthropometric variables measured in the streamline position differentiated the subjects based on their sex.

Tab. 3

The results of the t-test and sex-stratified descriptive statistics for anthropometric variables of the swimmers researched. Data of means ± SD are presented.

Variable	Females	Males	
Body mass (kg)	58.12 ± 6.25	70.02 ± 9.55	*
Body height (cm)	169.5 ± 4.3	177.2 ± 8.7	*
Body height $_{ST}$ (cm)	218.6 ± 8.4	230.7 ± 12.6	
Shoulder breadth (cm)	31.14 ± 2.48	35.24 ± 2.43	*
Shoulder breadth $_{ST}$ (cm)	39.16 ± 2.18	40.98 ± 3.33	
Pelvic breadth (cm)	33.36 ± 3.05	33.66 ± 2.18	
Upper limb length (cm)	62.50 ± 2.27	63.64 ± 4.52	
Upper limb length $_{ST}$ (cm)	66.16 ± 9.75	67.87 ± 8.42	
Torso length (cm)	62.68 ± 4.99	69.60 ± 4.51	*
Lower limb length (cm)	78.00 ± 2.79	77.30 ± 5.87	
Foot length (cm)	19.52 ± 1.04	21.15 ± 1.63	*

$_{ST}$, in the streamline position, * statistical significance level at p ≤ 0.05

On table 4 there are presented the selected variables describing the kinematic structure of the swimming start. Compared to females, males achieved a shorter start time measured at 15 m from the starting line (p < 0.001). Male swimmers needed less time to complete all the 5-meter sections of the swimming start analyzed (p < 0.024) and obtained higher flight distance values (p = 0.006).

Tab. 4

The results of the t-test and descriptive statistics of selected variables describing the kinematic structure of the swimming start. Data are presented by sex.

Variable	Females	Males	
Hands take-off (s)	0.25 ± 0.08	0.29 ± 0.07	
Rear foot take-off (s)	0.46 ± 0.04	0.45 ± 0.04	
Front foot stand (s)	0.10 ± 0.04	0.10 ± 0.04	
Movement time (s)	0.56 ± 0.05	0.56 ± 0.03	
Flight time (s)	0.27 ± 0.07	0.29 ± 0.04	
Flight distance (m)	2.87 ± 0.22	3.13 ± 0.22	*
5 time (s)	1.71 ± 0.09	1.57 ± 0.09	*
5-10 time (s)	2.75 ± 0.19	2.29 ± 0.23	*
10 time (s)	4.46 ± 0.24	3.86 ± 0.31	*
10-15 time (s)	2.80 ± 0.17	2.57 ± 0.30	*
15 time (s)	7.26 ± 0.29	6.43 ± 0.53	*

*statistical significance level at p ≤ 0.05.

Tab. 5

The results of Pearson's correlation analysis (r) between the anthropometric variables considered and the variables describing the temporal structure of the block phase execution. Data are presented by sex.

Variable	Females				Males			
	Hands take-off	Rear foot take-off	Front foot stand	Movement time	Hands take-off	Rear foot take-off	Front foot stand	Movement time
Body mass	-0.15	-0.42	0.34	-0.06	0.29	-0.15	0.47	0.25
Body height	-0.19	-0.13	0.63*	0.38	0.50	0.28	0.41	0.64*
Body height $_{ST}$	0.53*	-0.24	-0.15	-0.29	0.54*	0.39	0.25	0.62*
Torso length	0.19	-0.60*	-0.17	-0.58*	0.43	-0.07	0.07	-0.02
Shoulder breadth	0.32	-0.31	0.09	-0.16	0.12	-0.07	0.12	0.09
Shoulder breadth $_{ST}$	0.14	-0.03	-0.36	-0.53	0.18	-0.11	0.28	0.35
Pelvic breadth	0.08	-0.02	0.56*	0.40	0.06	-0.01	0.23	0.06
Lower limb length	0.74*	0.18	0.08	0.20	0.54*	0.50	0.19	0.68*
Upper limb length	0.27	0.19	0.58*	0.57*	0.45	0.08	0.45	0.48
Upper limb length $_{ST}$	-0.08	-0.01	-0.31	-0.24	-0.02	0.01	0.07	-0.34
Foot length	0.20	-0.13	-0.39	-0.39	0.12	-0.08	0.22	-0.33

$_{ST}$, in the streamline position, * statistical significance level at $p \le 0.05$

Examining the correlations between the anthropometric variables considered and the spatio-temporal variables of different phases of the start (Table. 6), in the female group, a significant correlation was shown between the time and the distance of the flight and torso length (p = 0.002; p = 0.010). In contrast, in the male group, flight distance significantly correlated with greater body mass (p = 0.002) and greater upper limb length (p = 0.032).

Tab. 6

Results of Pearson's correlation analysis (r) between selected anthropometric variables and variables describing the spatio-temporal structure of flight phase execution. Data are presented by sex.

Variable	Females		Males	
	Flight distance	Flight time	Flight distance	Flight time
Body mass	0.45	0.42	0.75*	0.25
Body height	0.12	-0.17	0.50	-0.18
Body height $_{ST}$	0.22	0.17	0.28	0.30
Torso length	0.74*	0.67*	0.49	0.40
Shoulder breadth	0.29	0.32	0.27	0.19
Shoulder breadth $_{ST}$	-0.18	-0.02	0.01	0.06
Pelvic breadth	0.25	0.01	0.11	-0.03
Lower limb length	-0.04	-0.27	0.21	-0.25
Upper limb length	-0.09	-0.35	0.58*	0.01
Upper limb length $_{ST}$	0.05	0.13	0.03	0.10
Foot length	0.03	-0.07	0.12	-0.07

$_{ST}$, in the streamline position, * statistical significance level at $p \le 0.05$

The results of the analyses of the start phases taking place in water are presented in Table 7. Considering the temporal structure in these phases, in females the strongest correlation was obtained between 10-15 m time and anthropometric variables including body height in anatomical position (p = 0.047), shoulder breadth in the streamline position (p = 0.003), and upper limb length (p = 0.010). In the males, greater shoulder breath (p = 0.049) and lower upper limb length measured in a streamline position (p = 0.045) were related to shorter total start time measured over a 15 m distance. Males of higher body mass needed less time not only to cover the distance of 15 m from the starting line (p = 0.008) but also its subsequent 5-meter sections. For males in the water section (10-15 m), negative values of correlation coefficient were noted with shoulder breadth (p = 0.036) and body height (p = 0.045).

Tab. 7

The results of Pearson's correlation analysis (r) between the anthropometric variables considered and the variables describing the kinematic structure of the execution of the phases taking place in the aquatic environment. Data are presented by sex.

	Females				Males			
Variable	5 time	5-10 time	10-15 time	15 time	5 time	5-10 time	10-15 time	15 time
Body mass	-0.11	0.10	-0.35	-0.17	-0.60*	-0.47	-0.67*	-0.67*
Body height	-0.03	0.15	-0.57*	-0.24	-0.18	-0.13	-0.54*	-0.38
Body height $_{ST}$	-0.21	-0.29	-0.07	-0.29	0.05	0.11	-0.22	-0.07
Torso length	-0.39	-0.28	-0.04	-0.33	-0.35	-0.23	-0.18	-0.26
Shoulder breadth	0.17	0.30	-0.15	0.16	-0.58*	-0.29	-0.56*	-0.53*
Shoulder breadth $_{ST}$	-0.24	-0.21	0.72*	0.20	0.50	0.52	0.15	0.39
Pelvic breadth	0.18	0.45	-0.43	0.10	-0.36	-0.18	-0.18	-0.24
Lower limb length	0.15	-0.20	-0.14	-0.16	0.26	0.23	-0.06	0.11
Upper limb length	0.13	-0.10	-0.64*	-0.40	-0.24	-0.23	-0.37	-0.34
Upper limb length $_{ST}$	-0.16	-0.39	0.34	-0.11	0.49	0.50	0.44	0.54*
Foot length	-0.14	-0.31	0.33	-0.05	0.10	0.22	-0.16	0.03

$_{ST}$, in the streamline position, * statistical significance level at p ≤ 0.05

The correlations between selected anthropometric variables and participants' preferred back plate position are presented in Table 8. Swimmers of both sexes characterized by greater upper limb length preferred to position the back plate further from the front edge of the starting block (p < 0,017). It is noteworthy that among females, the results of body height in the anatomical position correlate positively with the position of the back plate (p = 0.016), as opposed to the non-significant correlation noted for the measurements taken in the streamline position (p > 0.05). In the males more backward position of the back plate was related to a longer lower limb and foot (p > 0.05).

Tab. 8

The results of Pearson's correlation analysis (r) between selected anthropometric variables and the subjects' preferred back plate position of the starting block. Data are presented by sex.

Variable	Females	Males
Body mass	0.00	0.44
Body height	0.65*	0.51
Body height $_{ST}$	-0.04	0.31
Torso length	-0.26	0.21
Shoulder breadth	-0.31	0.06
Shoulder breadth $_{ST}$	-0.13	0.07
Pelvic breadth	0.49	0.42
Lower limb length	0.34	0.43
Upper limb length	0.62*	0.68*
Upper limb length $_{ST}$	0.18	0.28
Foot length	-0.11	0.44

$_{ST}$, in the streamline position, * statistical significance level at p ≤ 0.05

Discussion

This study aimed to investigate the relationships between selected anthropometric variables of the elite swimmers and their starting performance in terms of biomechanics. The analyses included the relationship between the somatic characteristics of the simmers and their preferred position on the back plate. We predicted that a comparison of the spatio-temporal variables in the various phases of the swimming start with the set of easy-to-measure anthropometric variables would reveal the set of factors that determine the performance of the swimming start.

A comparison of the results of anthropometric variables in swimmers representing the international sports level confirmed the existence of sex differences within the considered somatic variables (Table 3). Compared to females, males were shown to have higher body mass, body height, torso length, shoulder breadth, and foot length (Table 3). The statistical range of variation in anthropometric variables in both groups was similar to the results obtained by other researchers [8,13,14,23,24,25,26]. Considering this background, the differentiation of anthropometric variables as a consequence of sex seems indisputable. Nevertheless, it should be emphasized that the somatic variables of swimmers are also determined by their susceptibility to specific training stimuli applied during many years of targeted high-stress swimming training [8,25]. Also, the influence of swimmers' anthropometric variables on predisposition to successful performance has been frequently indicated [6,7]. Nevertheless, somatic differences in the motor potential of males and females are revealed both in the efficiency and economy of swimming as well as in the other technical elements that determine the race result (swimming start, turns) and are compounded by the specific conditions of movement of the human body in water (hydrodynamics) and in space (flight phase - without contact with the ground).

In general, female swimmers are characterized by shorter lower limbs, together with lower body height, lower body mass, and a higher percentage of body fat. Consequently, body density is lower [26-28]. Sex differences will be also manifested in the ability to generate muscle force [29].The aforementioned traits support in females the economy of swimming [27,28] while they do not predispose them to generate and use explosive power, which is crucial for swimming start performance[18]. Hence, discrepancies between eficiency and economy of movement in both sexes will be more pronounced in exercises performed on land than those performed in water, due to the effects of buoyancy force [22,30]. So, in conclusion - the fact that male swimmers gained an advantage over female swimmers by reducing their starting times measured over 15 m, as well as 5m distances (Table 3) (as Wądrzyk et al. [13,14], should be interpreted in a broader context; namely, taking into account the emerging differences in the spatio-temporal structure of the swimming start of males and females depending on the specifics of the activities taking place on land (block phase), in the air - without contact with the ground (flight phase) and in phases performed in the water.

INITIAL STARTING POSITION

The analyses conducted showed that swimmers of both sexes characterized by greater body height and longer upper limbs prefer to position the back plate further from the front edge of the starting block (Table 8). For the male group, the back plate positioning seems to rely also on the length of the lower limb and feet, but no statistical significance level was reached (Table 8). Due to the fixed position of the stride lower limb (in contact with the front edge of the starting block), the location of the back plate determines the distance between the feet on the starting block. Consequently, the length of the limbs will further determine position of the body segments while starting. Thus, the flexion ranges in the various joints of the lower limb, the position of the hips in relation to the front edge of the starting block, and the alignment of the torso are also influenced [21,31]. Here the body position and its changes would determine the values of ground reaction forces, which are the main component of the block phase performance resulting in the velocity reached during the take-off, as well as its translation into the performance of the subsequent phases of the swimming start [20]. Scientific reports indicate that positioning the back plate at a distance equal to the length of the swimmer's shin has a beneficial effect on starting performance. This arrangement resulted in the shortest response time to the start signal [15] and reduced the block time duration [16]. Thus, the positioning of the various body segments relative to each other in the starting position and controlling their displacement during the subsequent start phase would determine the performance of the swimming start [32,33].

Until now more analysis has been carried out with regard to the track and field start. In the available literature many examples and analogies between initialization of the track and field start have been provided to the beginning of the swimming start (Rejman et al. 2017). The sprint start, the simplest yet most common way to set up a starting block relates to the length of the athlete's foot [34]. Those authors, as well as Cavedon et al. [35] indicated that the position of the starting block pads should take into account the length of the lower limbs. Importantly, the proper placement of the block's components will determine the achievement of a start position that is optimal from a mechanical point of view, and consequently the development of a high velocity [36]. Therefore, while searching for optimal body position during the sprint start and positioning the supports of the starting block, the main focus has been brought to the angular values in the lower limb joints and the height of the hip alignment [35,37,38,39]. Also, the importance of torso positioning has been emphasized in terms of maximizing the muscle potential possessed by sprinters [37].

The results obtained and their confrontation with the current state of knowledge in this field indicate the necessity to continue the search for objective premises describing how the swimmer's body should be positioned on the starting block. This should allow to deeply understand the cause-and-effect correlation between swimmers' anthropometric characteristics and the optimal starting position. In consequence, due to inclusion of individual athletes' somatic predispositions, the swimming start training should be more effective.

BLOCK PHASE

In the male group, greater body height went hand in hand with increased movement time, while in the female group, increased movement time was correlated with a shorter torso and longer upper limb (Table 5). Kibele et al. pointed out the differences in the block time as a consequence of the position of the hips relative to the starting block [31]. The results obtained in the scope of the height of the swimmer's body as well as the length of limb segments, that determine the position of the hips placement, confirm this thesis. The interpretation of these results is based on the relation of the laws of rotational motion to a system of segments of the swimmer's body moved relative to each other and relative to a given reference system. This way the objective information to explain the mechanism of a successful swimming start could be provided [40]. The total torque, defined as the product of the force (muscles) and the length of the lever (bone levers of the lower limbs) at take-off, induces body rotation relative to the front edge of the starting block and then initiates body rotation around the lateral axis [41].This way the dynamics (angular acceleration) of the take-off from the starting block) is achieved. Taking into account the moment of inertia (at a given velocity or force generated up to the moment of take-off). The greater the length of the swimmer’s body (or its segments), would result with the increase in the time of displacement of the swimmer's body (by a certain distance in a straight line) from the moment of start signal to the moment of completion of the swimming start. In turn, the angular momentum generated in the sagittal plane during the push-off from the starting block will determine the angular velocity during the flight phase, and consequently the trajectory of the flight and the angle at which the swimmer's body enters into the water [42].

FLIGHT PHASE

In the male group, flight distance extended significantly with increasing body mass and upper limb length (Table 6). A moderate positive correlation was also with body height (r=.50). In the female group, flight time and flight distance significantly correlated with torso length (Table 6). Based on the available on-land jumping performance analyses, it can be expected that in addition to biomechanical and physiological factors, the height of the jump can be determined by the somatic characteristics of the athlete, including body mass, body height, and length of the lower limbs [43,44]. However, the direction of the flight in the swimming start is forward rather than upward like in the vertical jump [45]. While there is no doubt about the negative impact of a high percentage of body fat on flight variables [46,47], an increase in muscle cross-sectional area (muscle mass) results in an increase in muscle strength, transferred to the velocity and acceleration at take-off which largely determines flight distance in the swimming start [24,48]. Given that, male athletes, compared to females, are characterized by greater muscle strength and power [49] which are useful in start performance [50], it is not surprising to see differences in variables characterizing the flight [51,52]. While researchers do not agree on the benefits of a large body height on the relative height of the vertical jump or long jump [53-56], though limb length seems to be eligible to obtain better performance.

WATER PHASES

The duration of the start phases involving activities in the water takes about 84% of the total start time [57]. These phases have been named glide phase (maintaining streamline position), underwater leg propulsion phase, and swim phase (propulsion produced by both, upper and lower limbs) due to the specificity of movement activities [9,10]. This is the reason to base the analysis of the influence of anthropometric variables on the performance of the listed start phases on correlations derived from fluid mechanics [7,58].

In the male group, swimmers with higher body mass took less time to cover each of the 5 m segments of the 15 m distance from the starting line (Table 7). While, for both groups, negative correlation values were observed between body mass or body height and 10-15 m time (Table 7). The results obtained confirm the inverse correlation between the body height and the dimension of the generated wave resistance [59] resulting from the magnitude of Freud's number determined by the length of the body and the swimming velocity [6]. Barbosa et al., studied the body shape of swimmers in terms of evaluating the hydrodynamics of the glide phase [60]. Those authors showed that body mass, body height, and body surface area had a significant effect on the performance of this phase. At the same time, the influence of the studied anthropometric variables on the amount of buoyancy force was excluded. Such a correlation in the case of tissue body composition confirms the thesis (true for the surface swimming phase) that due to greater buoyancy, the swimmer's body is less submerged and generates fewer drag forces [61,62]. In the glide phase taking place at least 0.6 m below the water surface, the wave drag component is reduced [63,64], and thus, compared to swimming on the surface, the importance of body mass and length decreases during underwater swimming [59].

In the female group, in the underwater phase (5-10 m), it was observed that hip breadth had the greatest effect on that segment duration (Table 7). In contrast, in men, there was a dominant correlation between 5-10 meters time and shoulder breadth measured in streamline position and upper limb length measured in the streamline position (Table 7). It is worth noting that these results reflect the basic anthropometric variables characteristics that differentiate the two sexes.

Direct proportion to the size of the frontal cross-section" and so wider shoulders and wider hips increase the projection of the cross-section area of the body of males and females. At the same time, however, both the coefficient of total hydrodynamic resistance and its components depend on the shape of the body moving through the water. In the case of the human body, the shape of the torso is the most significant [65]. Here, the torso shape, characteristic of male swimmers, which resembles an inverted triangle (identified with the shape of a water droplet) and determined by the biacromial/bi-iliac diameter index, is conducive to minimizing the drag coefficient [17,66].

In the group of females with less favorable hip and shoulder proportions, swimmers with narrower shoulders and longer upper limb showed shorter 10-15 m time (Table 7). It seems, therefore, that due to the aforementioned proportions, the feature that favors the performance of this element of the swimming start in females will be long upper limb. Considering that in the discussed part of the start, the movement of the lower limbs is the main source of propulsion of the swimmer, thus, their length is a feature that has a positive impact on swimming performance [7,24,67,68,69]. With longer limbs, the swimmer is able to cover a longer distance with relatively fewer movement cycles [70], as well as generate more propulsive force [71].

The relationships between swimmers' somatic characteristics and the complexity of swim start performance described in this paper explore only one aspect of the problem of its effective use to achieve success in a swimming race. The start time – as the main criterion for its performance - is significantly influenced by many factors from the areas of biomechanics, physiology, genetics psychology, etc. What's more, these fetors remain in close correlations with each other and with a variety of configurations. So in this study, we described only the minor aspect in the way to solve the problem of how to improve the complex structure of performance in swimming start. In this scope, limited number of anthropometric variables taken for the analyses can be interpreted as the limitation of this research. However, the choice of them was based on the prerequisites arising from the current state of knowledge, with the intention to provide a set of variables easy to measure also for training staff.

CONCLUSIONS

A comparison of spatio-temporal variables describing the starting position and the various phases of the swimming start with anthropometric variables in swimmers of both sexes, revealed a set of the following characteristics having a significant impact on the quality of the starting technique in terms of the performance:

body mass, body height, shoulder breadth, and upper limb length. Importantly, depending on the phase of the swimming start, the relevance of the swimmers' individual anthropometric variables has been changing. In addition, the dependence between the somatic characteristics and the kinematic structure of swimming start performance is strongly differentiated in terms of the sex of the athlete.

The analyses showed that swimmers (without regard to sex) with smaller body height and shorter upper limbs prefer to position their backward foot on the back plate closer to the front edge of the starting block. There is reason to believe that a conscious choice of starting based on an athlete's individual anthropometric profile can result in an improvement in the quality of the swimming start execution technique. The performance in the block phase (shorter movement time) for females was determined by the length of the torso (longer) and upper limb (shorter), while for men by the greater body height and lower limb length. During the flight phase, males characterized by greater height and body mass gained an advantage by covering a longer distance above the water surface. Females with longer torso spent less time on the flight phase and achieved farther during in this part of the swimming start. In the males, higher body mass, and broader shoulders determined the shortening of not only the total start time but also the particular 5-meter parts of the start distance.

This study has provided the practical outcomes based on a set of easy-to-measure anthropometric variables of males and females, which seem to be crucial in the monitoring of the functional potential of the technique of the swimming start, to individualize and rationalize the technical training of this element of swimming race, leading to performance improvement. In the long term, the findings are to be used as reference data to model predictive changes in the swimming start technique to improve the performance.

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References

1. Marinho DA, Barbosa TM, Neiva HP, Silva AJ, Morais JE. Comparison of the Start, Turn and Finish Performance of Elite Swimmers in 100 m and 200 m Races. *J Sports Sci Med* 2020; 19(2):397-407, PMID: 32390734; PMCID: PMC7196746
2. Figueiredo P, Silva A, Sampaio A, Fernandes RJ. Front crawl sprint performance: a cluster analysis of biomechanics, energetics, coordinative, and anthropometric determinants in young swimmers. *Motor Control* 2016; 20(3):209-21, DOI 10.1123/mc.2014-0050
3. Morais JE, Saavedra JM, Costa MJ, Silva AJ, Marinho DA, Barbosa TM. Tracking young talented swimmers: follow-up of performance and its biomechanical determinant factors. *Acta Bioeng Biomech* 2013;15(3):129-38, PMID 24215298
4. Pelayo P, Alberty M. The history of swimming research. World book of swimming: From Science to Performance; 2011, ISBN 978-1-61668-202-6
5. Zacca R, Azevedo R, Chainok P, Vilas-Boas JP, Castro FADS, Pyne DB, Fernandes RJ. Monitoring age-group swimmers over a training macrocycle: energetics, technique, and anthropometrics. *J Strength Cond Res* 2020; *34*(3):818-827, DOI 10.1519/JSC.0000000000002762
6. Kjendlie PL, Stallman R. Morphology and swimming performance. *World Book of Swimming. From Science to Performance. New York: Nova;* 2011:203-222, ISBN 9781616682026
7. 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, DOI 10.3390/ijerph19052543
8. Rejman M, Tyc Ł, Kociuba M, Bornikowska A, Rudnik D, Kozieł S. Anthropometric predispositions for swimming from the perspective of biomechanics. *Acta Bioeng Biomech* 2018; 20(4):151-159, PMID 30821288.
9. Blanco, S. T., de la Fuente Caynzos, B., & Colomina, R. A. (2017). Ventral swimming starts, changes and recent evolution: A systematic review. *RETOS. Nuevas Tendencias en Educación Física, Deporte y Recreación* 2017; 32:279-288, DOI 10.47197/RETOS.V0I32.49535
10. Vantorre J, Chollet D, Seifert L. Biomechanical analysis of the swim-start: a review. J Sports Sci Med 2014; 13(2):223-231. PMID 24790473; PMCID PMC3990873
11. Alpetkin A. Body composition and kinematic analysis of the grab start in youth swimmers. *J Hum Kinet* 2014; 10(42):15–26, DOI 10.2478/hukin-2014-0057
12. Cornett A, White J, Wright B, Willmott A, Stager J. Racing start safety: head depth and head speed during competitive swim starts into a water depth of 2.29 m. *Int J Aquatic Research Edu* 2011; 5(1): 14–18, DOI 10.25035/ijare.05.04.06.
13. Wądrzyk Ł, Staszkiewicz R, Kryst Ł. Somatic build and kinematic variables of a swim start of young swimmers. In: ed. Rejman M, Zatoń K, Szczepan, *S. SWIMMING VII* 2018; 99, ISBN 978-83-64354-35-9
14. Wądrzyk Ł, Staszkiewicz R, Zeglen M, Kryst Ł. Relationship between somatic build and kinematic indices of underwater undulatory swimming performed by young male swimmers. *Int J Perf Anal Sport* 2021; *21*(3):435-450, DOI 10.1080/24748668.2021.1909450
15. Cicenia, A., Oster, C., & Mokha, M. (2019). Kick plate position and track start biomechanics in elite swimmers. *J. Exerc. Nutr. 2019;2(3):12, ISSN 2640-2572*
16. Cicenia A, Oster C, Mokh G. Using shin length to determine kick plate position optimizes select swim start mechanics in elite swimmers. In: Robinson MA, Lake MJ, BaltzopoulosV, Vanrenterghem J (ed.), Proceedings of the 38th Conference of the International Society of Biomechanics in Sports *ISBS Proceedings Archive* 2020; *38*(1): 880-883.
17. Maglischo EW. *Swimming fastest*, Human Kinetics, Leeds, 2003, ISBN 0-7360-3180-4
18. Rejman M, Bilewski M, Szczepan S, Klarowicz A, Rudnik D, Maćkała K. Assessing the impact of a targeted plyometric training on changes in selected kinematic parameters of the swimming start. *Acta Bioeng Biomech* 2017; 19(2):149-160, PMID 28869635
19. Vilas-Boas, J, De Jesus K, Mourão L, Roesler H, De Jesus K, Fernandes RJ, Vaz M. A novel dynamometric central for 3D forces and moments assessment in swimming starting. In: the XIIth International Symposium on Biomechanics and Medicine in Swimming 28 April to 2 May 2014 Australian Institute of Sport, Canberra 2014; 135-136, ISBN 978-0-646-91869-3
20. de Jesus K, de Jesus K, Fernandes RJ, Vilas-Boas JP. Back plate and wedge use and individual ventral and dorsal swimming start performance: a systematic review. *Sports Biomech* 2023; 22(12):1634-1658, DOI 10.1080/14763141.2021.2016924
21. Rudnik, D, Rejman M, Machado L, Fernandes RJ, Vilas-Boas JP. Does the back plate position influence swimming start temporal characteristics?. *Int J Environ Res Public Health* 2022; 26;19(5):2722, DOI 10.3390/ijerph19052722
22. Rudnik DM, Rejman M, Vilas-Boas JP. The kinematic profile of ventral swimming start: sex diversity. *Front Physiol* 2023; 14:1157359, DOI 10.3389/fphys.2023.1157359
23. Morais JE, Marques MC, Rodríguez-Rosell D, Barbosa TM, Marinho DA. Relationship between thrust, anthropometrics, and dry-land strength in a national junior swimming team. *Phys Sports Med* 2020; 48(3):304–311, DOI 10.1080/00913847.2019.1693240

24. Oliveira M, Henrique RS, Queiroz DR, Salvina M, Melo WV, Moura Dos Santos MA. Anthropometric variables, propulsive force and biological maturation: A mediation analysis in young swimmers. *Eur J Sport Sci* 2021; 21(4):507-514, DOI 10.1080/17461391.2020.1754468
25. Rejman M, Nevill AM, Garrido ND, Rudnik D, Morais JE. Identification of key somatic features that are common and the ones that differ between swim strokes through allometric modeling. *Front Sports Act Living* 2023;5:1308033, DOI 10.3389/fspor.2023.1308033.
26. Rudnik D, Vilas-Boas JP, Rejma M. A body composition profile of high-level swimmers: the reference data. In: *Młodzi Naukowcy Nauki medyczne i nauki o zdrowiu* 2019; 104-110, e-ISBN 978-83-66139-94-7
27. Lavoie JM, Montpetit RR. Applied physiology of swimming. *Sports Med* 1986; 3(3):165-189, DOI 10.2165/00007256-198603030-00002
28. Pendergast DR, Di Prampero PE, Craig AB Jr, Wilson DR, Rennie DW. Quantitative analysis of the front crawl in men and women. *J Appl Physiol Respir Environ Exerc Physiol* 1977; 43(3):475-49, DOI 10.1152/jappl.1977.43.3.475
29. Newton R. Strength and conditioning priorities for elite swimming athletes. In: the XIIth International Symposium on Biomechanics and Medicine in Swimming 28 April to 2 May 2014 Australian Institute of Sport, Canberra. 2014, ISBN 978-0-646-91869-3
30. Senefeld J, Joyner MJ, Stevens A, Hunter SK. Sex differences in elite swimming with advanced age are less than marathon running. *Scand J Med Sci Sports* 2016; 26(1):17-28, DOI 10.1111/sms.12412
31. Kibele A, Biel K, Fischer S. Optimising individual stance position in the swim start on the OSB11. In: the XIIth International Symposium on Biomechanics and Medicine in Swimming 28 April to 2 May 2014 Australian Institute of Sport, Canberra. 2014; 158–163, ISBN 978-0-646-91869-3
32. Harland MJ, Steele JR. Biomechanics of the sprint start. *Sports Med* 1997; 23(1):11-20, DOI 10.2165/00007256-199723010-00002
33. Takeda, T, Takagi H, Tsubakimoto S. Effect of inclination and position of new swimming starting block's back plate on track-start performance. *Sports Biomech* 2011; 11(3):370–381, DOI 10.1080/14763141.2011.637122
34. Schot PK, Knutzen KM. A biomechanical analysis of four sprint start positions. *Res Q Exerc Sport* 1992; 63(2):137-47, DOI 10.1080/02701367.1992.1060757
35. Cavedon V, Bezodis NE, Sandri M, Golia S, Zancanaro C, Milanese C. Effect of different anthropometry-driven block settings on sprint start performance. *Eur J Sport Sci* 2023; 23(7):1110-1120, DOI 10.1080/17461391.2022.2153347
36. Cavedon V, Sandri M, Pirlo M, Petrone N, Zancanaro C, Milanese C. Anthropometry-driven block setting improves starting block performance in sprinters. *PLoS One* 2019; 27;14(3):e0213979, DOI 10.1371/journal.pone.0213979
37. Borzov, V. The optimal starting position in sprinting. *Legkaya Atletika* 1978; 4(10), 173-174.
38. Čoh M, Jošt B, Škof B, Tomažin K, Dolenec A. Kinematic and kinetic parameters of the sprint start and start acceleration model of top sprinters. *Gymnica* 1998; *28*, 33-42.
39. Mero A, Luhtanen P, Komi PV. A biomechanical study of the sprint start. *Scand J Med Sci Sports* 1983; 5(1):20-8,
40. Taladriz S, de la Fuente-Caynzos B, Arellano R. Analysis of angular momentum effect on swimming kick-start performance. *J Biomech 2016; 14;49(9):1789-1793, DOI 10.1016/j.jbiomech.2016.04.012*
41. Grimshaw P, Fowler N, Lees A, Burden A. BIOS Instant Notes in Sport and Exercise Biomechanics (1st ed.). *Routledge* 2006; 115-148 DOI 10.4324/9780203488300
42. McLean SP, Holthe MJ, Vint PF, Beckett KD, Hinrichs RN. Addition of an Approach to a Swimming Relay Start. *J Appl Biomech* 2000; 16(4):342-355, DOI 10.1123/jab.16.4.342
43. Fattahi A, Ameli M, Sadeghi H. Relationship between anthropometric parameters with vertical jump in male elite volleyball players due to game's position. *J Human Sport Exer* 2012; 7(3):714-726, DOI 10.4100/jhse.2012.73.11
44. Aouadi R, Jlid M, Khalifa R, Hermassi S, Chelly M, Van Den Tillaar R, Gabbett T. Association of anthropometric qualities with vertical jump performance in elite male volleyball players. *J Sports Med Phys Fitness* 2012; 52(1):11-7, DOI 10.4100/jhse.2012.73.11
45. Arellano R, Llana S, Tella V, Morales E, Mercade J. (2005). A comparison CMJ, simulated and swimming grab-start force recordings and their relationships with the start performance. In Q Wang (Ed.), Proceedings of the XXIII international symposium of biomechanics in sports. Beijing: China Institute of Sport Science 2005; 923-926,
46. Roschel H, Batista M, Monteiro R, Bertuzzi RC, Barroso R, Loturco I, Ugrinowitsch C, Tricoli V, Franchini E. Association between neuromuscular tests and kumite performance on the brazilian karate national team. *J Sports Sci Med* 2009; 1;8(CSSI3):20–24, PMID 24474882
47. Abidin NZ, Adam MB. Prediction of vertical jump height from anthropometric factors in male and female martial arts athletes. *Malays J Med Sci* 2013; 20(1):39-45, PMID 23785254; PMCID PMC3684376
48. Pelayo P, Sidney M, Kherif T, Chollet D, Tourny C. Stroking characteristics in freestyle swimming and relationships with anthropometric characteristics. *J. Appl. Biomech* 1996; 12:197–206, DOI 10.1123/JAB.12.2.197
49. Nuzzo, James L. Narrative Review of Sex Differences in Muscle Strength, Endurance, Activation, Size, Fiber Type, and Strength Training Participation Rates, Preferences, Motivations, Injuries, and Neuromuscular Adaptations. *J Strength Cond Res* 2023; 37(2)494-536, DOI 10.1519/JSC.0000000000004329
50. West DJ, Owen NJ, Cunningham DJ, Cook CJ, Kilduff LP. Strength and power predictors of swimming starts in international sprint swimmers. *J Strength Cond Res* 2011;25(4):950-5, DOI 10.1519/JSC.0b013e3181c8656f
51. Bishop C, Cree J, Read P, Chavda S, Edwards M, Turner A. Strength and conditioning for sprint swimming. *Strength Cond J 2013; 35*(6):1-6, DOI 10.1519/SSC.0000000000000019
52. Cossor J, Slawson S, Shillabeer B, Conway P, West A. Are land tests a good predictor of swim start performance?. 29 International Conference on Biomechanics in Sports Proceedings. Portuguese J Sport Scien 2011; 11(2):183-186,
53. Ackland T, Elliott B, Bloomfield J. Applied anatomy and biomechanics in sport. Champaign, IL USA: Human Kinetics 2009, ISBN 0736063382
54. Davis DS, Briscoe DA, Markowski CT, Saville SE, Taylor CJ. Physical characteristics that predict vertical jump performance in recreational male athletes. *Phys Ther in Sport* 2003; *4*(4):167-174, DOI 10.1016/S1466-853X(03)00037-3
55. Jandová, S. Jumping performance and take-off efficiency correlation with the basic anthropometric parameters in female volleyball players. *Acta Gymnica* 2021; 51(5):e2021.020, DOI 10.5507/ag.2021.020
56. Wyon M, Allen N, Angioi M, Nevill A, Twitchett E. Anthropometric factors affecting vertical jump height in ballet dancers. *J Dance Med Scie* 2006; 10(3-4), 106-110, DOI 10.1177/1089313X06010003-
57. Tor E, Pease D, Ball K. Characteristics of an elite swimming start. In: the XIIth International Symposium on Biomechanics and Medicine in Swimming 28 April to 2 May 2014 Australian Institute of Sport, Canberra 2014; 1257-1263, ISBN 978-0-646-91869-3
58. 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):262-269. DOI 10.1016/j.jsams.2009.01.003
59. Toussaint HM, de Looze M, Van Rossem B, Leijdekkers M, Dignum H. The Effect of Growth on Drag in Young Swimmers. *Int J Sport Biomech* 1990; 6(1):18-28, DOI 10.1123/ijsb.6.1.18
60. Barbosa TM, Costa MJ, Morais JE, Moreira M, Silva AJ, Marinho DA. How Informative are the Vertical Buoyancy and the Prone Gliding Tests to Assess Young Swimmers' Hydrostatic and Hydrodynamic Profiles? *J Hum Kinet* 2012; 32:21-32, DOI 10.2478/v10078-012-0020-x
61. Yanai, T. Buoyancy is the primary source of generating bodyroll in front-crawl swimming. *J Biomech* 2004; *37*(5):605-612, DOI: 10.1016/j.jbiomech.2003.10.004
62. Zamparo P, Antonutto G, Capelli C, Francescato MP, Girardis M, Sangoi R, Soule RG, Pendergast DR. Effects of body size, body density, gender and growth on underwater torque. *Scand J Med Sci Sport* 1996; 6(5):273-80, DOI 10.1111/j.1600-0838.1996.tb00470.x.
63. Lyttle AD, Blanksby BA, Elliott BC, Lloyd DG. Optimal depth for streamlined gliding. *Proceedings of the VIII International Symposium on Biomechanics and Medicine in Swimming, University of Jyväskylä, Finland, June 28-July 2 1998*; 165-170, ISBN 9513906078
64. Novais ML, Silva AJ, Mantha VR, Ramos RJ, Rouboa AI, Vilas-Boas JP, Luís SR, Marinho DA. The Effect of Depth on Drag During the Streamlined Glide: A Three-Dimensional CFD Analysis. *J Hum Kinet* 2012;33:55-62, DOI 10.2478/v10078-012-0044-2.
65. Li T-Z, Zhan J-M. Hydrodynamic body shape analysis and their impact on swimming performance. *Acta Bioeng Biomech* 2015; 17(4):3–11, PMID: 26898107
66. Clarys JP. Human morphology and hydrodynamics. In Swimming III; Terauds J, Beddingfield W (Ed); University Park Press: Baltimore, Maryland 1979; 8:3–41, ISBN0839113528
67. Demirkan E, Can S, Özkadı T, Alagöz I. Fifty-meter swimming performance in young swimmers: The effect of anthropometric and motoric values on performance. *Med Dello Sport* 2019; 72(4), DOI 10.23736/S0025-7826.18.03386-0

68. Rozi G, Thanopoulos V, Geladas N, Soultanaki E, Dopsaj M. (2018). Anthropometric characteristics and physiological responses of high level swimmers and performance in 100 m freestyle swimming. *Mov Sport Sci/Sci Mot* 2018; *101*(3):3-7, DOI 10.1051/sm/2018007
69. Sammoud S, Nevill AM, Negra Y, Bouguezzi R, Chaabene H, Hachana Y. Allometric associations between body size, shape, and 100-m butterfly speed performance. *J Sports Med Phys Fitness* 2018; 58(5):630-637, DOI 10.23736/S0022-4707.17.07480-1
70. Potdevin F, Bril B, Sidney M, Pelayo P. Stroke frequency and arm coordination in front crawl swimming. *Int J Sports Med* 2006;27(3):193-198, DOI 10.1055/s-2005-837545
71. Grimston SK, Hay JG. Relationships among anthropometric and stroking characteristics of college swimmers. *Med Sci Sports Exerc* 1986; 18(1):60–8, DOI 10.1249/00005768-198602000-00011

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