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Relationship between somatic build and kinematic indices of underwater undulatory swimming performed by young female swimmers

Leszek Nosiadek[1*], Łukasz Wądrzyk[2], Robert Staszkiewicz[1], Magdalena Żegleń[3,4], Łukasz Kryst[3], Marek Strzała[2]

[1]Department of Biomechanics, University of Physical Culture in Kraków, Kraków, Poland

[2]Department of Water Sports, University of Physical Culture in Kraków, Kraków, Poland

[3]Department of Anthropology, University of Physical Culture in Kraków, Kraków, Poland

[4]Department of General Psychology, Jagiellonian University in Kraków, Kraków, Poland

[*]Corresponding author: Leszek Nosiadek, Department of Biomechanics, University of Physical Culture in Kraków, Kraków, Poland, e-mail address: leszek.nosiadek@awf.krakow.pl

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Abstract

Purpose

The aim was to determine the relationship between anthropometric indices and kinematic underwater undulatory swimming (UUS) variables among young female swimmers.

Methods

The following parameters were determined in 34 participants (age 16.74±0.70 years, World Aquatics score 561±64): body height (H), mass (M) and fat percentage (BF), BMI, lengths of the lower limb (LL), thigh (LT), and calf (LC), circumferences of thigh (CT), maximum calf (CCMAX) and distal lower leg (CCDIS), skinfolds on the thigh (FT) and calf (FC), as well as foot length (FL) and width (WF), based on which an estimated foot surface area was calculated (SF). Using the kinematic analysis of UUS recordings, the following were determined: velocity (v), frequency (f), distance per cycle (DPC), amplitude of toe (A), and product of A×f (IAf). Pearson r correlation analysis was performed.

Results

A relationship was observed between v and: CCMAX (r=0.48), CCDIS (r=0.39) and LF (r=0.35). IAf was correlated with: CCDIS (r=0.40), CCMAX (r=0.39) and M (r=0.35). A relationship was observed between A and FT (r=0.45) and CT (r=0.42), as well as DPC with FT (0.40) and CCMAX (0.37).

Conclusions

The results indicate that the somatic structure has a small effect on the effectiveness and kinematic indices of UUS among young female swimmers.

Keywords

kinematics, biomechanics, swimming, anthropometry, youth sport, performance

1. Introduction

In swimming, individual races are performed using full strokes: butterfly, backstroke, breaststroke, front crawl (in freestyle events). In addition to the speed of swimming in these techniques, the final result also depends on the effectiveness of the starts and turns [6]. Athletes spend the majority of these phases underwater [34~~3~~]. To effectively move below the surface, in freestyle, butterfly and backstroke races swimmers use underwater undulatory swimming (UUS) ~~(except for the breaststroke)~~. Even in breaststroke events, where only one UUS cycle after start and every turn is allowed, swimmers should master this technique, including synchronization with the arm pull-out phase [28]. During underwater swimming ~~these movements~~, the upper limbs remain straight in front of the head, with one hand placed on top of the other one (so-called streamlined position), and the torso and lower limbs perform wave-like movements [3], [36~~5~~]. Due to its similarity to the movement of aquatic mammals, the UUS technique is sometimes referred to as dolphin kicking [9].

It is often observed that during races, swimmers cover the maximum possible distance specified in the rules (15 m from the starting or turning wall) under the water [6]. This is due to the fact that many of them are able to swim faster using the UUS technique than using full strokes [40~~39~~]. The reason for this is primarily the exposure to smaller resistance during underwater movement [36~~5~~]. It is assumed that from a depth of approx. 0.5 m, wave drag, which constitutes approx. 50-60% of the total resistance in the case of surface swimming, has a small effect on the competitor performing UUS [25]. It is worth pointing out that form drag may also be smaller, due to the fact that athletes remain underwater in a streamlined position [3]. Moreover, undulatory movements involve strong trunk and lower limb muscles, which facilitates the development of high mechanical power [41~~0~~].

So far, the UUS technique has been characterized using many kinematic variables [8], [9], [12], [25], [36~~5~~]. For instance, both the course of lower limb and trunk movements and even the mutual movement synchronization of individual body segments have been described in this context [10], [40~~39~~]. This allowed for the identification of key variables influencing the effectiveness of UUS [8]. However, up to this day, little attention has been paid to individual determinants of the UUS technique. So far, a relationship has been noted between the somatic structure and full stroke swimming techniques [16], [21], [22], [30~~29~~]. It has been established, among others, that the speed of swimming on the surface depends on the size of the body, the arm span, and the structure of the upper limb segments [19]. Concerning the UUS technique, it cannot be ruled out that, for example, that athletes with relatively long lower limbs may be more predisposed to swimming underwater - having longer lever arm, they may be able to generate propulsion more effectively [22]. At the same time, it has been established so far that in full stroke swimming, competitors with shorter lower limbs have an advantage [26]. Research on the individual determinants of the UUS technique is crucial because it may provide a basis for selecting events that are better suited to swimmers. So far, the subject of research on the relationship between somatic structure and UUS technique has been only junior boys [39~~8~~]. Due to the fact that individual determinants of athletes' sports results may differ depending on gender ~~sex~~ [21], it is reasonable to undertake this type of research also among girls.

The subject of this study was to determine the relationship between somatic structure and the technique of underwater undulatory swimming among young female athletes. For this purpose, the following research questions were asked:

Is the velocity of underwater undulatory swimming related to the basic indicators describing body structure - height, mass, BMI and fat tissue content?

Do the dimensions of the lower limb and its segments (lengths and circumferences) have a positive effect on the kinematic indicators describing the technique of underwater undulatory swimming?

Does the size of the foot affect the effectiveness and technique of underwater undulatory swimming?

2. Materials and Methods

2.1. Study group

The research was carried out on a 25-m long, 8-lane swimming pool (depth 2-2.5 m) homologated by the National Swimming Association. There was an underwater window at the side of the pool, allowing for video recording.

The study group consisted of 34 female swimmers (average age 16.74 ± 0.70 years). Their weekly training volume was 18 hours in the water and 6 hours on land. The average sports level in the 100 m freestyle, measured according to the World Aquatics scale, was 561 ± 64 points. According to the classification of Ruiz-Navarro et al. [24], 4 athletes represented the 3rd, 29 reached the 4th, and one participant reached the 5th sports level. On the day of testing, all participants had a valid medical examination, which qualified them to partake in professional swimming training. The study was approved by the Bioethics Committee at the Regional Medical Chamber (approval No. 3/KBL/OIL/2018). All procedures contributing to the study complied with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. Each subject was familiarized with the research procedure and gave written consent to participate in it. In the case of minors, such consent was also given by the subject's legal guardians. The participants were also instructed that they could withdraw from testing at any stage of the trial, without any consequences.

2.2. Anthropometric measurements

The anthropometric data collection was performed in accordance with the methodology developed by Martin and Saller [13], as well as Tanner [32~~1~~]. The measurements were carried out by 2 qualified persons with appropriate knowledge and experience in the field of anthropometry.

The anthropometer and small spreading calliper of the Sieber Hegner Machines SA set (GPM, Switzerland) were used to measure the length and width of the body and its segments (accuracy of 1 mm). Circumferences were measured using non-stretchable anthropometric tape (accuracy 0.5 cm). The skinfold thickness was measured using a Holtain calliper (GPM, Switzerland) with an accuracy of 0.5 mm. Body weight (with an accuracy of 0.01 kg) was determined using an electronic scale Tanita BC-418 (Japan). Included parameters (where necessary, measured on the right side of the body):

a) "global" measurements and indicators:
   - height – H [cm];
   - mass – M [kg];
   - Body Mass Index – BMI [kg/m^2];
   - body fat percentage: B_F [%] calculated according to Slaughter et al. [29~~8~~] as:

$$B_F = 1.21 \times (F_A + F_S) - 0.008 \times (F_A A + F_S)^2 - f$$

   where: F_A – fold on triceps, F_S – fold on shoulder blade, f = 5.5 (constant for post-pubertal phase);

b) lower limbs measurements and indicators:
   - Lower limb length (*symphysion* height) – L_L [mm];
   - Thigh length – L_T [mm];
   - Maximum thigh circumference – C_T [mm];
   - Front Thigh Skinfold - F_T [mm];
   - Calf length – L_C [mm]
   - Maximum calf circumference – C_{CMAX} [mm];
   - Distal calf circumference – C_{CDIS} [mm];
   - Calf skinfold (medial) – F_C [mm];

c) foot measurements and indicators:

- Foot length – L_F [mm];
- Foot width – W_F [mm];
- Estimated foot surface – S_F~~F~~ [-] calculated according to Kryst et al. [11] as:

$$S_F = 3.14 \times (L_F \div 2) \times (W_F \div 2) \div 10$$

where: L_F – foot length, W_F – foot width.

2.3. Video registration

Video recordings were carried out in accordance with the methodology developed in 2014 by L. Nosiadek, originally for the analysis of swimming starts [20], including above-water and underwater movements, and then adapted for the analysis of underwater undulatory swimming as widely described in a number of publications [37~~6~~], [38~~7~~], [39~~8~~]. Before the video recording, the centers of rotation of the: upper ankle, knee, hip, shoulder, elbow and radial-wrist joints were marked with a waterproof marker on the left lateral side of the body. The V toe (of the left foot) and the V finger (of the left hand) were also marked on the lateral side. These markings were placed in a way that ensured constant visibility on video material.

After a short warm-up on land and in the water (approx. 1000 m, including underwater swimming exercises) supervised by a certified swimming coach, the subjects were familiarized with the task. The participants started in the water ~~and submerged~~ without pushing off the wall~~.~~ and performed free-dive in front of the aluminium rod to a depth of about 1 m, and then accelerated covering about 5 m until they reached their maximum velocity. Then, using only the UUS technique, covered the distance of 5 m (defined by markings on the bottom of the pool) [37]. Taking into account the ascent, the subjects covered a distance of about 12 m and trial lengths were consistent across participants. ~~Their task was to swim a distance of approximately 12 m at a depth of about 1 m below the surface of the water as quickly as possible, using UUS.~~ Subjects were not forced to make a specific frequency of movements (kicking frequency was self-selected). The subjects performed the test in the prone position. Each participant performed 3 trials with approximately 3 minutes of rest between them. In the case of failure to meet the condition of reaching the correct depth (visual assessment made from an underwater perspective by the test supervisor), the subjects were informed about the need to improve this element in the next repetition. At least two attempts performed at the correct depth were recorded for each subject.

All trials were recorded using Casio Exilim EX-FH25 in the "movie" mode at a frequency of 120 frames/s. The camera lens was set perpendicularly to the course of participants' movements. The device was placed on a stable tripod behind the underwater window about 1 m below water level, about 8 m from the tested participant. This arrangement made it possible to cover a space of about 7 m, which allowed for the recording of at least three full movement cycles in each trial. It was assumed that the cycle was initiated with an upward movement of the V toe (then, the end of movement equalled the end of the downward movement) or a downward move (then, the end of movement equalled the end of the upward movement).

After collecting all the recordings, a square calibration frame with a side length of 1.02 m was placed in the centre of the recorded area, perpendicular to the water level and parallel to the underwater window. It was later used to scale images.

2.4. Kinematic analysis

The analysis of the recordings was carried out using the Skill Spector program (version 1.3.2, Video4coach, Denmark). A 10-point model dividing the body into 8 segments ("Full Body Left Side") was used for kinematic analysis. The model made it possible to determine the position of the center of mass (CoM) on each recording frame. First of all, for each trial, the average horizontal velocity CoM at which the subjects moved was determined. Based on the analysis of the film material in which the subjects moved the fastest (results based on the best performance), according to the description of Wadrzyk et al. [38], the following variables were determined:

- horizontal velocity of CoM – v [m/s]
- frequency of movement – f [Hz]
- distance per cycle – horizontal displacement of – DPC [m]
- amplitude of toe movement – A [m]
- product of A × f – I_{Af} [-]

2.5. Statistical analysis

Statistical analysis was performed via the Statistica program (version 13, StatSoft, Poland). After obtaining the characteristics of variables in the group (mean, standard deviation), based on the Shapiro-Wilk test, it was found that all indices had a normal distribution ($p < 0.05$). Then, scatter graphs were created to detect possible non-linear correlations between variables describing the somatic structure and the technique of underwater undulatory swimming [2]. After their exclusion, box-and-whisker plots were generated to locate possible outliers. Due to their absence, the Pearson *r* correlation coefficients between anthropometric and kinematic indicators were calculated next. The threshold of significance of correlation was assumed to be $p < 0.05$.

3. Results

The average velocity (v) achieved by the subjects was 1.26 ± 0.11 m/s. The participants moved with a frequency (f) of 1.83 ± 0.22 Hz, the distance per cycle (DPC) was 0.68 ± 0.10 m, and the amplitude of toe movement (A) was 0.58 ± 0.08 m. The product of the amplitude and the movement frequency (I_{Af}) had an average value of 1.06 ± 0.10. Table 1 presents the results of anthropometric measurements.

Table 1. Anthropometric characteristics of the study group

	Mean ± SD
Height H [cm]	167.31 ± 5.46
Mass M [kg]	60.75 ± 7.05
Body Mass Index BMI [kg/m^2]	21.68 ± 2.06
Body fat percentage B_F [%]	18.57 ± 3.57
Lower limb length L_L [mm]	873.91 ± 44.33
Thigh length L_T [mm]	443.59 ± 42.27
Calf length L_C [mm]	354.79 ± 27.01
Maximum thigh circumference C_T [mm]	544.09 ± 35.94
Maximum calf circumference C_{CMAX} [mm]	341.91 ± 19.92
Distal calf circumference C_{CDIS} [mm]	211.76 ± 13.64
Front thigh skinfold F_T [mm]	11.60 ± 2.55
Calf skinfold F_C [mm]	9.97 ± 2.27
Foot length L_F [mm]	244.12 ± 9.55
Foot width W_F [mm]	90.79 ± 5.95
Estimated foot surface S_F [mm^2]	1742.04 ± 158.44

Table 2~~1~~ presents the results of the correlation analysis between the indicators describing the "global" body build of the subjects and the kinematic variables of the underwater undulatory swimming. Of all the correlations, only one (between M and I_{Af}) was significant (r = 0.35).

Table 2. The coefficients of correlation between "global" anthropometric variables and kinematic indicators of underwater undulatory swimming (v – horizontal velocity of CoM, f – frequency of movement, DPC – distance per cycle, A – amplitude of toe movement, I_{Af} – product of A × f, H – height, M – mass, BMI – Body Mass Index, B_F – body fat percentage).

	v	f~~F~~	DPC	A	I_{Af}
H	0.05	-0.05	0.11	0.27	0.31
M	0.20	-0.08	0.26	0.30	0.35*
BMI	0.20	-0.06	0.24	0.17	0.20
B_F	0.12	-0.01	0.17	0.12	0.21

* - p<0.05

The relationships between kinematic parameters and indices describing the structure of the lower limb are presented in Table 3.

Table 3. The coefficients of correlation between lower limb anthropometry and kinematic indicators of underwater undulatory swimming (v – horizontal velocity of CoM, f – frequency of movement, DPC – distance per cycle, A – amplitude of toe movement, I_{Af} – product of A × f, L_L – lower limb length, L_T – thigh length, L_C – calf length, C_T – maximum thigh circumference, C_{CMAX} – maximum calf circumference, C_{CDIS} – distal calf circumference, F_T – front thigh skinfold, F_C – calf skinfold).

	v	f	DPC	A	I_{Af}
L_L	0.21	0.14	0.09	0.05	0.24
L_T	0.03	0.04	0.09	-0.03	-0.01
L_{SC}	0.26	0.09	0.03	0.12	0.31
C_T	0.15	-0.26	0.31	0.42*	0.29
C_{CMAX}	0.48*	0.01	0.37*	0.26	0.39*
C_{CDIS}	0.39*	0.17	0.23	0.09	0.40*

F_T	0.17	-0.31	0.40*	0.45*	0.25
F_{SC}	0.25	-0.15	0.23	0.28	0.22

* - p<0.05

In this case, significant correlations were found between the velocity and the maximum (r = 0.48) and distal (r = 0.39) circumferences of the lower leg. The mentioned dependencies are presented in Figures 1 and 2.

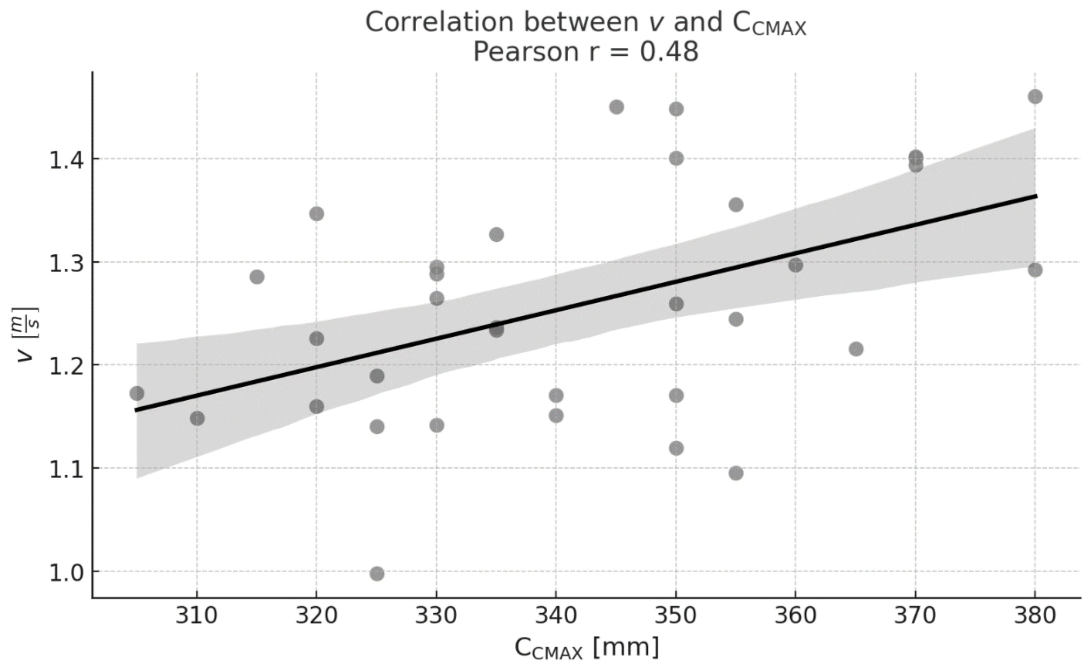

Figure 1. Scatterplot showing the relationship between horizontal velocity of CoM (v) and maximum calf circumference (CCMAX).The black line represents the fitted linear regression model, while the grey shaded area indicates the 95% confidence interval for the regression line.

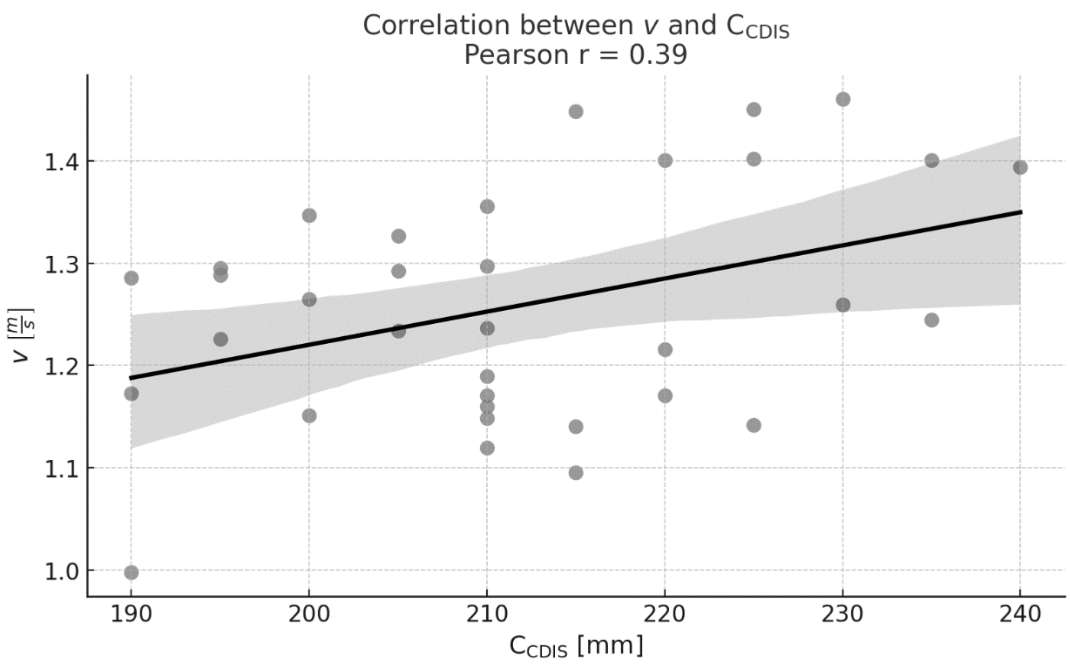

Figure 2. Scatterplot showing the relationship between horizontal velocity of CoM (v) and distal calf circumference (CCDIS).The black line represents the fitted linear regression model, while the grey shaded area indicates the 95% confidence interval for the regression line.

C_{CMAX} was also related to DPC (r = 0.37) and I_{Af} (r = 0.39). Significant correlation coefficients were also found between F_T and DPC (r = 0.4) and A (r = 0.45) and C_{CDIS} and I_{Af} (r = 0.40).

Table 4~~3~~ presents the coefficients of correlation between variables describing the foot structure and kinematic indices of UUS.

Table 4. The coefficients of correlation between foot anthropometry and kinematic indicators of underwater undulatory swimming (v – horizontal velocity of CoM, f – frequency of movement, DPC – distance per cycle, A – amplitude of toe movement, I_{Af} – product of A × f, L_F – foot length, W_F – foot width, S_F – estimated foot surface)

	v	f	DPC	A	I_{Af}
L_F	0.35*	-0.03	0.30	0.06	0.05
W_F	0.21	-0.16	0.31	0.15	0.02
S_F	0.30	-0.12	0.35*	0.13	0.04

* - p<0.05

Among all the analysed relationships, a significant ones were found only between v and L_F (r = 0.35), as well as S_F and DPC (r = 0.35). The first of the mentioned relationships is illustrated in the form of a scatter plot in Figure 3.

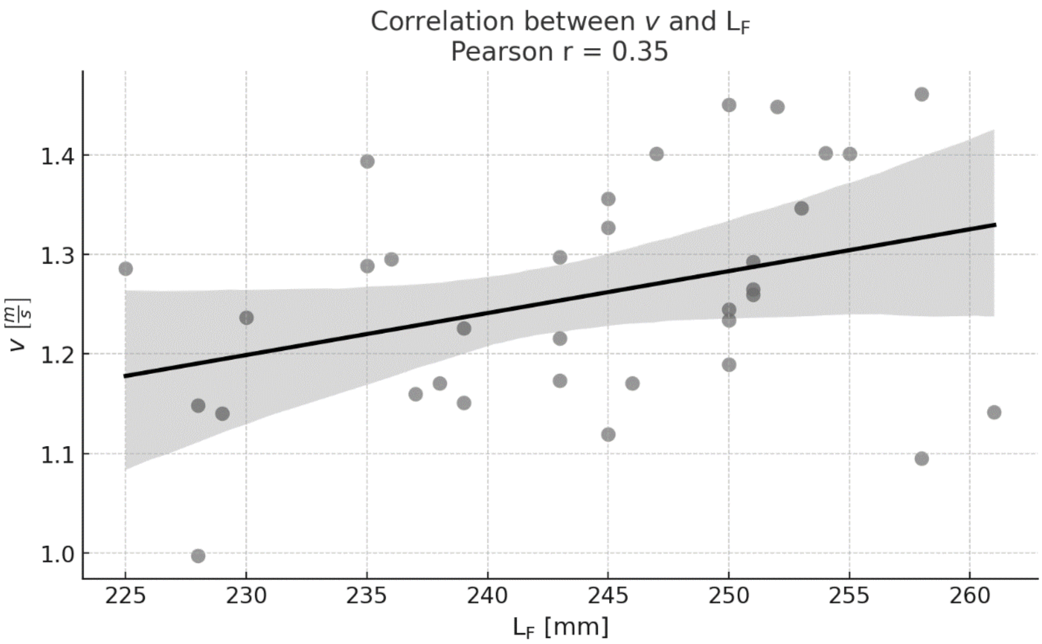

Figure 3. Scatterplot showing the relationship between horizontal velocity of CoM (v) and foot length (LF).The black line represents the fitted linear regression model, while the grey shaded area indicates the 95% confidence interval for the regression line.

4. Discussion

The aim of the study was to determine the relationship between the somatic structure and the UUS technique performed by junior female swimmers. A set of kinematic variables used in this research was selected based on data from the literature – previous studies described in detail the relationships between the effectiveness of UUS and the chosen parameters. For instance, so far, a positive relationship has been established between velocity and f, DPC or I_{Af} in different genders ~~sexes~~ and groups of various sports levels [8], [36~~5~~], [38~~7~~], [39~~8~~]. For this reason, this work focused primarily on the relationships between anthropometric and kinematic indices, without considering the associations between v and other indices characterizing the UUS technique.

Due to the density of water, a moving swimmer experiences significant resistance in the aquatic environment [17]. Overcoming it at high speed requires the athlete to have sufficiently high mechanical muscle power, which is positively related to muscle mass [21]. Its higher level is usually found in athletes with relatively larger bodies [14]. Therefore, it should not be surprising that previous studies on swimmers' body build have found that athletes with relatively larger bodies have an advantage in full stroke swimming [15], [22]. For this reason, in the present study, a relationship between height, mass, BMI and UUS velocity was expected. However, none of the above-mentioned indicators was significantly related to v. The lack of this relationship may be due to differences in the amount of wave drag experienced by a swimmer moving on and under the surface. It is known that in full strokes swimming, this type of resistance is dominant over the others (form and friction drag) [25], while being significantly lower when the underwater movement is considered [5]. This means that in the UUS technique, form drag dominates (friction is small) [33~~2~~]. The aforementioned resistance is positively related to the maximal cross-section body area [17]. Thus, it cannot be ruled out that in underwater swimming, competitors with large bodies may simultaneously experience significant resistance. Therefore, their advantage in the form of having a larger muscle mass may not provide such benefits as in the case of swimming on the surface.

The positive relationship between swimming results and upper limbs length is well documented in the literature. Athletes with a large arm span can achieve, for instance, greater speed when swimming the front crawl [19], [27]. Long upper limbs are associated with longer lever arms, which, with appropriate muscle mass and proper training, allow for generating more effective propulsion [22]. In studies on the front crawl technique, a positive relationship between upper limb length and stroke length was also noted [1], [27]. This is because the swimmer has a greater arm reach, which allows for extending the underwater movement path [22]. In this study, a similar type of relationship was expected between lower limb length and v, as well as DPC. However, such observations were not recorded. This is probably due to differences in the trajectory of movements of the upper and lower limbs. When swimming full strokes, the upper limb movement path is characterized by a significant backward displacement [7]. In this situation, it is assumed that propulsion is mainly due to the drag force, which dominates over lift [354]. In the case of UUS swimming, the movement of the lower limbs is performed primarily in the vertical direction, with a small backward displacement [8]. Some authors indicate that, in this case, the movement of the swimmer is the result not only of the drag and lift forces but also of the vortex propulsion [18]. Due to differences in the mechanism generating the propulsion, the length of the upper limbs may be related to the speed of full strokes, while the length of the lower limbs is not a factor influencing the effectiveness of UUS. It cannot be ruled out that other individual factors, such as the mobility of the lower limb joints, especially the ankle, may, to a greater extent, determine underwater swimming speed [12].

The present study observed a positive relationship between the circumferences of the lower leg (maximum and distal) and the v, as well as the I_{Af}. Similar observations were made by Nevill et al. [19] in studies on the butterfly stroke, in which the movement of the lower limbs resembles the UUS technique. Of course, due to differences in the course of the movement of the upper limbs, the results of the cited studies cannot be fully compared with the present ones. In the our study, the calf skinfold was not associated with the kinematic indices describing the UUS technique. Therefore, it can be assumed that the larger thigh and lower leg circumferences were not the result of differences in adiposity in these segments but of greater muscle mass. Although the "global" indices describing the somatic structure did not affect the UUS velocity, the greater muscle mass of the lower limbs' could positively affect the efficiency of underwater swimming. This is probably due to the well-described phenomenon of a positive relationship between muscle mass and the ability to develop mechanical power [4]. This allows us to assume that the mechanical power of the lower limbs may be a factor positively related to UUS swimming velocity. So far, this type of relationship has been, to a limited extent, studied by the team of Ruiz-Navarro et al. [23], [25]. Thus, further research could aim to search for the relationship between the mechanical power of the lower limbs and the UUS technique.

This work has several limitations. The group of participants included athletes with different levels of sports performance, measured using the classification introduced by Ruiz-Navarro et al. [24]. This decision was made due to the greater likelihood of detecting potential relationships – as a result of the size of the group and sports performance. Future studies in this area could take into account a more uniform competitive level of the participants. At the same time, it would be reasonable to include groups of both genders in one study. ~~One of them is the fact, that~~ Moreover, the kinematic analysis was only two-dimensional. Although it should be stressed that this is a common practice in UUS research [36~~5~~], some authors indicate that the inversion movement in the ankle joint is important for the effectiveness of this technique [12]. The current research also focused primarily on describing the lower limb segments, which mainly determine the UUS velocity [8]. However, it should be emphasized that the movement of the trunk is also responsible for the course of movement of the lower body parts [31~~0~~]. Particularly, the undulation synchronization between the mentioned body segments, which is not described in this work, can be crucial [40~~39~~].

Conclusions

The results of this study provided a basis for answering the previously established research questions. Based on the obtained results, it can be concluded that in young girls, body size does not affect the effectiveness of underwater undulatory swimming. However, it was found, that the structure of the lower limb determines the technique of UUS to a small extent. Particularly, the circumference of the calf (maximal and distal) was positively associated with the effectiveness of the undulatory movements. Additionally, the foot measurements had a small positive effect on the effectiveness of UUS.

Based on the research, several practical implications can be indicated. Among female athletes, the effectiveness of underwater undulatory swimming depends primarily on the level of mastery of the technique. Proper movement patterns should be developed especially in swimmers with smaller bodies and relatively large leg musculature. By effectively developing underwater undulatory swimming techniques, the aforementioned athletes can maximize the distance covered underwater, and thus compensate for any lower predispositions to swimming on the surface. It can also be indicated that, due to the greater number of turns in 25-m pools, body size may have less of an impact on results in short-course facilities. This fact is the basis for taking into account the somatic structure when comparing the results achieved by female athletes in the short and long course pool.

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Disclosure statement

No potential conflict of interest is reported by the authors.

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