

Experimental analysis of diving fins energy efficiency using hydrodynamic modelling

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ABSTRACT

This study presents a research methodology and test setup to analyze different types of recreational fins for specific tasks: beginner recreational swimming, deep-water diving, and sports swimming. The fins tested were Aqualung, Scubapro, and Exotech. The primary goal is to present the diving fins research methodology, experimental results, and conclusions. The study achieves high reliability in real-world conditions by combining experimental design with mathematical models based on hydrodynamic similarity. Key to this approach is conducting methodologically sound experiments on a controllable object, allowing precise energy measurements of the swimmer's leg. Despite the challenges posed by the variable thrust force of diving fins in different leg positions, this method remains the most reliable way to integrate experimental data with hydrodynamic theories in comprehensive, multivariate research. Presented results show that fin energy efficiency strongly depends on the interaction between fin geometry, flexural stiffness, and swimming style, with different fin designs achieving maximum efficiency under different operating conditions

Keywords: fins, efficiency, modelling, tests.

INTRODUCTION

Diving fins differ in geometry, the size of the active surface and the mechanical properties of the material from which they are made. Another factor that influences the rating of fins is how they are used. In the first approach to assessing fins, fins with the same active working surface could be compared for the same swimming style [1]. However, such a task is challenging because, depending on the fin type, the surfaces of the fins for the same foot size are significantly different [2].

Another criterion could be to compare the driving force generated by the fins, assuming the leg manipulator moves at the same frequency and deflection [3]. However, this would mean adopting the hypothesis that the fins should have only one task and one progressive speed of the swimmer's movement. The same conclusion can be made if we used different fins by one swimmer

and assessed their effectiveness based on a speed test over a distance of, for example, 50 meters. The initial analysis of these considerations indicates that efficiency for a specific fin application should be considered using the criterion of hydrodynamic similarity and energy efficiency.

Research was also conducted to determine fins performance [4] as a function of the diver's performance characteristics [5]. However, such tests are subject to errors resulting from changes in the diver's health and physiological condition, which are difficult to measure.

Numerical studies of fluid-structure interactions and thrust force generation by a skeleton-reinforced fin were conducted by Shoele and Zhu [6]. The fin undergoes a combination of flapping (lift-based) and paddling (drag-based) movements typical of labriform swimming. In the tests, the thruster movement included two strokes:

recovery and power types. The authors noted that the ray at the leading edge plays a key role in improving performance by reducing the effective angle of attack and reducing power expenditure during the recovery stroke.

Interesting research related to the relationship between changes in swimming movement and the resulting changes in flow field due to changes in test flow velocity in a water flume was conducted by the authors of the publication [7]. Research using similar methods was also conducted by the authors of the publication [8]. In this, the focus was on the visualization of the three-dimensional (3D) flow field in the wake region during human tests in a water flume. In both publications, in order to achieve the assumed goal, the authors used the PIV (particle image velocimetry) method. While both publications deal with research using human swimmers, the publication [9] used the same research methods on a slightly modified stand, but the object of the research was a robotic arm. The authors of the publication [10] have a different approach to constructing a stand to examine a swimmer's anatomical limitations. They examined the kinematics of two female swimmers while swimming in a still-water pool. Also, the flow around and behind the swimmers was measured using the PIV method.

Authors of the publication [11] prepared a test stand called HERMES. According to their declarations, it enables the acquisition of dynamic measurements at the ankle joint during an adjustable, standardised and reproducible fin-swimming motion. The test stand is equipped with two cameras. The article presents initial results in which we may find a conclusion that the stiffest fin induced the highest force at the ankle joint. The presented test stand and measuring procedure are completely different from those presented in this article. Similar results were obtained by authors of [1]. The authors conducted research on the subjective feelings of 10 divers diving in the same conditions (depth and distance) wearing fins of different stiffness. Theoretical calculations of the possible pressure for various types of tested fins were also performed. According to diverse opinions, the stiff fins are the best and the flexible fins are the worst, which did not correlate with the conducted theoretical evaluation of these fins. Interesting research in the area directly related to the subject of the article was presented by the

authors of the publication [12], where detailed studies of the fin-driven biomimetic artificial fish were conducted.

Based on the reviewed literature, methods used for fin performance evaluation can be classified into four main groups: experimental studies involving human swimmers, laboratory investigations using robotic or mechanical manipulators, numerical analyses of fluid–structure interaction, and subjective or physiological assessments.

Human-based experiments reflect real swimming conditions but are affected by limited repeatability and high variability resulting from individual physiological factors and swimming technique. Subjective assessments, although important from the user perspective, do not allow direct correlation with hydrodynamic performance. Numerical studies provide detailed insight into flow structures and thrust generation; however, they rely on simplifying assumptions that limit their applicability to real fins operating under unsteady conditions. Robotic and manipulator-based approaches improve experimental repeatability, yet many existing studies focus primarily on thrust generation or kinematics, without directly addressing energy efficiency under hydrodynamically similar flow conditions. In particular, the combined use of hydrodynamic similarity criteria and energy-based performance measures is rarely reported in the literature.

Therefore, a research gap exists in experimental methodologies that enable objective comparison of fins with different geometry, stiffness, and operating regimes while ensuring kinematic repeatability and hydrodynamic similarity. The present study addresses this gap by applying an energy-based efficiency criterion supported by hydrodynamic similarity principles, implemented using a controllable leg manipulator in a water tunnel. This approach allows repeatable and physically consistent evaluation of fin performance across different swimming styles and flow velocities. In addition to fin geometry and material properties, swimming style is a critical parameter that influences fin performance and energy efficiency. Different swimming techniques impose distinct kinematic constraints on the lower limb, resulting in variations in fin oscillation amplitude, frequency, effective angle of attack, and interaction with the surrounding flow. Consequently, swimming style directly affects both thrust generation mechanisms and

hydrodynamic similarity conditions. For this reason, fin performance cannot be evaluated independently of the swimming technique for which the fin is intended, and a meaningful assessment requires explicit consideration of representative swimming styles.

Swimming with fins allows one to perform many swimming styles depending on their needs. This work considered three water flow speeds on the diver leg manipulator and three swimming styles: crawl, modifying crawl (i.e. a diver-specific modified flutter kick with increased knee flexion) and flutter kick.

The first technique of swimming with fins is the crawl. The swimmer's body is horizontal, and the legs working from the hip power the fins. The legs are almost straight at the knees, and the amplitude of the fins is quite large. The upper and lower sides of each fin work alternately. The advantage of this technique is the naturalness and ease of mastering the movement and the most excellent efficiency of all styles, especially important when swimming against the current, as well as the ability to easily swim close to objects or a partner without getting into contact. The disadvantage of this technique is that when working with the upper side of the fin, water is thrown backwards and towards the bottom, which causes sediment to rise from the bottom.

Another problem is working the foot in a stretched position without moving the ankle joint, which causes muscle spasms in swimming beginners. Another problem arises when swimming in cold water. A swimmer's legs work most effectively during a crawl when they are almost straight at the knees, and with straight legs in a dry suit, the feet have positive buoyancy and float up. This swimming technique is designed for experienced divers to swim quickly and efficiently [13].

The modifying crawl bends legs more and more at the knees, working with our fins higher and thus farther from the bottom. Then, the amplitude of movements is limited, and the movement is restricted, finally powering the fins only with the work of the feet at the ankles. In an extreme modification, the body and legs up to the knees form one horizontal line, the legs are bent at the knees, and the feet point the fins backward and close to each other. The modifying crawl moves feet at the ankles in this position, driving the fin blades. The advantage is the maximum limitation of sideways hooking. The disadvantages are low efficiency, worse than in highly modified

frog style, and easy hooking of objects we swim under. This technique allows for quick changes in the direction of the thrust force, which is why it is intended to explore underwater objects at low swimming speeds.

The flutter kick is the first kick we learn for diving and the one that comes most naturally. To perform a flutter kick, you must kick your leg forward and backward once. This way, it should avoid performing a "bicycle kick", in which you bend your knees significantly, as when riding a bicycle. Kicking on a bike is inefficient, and you lose energy. In this technique, it must keep your toes pointed forward during the flutter kick to fully use the flippers. The flutter kick is easy to learn, easy to master, and gives you plenty of power to propel yourself forward through the water. In this swimming style, the kick should come from the hips instead of the knees, and the legs must be straight. More information on the use of fins by swimmers and divers in various styles can be found in publications [2,14]

MATERIALS AND METHODS

The tests were carried out in an open water tunnel with dimensions of 13.9×7.9 m and $D = 1.4$ m channel diameter – Figure 1. The tunnel was filled with water at a temperature of 20°C ($\pm 1^\circ\text{C}$), and the hydrodynamic drive system consisted of an electric motor and a 4-blade propeller, allowing for reaching the speed of the water stream up to $V = 1.5$ m/s. To minimize flow disturbances and prevent the development of excessive turbulence in the test section, water current vanes were installed at a distance of 3 m upstream of the tested fins. The flow velocity was measured using ultrasonic sensors.

Following the research assumptions, the energy efficiency of the fins was evaluated using a manipulator simulating the movement of the diver's leg – Figure 1. The simulator could adjust the frequency and amplitude of the thigh and lower leg flapping, while the ankle joint was made as a flexible element with a maximum angle of 15 degrees. The manipulator's measurement system determined the electrical demand of two DC motors ($U=24$ V) and the force values on the dynamometer with a sampling frequency of $f=1$ Hz or $f=5$ Hz. The authors presented a detailed description of the research stand in the publication [3].

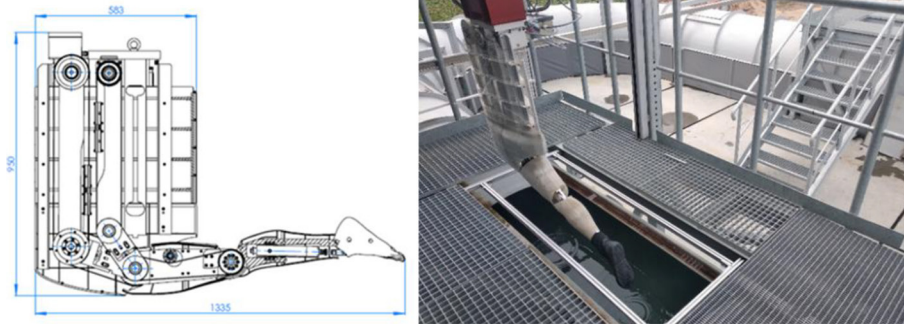


Figure 1. The cross-section view of the manipulator (left figure) and the system above the surface of the water tunnel before tests (right figure)

Characteristics of fins and materials

The research selected three fin models that best suited the analyzed swimming styles and strokes. It can be noticed that the most frequently chosen fin for diving purposes (the modifying crawl style) is the Jet Fin fin by Scubapro and for speed swimming purposes, the Express fin by Aqualung (the crawl style). An innovative, foldable fin from Exotech was selected as an alternative fin for further research – see Figure 2.

In the adopted research methodology, tests were carried out on the bending properties of materials used on Aqualung S and Jet Fin Scubapro fins. The material from the Exotech fin was not taken due to its foldable design. By the recommendations of the ISO 178:2019 Plastics Determination of flexural properties standard, the bending properties of materials were determined. The method was used to test the samples bending behaviour and determine the bending strength and elastic modulus. The test consisted of symmetrically placing the test piece by the standard on two supports and loading it in the middle between them.

Samples with a rectangular shape, height of 60 mm, width of 25 mm, and thickness of 3 mm were subjected to stresses up to $F = 10 \text{ kN}$. The rubber sample of the Scubapro fin obtained an average bending stress of $\sigma_B = 1.23 \text{ MPa}$ while the polymer sample of the Aqualung fin obtained $\sigma_B = 14.82 \text{ MPa}$.

Hydrodynamic similarity criteria

When the fin is operating in the water, rapid changes in the fluid stream occur [15]; there is a differential pressure component necessary to generate a momentary acceleration (related to the local

velocity derivative) in addition to the convective acceleration associated with the acceleration of the fluid elements as they flow at the trailing edge of the fin. The equation describing the flux to the pressure drop can then take the form [16]:

$$\Delta p_p = K_1 \frac{dq_m}{dt} + K_2 q_m^2 \quad (1)$$

At low pulsation frequencies, the coefficients K_1 and K_2 can be assumed as constants and defined as follows:

$$K_1 = \frac{4L}{\pi d^2 C_c} \quad (2)$$

$$K_2 = \frac{1 - C_c^2 \beta^4}{C_v^2 C_c^2 \left[\frac{\pi d^2}{4} \right]^2} \cdot \frac{1}{2\rho} \quad (3)$$

where: C – flow coefficient, C_c – contraction coefficient, C_v – inflow velocity coefficient, d – cross-sectional area of the inlet in front of the fin, L – fin length, β – contraction – the ratio of the cross-section of the inlet in front of the fin to the cross-section behind the fin

The initial research adopted a physical model assuming the operation of fins in an incompressible water medium at constant density and temperature.

The unsteady motion of water is described not only by characteristic quantities such as flow speed (v), kinematic viscosity of the fluid (γ) and fin length (L) but also by the value of any time interval (τ) characteristic of this motion, determining the change in motion over time [17]. Thus, in the case of a flapping fin of a specific shape, it can be assumed that it will be a period



Figure 2. Aqualung S. (Fin 1), Jet Fin Scubapro (Fin 2) and Exotech (Fin 3) fins – objects of research.

of oscillation [4]. For these four quantities, two independent dimensionless combinations can be created. The study adopted the Strouhal and Reynolds number criteria and used them to characterize the structure of the stream following the fin in the formula [4]:

$$St = \frac{fA}{v} \tag{4}$$

$$Re = \frac{L \cdot v}{\gamma} \tag{5}$$

where: f – flipper frequency, v – water stream speed, γ – kinematic viscosity of water, A – amplitude of the fin trailing edge.

The value of the Strouhal number was used as a criterion characterising unsteady flows of a pulsating nature typical of the operation of fins. Additionally, two flows were considered similar if the same Reynolds and Strouhal numbers characterised them. Due to the different lengths of the tested fins, it is assumed that the Reynolds numbers for each tested speed may differ slightly. The main criterion is a constant Strouhal number for each water stream speed and all fins. In the adopted research model, obtaining compliance with both numbers required adjusting the amplitude of the trailing edge movement and flipper frequency for the three fins. It was decided that the speeds of the water stream would be constant: $V_1 = 0.21$ m/s, $V_2 = 0.26$ m/s and $V_3 = 0.29$ m/s.

The adopted assumptions allowed for flexible planning of experiments, maintaining significant water masses at a constant speed, and obtaining compliance with both criteria numbers, which required averaging the measurement of the electrical energy necessary for both manipulator drive motors. Taking into account the non-stationarity fins operation, it was assumed that the

measurement would concern a time interval of 15 seconds, starting from the upper maximum position of the fin. The energy demand was calculated as the arithmetic mean of the power required by both engines for a constant time interval, i.e. $t = 15$ sec. The fundamental problem of the research methodology adopted in this way was the failure to obtain average values of the balance of the resistance force of the manipulator in the water stream and the average thrust force generated by the fins oscillation on the measuring dynamometer. The problem was solved by using additional formulas to determine the excess or deficiency of the thrust force generated by the fin. The operation of the non-stationary drive, which is the fins, creates problems with assessing the value of the thrust force, which varies over time and depends on the type of fins and swimming technique [1]. The study used a single-leg manipulator. Hence, the assumption was made that the work of the diver’s legs with fins is kinematically symmetrical and phase-shifted. This assumption does not eliminate the problem of non-stationarity of the fin thrust force, but it allows for an objective assessment of effectiveness. A two-stage measurement was performed to assess energy efficiency. In the first stage, a research model of compliance with Strouhal and Reynolds criterion numbers was adopted. As mentioned, the variable parameters were the fin length, the movement amplitude and the flapping frequency, while the three water jet speeds were constant. This action aimed to comply with both criteria numbers for the water jet velocities. The adopted procedure enabled the determination of the electrical power demand of both DC motors of the manipulator. It should be noted, however, that for the measurements performed, the average values of the force indicated by the dynamometer on the manipulator had values other than zero. Hence, it was assumed that the power demand of the fins P_f at a constant speed of water stream flow around the manipulator would be the sum of the electrical power P_E required by the motors and the surplus/deficiency of the fin thrust power P_{TH} referred to as an average value to the considered time section, which is presented in the form of formulas below:

$$P_E = \sum_{i=1}^2 (P_{Mi} - P_{FRi}) \tag{6}$$

$$\overline{P_{TH}} = \frac{\sum_{t=1}^{t=15} T_i \cdot v}{t} \tag{7}$$

$$T_i = \overline{T}_F - \overline{T}_M \quad (8)$$

$$P_F = P_E + P_{TH} \quad (9)$$

$$\eta_F = \frac{|\sum_{t=1}^{t=15} T_i \cdot v|}{P_F} \cdot 100\% \quad (10)$$

where: P_{Mi} – the power of electric motor DC, P_{FR} – power consumed by the friction of driving system of the manipulator for the selected swimming style measured in the no-fin mode, out of water stream, T_i – average thrust of fin for $t=15$ sec, v – velocity of water flow, \overline{T}_F – average thrust forced by the manipulator with the fin mounted on the foot, \overline{T}_M – average thrust forced by the manipulator without the fin, $t = 15$ sec, η_F – the fin efficiency.

Kinematic modelling of swimming styles

To develop a model of the movement of a human leg with a fin, movies with the movement of the leg marked in three places ((1) – knee joint, (2) – ankle joint, (3) – end of the fin trailing edge) were recorded. Fins were marked with unique coloured square tags. By determining the markers' positions in a specific adopted coordinate system, it is possible to reconstruct the leg's movement – see Figure 3 [18].

In the second simulation phase during model construction, videos of all swimming styles were recorded in the swimming pool. The first videos recorded the movement of a leg with a standard wide diving fin (fin no. 1), while subsequent videos corresponded to the movement of a leg equipped with a light, flexible, narrow swimming fin and the last one – Exotech type [19] (fins no. 2 and no. 3). Each recording for a selected fin and swimming style was made for three different leg movement speeds – the diver determined the leg speed in a completely subjective way, his task

was only to vary the effort he put into movement during each of the three recordings [18].

The third simulation phase during model construction involves implementing software for extracting markers from the video stream and determining their position in the selected local coordinate system. This phase requires defining the extraction method and its parameters.

The application implements the following algorithm to determine the position of markers separately for each video frame. This is achieved by transforming the image from RGB format to HSV format and extracting pixels with the appropriate HSV parameters from the image – see Figure 4.

The resulting positions of the diver's fin and leg indicated by the markers were then programmed into the manipulator as subsequent swimming styles using the designed control application [20]. The variables were the amplitude, frequency, and position of the joint points (knee and ankle joints). The operation's accuracy was verified using the video method [21]. Figure 5 depicts the developed graphical user interface of the manipulator's control application.

The described procedure enabled accurate reconstruction of lower-limb kinematics for different swimming styles and fin types under controlled conditions. The extracted kinematic parameters were subsequently implemented as input data for the leg manipulator, ensuring repeatable and physically consistent reproduction of swimmer motion. This approach provided a reliable basis for subsequent hydrodynamic and energy efficiency measurements.

RESULTS AND DISCUSSION

The results of the video-based kinematic analysis of the diver's lower limb are presented in the form of graphs illustrating the temporal and spatial characteristics of leg motion. These



Figure 3. Fins with coloured markers during the pool tests

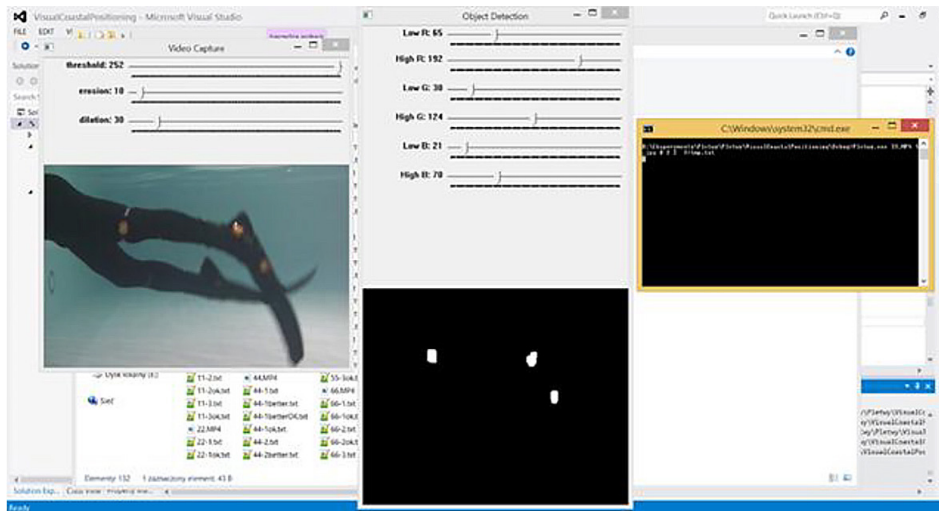


Figure 4. A graphical interface for a computer application to determine the location of markers on a diver's leg [18]

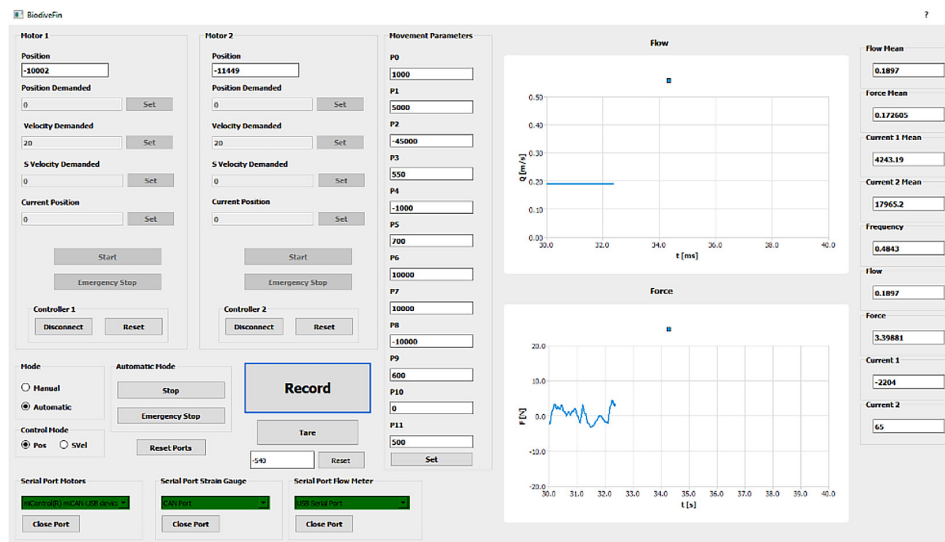


Figure 5. A graphical interface of the manipulator's control application [18]

results provide quantitative input for evaluating the repeatability of the implemented kinematic models and constitute the basis for subsequent analysis of hydrodynamic performance and energy efficiency. Representative examples of the reconstructed kinematic trajectories are shown in Figures 6–10.

For different Strouhal numbers, the test input and output parameters are presented in Table 1.

Based on the reconstructed kinematic models and the adopted hydrodynamic similarity criteria, experimental tests were subsequently conducted to determine the energy efficiency of the investigated fins under different swimming styles and water flow velocities. The tests were performed using parameters defined by equations (6–10),

and the resulting thrust, power demand, and efficiency values are summarised in Tables 2–5.

Analysis of the test results indicated that the fin efficiency differed significantly in different swimming styles. The analysis concerned the value of efficiency vs. swimming style and the value of the generated thrust for various water stream speeds. The factors that determined changes in energy efficiency were:

- The shape of the fin,
- Active surface area of the fin,
- Bending resistance.

As the fin surface (blade) increased (Exotech – Fin 3 fins had the largest surface), the energy demand and the average thrust value increased

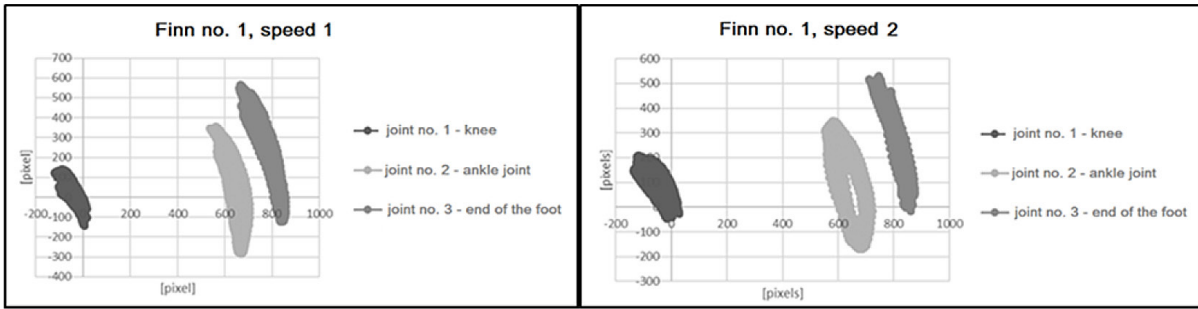


Figure 6. Location of markers for fin number 1 and different leg speeds – crawl swimming style

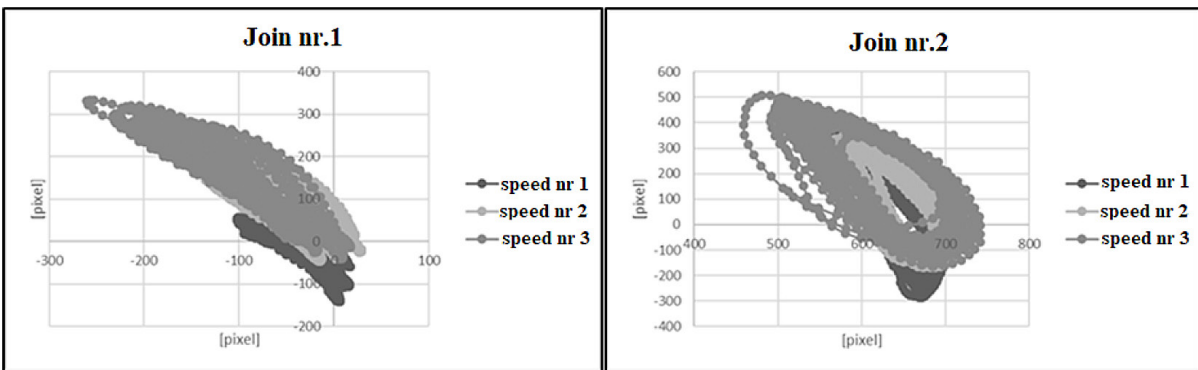


Figure 7. Location of markers for fin number 3 and two different leg speed – the modified crawl swimming style

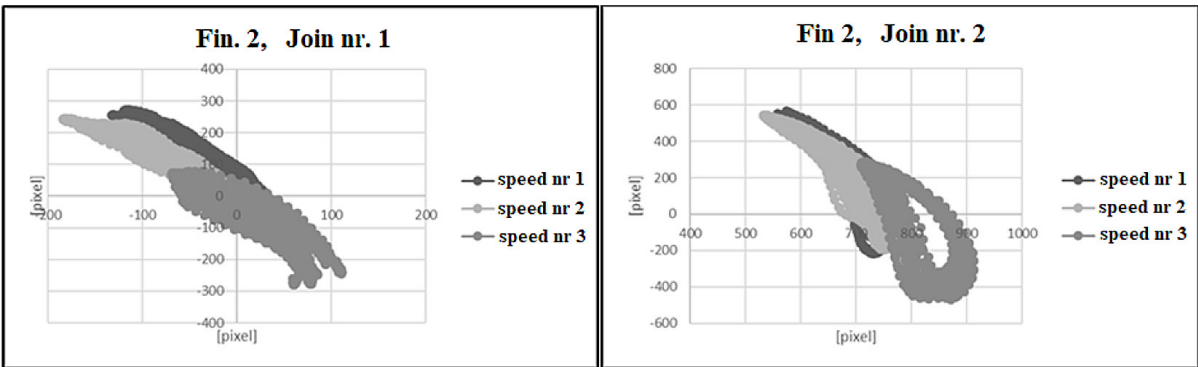


Figure 8. Location of markers for fin number 2 and three different leg speeds – the flutter kick swimming style

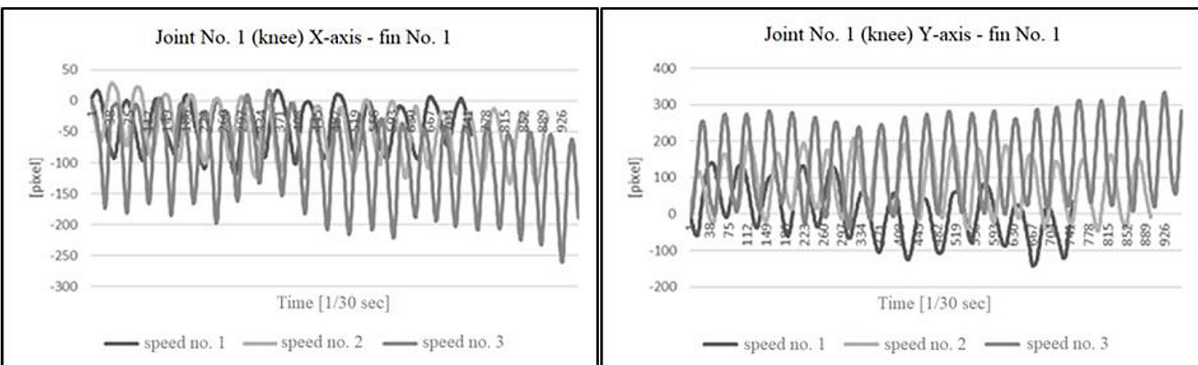


Figure 9. Position in the X and Y axes of joint No. 1 (knee) for three speeds – fin No. 1 – crawl swimming style

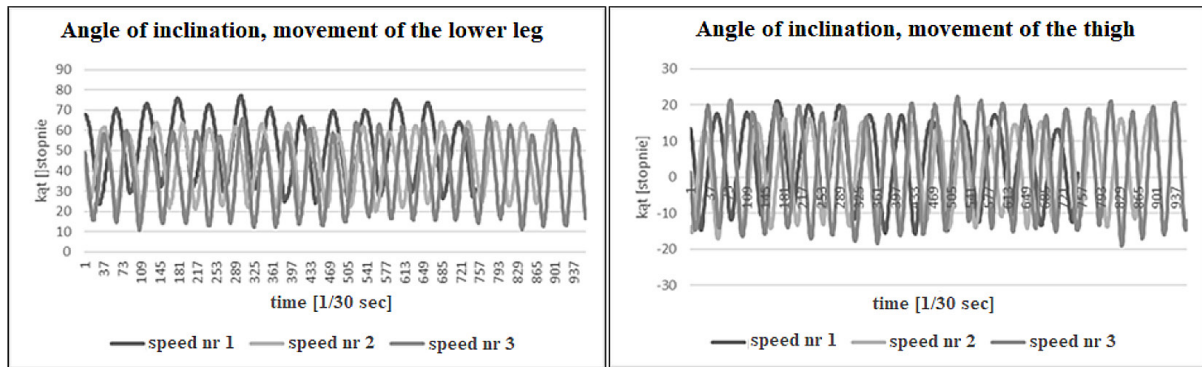


Figure 10. Thigh and lower leg inclination angles for different speeds of manipulator leg movement for Exotech fin no. 3 – the flutter kick swimming style

Table 1. The tests input and output parameters for Strouhal number (St) errors of Reynolds number: L_M – is the sum of the length of the manipulator with the fin attached to the foot, f – flutter frequency, the maximum error is the percentage of deviation from the Re arithmetic mean at a constant water stream speed

Movement parameters	Reynolds number	Maximum error of Re
$St_1=1.857; V_1=0.21$ m/s; Manipulator: $L_{1M}=1.66$ m; $L_{2M}=1.635$ m; $L_{3M}=1.745$ m; $f_1=1.2$ s ⁻¹ ; $f_2=1.3$ s ⁻¹ ; $f_3=0.95$ s ⁻¹ ;	$Re_{(F1)}=0.341 \cdot 10^4$	0.2%
	$Re_{(F2)}=0.341 \cdot 10^4$	
	$Re_{(F3)}=0.342 \cdot 10^4$	
$St_2=1.375; V_2=0.26$ m/s; Manipulator: $L_{1M}=1.66$ m; $L_{2M}=1.635$ m; $L_{3M}=1.745$ m; $f_1=1.1$ s ⁻¹ ; $f_2=1.19$ s ⁻¹ ; $f_3=0.87$ s ⁻¹ ;	$Re_{(F1)}=0.43 \cdot 10^4$	2.1%
	$Re_{(F2)}=0.423 \cdot 10^4$	
	$Re_{(F3)}=0.44 \cdot 10^4$	
$St_3=1.457; V_3=0.29$ m/s; Manipulator: $L_{1M}=1.66$ m; $L_{2M}=1.635$ m; $L_{3M}=1.745$ m; $f_1=1.3$ s ⁻¹ ; $f_2=1.41$ s ⁻¹ ; $f_3=1.03$ s ⁻¹ ;	$Re_{(F1)}=0.479 \cdot 10^4$	3.9%
	$Re_{(F2)}=0.472 \cdot 10^4$	
	$Re_{(F3)}=0.504 \cdot 10^4$	

significantly. This is evident in the crawl style. Using a soft membrane between the ribs in Exotech fins increased the hydroelasticity effect [3, 19], resulting in a smooth transition in the crawl mode by generating thrust during the alternating movement of the manipulator’s leg up and down. Changes in the thrust value were the smallest. In this style, Aqualung and Scubapro fins achieved significant changes in thrust value during a 15-second measurement cycle. The standard deviation σ values for the water stream speed $V = 0.29$ m/s were: Exotech: $\sigma = 7.486$ N, Aqualung: $\sigma = 11.391$ N and Scubapro $\sigma = 12.581$ N. In this swimming style, the Exotech (Fin 3) fins got the highest efficiency.

The modifying crawl style requires increased knee flexion due to the greater amplitude in the alternating movement of the lower leg. Because the lower leg is limited by the knee when moving down, this style is much more asymmetrical than the crawl style. The difference also concerns the movement of the thigh, which has a smaller

amplitude. For the operation of the manipulator, this meant a significant difference in the power load on the thigh and lower leg drive motors. Also, changes in the value of the generated thrust were substantial for all types of fins and all water stream speeds. In modifying crawl style, the Aqualung S Fin 1 (Fin 1) achieved the highest efficiency, and the Exotech (Fin 3) fins got the lowest efficiency.

The large amplitude of the lower leg movement allowed fins with greater bending strength to behave more flexibly, which makes them more efficient. Exotech fin achieved significant changes in thrust value during a 15-second measurement cycle.

The standard deviation σ values for the water stream speed $V = 0.29$ m/s were: Exotech: $\sigma = 18.86$ N, Aqualung: $\sigma = 9.974$ N and Scubapro $\sigma = 13.812$ N. All results of the standard deviation analysis of thrust forces are presented in Table 5.

The flutter kick style also demonstrated higher efficiency with Aqualung and Scubapro

Table 2. Results of energy efficiency measurements of three types of fins for the crawl style

Water stream speed	The average thrust of fin	The power demand of the fin	Fin efficiency	Parameter
	$T_f [N]$	$P_f [W]$	[%]	
V=0.21 m/s	53	20	55.7	Aqualung S Fin 1
V=0.26 m/s	49	22	57.9	
V=0.29 m/s	55	27	59.1	
V=0.21 m/s	55	20	57.8	Jet Fin Scubapro Fin 2
V=0.26 m/s	56	25	58.2	
V=0.29 m/s	58	26	64.7	
V=0.21 m/s	58	20	60.9	Exotech Fin 3
V=0.26 m/s	60	26	60.0	
V=0.29 m/s	67	31	62.7	

fins. Jet Fin Scubapro (Fin 2) fin had the shortest active blade length of fin and were best suited to this swimming style. The standard deviation of the thrust force of these fins had the lowest value.

It should be noted that the experimental setup does not reproduce the global wake structure generated by a full human body during swimming. The applied single-leg manipulator operates in a controlled, uniform incoming flow and therefore does not account for body-induced vortical structures, torso drag, or wake-fin interaction effects. This simplification was intentional and aimed at isolating the propulsion characteristics of the fin itself under hydrodynamically similar conditions. As a result, the proposed methodology is designed primarily for comparative assessment of fin performance and energy efficiency, rather than for full-scale replication of the complete swimmer–flow interaction.

Given the limitations of the test stand, the following results should be regarded as preliminary. When combining all swimming styles and flow velocities, it becomes clear that no single fin dominates across the entire test space. The Exotech fin (Fin 3) generated the highest thrust in crawl at higher velocities, but at the cost of increased variability and reduced efficiency in modifying crawl and flutter kick. The Aqualung S (Fin 1) maintained stable efficiency in crawl and modifying crawl, but its flutter kick performance deteriorated at higher velocities. The Jet Fin Scubapro (Fin 2) consistently offered the most balanced performance, excelling in flutter kick and maintaining competitive efficiency in crawl, although less suitable for modifying crawl.

Practical guidance can therefore be drawn: accordingly, for high-speed swimming with

stable propulsion, hydroelastic fins like Exotech are recommended. For tasks requiring manoeuvrability and knee-driven propulsion (modifying crawl), fins with greater bending strength, such as Aqualung S, are recommended. It should be noted that, irrespective of the measured variability, divers testing the Exotech fin (Fin 3) reported very favourable impressions of its manoeuvrability. For straightforward propulsion with minimal energy expenditure in flutter kick, the shorter and stiffer Jet Fin Scubapro provides the best balance of efficiency and stability.

The bending tests (performed just for Aqualung S and Jet Fin Scubapro fins, the material from the Exotech fin was not taken due to its foldable design) provide a quantitative reference for interpreting the experimentally obtained fin efficiency. Differences in bending resistance between the tested materials are reflected in the hydrodynamic performance under various swimming styles. Fins with higher bending stiffness achieved higher efficiency in swimming styles involving large lower-leg amplitudes and pronounced knee flexion (modified crawl and flutter kick), as increased stiffness reduces excessive blade deformation and non-propulsive energy losses. In contrast, in the crawl swimming style, fins with lower effective bending resistance or hydroelastic structures exhibited higher efficiency due to smoother thrust generation and reduced force variability. These findings indicate that flexural stiffness, combined with fin geometry, directly affects propulsion efficiency and should be treated as a functional parameter dependent on swimming style and kinematic conditions.

Analysis of the fin efficiency results for various swimming styles confirms the correctness of the adopted methodology; however, the ratio

Table 3. Results of energy efficiency measurements of three types of fins for the modifying crawl style

Water stream speed	The average thrust of fin	The power demand of the fin	Fin efficiency	Parameter
	$T_f [N]$	$P_f [W]$	[%]	
V=0.21 m/s	61	26	49.3	Aqualung S Fin 1
V=0.26 m/s	54	25	56.2	
V=0.29 m/s	61	28	63.2	
V=0.21 m/s	61	27	47.4	Jet Fin Scubapro Fin 2
V=0.26 m/s	60	28	55.7	
V=0.29 m/s	62	32	56.2	
V=0.21 m/s	61	30	42.7	Exotech Fin 3
V=0.26 m/s	61	35	45.3	
V=0.29 m/s	61	36	49.1	

Table 4. Results of energy efficiency measurements of three types of fins for the flutter kick style

Water stream speed	The average thrust of fin	The power demand of the fin	Fin efficiency	Parameter
	$T_f [N]$	$P_f [W]$	[%]	
V=0.21 m/s	57	23	52.0	Aqualung S Fin 1
V=0.26 m/s	55	26	55.0	
V=0.29 m/s	46	27	49.4	
V=0.21 m/s	57	23	52.0	Jet Fin Scubapro Fin 2
V=0.26 m/s	56	26	56.0	
V=0.29 m/s	62	29	62.0	
V=0.21 m/s	45	25	37.8	Exotech Fin 3
V=0.26 m/s	47	26	47.0	
V=0.29 m/s	46	29	46.0	

Table 5. The results of the thrust forces standard deviation σ in test campaigns

Water stream speed	V=0.21 m/s	V=0.26 m/s	V=0.29 m/s	V=0.21 m/s	V=0.26 m/s	V=0.29 m/s	V=0.21 m/s	V=0.26 m/s	V=0.29 m/s
Style	The crawl style			The modifying crawl style			The flutter kick style		
Fin 1	$\sigma = 9.871$	$\sigma = 11.03$	$\sigma = 11.39$	$\sigma = 8.02$	$\sigma = 8.88$	$\sigma = 9.974$	$\sigma = 10.1$	$\sigma = 12.6$	$\sigma = 15.1$
Fin 2	$\sigma = 9.034$	$\sigma = 11.03$	$\sigma = 12.58$	$\sigma = 9.781$	$\sigma = 11.91$	$\sigma = 13.81$	$\sigma = 8.235$	$\sigma = 9.101$	$\sigma = 9.903$
Fin 3	$\sigma = 6.451$	$\sigma = 7.021$	$\sigma = 7.486$	$\sigma = 13.76$	$\sigma = 16.01$	$\sigma = 18.8$	$\sigma = 15.01$	$\sigma = 16.23$	$\sigma = 18.91$

of energy lost in the manipulator mechanism to the energy used for propulsion is too high. This suggests the need to modify the manipulator design to improve mechanical efficiency in power transmission. This solution is currently being tested, allowing a significant reduction in mechanical losses. The analysis of the obtained results provides a clear recommendation for the new types of Exotech Fin fins, as they are quite effective for speed swimming. However, the fins that demonstrated the highest efficiency across the entire range of tested water flow speeds,

except for the modifying crawl style, were the No. 2 fins.

The results of the research show the need for leg manipulator modernization in several aspects. The fundamental problem is the issue of power transmission inside the leg movement mechanism, the losses of which are significant when changing the direction of movement of the thigh and lower leg. The ratio of the power required by the manipulator when working without a fin to when working with a fin was approximately 80–85%, which suggests that systematic errors may occur when assessing the energy efficiency

of the fins. It is also assumed that it will be necessary to change the shape of the manipulator, which will correspond to the diver's body in terms of length and wetted area similarity.

CONCLUSIONS

This study presented an experimental methodology for evaluating the energy efficiency of diving fins based on hydrodynamic similarity criteria and controlled reproduction of swimmer leg kinematics. The proposed approach enables objective and repeatable comparison of fins with different geometry, stiffness, and intended application across multiple swimming styles and flow velocities.

The results demonstrated that fin performance and energy efficiency strongly depend on the interaction between fin geometry, flexural stiffness, and swimming style. No single fin design proved optimal for all tested conditions; instead, different fins exhibited maximum efficiency in different swimming techniques and velocity ranges.

The conducted experiments confirm that combining kinematic repeatability with an energy-based efficiency criterion provides a reliable framework for fin performance assessment, overcoming limitations associated with swimmer-dependent or purely subjective evaluation methods. The presented methodology constitutes a robust basis for further systematic studies of fin propulsion under controlled hydrodynamic conditions.

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