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Biomechanics of diving: the influence of the swimming speed on the kinematics of lower limbs of professional divers

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Purpose: The aim of this study is to evaluate the influence of the swimming speed during diving on the biomechanical parameters describing the movement of selected measurement points of the lower limb in professional divers. *Methods:* The study involved a group of 4 professional divers whose movement was recorded during underwater swimming at slow (approx. 0.4 $\text{m} \cdot \text{s}^{-1}$), medium (approx. 0.5 $\text{m} \cdot \text{s}^{-1}$), and fast (approx. 0.8 $\text{m} \cdot \text{s}^{-1}$) pace. *Results:* During swimming at medium speed, the divers made a smaller displacement (along the axes *Y*) of the midpoint of fin than during swimming at fast speed. The range of motion in the ankle joint increased in fast speed in comparison with low and medium swimming speed. The same relationship was noted for the obtained velocity and angular acceleration in the hip, knee and ankle joints. The authors observed that during swimming at slow pace the divers choose movement ensuring high swimming comfort while the efficiency of motion is a secondary factor. On the other hand, during swimming at higher pace, the applied movement pattern ensures far greater efficiency rather than swimming comfort. *Conclusion:* The conducted analysis showed that divers adjust the movement of their lower limbs to the swimming pace.

Key words: *kinematics, underwater swimming, diving, fin swimming, swimming velocity*

1. Introduction

During movement in the aquatic environment there are four different forces acting on the human body: buoyant force (*B*), body weight (*W*), propulsive force (F_p), and hydrodynamic resistance (*D*) [1]. The ratio of these forces and their mutual relationships provide the ability to move underwater. Divers aim to achieve zero buoyancy which occurs when the *B* and the *W* balance each other. When the body remains motionless, it is primarily affected by the *B*. As the speed of movement increases so does the force of resistance to motion, becoming the most important force acting on the body [7], [12]. Thanks to the ability to control the position of the body, the diver can reduce the impact of the force by putting the body in horizontal position and swimming at slow pace (drag increases with swimming speed). The relationship between the force of motion resistance and the swimming speed in diving has been derived by Pendergast et al. [14] and described with an Eq. (1).

$$D = 115.7 \cdot V^{1.57} \tag{1}$$

In diving, *D* is a component of viscous resistance (dependent on the surface of the submerged body) and form resistance (associated with the shape of the submerged body) [6]. Movement occurs when the F_p of the diver is large enough to overcome the resistance to their motion. The best performance during diving can be defined as swimming at pace that ensures efficient movement of the lower limb (biggest possible F_p) without excessive fatigue and energy expenditure [9], [11]. The value of the forces acting on the diver can also be shaped by selection of the appropriate equipment.

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Diving equipment not only enables the diver to stay underwater but also allows to adjust the ratio of the respective forces acting on his body. In order to enable submersion (overcome the B of the body), diving ballast is used, i.e., additional load that increases the weight of the diver. On the other hand, buoyancy control devices (BCD's) are used to increase the B. The amount of air that they hold can be regulated. This makes it possible to adjust the buoyant force to obtain neutral, positive and negative buoyancy. The use of BCD's also increases form resistance. In order to reduce hydrodynamic resistance, highly hydrophobic coatings can be used on fins and diving suits, which decreases viscous resistance [6]. In addition, appropriate distribution of ballast, so-called trimming, allows the diver to maintain a horizontal position, which significantly reduces the front area of the diver, thus decreasing motion resistance [16].

Fins are an element of the gear that facilitates movement in aquatic environment. As shown by Zamparo et al., fins increase the efficiency of the propulsive force during locomotion by improving the swimming economy, whereas the propulsive force is generated by the muscles of the lower limbs of the diver. The propulsive force depends on the frequency of movements made by the diver and the kinematics of movement of the lower limbs, which reflects the swimming technique used by the diver. The use of fins during swimming reduces energy expenditure by about 40% and increases the swimming speed by about $0.2 \text{ m} \cdot \text{s}^{-1}$ compared to swimming without fins while metabolic cost is kept constant [18]. Improved swimming efficiency resulting from the use of fins depends on the shape of the fin itself and the mechanical properties of the particular fin material (stiffness).

Research related to the diving usually concerns the effect of different models of fins on the swimming economy and the measurements of the activity of the individual muscles of the lower limb [8]. Pendergast et al. have shown that long and stiff fins provide greater propulsive force but their use is associated with a large energy expenditure [13]. According to Marion et al., muscle activity during swimming is influenced by the size of the fin blade, but no significant differences were noticed in muscle activity for different amounts of fin stiffness. In addition, the study results show that during swimming at higher frequency muscle activity increases. On the other hand, no such relationship was found for different amplitudes of movement of the lower limbs [8]. Numerous authors have shown that kinematics of movement of the lower limb of divers depends on the fin model used [8], [18].

Sports technique is a set of movement activities, taking place in an orderly manner and subordinated to biomechanical principles, used to exploit the motor and structural potential of man [2], [3], [8], [13]. Biomechanical evaluations of the effectiveness of the diving technique in terms of kinematic analysis of selected measurement points of the lower limb of professional divers seem to be a very important element enriching the training process of both novice divers and experienced divers who want to improve their diving technique. Appropriate swimming technique also reduces energy demand, oxygen consumption, and fatigue during diving, which results in more pleasant, longer and, most importantly, safer diving [17].

The aim of this study is to determine the biomechanical parameters in terms of kinematic analysis of the elements taking part in each movement cycle of the lower limb of profession divers during swimming at variable speeds.

2. Materials and methods

2.1. Participants

The study group consisted of 4 professional divers (Master Scuba Diver Trainers, PADI), comprising

Table 1. Divers' anthropometric data, total weight with equipment and additional weight

Diver	Sex (–)	Age (years)	Height (cm)	Subjects weight		
				Weight (kg)	Weight with equipment (kg)	Additional weight (kg)
F1	Female	22	160	61.9	85.7	4
F2	Female	33	172	56.7	90.9	4
M1	Male	22	170	66.1	95.1	6
M2	Male	35	190	103.0	132.0	6
	Mean	28	173	71.9	100.9	5
	SD	7	12	21.1	21.1	1.2

SD – standard deviation.

2 women and 2 men. All participants had extensive diving experience, including at least 5 years of training and 300 logged dives. The average age of the divers was 28 ± 7 years, the average height was 173 ± 12 cm, and the average weight was 71.9 ± 21.1 kg (Table 1).

During the study, the divers used diving equipment consisting of: a 10 litre steel scuba tank (Faber, Italy), regulator with pressure gauge, BCD, 3 mm neoprene wet suit, mask and fins (Aqualung, USA). Additionally, the divers descended with the help of a diving weighing system with the average weight of 5 ± 1.2 kg, which had no effect on the kinematics of diving. The study used Express fins in three sizes fitting the foot sizes of the divers (Table 2).

Table 2. Physical characteristics of the fins (Aqualung Express)

Fin size	Fin characteristics			
	length [m]	width[1] [m]	width[2] [m]	surface area [m^2]
36/37	0.60	0.24	0.17	0.072
42/43	0.67	0.25	0.19	0.085
44/45	0.71	0.27	0.20	0.097

Fin length measured from the feet to the end of blade; fin width[1] measured at the end of blades, fin width[2] measured under the foot pocket.

2.2. Methods

The studies were conducted on two lanes of a swimming pool with a maximum depth of 1.9 m, the length of 25 m, and the lane width of 2.25 m (Fig. 1). The divers being tested were swimming along one of the tracks, while a camera (Sony HDR-cx550, Japan) set on the other lane recorded their movement at a rate of 25 frames per second. The camera was inside an underwater housing additionally fitted with lighting (GRALmarine, Poland). The local ethics committee approved the protocol of study.

Measurement of movement of the divers was recorded during three assigned swimming speeds, defined as slow, medium, and fast underwater swimming speed of the diver (the subjects themselves chose the swimming speed). Initially, the subjects were swimming at slow pace. Then, when swimming another length of the pool, they increased their pace so that it matched their medium and fast underwater speed, successively. Slow speed represented the movement of divers during recreational diving, while medium speed represented the speed at which the diver could swim without excessive fatigue. Finally, fast speed represented the fastest possible swimming speed of the diver. Movement was recorded twice (over the course of two training sessions) for each of the assigned speeds.

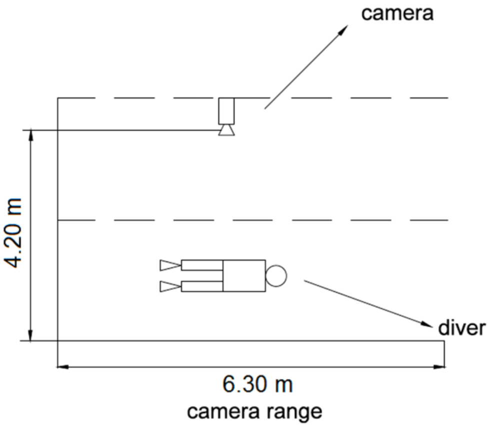

Fig. 1. Schematic representation of the measuring system

2.3. Kinematic analysis

A kinematic analysis was performed for five selected anatomical points (in the sagittal plane) located on the lower limb of the diver and on the fin, at the level of: 0 – centre of the hip joint, 1 – centre of the knee joint, 2 – centre of the ankle joint, 3 – half the fin length, and 4 – end of fin blade (Fig. 2). Before testing, the analysed sites were marked on the left side of the body of the subjects with markers. The films obtained during the performed testing were processed in iMovie (Apple Inc., USA), to generate freeze frames (25 fps) illustrating the various stages of the performed movement.

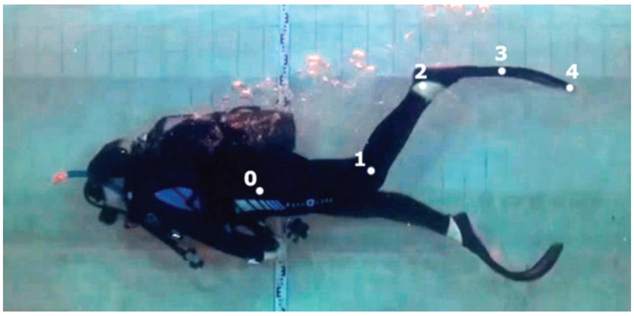

Fig. 2. Anatomical landmarks selected for kinematic analysis: 0 – hip, 1 – knee, 2 – ankle, 3 – midpoint of fin, 4 – end of fin

The obtained results were used to analyse the movement trajectory of the examined points. Describing the kinematics of movement of the lower limbs during diving with the use of fins 14 parameters were determined [5]. These are: swimming speed V

($m \cdot s^{-1}$); displacement range of the examined points along the axes Y-RoD_1, RoD_2, RoD_3, RoD_4 (m); range of movement in the hip joint RoM_{hip}, knee joint RoM_{knee}, and ankle joint RoM_{ankle} (°); angular velocity AV_{hip}, AV_{knee}, AV_{ankle} ($° \cdot s^{-1}$); and angular acceleration AA_{hip}, AA_{knee}, AA_{ankle} ($° \cdot s^{-2}$) performed in the hip, knee, and ankle joints.

The recorded curves allowed to calculate the average speed of displacement of the divers underwater during swimming at three speeds. V was calculated as the difference in the horizontal component of the displacement of the diver in relation to the time required to cover the measuring section.

The data on displacement of individual points (marker positions on the horizontal and vertical axes) were analysed with the MATLAB R2015a (The MathWorks, USA), using the sum of 5 sines in accordance with the formula (2).

$$Y = A \cdot \sin(2 \cdot \pi \cdot \Phi \cdot t + d) \tag{2}$$

where: A – amplitude, Φ – phase, d – displacement, and t – time. The smoothed angular displacement data were used to calculate the maximum and minimum angles obtained in the analysed joints, with the range of motion in the joints constituting the difference between those angles (the measured angles representing movement in the respective joints are shown in Fig. 3). Using our own original program, we calculated the first two derivatives of displacements of the examined points, which allowed us to obtain the values of velocity and angular acceleration in the hip, knee, and ankle joints.

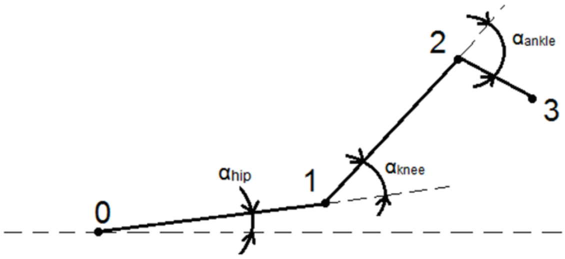

Fig. 3. Diagram showing angles representing movement in the respective joints. The diagram shows distinctive points (0–3, see Fig. 2) and measured angles in the joints of: α_{hip} – the hip, α_{knee} – the knee, and α_{ankle} – the ankle. The horizontal dashed line shows the line determined by the torso of the diver

2.4. Statistics

The results obtained in this study were statistically analysed (Statistica 10, StatSoft, Inc., USA). The results of the performed swimming velocities were compared statistically using one-way analysis of variance (ANOVA) with a Turkey post-hoc test. We analysed the differences in the values of the obtained parameters between the speeds of 0.38 $m \cdot s^{-1}$ and 0.49 $m \cdot s^{-1}$, 0.38 $m \cdot s^{-1}$ and 0.81 $m \cdot s^{-1}$, as well as between 0.49 $m \cdot s^{-1}$ and 0.81 $m \cdot s^{-1}$. This analysis was performed at statistically significant level of $p < 0.05$.

3. Results

3.1. Velocity

In the case of slow swimming pace, the average V was 0.38 ± 0.02 $m \cdot s^{-1}$ ($V_{0.38}$) while in the case of medium pace the obtained velocity was greater by 30%, i.e., 0.49 ± 0.02 $m \cdot s^{-1}$ ($V_{0.49}$, $p < 0.001$). Finally, during swimming at a fast pace, the divers achieved the average V of 0.81 ± 0.04 $m \cdot s^{-1}$ ($V_{0.81}$), representing a 65% increase in the swimming speed compared to the medium pace ($p < 0.001$).

3.2. Trajectory of the examined points and range of displacement

The trajectory of movement of the respective points depending on the swimming speed was analysed. Figure 4 shows trajectories of movement of the knee and the ankle during one cycle of movement of the lower limb. Analysis of the presented graphs revealed the biggest difference between the subjects in the displacement values of the obtained trajectories during swimming at a speed of $V_{0.49}$.

The mean values of the range of displacement (*RoD)* of all analysed points and the range of motion (*RoM)* in the hip, knee and ankle joints are shown in detail in Table 3.

The conducted measurements have shown that during swimming at $V_{0.49}$ (medium pace) the divers swim with smaller depth of kick than in the case of fast paces. The RoD_1 (Fig. 2) during swimming at $V_{0.49}$ averaged 0.34 m. In the case of swimming speeds of $V_{0.38}$ and $V_{0.81}$, the same value of 0.36 m was obtained. The above trend was maintained for each of the examined points. The values of displacements obtained for the slow and fast swimming paces are very similar (the maximum difference was 8%, point 3). In the case of RoD_2 and RoD_3, the greatest displacement was observed at a swimming speed of $V_{0.81}$, while in the case of RoD_4, the greatest displacement, averaging 0.94 m, was obtained at $V_{0.38}$. Statistically significant differences were only observed for the displacement made by point 3, between the speed $V_{0.49}$ and $V_{0.81}$ ($p = 0.0151$).

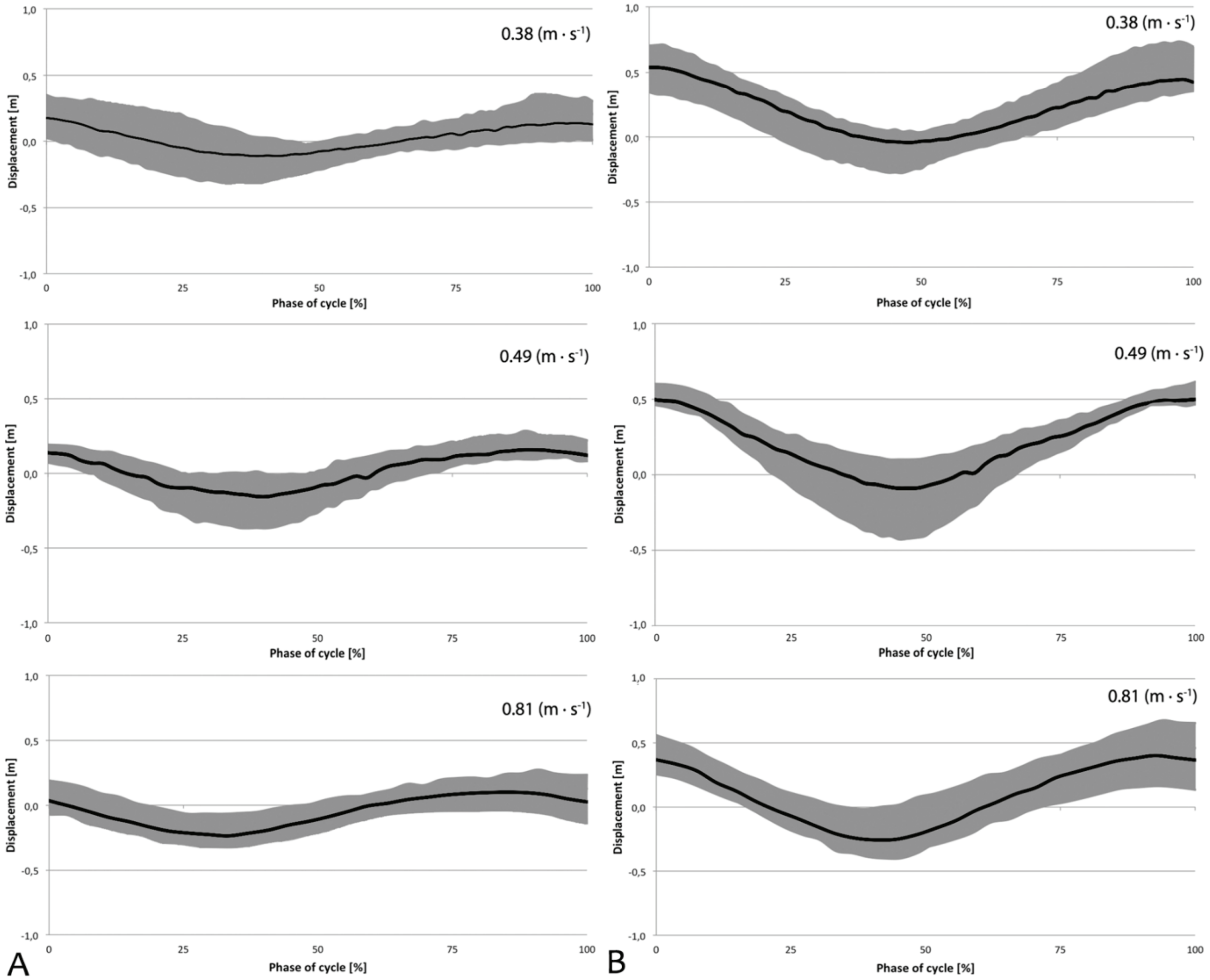

Fig. 4. The trajectories of movement of the selected anatomical points during three swimming speeds for one cycle of movement of the lower limb: a) point 1; b) point 2 (acc. to Fig. 2). The bold black line on the graphs shows the averaged movement trajectory, while the grey area shows the range of values obtained for subjects

Table 3. Displacement range of the examined points (*RoD*) and range of flexion (*RoM*) in the hip, knee, and ankle joints during three swimming speeds

	Velocity (m · s^{-1})						ANOVA
	0.38		0.49		0.81		
	Mean	SD	Mean	SD	Mean	SD	
RoD_1 (m)	0.36	0.09	0.34	0.10	0.36	0.05	n.a.
RoD_2 (m)	0.66	0.12	0.61	0.16	0.68	0.09	n.a.
RoD_3 (m)	0.83	0.16	0.71	0.10	0.90	0.10	0.0195*
RoD_4 (m)	0.94	0.16	0.85	0.21	0.92	0.10	n.a.
RoM_{hip} (°)	39	9	40	12	42	7	n.a.
RoM_{knee} (°)	57	17	61	21	63	14	n.a.
RoM_{ankle} (°)	68	17	68	18	100	24	0.0044*,†

SD, standard deviation; ANOVA, statistical hypothesis test; n.a. – no applicable difference; * – statistical significance 0.49 vs. 0.81 m· s^{-1}; † – statistical significance 0.38 vs. 0.81 m· s^{-1}.

3.3. Range of motion

The RoM_{hip} analysis showed similar values for all swimming speeds, with a slight increase in the RoM corresponding to an increase in the swimming speed, reaching the values of 39°, 40°, and 42° for the speeds of $V_{0.38}$, $V_{0.49}$ and $V_{0.81}$, respectively. At the same time, the increase in speed was accompanied by a slight increase in the RoM of the knee and ankle joints of the subjects. RoM_{knee} increases from 57° at $V_{0.38}$ to 63° at $V_{0.81}$. The biggest increase in the RoM between the analysed velocities was observed for the ankle joint. RoM_{ankle} amounted to 68° for both slow and medium paces and 100° for fast pace ($p < 0.005$). Statistically significant differences for RoM_{ankle} were observed between the speed of $V_{0.49}$ and $V_{0.81}$ ($p = 0.0098$), as well as $V_{0.38}$ and $V_{0.81}$ ($p = 0.0100$).

3.4. Velocity and angular acceleration

The mean values of maximum angular velocity (*AV*) and maximum angular acceleration (*AA*) achieved in the hip, knee, and ankle joints are shown in Table 4.

Based on the obtained results, it was observed that *AV* increased for all analysed joints in parallel with an increase in the swimming speed ($p < 0.0001$ for each analysed joint). In addition, we observed that the measured values increased as the distance increased between the measuring points and the hip joint. In the case of AV_{hip}, values of,72° · s^{-1} at $V_{0.38}$, 89° · s^{-1} at $V_{0.49}$ (23% increase), and 171° · s^{-1} at a speed of $V_{0.81}$ (a 92% increase compared to $V_{0.49}$, $p < 0.0001$ and a 138% increase, respectively, were obtained compared to $V_{0.38}$, $p < 0.0001$). For AV_{knee}, the increase in speed provided the values of, respectively, 123°· s^{-1}, 157° · s^{-1} (a 28% increase), and 308° · s^{-1} (a 97% increase compared to $V_{0.49}$, $p < 0.0001$ and a 150% increase compared to $V_{0.38}$, $p < 0.0001$). The highest values of *AV* were observed in the ankle joint of the subjects. The obtained values were, respectively, 170° · s^{-1} at $V_{0.38}$, 189° · s^{-1} at a speed of $V_{0.49}$ (a 12% increase), and 630° · s^{-1} at a speed $V_{0.81}$ (a 233% increase compared to $V_{0.49}$, $p < 0.0001$ and a 271% increase compared to $V_{0.38}$, $p < 0.0001$).

Analysis of *AA* obtained in the hip, knee, and ankle joints showed a similar upward trend relative to the increase in the swimming speed. Namely, an increase in *V* was accompanied by an increase in *AA* of the respective joints. There was an observable increase in acceleration in the hip and knee joints between the $V_{0.38}$ and $V_{0.49}$, with the respective increases of 85% in AA_{hip} and 29% in AA_{knee}, as well as between the $V_{0.49}$ and $V_{0.81}$, which showed a 210% increase in AA_{hip} ($p = 0.0036$) and a 359% increase in AA_{knee} ($p < 0.0001$). An exception to the above trend is AA_{ankle}. Here, during swimming at medium pace, there was a small, 16% decrease in acceleration relative to a $V_{0.38}$ and a 310% increase in acceleration between $V_{0.49}$ and $V_{0.81}$ ($p < 0.0001$).

Table 4. The obtained values of angular velocity (*AV*) and angular acceleration (*AA*) achieved in the hip, knee, and ankle joints during three swimming paces

	Velocity (m · s^{-1})						ANOVA
	0.38		0.49		0.81		
	Mean	SD	Mean	SD	Mean	SD	
AV_{hip} [° · s^{-1}]	72.33	23.59	88.71	20.50	171,40	38,78	<0.0001*,†
AV_{knee} [° · s^{-1}]	122.84	38.12	156.80	41.59	308,47	57,04	<0.0001*,†
AV_{ankle} [° · s^{-1}]	169.56	15.68	189.29	71.27	629.78	66.97	<0.0001*,†
AA_{hip} [° · s^{-2}]	520.97	222.06	964.44	587.83	2993.15	1732.04	0.0005*,†
AA_{knee} [° · s^{-2}]	1097.84	653.02	1418.35	626.20	6506.61	2041.09	<0.0001*,†
AA_{ankle} [° · s^{-2}]	2758.32	1824.76	2308.07	919.33	9466.79	2654.08	<0.0001*,†

SD – standard deviation; ANOVA – statistical hypothesis test; n.a. – no applicable difference; * – statistical significance 0.49 vs. 0.81 m· s^{-1}; † – statistical significance 0.38 vs. 0.81 m· s^{-1}.

4. Discussion

The aim of the present study was to assess the influence of the swimming speed on the kinematics of the lower limbs of professional divers during underwater scuba diving (range of 0.3 to 0.8 $\mathrm{m \cdot s^{-1}}$). We evaluated movement of distinctive points located on the lower limb of the divers as well as on the fins used by them.

A very important element of the research in the aquatic environment is the use of an appropriate test protocol. Connaboy et al. drew attention to the importance of selecting an appropriate number of recorded swimming tests during one training session due to the occurrence of errors arising from swimmer fatigue [4]. The authors recommend performance of 4–5 swimming tests during one training session of swimmers using undulating movements. Given the fact that divers are subjected to greater resistance forces compared to swimmers and they get tired quicker, the authors of this study decided to split the training sessions into two parts. Both sessions were conducted on the same day with an interval of 30 minutes. As a result, the applied test protocol eliminated the effect of fatigue of the divers, which could change the kinematics of movement of the lower limbs during successive tests. In addition, it eliminated the phenomenon of a "memorised movement pattern", which would probably be formed during multiple tests carried out one after another without interruption.

The hip joint and the knee joint are the most important places from the point of view of biomechanics of diving, providing the ability to generate the propulsive force, whose movement depends mostly on the swimming technique. Trajectories of the points located on the fins of the participants depend on the fin design and its mechanical properties. Movement of the fins, in turn, determines the range of motion in the ankle joint of the divers. Based on the Lighthill model and the conducted research, Samimy et al. described the most effective method of underwater swimming with fins. The researchers proved that movement should be generated in the hip joint, with a small range of motion performed in the knee and ankle joints. The use of such kicking technique ensures that the fin blade moves perpendicularly to the water surface, generating a greater propulsive force. In addition, Samimy et al. believe that divers having weak muscles around the hip joint and the muscle supporting the thigh in the proper position will not be able to obtain such motion path of the fin because those muscles will become overloaded, causing thigh rotation and a change in the displacement path of the fin [15]. In such case the fin will not move perpendicularly to the water surface, but will cut through water at an angle which is less efficient in terms of energy expenditure and propulsion. In our study the obtained displacement trajectories of the points located on the fins showed the greatest similarity of behaviour of the end of the fin blade to the diagram described by Samimy et al., in the case of swimming at a speed of about 0.8 $\mathrm{m \cdot s^{-1}}$. However, the obtained movement was not perfectly perpendicular, as the fin end cut through the water at about 45°. However, according to the authors of this study, such position of the fin blade is not due to weak muscles of the lower limbs of the examined divers but is dependent on the design of the used fins, which makes it impossible to obtain the presented path of motion. The trajectory presented by Samimy et al. cannot be obtained for all types of fins, particularly in the case of stiff fins or fins strengthened with side ribs, so as effective the technique described by Samimy et al. is, it is not appropriate for every type of fins. Therefore, due to the fin model used in our study, the obtained trajectory of fin movement could not be perfectly perpendicular to the water surface during displacement of the lower limb toward the bottom of the pool.

In the case of slower speeds divers chose the movement pattern that gave them greater swimming comfort rather than greater efficiency. During diving, the subjects usually use dry suits, which force a different movement of the lower limb than the commonly tested flutter kick. Swimming with the use of the flutter kick is difficult to achieve when wearing a dry suit because it significantly restricts the movements of the divers. The swimming action used in this case, also commonly used by technical divers, is called the frog kick [10]. Frog kick is characterized by a horizontal position of the trunk and the thighs, with approximately 90° flexion of the knee joint and a similar flexion in the ankle joint, where the movement is generated by a twist of the ankle combined with an extension of the lower limbs. Swimming with the technique presented above resulted in generation of a locomotor pattern in the examined divers, whose impact was observed in swimming with the flutter kick in our study.

The influence of the developed motor habits manifested itself by increased range of flexion performed in both knee and ankle joints and decreased movement in the hip joint at swimming speeds up to 0.5 $\mathrm{m \cdot s^{-1}}$ compared to the data acquired by Samimy et al. [15]. In our study, authors obtained a 39° range of motion in the hip joint of the divers compared to 54° obtained by Samimy et al. The relationships between the obtained values in the knee and ankle joints amounted to, respectively, 57° compared to 25° and 68° compared to 20°. However, during swimming at a speed of about 0.8 m $\cdot$ s^{-1} all examined divers changed the performed range of motion in the examined joints, adjusting it so as to obtain higher swimming speed without excessive fatigue. At such times the movement was characterized by greater range of motion in the hip joint (42°), knee joint (63°), and ankle joint (100°). The range of motion in the hip joint at a speed of 0.8 m $\cdot$ s^{-1} refers to the locomotor pattern required to achieve the best efficiency during swimming with the flutter kick, described by Samimy et al. [15]. On the other hand, the range of motion in the knee joint is about 2.5 bigger and motion in the ankle joint is 5 times greater in relation to the data obtained by Samimy. The authors of this study believe that the increased range of motion in the knee joint is due to the above-mentioned motor habit associated with the use of a different swimming technique during diving than during the conducted tests. The presence of a motor habit can be observed in actively diving professional divers, such as the examined group, who dive with a high frequency. On the other hand, such steep increase in the range of motion in the ankle joint may be caused by use of other fin models which are characterized by a different path of motion, forcing a greater range of motion in the analysed joint.

Our study showed that movements performed by the lower limb of divers are characterised by the greatest range of displacements of the examined points (Y axis) during swimming at slow and fast paces. By contrast, for the medium pace, i.e., a swimming speed of about 0.5 m $\cdot$ s^{-1}, the range of displacement is smaller on average by 9% compared to a speed of 0.38 m $\cdot$ s^{-1} and by 10% compared to a speed of 0.81 m $\cdot$ s^{-1}. The obtained relationship is consistent with the results presented by Zamparo et al. [18], in which the average value of the kick depth increased in line with the increase in the swimming speed in the range of 0.6–1.0 m $\cdot$ s^{-1}. However, the values of kick depth obtained by us are almost twice higher than the results obtained by Zamparo and amount to, respectively, 0.68 m compared to 0.34 m at a swimming speed of 0.8 m $\cdot$ s^{-1}.

5. Conclusion

Our study has demonstrated that the kinematics of motion of the lower limbs of professional divers changes depending on the swimming speed. We had found differences between analysed velocities in the range of displacement of the midpoint of fin and range of flexion in the ankle joint. Moreover, both angular velocities and angular accelerations for all analysed joints differ significantly between the swimming speeds. During swimming at a speed of up to 0.5 m $\cdot$ s^{-1} divers perform movement ensuring greater swimming comfort in place of efficiency. By contrast, the situation is reversed at a swimming speed of about 0.8 m $\cdot$ s^{-1}. Then, due to greater energy demand associated with high resistance acting on the body of the divers, the movement performed by the lower limbs is intended to provide the highest efficiency.

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References

[1] ABBOTT A., BROOKS A., WILSON D., *Human powered watercrafts*, [in:] A. Abbott, D. Wilson (Eds.), *Human-Powered Vehicles*, Human Kinetics Pub, 1995, 47–92.

[2] BOBBERT M.F., HUIJING P.A., SCHENAU G.J.V., *Drop jumping 1. The influence of jumping technique on the biomechanics of jumping*, Med. Sci. Sports Exerc., 1987, 19(4), 332–338.

[3] BOBBERT M.F., HUIJING P.A., SCHENAU G.J.V., *Drop jumping 2. The influence of dropping height on the biomechanics of drop jumping*, Med. Sci. Sports Exerc., 1987, 19(4), 339–346.

[4] CONNABOY C., COLEMAN S., MOIR G., SANDERS R., *Measures of Reliability in the Kinematics of Maximal Undulatory Underwater Swimming*, Med. Sci. Sports Exerc., 2010, 42(4), 762–770.

[5] CONNABOY C., NAEMI R., BROWN S., PSYCHARAKIS S., MCCABE C., COLEMAN S., SANDERS R., *The key kinematic determinants of undulatory underwater swimming at maximal velocit*, Journal of Sport Sciences, 2015, 1–8.

[6] GRIMSHAW P., LEES A., FOWLER N., BURDEN A., *Instant Notes Sports and Exercise Biomechanics*, Garland Science Taylor and Francis Group, 2006.

[7] LI T.Z., ZHAN J.M., *Hydrodynamic body shape analysis and their impact on swimming performance*, Acta Bioeng, Biomech, 2015, 17(4), 3–11.

[8] MARION K., GUILLAUME G., PASCALE C., CHARLIE B., ANTON S., *Muscle activity during fin swimming*, Procedia Eng., 2010, 2, 3029–3034.

[9] MASON B., COSSOR J., *What can we learn from competition analysis at the 1999 Pan Pacific Swimming Championships?*, Paper presented at the XVIII International Symposium on Biomechanics in Sports, Hong Kong, China, 2000.

[10] MOUNT T., *Tech, as in technique*, Sport Diver, 1997, 5(3), 18–20.

[11] PENDERGAST D.R., MOLLENDORF J., LOGUE C., SAMIMY S., *Evaluation of fins used in underwater swimming*, Undersea Hyperb. Med., 2003a, 10(1), 55–71.

[12] PENDERGAST D.R., MOON R., KRASNEY J., HELD H., ZAMPARO P., *Human Physiology in an Aquatic Environment*, Compr. Physiol., 2015, 5, 1705–1750.

[13] PENDERGAST D.R., TEDESCO M., NAWROCKI D.M., FISHER N.M., *Energetics of underwater swimming with SCUB*, Med. Sci. Sports. Exerc., 1996, 28(5), 573–580, DOI: 10.1097/00005768-199605000-00006.

[14] PENDERGAST D.R., ZAMPARO P., DI PRAMPERO P.E., CAPELLI C., CERRETELLI P., TERMIN A., CRAIG A., BUSHNELL D., PASCHKE D., MOLLENDORF J., *Energy balance of human locomotion in water*, Eur. J. Appl. Physiol., 2003b, 90(3–4), 377–386.

[15] SAMIMY S., MOLLENDORF J.C., PENDERGAST D.R., *A theoretical and experimental analysis of diver technique in underwater fin swimming*, Sports Eng., 2005, 8(1), 27–38.

[16] TAYLOR L., *Diving Physics*, [in:] A. Bove, J. Davis (Eds.), *Bove and Davis' diving medicine*, 4th ed., Elsevier, 2003, 11–35.

[17] WOJTKÓW M., NIKODEM A., *Analiza kinematyki kończyny dolnej nurka*, Paper presented at the X Sympozjum *Analiza ruchu – teoria i praktyka w zastosowaniach klinicznych*, Warsaw, Poland, 2015, (in Polish).

[18] ZAMPARO P., PENDERGAST D.R., TERMIN B., MINETTI A.E., *How fins affect the economy and efficiency of human swimming*, J. Exp. Biol., 2002, 205(17), 2665–2676.