UNDERWATER DOLPHIN KICKS OF YOUNG SWIMMERS – EVALUATION OF EFFECTIVENESS BASED ON KINEMATIC ANALYSIS

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ABSTRACT
Purpose. The aim of the study was to distinguish the kinematic indicators influencing the average horizontal velocity of swimming (v_{COM}) with underwater dolphin kicks (UDK).
Methods. The study involved 15 boys and 20 girls (mean age, 11.5 ± 1.00 years; height, 1.57 ± 0.09 m; training experience, 2.5 ± 1.00 years) practicing swimming 7 times a week. We determined the body height (H), the length of the body with the arms lifted (L_b), and the best result in the 50-m freestyle (pbt); characteristic anthropological points were marked on the body. The subjects performed UDK after a water-start for a distance of ca. 8 m (without a push-off from the wall). Movements were recorded with an underwater camera. The recordings were kinematically analysed with the SkillSpector program. On this basis, we calculated v_{COM}, frequency of movement (f), amplitude of movement (A), horizontal displacement in one cycle (D_{pk}), maximum flexion in the knee joints (KF_{max}), the product of f and A (I_{Af}), the Strouhal number (St), and relative amplitude of toe movement (A_{REL}).
Results. The movements of the subjects were characterized as follows: v_{COM} = 1.08 ± 0.13 m/s, f = 2.00 ± 0.39 Hz, A = 0.46 ± 0.08 m, D_{pk} = 0.58 ± 0.10 m, I_{Af} = 0.90 ± 0.11, KF_{max} = 71.37 ± 9.15°, St = 0.83 ± 0.08, A_{REL} = 0.22 ± 0.04. A statistically significant correlation was found between v_{COM} and: H (r = 0.35), pbt (r = –0.52), f (r = 0.47), I_{Af} (r = 0.72), KF_{max} (r = –0.53), and St (r = –0.36).
Conclusions. UDK of young swimmers is characterized by low-speed swimming. This is effected by low swimming efficiency (low values of I_{Af} and St, high value of KF_{max}). The proper amplitude and frequency of movements should be a priority in improving UDK. The UDK technique should be particularly enhanced among short competitors.
Key words: biomechanics, kinematics, swimming, youth sports

Introduction

Swimming with the use of underwater dolphin kicks is part of the structure of every butterfly stroke, backstroke, and freestyle race. During the race, an athlete can perform underwater swimming up to 15 m after the start and each turn. For short distances (50–200-m races) in a 25-m pool, swimmers cover 50–60% of the distance precisely in this way [1]. Some swimmers are able to swim faster underwater than on the surface [2]. This may seem surprising since under the water the body is propelled only with the lower limbs, whereas on the surface the swimmer uses all four limbs for propulsion.

Underwater swimming is more effective owing to reduced wave resistance compared with swimming on the surface. Human motion in water is normally affected by three types of resistance: frontal, frictional, and wave-related [1, 3]. Frontal and frictional resistance achieve higher values under the surface of water than on the surface [1, 4]. However, the wave resistance at the depth of 0.7 m and more is much lower than on the surface [5, 6]. This reduction in wave resistance in underwater swimming means that some athletes are able to swim much faster underwater than on the surface. Apart from swimming underwater, competitors can reduce the total resistance in many other ways, such as using specialized swimming costumes, body shaving, and optimising their technique (i.e. swimming in the so-called streamlined position).

In recent years, a number of studies on underwater dolphin kicks have been carried out, most of which were based on a kinematic analysis of video material [7–12]. The method, notwithstanding its limitations, is still a very popular way of determining selected parameters of movement [13]. Its main advantages are high reliability and simplicity of measurement; a disadvantage is the long processing time [13]. Some authors [14, 15] limit the time of video footage analysis by replacing the centre of mass with a selected point on the body (usually the centre of the transverse axis of the hip joint) during calculations. In this way, the athlete's velocity can be determined without the need for determining the cen-

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tre of mass, which is a very time consuming process. The popularity of this type of analysis continues to grow owing to infrastructure advancement (swimming pools equipped with underwater windows) and the general availability of recording devices (waterproof cameras). The result is the ability to perform tests among large groups within a short period of time. This all means that a reliable assessment of swimming technique is not limited only to the top-class athletes, as it was in the past [16], but now becomes widespread amongst children and youth. However, the kinematic analysis of underwater swimming of young swimmers has not been widely discussed. Therefore, a comparison between young and adult swimmers in terms of underwater dolphin kicks is necessary.

The aim of this study was a kinematic analysis of the underwater dolphin kick movements in young swimmers. What was sought after was the relationship between the average horizontal velocity of the centre of mass in a cycle (hereinafter referred to as v_{COM}) and selected kinematic parameters of the movement. The following hypotheses were put forward:

1. Higher velocity is achieved by competitors whose technique of underwater swimming is characterized by a high frequency of dolphin kicks combined with their significant amplitude.

2. Increasing flexion of the lower limbs in the knee joints reduces the velocity of underwater dolphin kicks.

Material and methods

The tests were carried out at the indoor swimming pool complex at the University School of Physical Education in Krakow, Poland. The dimensions of the pool are 25 m (length) and 2–2.5 m (depth). There was an underwater window at the side of the pool, allowing for underwater video recording.

The study design and procedures were approved by the Commission of Bioethics of the Regional Medical Chamber. The participants and their legal guardians submitted a written consent to take part in the study and were acquainted with the procedures, apparatus, and aim of the study.

Participants

The study involved 35 young swimmers (15 girls, 20 boys) aged 10–12 years. The participants trained swimming daily at the Krakow Sports Championship School (for the total of ca. 8 hours per week). Detailed information on the participants are included in Table 1.

Table 1. Data characterizing the studied group

Name (unit)	Symbol	± *SD*
Age (years)	y	11.50 ± 1.00
Body height (m)	H	1.57 ± 0.09
Body mass (kg)	m	46.20 ± 9.00
Body length with lifted arms (m)	L_b	2.14 ± 0.13
Best result in 50-m freestyle (s)	pbt	34.50 ± 2.39
Training experience (years)	y_t	2.50 ± 1.00

Procedure

Before underwater recording, each participant had their body marked with tags (markers) placed at anatomical points, in accordance with the literature [17], to determine the position of the axis of the joint during the subsequent work on the recorded material. A black waterproof pen was used to mark the V toe and the V finger, and map the location of the centre of the ankle, knee, hip, shoulder, elbow, and radial-wrist joints.

Each participant was familiarized with the task they were to perform. After entering the water, on the whistle signal, the competitors began the trial. They submerged in front of the aluminium rod, accelerated until they reached their maximum velocity, and, using only the dolphin kick movement, covered the distance of 4.60 m (ca. 1 m below the water surface). Each participant performed 4 trials, between which 5 minutes of passive rest was applied.

Each trial was recorded with a Casio Exilim EX-FH25 digital camera (frequency, 120 frames/s; shutter, 1/200 s; aperture, 2.8; single frame size, 640 × 480 pixels). The camera was placed 7.95 m from the lane in which the participants swam (the third lane from the side wall of the pool), 0.96 m below the water level, and 8 m from the beginning of the swimming pool wall with starting blocks (Figure 1). The camera lens was directed perpendicularly to the direction of motion and could record more than 5-m distance of the lane in which the participants were swimming (Figure 1). As a result, each recording could register 3–5 full swimming cycles. 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 recording the underwater dolphin kicks of all the participants, a calibration frame was mounted on the lane. It was later used to scale the images. It was set horizontally against the water surface, in the middle of the registered area.

Data analysis

For the analysis, the SkillSpector computer program was used. The program is capable of providing kinematic data from the course of movement. Initially, a simplified body model was chosen in the programme, covering only the position of the transverse axis of the centre of the hip joints. On the basis of the point displacement in time, it was decided during which trial

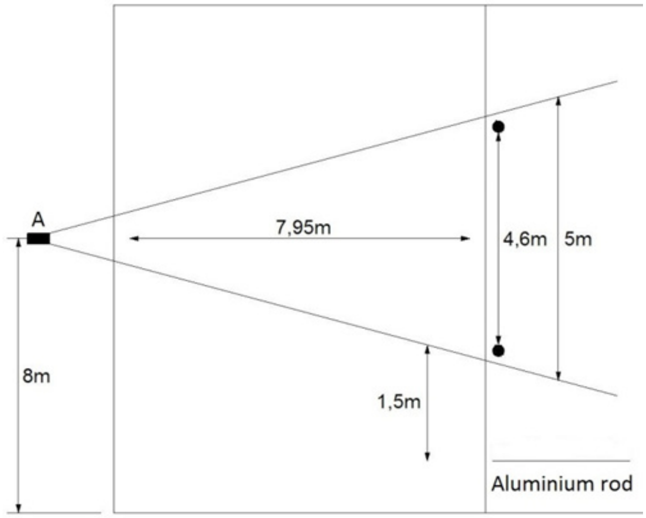

Figure 1. View of the measuring position on the lane in which the subjects moved (7.95 m) with the location of the camera (A) – in relation to the starting wall, the registered area (5 m), the maximum swimming speed area (4.6 m), and its distance from the rod (1.5 m)

the horizontal velocity of the centre of the transverse axis of the hip joints was the highest. The pen-marked points were mapped on the specially chosen footage; a 10-point model of the human body ('Full Body Left Side') was used, and the body was divided into 8 segments (foot, lower leg, thigh, torso, arm, forearm, hand, and head). Then, the points were marked on consecutive frames of the film footage, which was then calibrated. The process made it possible to determine the positions and velocities of the points marked with the pen in linear motion and the angular positions of selected joints (ankle, knee, hip, shoulder, elbow, and radial-wrist) in rotation in each frame of the footage. The study focused on describing the changes in the angle in the knee joints. The way to determine the angular value of knee joints is shown in Figure 2.

Data from the generated charts were exported to Microsoft Excel, in which we performed the appropriate calculations to determine the values of selected indicators (Table 2).

In the case of each variable, the normality of its distribution was analysed; basic descriptive statistical characteristics were also established. The direction and strength of the linear dependence between v_{COM} and other variables were calculated with the Pearson

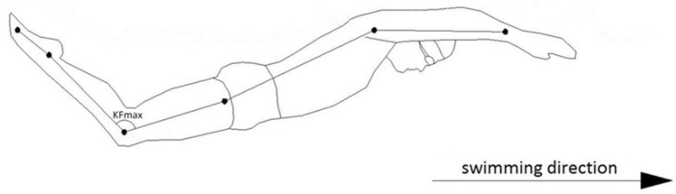

Figure 2. Scheme of determining flexion in the knee joints

Table 2. Names, symbols, and manners of determining selected indicators describing movement

Name (unit)	Symbol	Calculation method
Frequency of movements (Hz)	f	Number of complete movement cycles divided by their duration
Amplitude of toe movements (m)	A	Vertical distance between the highest and lowest position of the V toe
Relative amplitude of toe movement (n)	A_{REL}	$A_{REL} = A \cdot 100 / L_b$
Strouhal number (n)	St	$St = A \cdot f / v_{COM}$
Horizontal displacement of the centre of mass in a cycle (m)	D_{pk}	The quotient of the distance swum in the complete movement cycles divided by the number of cycles
Maximal flexion of the knee joints (rad)	KF_{max}	The arithmetic average of the maximal values of knee joints flexion in the analysed cycles
Indicator of movement amplitude and frequency (n)	I_{Af}	$I_{Af} = A \cdot f$

product-moment correlation coefficient (*r*). According to the literature [18], the threshold *r* values for weak, moderate, strong, and very strong correlations were ± 0.1, 0.3, 0.5, and 0.7, respectively. The 90% confidence limits of the correlation coefficient were calculated with the use of the Fisher *z* transformation.

Ethical approval

The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

Results

The calculation of coefficients of variation (*CV*) indicates that the variables were characterized by a low degree of value dispersion. Apart from the years of training (*CV* = 40%) and movement frequency (*CV* = 20%), the coefficient of variation for each variable was less than 20%. Data presented in Table 3 indicate that the v_{COM} in the study group equalled 1.08 m/s.

Table 3 also denotes the kinematic variables which showed correlations with the v_{COM} value. Among them, a very strong correlation coefficient was found for the indicator of amplitude and frequency (*r* = 0.72). It was also noted that the velocity of the centre of mass in the swimmers was moderately related to frequency of

Table 3. Statistical kinematic characteristics of the variables describing the movement course of the study participants

Variable	± SD	Correlation coefficient ± 90% Cl	*p*-Value
v_{COM}	1.08 ± 0.13 m/s	–	–
y	11.5 ± 1.00 years	0.25 ± 0.27	ns
H	1.57 ± 0.09 m	0.35 ± 0.25	0.039*
m	46.2 ± 9.0 kg	0.21 ± 0.27	ns
L_b	2.14 ± 0.13 m	0.24 ± 0.27	ns
pbt	34.50 ± 2.39 s	–0.52 ± 0.21	0.001*
y_t	2.5 ± 1.0	–0.01 ± 0.28	ns
f	2.00 ± 0.39 Hz	0.47 ± 0.23	0.004*
D_{pk}	0.58 ± 0.10 m	0.22 ± 0.27	ns
A	0.46 ± 0.08 m	0.02 ± 0.28	ns
I_{Af}	0.90 ± 0.11	0.72 ± 0.14	< 0.001*
KF_{max}	71.37 ± 9.15°	–0.53 ± 0.21	0.001*
St	0.83 ± 0.08	–0.36 ± 0.25	0.034*
A_{REL}	0.22 ± 0.04	–0.06 ± 0.28	ns

v_{COM} – average horizontal velocity of swimming, y – age, H – body height, m – body mass, L_b – body length with lifted arms, pbt – best result in 50-m freestyle, y_t – training experience, f – frequency of movements, D_{pk} – horizontal displacement of the centre of mass in a cycle, A – amplitude of toe movements, I_{Af} – indicator of movement amplitude and frequency, KF_{max} – maximal flexion of the knee joints, St – Strouhal number, A_{REL} – relative amplitude of toe movements
* $p < 0.05$; ns – not significant at $p = 0.05$

the dolphin kick movements ($r = 0.47$). During the statistical analysis, a negative correlation was also observed: with the angle of maximum flexion in the knee joints ($r = –0.53$) and with the value of the Strouhal number ($r = –0.36$). The correlation analysis also allowed to demonstrate moderate relationship between v_{COM} and body height ($r = 0.35$), as well as a strong correlation with the personal best in the 50-m freestyle ($r = –0.52$) (the smaller the time of the 50-m freestyle, the greater the values of velocity of underwater swimming).

Discussion

In the present study, the v_{COM} by using only underwater dolphin kicks was 1.08 m/s on average, which turns out very similar to that obtained by an adult recreational swimmer (1.07 m/s) [8] and only 0.06 m/s lower than that at the junior national level [19]. As expected, the velocity recorded in young swimmers was substantially lower than the value for the adult international swimmers (1.6–2.0 m/s) [8, 19]. The main reasons for the difference between adult and young swimmers is that the latter can generate less muscular power in the lower limbs, are smaller and so have a lesser propelling surface area, and possibly represent a less effective dolphin kick technique [20].

In a 25-meter pool, starts (dive, glide, and kicks phase) and turns (push, glide, and kicks phase) make up 30 m of a 50-m race distance. Swimmers with greater muscular power should be faster in the dolphin kick phase, in the swimming phase, and also in the dive and push-off phases. It explains the strong correlation between swimming underwater and personal records in the 50-m freestyle ($r = –0.52$) among young swimmers.

It is generally agreed that taller athletes swim faster because the wave resistance for long objects which slide over the water surface is lower than for short objects [1, 21, 22]. However, when swimming fully submerged, tall competitors lose this advantage because the main drag force is now frontal resistance, which depends on the fluid density, coefficient of form resistance, maximal cross-sectional area interacting with flowing water, and swimming velocity. This was confirmed in the present study by the moderate relationship between underwater swimming velocity and body height, and no relationship with body length.

Data obtained by Arellano et al. [19] and Sugimoto et al. [23] show that the frequency of underwater dolphin kicks has a great impact on the value of v_{COM}. In turn, Cohen et al. [24] proved that an increase in the velocity of underwater dolphin kicks is achieved by a raise in the frequency. The present study also confirmed this relationship ($r = 0.47$). The average observed frequency was 2 Hz and turned out about 15–20% lower than the values recorded in the studies by Arellano et al. [19], Gavilán et al. [11], and von Loebbecke et al. [25]. It can be assumed with a high degree of probability that the differences in the frequency of the propulsive movements resulted from variations in the subjects' proficiency. Obviously, the study was performed amongst young swimmers, and the results were compared in terms of frequency with those of adult athletes. It is worth noting at this point that the percentage differences in v_{COM} in comparative studies amounted to more than 50% and were significantly higher than the frequency differences. This proves the higher efficiency of movements performed by advanced swimmers. However, it seems to indicate that the frequency of underwater dolphin kicks has its optimal level, which is slightly higher than 2 Hz. Above this level, increasing the frequency does not translate into a raise in v_{COM}.

The results of the present study reveal that the amplitude value showed no tendency to form statistical relationships with the velocity of underwater swimming. This thesis is consistent with the conclusions of other studies [9, 19] showing that the amplitude does not affect v_{COM}.

A very strong correlation between underwater swimming velocity and the indicator of movement amplitude and frequency (I_{Af}) ($r = 0.72$), as well as a comparison with other studies [7, 8, 19] show that this indicator differentiates fast and slow underwater dolphin kickers. According to some authors, only the right combination of the amplitude of movements and their frequency allows to generate effective propulsion using the lower limbs [26].

In their study, Atkison and Nolte [8] did not show statistically significant relationships between v_{COM} and the frequency or amplitude of underwater dolphin kicks; however, their product was strongly correlated with the speed of underwater movement. The authors of the study mentioned came to the conclusion that I_{Af} was a good equivalent of the average vertical velocity of the foot, since it contains information about the distance between the highest and lowest position of the foot and the duration of the underwater dolphin kick cycle (the frequency is the inverted value of the cycle time). The I_{Af} value may therefore be useful in the kinematic analysis of underwater swimming for two reasons. Firstly, on its basis, one can evaluate the effectiveness of swimming. Secondly, it can replace the average vertical velocity of the feet, which is of great practical importance because it facilitates a significant reduction in processing the collected video footage time.

Arellano et al. [27] observed a clear and strong relationship between the velocity of underwater movement and the maximum angle of knee joints flexion (KF_{max}) during underwater dolphin kicks. It should be emphasized that the correlation of velocity and KF_{max} was negative ($r = -0.53$). In this aspect, the results of our study are fully supported by the cited work [27], although the relationship between these variables in the paper by Arellano was stronger ($r = -0.70$). It turns out that restricting the range of the knee motion during underwater swimming with the use of underwater dolphin kicks facilitates achieving higher swimming velocity. One possible reason for this relationship is indicated in the work by Willems et al. [12]. It was found that with decreasing plantar flexion of the foot, the area of the foot pointing towards the rear (with which the swimmer can interact with water) also decreases. Maglischo [2] points to that as well, proving that in this case, the force exerted on the water to the rear decreases, resulting in reduced velocity of swimming. That is why some swimmers perform larger knee flexion – to increase the area of propulsion. However, in turn, this leads to an increase in frontal resistance and decrease in swimming velocity. Therefore, the v_{COM} value is lower in athletes whose technique of dolphin kicks is characterized by excessive flexion of the knee joints.

The correlational analysis of the results of the present study did not reveal a significant relationship between the horizontal displacement of the centre of mass in one cycle (D_{pk}) and the underwater swimming speed (v_{COM}). This type of observation may be somewhat surprising in the context of the well-known relationship between kinematic motion indicators. However, the described observation finds its support in the data provided by Arellano et al. [27], who reported no relationship between D_{pk} and the v_{COM} with which junior swimmers moved while executing underwater dolphin kicks. The same research team also showed no correlation between D_{pk} and v_{COM} measurements in adult swimmers at the international level, which may suggest that this observation applies to most professional swimmers. This can constitute an incentive for further research, especially that the rate of D_{pk} in underwater dolphin kicking can be considered equivalent to the so-called swimming stroke length (SL) [28]. It is generally agreed upon that the greater the SL, the higher the efficiency of swimming [29]. However, only an optimal combination of SL and the frequency of movements allows for maximising v_{COM} [2, 30]. The presently analysed lack of connection between the displacement per kick and the velocity of underwater swimming, with a concurrent positive correlation between v_{COM} and frequency, indicates that the 'swimming rhythm' has a clear impact on the horizontal velocity of the centre of mass in swimming with the application of underwater dolphin kicks. Although the unduly extended cycle does increase D_{pk}, it simultaneously and substantially reduces the frequency of motion (as in swimming full strokes) [31]. Only determining the optimal level of the interdependence between D_{pk} and the frequency of underwater dolphin kick movements can lead to an increase in the value of v_{COM}.

According to Arellano et al. [27] and von Loebbecke et al. [25], the differentiating parameter for the efficiency of underwater swimming is the Strouhal number (St). As already mentioned, it is a dimensionless ratio combining the amplitude, frequency, and velocity of swimming. It is assumed that the lower the value of St, the greater the efficiency of swimming and the higher the swimming speed [10]. The relationship between St and sports proficiency is highlighted by Arellano et al. [27]. The St value remains within the range of 0.59–0.88 in humans [9] and of 0.25–0.35 among fish and dolphins [25]. In the present study, concerning young swimmers, the St amounted to an average of 0.83. This indicates relatively low efficiency of swimming, not only in comparison with fish and marine mammals, but also with adult swimmers. At the same time, attention should be paid not to reduce I_{Af} (denominator of the formula for Strouhal number calculation) while aiming at the St value decrease. The I_{Af} is strongly positively correlated with the velocity of swimming, which was strongly accentuated in the present study.

Conclusions

Young swimmers are characterized by a lower velocity of swimming with the use of underwater dolphin kicks when compared with adult competitors. The analysed element of the swimming technique in young swimmers was described by low values of the product of movement amplitude and frequency, large values of flexion at the knees, and high values of the Strouhal number. Young swimmers should pay attention to the normal rhythm of performing underwater dolphin kick movements, manifesting itself in the high values of the indicator of amplitude and frequency. It should be emphasized that the amplitude of movement should not be heightened by an increase in knee flexion. The underwater dolphin kick movement technique should be practiced, especially amongst short competitors.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

Authors state no conflict of interest.

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