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Coordination and propulsion and non-propulsion phases in 100 meter breaststroke swimming

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Purpose: The main purpose of this study was to analyze the coordination, propulsion and non-propulsion phases in the 100 meter breaststroke race.

Methods: Twenty-seven male swimmers (15.7 ± 1.98 years old) with the total body length (TBL) of 247.0 ± 10.60 [cm] performed an all-out 100 m breaststroke bout. The bouts were recorded with an underwater camera installed on a portable trolley. The swimming kinematic parameters, stroke rate (SR) and stroke length (SL), as well as the coordination indices based on propulsive or non-propulsive movement phases of the arms and legs were distinguished.

Results: Swimming speed ($V100_{\text{surface breast}}$) was associated with SL ($R = 0.41$, $p < 0.05$) and with TBL tending towards statistical significance ($R = 0.36$, $p < 0.07$), all relationships between the selected variables in the study were measured using partial correlations with controlled age. SL interplayed negatively with the limbs propulsive phase Overlap indicator ($R = -0.46$, $p < 0.05$), but had no significant relationship to the non-propulsion Glide indicator.

Conclusions: The propulsion in-sweep (AP3) phase of arms and their non-propulsion partial air recovery (ARair) phase interplayed with $V100_{\text{surface breast}}$ ($R = 0.51$, $p < 0.05$ and 0.48 $p < 0.05$) respectively, displaying the importance of proper execution of this phase (AP3) and in reducing the resistance recovery phases in consecutive ones.

Key words: *breaststroke, body length, kinematic indices, water sport*

1. Introduction

Competitive breaststroke is a challenging swimming technique extraordinary in the complexity of its techniques in comparison with other swimming styles. Experienced swimmers claim that coaches have their own thoughts about this swim stroke. These details may be of such a fundamental nature as, for example, stroke rate and stroke length, depending on the distance [12], [29]. Stroke rate and stroke length ratio may therefore also be due to differences invisible to the naked eye (e.g., differences in the timing of propulsion phase execution by arms and legs in the cycle, or duration of gliding) as in the shaping of intra-cyclic propulsion and recovery phases, intra- and inter-cyclic

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limb coordination [4], [8], [13]–[15], [23], [28], [30]. Differences in the performance of each movement phase, however seemingly minor, may translate into increased propulsion force and minor modifications in the streamlined glide or recovery with limited active drag may increase the speed of breaststroke swimming. For example, increasing the propulsion force of a chosen stroke phase, continuity of propulsion in the movement cycle or minimizing intra-cyclic velocity variation in the stroke cycle after analysis of swimmers in a chosen age group [4], [5], [27].

Our search for differences in breaststroke swimming coordination and kinematics relevant to the swimming speed will certainly be based on studies already conducted in this area [7], [8], [13], [14], [16], [17], [23], [28]. These and subsequent work [4], [24], [25] will allow us to choose the temporal indices defining structure of movements of the arms and legs, and their mutual co-ordination.

The main purpose of this study was to analyze the coordination, propulsion and non-propulsion phases in the 100 meter breaststroke race in a group of young swimmers. We can assume that differences in the timing of propulsion phase execution by arms and legs in the breaststroke cycle, or duration of particular propulsion, recovery and gliding phases can diversify the breaststroke swimming results achieved. Additionally, anthropometrics such as body mass and total body length have an effect on the breaststroke speed.

2. Methods

Participants: The 27 male swimmers recruited from two sports schools as well as from the university swim club were 15.7 ± 1.98 years old: 26 were between the ages of 14 to 19, and one participant was 21 years old. An informed consent form (approved by the Bioethics Commission in Cracow) was signed by either the participant and his parents or guardians if the subjects were under 18 years old. The swimmers were specialized in the breaststroke as well as in individual medley. They competed at regional, national or international (only 5 subjects) level. All of them trained twice a day six times a week. Their average height was 180.1 ± 21 cm, and body mass 70.03 ± 9.35 kg.

Total body length (TBL): the swimmers wore sportswear when lying back while measuring the distance from the tips of the fingers, with the arms extended above the head, to the toes of plantar-flexed bare feet. The measurements were conducted with an anthropometer (Sieber Hegner Maschinen AG) by an experienced physiotherapist (with reliability of measurments – ICC: –0.111; 95% lower; upper CI: –0.111 and –0.111, respectively).

Underwater recordings: The underwater recording was done according to what was described by Strzała et al. [26] with a camcorder (Canon, Legria HV40, Japan) and an underwater camera (Sony, Color Submergible Camera IP:68, Japan). The camcorder was working in the recording mode, receiving the video signal from the underwater camera (sampling rate at 50 Hz). The camcorder and underwater camera was set on a portable trolley, which moved along the swimming pool deck and parallel to the swimmer, providing a side-shot keeping the lens of the underwater camera. A person trained in maintenance of the above mentioned device moved the trolley in both directions alongside the swimming pool so as not to cross, with the lens of the underwater camera, the perpendicular lines between the swimmer's fingertips of the straightened arms in the front and toes of the stretched legs in the back. The underwater camera was set on the lower arm of trolley and at 1 meter depth, approximately 5 meters from the swimmer's line of displacement.

Sw*imming test*: The all-out swimming 100 m breaststroke race was performed in a 25 meter-long swimming pool (i.e., start was from the block, alone and with no other swimmers in the lane, subjects raced without any drafting, pacing or being affected by extra drag force due to exogenous factors), the test was preceded by a warm-up the same as prior to competition.

Video analysis of breaststroke swimming: Recordings enabled the determination of the moments in which characteristic events of the swimming cycle occurred, such as specific movements of the arms and legs. The cyclic movement of the arms and legs was broken down into phases by an experienced evaluator according to its role in accelerating or decelerating the swimmer's body using an identification method proposed by Maglischo [16] modified by Strzała et al. (with reliabiblity of measurments – ICC: –0.110; 95% lower; upper CI: –0.113 and –0.107, respectively [26].

Three arm propulsion phases were determined: first phase – AP1 starts from the beginning of the arm movement toward the outside with the hands twisted out in pronation, and lasts until the elbows are bent outwards and move back.; second phase – AP2 begins with the end of the AP1 phase with the trough arm pull, a backward movement leading to the deepest immersion of the fingertips, which are moving inward.; third phase – AP3 starts at the end of the AP2 phase and lasts till the beginning of forward hand movement.

Total arm recovery was divided to at least partially emergent hands phase called AR_{air} and arms fully submerged phase ARwater. Arm recovery phases were determined as follows: first phase – $AR_{water\ 1}$ from the end of the AP3 phase till hand emersion (emergent hands become invisible); second phase – AR_{air} from the end of the $AR_{water\ 1}$ phase till hand submersion; third phase – $AR_{water\ 2}$ from the end of the ARair phase till the beginning of AP1.

If the AR_{air} phase did not occur, the swimmer obtained 0% contribution of this phase in the cycle according to the observation. If there was hand emerge $AR_{water} = AR_{water\ 1} + AR_{water\ 2}$. Conversely, if there was no emergence, then AR_{water} = Total AR.

Two leg propulsion phases were determined: first phase – LP1 after bending the legs at the hip and knees, the phase begins with the ankles moving backwards and ends when the knee straightens; second phase – LP2 from the end of the LP1 phase till the closure of feet approximation.

Two leg recovery phases were identified: first phase – LR1 starts at the end of the LP2 phase and ends when the swimmer bends the leg in the hip and knee while pulling feet towards the hips; second phase – LR2 from the end of LR1 till the ankles begin to move backward.

Collected data on the percentage of the execution time of the respective phases were used to distinguish the temporal propulsive movement coordination of the upper and lower limbs in the breaststroke cycle by three indicators:

1. Overlap – of the propulsive movement of the upper limbs on the propulsive movement of the lower limbs of the previous cycle, as a certain percentage of the movement cycle of the upper and lower limbs.
2. Glide – percentage of the cycle duration between the end of second leg propulsion phase and the beginning of the first arm propulsion phase.
3. TTG – total time gap is the sum of the different time gaps between propulsive movement of arm and leg, which include the above mentioned glide and the intra-cyclic gap between the propulsive phases produced by the upper and lower limbs [23].

The above mentioned analysis was used to identification of the characteristic cyclic elements of arm and leg movements in breaststroke swimming [26]. The analysis during the all-out swimming test was conducted in 10 m splits, in four laps, at a distance of 100 meters – respectively in the sections between the 10th to 20th meter, further between the 35th to 45th meter and 60th to 70th, and finally between 85th to 95th.

The duration of the race Δt_i and the times of the separate sectors were measured with a stopwatch with the accuracy of 0.01 s.

The following parameters were used to assess the swimming technique during each 10 m-long swim analyzed (i = 1, 2, 3, 4):

(1) Swimming speed: $V_i = 10\ \text{m}/\Delta t_i$, [m·s^{-1}];

(2) Stroke rate (SR_i): calculated as the reciprocal of the arithmetical average of the duration of three analyzed swimming cycles: $SR_i = 1/T_i$, [cycle·min^{-1}];

(3) Stroke length (SL_i), calculated as the average speed to SR_i ratio: $SL_i = V_i/SR_i$ [m].

Kinematic parameters (i.e., SR and SL) as well as the coordination indices are presented as an average value of twelve full stroke cycles, from which each 3 were identified on following 10 meter sector of each 25 meter pool as mentioned above.

Statistical methods. The normality, homoscedasticity and independence of data assumptions were checked respectively with Kolmogorov–Smirnov, the Levene and Durbin–Watson tests. Descriptive statistics of means and standard deviations were calculated for all variables. The partial correlations, controlling the effect of age, between the swimming speed ($V100_{surface\ breast}$), – anthropometrics (i.e., TBL), and the respective arm and leg propulsion and recovery phases as well as indexes of cycle coordination (i.e., Overlap, Glide and TTG) indicators or swimming stroke kinematics SR and SL were also calculated. The above metioned tests were conducted with STATISTICA ver. 10 software (StatSoft, Inc.). The significance level was set at $p < 0.05$. The intraclass correlation coefficient (ICC) estimation for TBL and kinematics data were conducted using the variance components from a one-way ANOVA, as well as the 95% confidence interval for such results (R Package "ICC" ver. 2.2.1).

3. Results

Figure 1 presents an example of the limbs coordination at breaststroke for one subject. For this specific case it is possible to verify that the fastest swimmer during the all-out breaststroke swimming test in average cycle performed separately propulsion movement of arms (AP1-AP3) while streamlined legs towing (LR1 = 34%). During arms recovery with partially emerged hand (AR_{air}) swimmer started bending the knees (LR2) along with legs recovery. After the kick and before beginning the next arm stroke there was a noticeable gliding phase (LR1 = 5%).

The $V100_{surface\ breast}$ was 1.18 ± 0.08 $m \cdot s^{-1}$ and the time duration of the whole 100 m breaststroke race was 76.1 ± 4.72 s. Among the anthropometrics and swimming kinematics and coordination presented in Table 1, those with a moderate statistically significant impact on the results of $V100_{surface\ breast}$ was the SL indice (with age control), while TBL was associated with borderline statistical significance, but with similar strength. This means that a greater $V100_{surface\ breast}$ was likely obtained through a longer stroke length, whilst having a greater total body length.

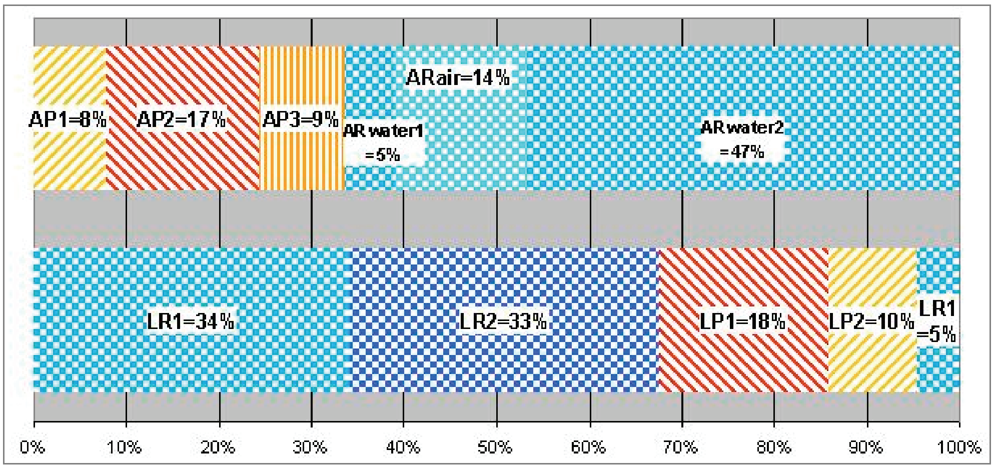

Fig. 1. One swimmer's movement cycle

Table 1. Somatic properties total body length (TBL), basic stroke kinematics: stroke length (SL), stroke rate (SR), the indexes of the cycle coordination: Overlap, Glide and total time gap (TTG) and their partial correlations with swimming speed ($V100_{surface\ breast}$) with controlled age. Statistically significant ($p < 0.05$) correlations are marked with an asterisk (*). Correlation close to or tending towards statistical significance ($p \leq 0.07$) is marked in *italics*

TBL [cm]	SL [m]	SR [cycle·min^{-1}]	Overlap [%]	Glide [%]	TTG [%]
247.0 ± 10.60	1.66 ± 0.17	40.4 ± 3.75	2.0 ± 4.58	7.3 ± 6.53	36.2 ± 6.18
partial correlation with V $100_{surface\ breast}$ [m·s^{-1}]					
0.36 *p* = 0.07	0.41* *p* = 0.04	0.11 *p* = 0.60	0.07 *p* = 0.73	–0.14 *p* = 0.50	–0.26 *p* = 0.20

Table 2. The partial correlations between stroke kinematics: stroke length (SR), stroke rate (SR) with controlled age with somatic TBL and the indexes of cycle coordination: Glide, Overlap and total time gap (TTG). Statistically significant ($p < 0.05$) correlations are marked with an asterisk (*) and $p < 0.01$ with (**)

Part. correlation	TBL [cm]	Overlap [%]	Glide [%]	TTG [%]
SL [m]	–0.01 *p* = 0.97	–0.46* *p* = 0.02	0.22 *p* = 0.32	0.16 *p* = 0.45
SR [cycle·min^{-1}]	0.26 *p* = 0.20	0.70** *p* < 0.01	–0.53* *p* = 0.01	–0.53* *p* = 0.01

Table 3. Propulsion phases – AP1, AP2, AP3, total AP and recovery phases AR_{water}, AR_{air}, Total AR of the arm breaststroke swimming cycle and their partial correlations with swimming speed – $V100_{surface\ breast}$ when controlled for age. Statistically significant correlations were marked as follows: $p < 0.05$*, $p < 0.01$**

Arm-Propulsion [%]				Arm-Recovery [%]		
AP1	AP2	AP3	Total AP	AR_{water}	AR_{air}	Total AR
12.0 ± 3.92	19.4 ± 3.55	8.8 ± 2.53	40.3 ± 6.04	52.3 ± 9.28	7.5 ± 4.67	59.7 ± 6.04
correlation with V $100_{surface\ breast}$ [m·s^{-1}]						
–0.10 *p* = 0.64	–0.21 *p* = 0.31	0.51** *p* = 0.01	0.03 *p* = 0.87	–0.26 *p* = 0.19	0.48* *p* = 0.01	–0.03 *p* = 0.87

Table 4. Leg propulsion phases – LP1, LP2, Total LP and leg recovery phases – LR1, LR2, Total LR and their partial correlations with swimming speed ($V100_{surface\ breast}$) when controlled for age. Statistically significant correlations were marked as follows: $p < 0.05$*, $p < 0.01$**

Leg-Propulsion [%]			Leg-Recovery [%]		
LP1	LP2	Total LP	LR1	LR2	Total LR
17.9 ± 2.41	7.7 ± 3.87	25.6 ± 5.21	39.8 ± 10.37	34.7 ± 6.43	74.4 ± 5.21
correlation with $V\ 100_{surface\ breast}$ [$m \cdot s^{-1}$]					
0.23 $p = 0.26$	0.27 $p = 0.18$	0.31 $p = 0.13$	–0.15 $p = 0.47$	–0.03 $p = 0.90$	–0.32 $p = 0.12$

There were no significant associations between SL and TBL which directly influenced $V100_{surface\ breast}$ but one cycle coordination index (Overlap) interplayed significantly and negatively with SL. Although a stronger correlation was verified between SR and Overlap. Glide and TTG were negatively associated with an equal strength of correlation (Table 2).

Phase separation of the propulsive and non-propulsive arms and leg movement in each cycle allowed us to check their influence on the breaststroke surface swimming speed. The result of V100surface breast had a strong and significant relation to a portion of the AP3 phase, named insweep phase, the $V100_{surface\ breast}$ was also moderately dependent on recovery – ARair phase, Table 3.

Checking the relationship between $V100_{surface\ breast}$ and individual propulsive and non-propulsive phases of leg movement revealed no significant association, Table 4.

4. Discussion

The main purpose of this study was to analyze the coordination, propulsion and non-propulsion phases in the 100 meter breaststroke race. The main findings of this research was swimmers' ability to lengthen the movement cycles – SL which directly correlated to $V100_{surface\ breast,}$ this clear swimming speed was also influenced by the efficiency of arm propulsion movement, especially – SP3 phase, and perform the subsequent phases with minimizing active drag thruogh partially hand emerged recovery phase – AR_{air}.

The significant influence of SL on $V100_{surface\ breast}$ was contrary to the breaststroke swimming speed at shorter distances of 50 meters measured for almost the same group of swimmers in other observation, where $V50_{surface\ breast}$ was dependent directly on SR [26]. Breaststroke is the less economical swimming technique [1], [31]. Increase in frequency of propulsive movements of lower and upper extremities and therefore of the SR, leads to an increase in energy cost [32]. However, increasing SR in breaststroke swimming causes increasing the energy cost as the total energy expenditure required for displacing the body over a given unit of distance, which is caused by: (i) the loss of energy with increasing resistance during rapidly performed non-propulsive movements of recovery phase of the legs [8], [18], [33]; (ii) during recovery of arms if executed with higher resistance, i.e., in total immersion; (iii) reducing glide causes the elimination os short time rest between each cycle.

Increased resistance as well as increased energy cost of breaststroke swimming in linked to intra-cyclic acceleration and deceleration which occur especially during leg recovery, which increases significantly the drag force while being bent in hip-joints – up to the angle between 54° and 68° when the feet flexed and rotated approach to buttocks [21]. In swimming with many movement cycles quick recovery movements of legs in opposite direction to the swimmers' body movement affect fluctuations of the horizontal velocity of displacement of centre of mass, and the significant resistance occurring in this movement cycle phase means the increased involvement of the constrictors in hip and knee joints, resulting in higher growth of fatigue [1], [18], [32]. In such a situation the ability to increase SL and due to this decrease in SR and intra-cycle speed fluctuation, which is visible with increasing distance, is very important [2], [25]. The ability to increase SL and decreasing SR was noted in this research comparing to other observations in this group of swimmers (containing less athletes) in half of the distance examined [23]. In the previous observations in swimming at a distance of 50 meters all-out the important factor affecting the swimming speed was SR, not SL. Such a change occurs only when the swimmer is able to synchronize their arm and leg movements so that the loss of instant velocity of the center of mass will remain minimal at the end of gliding [2]. Our results may coincide with the reports from Barbosa et al. [2], who showed that SL promotes significant decrease of energy cost, which is related to possible decreases in the intra-cycle speed fluctuations for sub-maximal performances at higher SL values. Other researchers observed that swimmers were faster at a distance of 100 meters or with their own race pace of 100 meter had longer SL [10], [9], [12]. In our study the SL index determining $V100_{surface\ breast}$ showed significant negative correlation with coordination index Overlap, which indicates that some swimmers cannot change intra- and inter-cyclic overlapping coordination of leg and arm movement with increasing race distance. Considering the above, for example, the SL of the fastest swimmer in our observations was 1.88 m with 5% duration of glide in each cycle (Fig. 1), in other research, in which he was one of the fastest swimmers at a distance of 50 meters, the SL was 1.80 with almost 14% overlapping of the propulsive movement of the upper limbs on the propulsive movement of the lower limbs of the previous cycle [23]. The swimmer was able to change upper and lower limb movement coordination in movement cycles from more continuous of generating propulsion to overlapping with longer glide phase during 100-meter-long race.

In our research, the total body length (TBL) swimmers was correlated close to the cutoff value with $100_{surface\ breast}$, $r = 0.36$. However, TBL had no significant correlation with SL and separate movement phases or coordination indices.

After distinguishing separate arm movement cycles we have verified significant influence of propulsive phase AP3 on $V100_{surface\ breast}$ (Table 2). Studying the subject of propulsion production in breaststroke swimming we learn how much may be gained or lost in the insweep phase. The arm stroke patterns in this technique are mainly curvilinear [6]. Some researchers suggest that without executing extensive transverse and vertical movements, thanks to which it is possible to achieve a high magnitude of lift force directed forward it is difficult to swim fast using the technique of breaststroke [19], [22], [30], [34]. Also Costill et al. [9] reported that highest velocities of swimmer during each stroke cycle were achieved during the later phases of the kick and arm pull. On the other hand, Haljand [11] suggests explaining swimmers in a simple way that the arms must make a wide pull, with good catch, hands turned out with high elbows and the hands during the pull should not slipping backward. Maglischo [17] claimed that the best swimmers' hands move out and in, as well as they travel down and up to a greater extent than they move backward. Discussing the subsequent phases of the upper limb cycle we come to the conclusions which states that starting recovery swimmers should shoot their hands rapidly up to the surface [10], but not everyone agrees that the hand transfer over the surface significantly reduces the active drag and the slowdown of the whole body [16]. Considering this, we decided to make additional calculations. We conducted the partial correlations with age control between $AR_{water\ 1}$ phase and $V100_{surface\ breast}$, which was –0.56; $p < 0.01$. $AR_{water\ 1}$ phase could be distinguished only for 22 swimmers, who had AR_{air} phase different from zero, that is why the $AR_{water\ 1}$ value and its dependence on $V100_{surface\ breast}$ is not described in the results section. This negative correlation between partial contribution of the duration of the $AR_{water\ 1}$ phase in the total recovery time and $V50_{surface\ breast}$ indicates that slow transport of the upper limbs after the end of propulsion production or prolonging their transfer in this phase is unfavorable for achieving higher swim speed. Further in our study the phase separation in motion of the upper limbs noted the relationship between the AR_{air} phase and $V100_{surface\ breast}$ (Table 2). This highlights the ability of swimmers to reduce drag during the recovery of the arms. This also means that some slower swimmers in this study were not able to transfer their hands above water. In large part, the best swimmers in the study group showed longer sliding of their hands across the water surface for the next catch. The separated lower limbs movement phases in breaststroke swimming (Table 3) did not reach statistically significant correlations with $V100_{surface\ breast}$, but the positive average interplay of total LP to $V100_{surface\ breast}$ may be observed. The results presented in this and other of our works [23] show how important it is to adapt basic kinematic indices SL and SR and related with them, calculated from the same movement cycles coordinative indices as Overlap, Glide and TTG.

It can be reported as main limitations of this research: (i) as the observations were conducted on a group that has a varied distribution of experience and number of years of training, it allows for conclusions that are applicable for the core of the group, but do not necessarily provide clear guidance for the most advanced swimmers; (ii) secondly, the process of analysing the videos of the swimmers' movement is rather time consuming, meaning that the results and the resultant discussions unfavorably prolong the time to application as the improvement tool in the current group; (iii) the use of body points trajectory tracking could develop collected data.

In this study swimmers' ability to lengthen the movement cycles – SL directly correlated to $V100_{surface\ breast}$, gave the best results. Simultaneously, $V100_{surface\ breast}$ was also influenced by efficiency of arms propulsion movement, especially SP3 phase. More skilled swimmers were able in the subsequent phases to minimize active drag through partially hand emerged recovery phase – AR_{air}.

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