The aim of this study was to develop a functional model of monofin swimming by assigning numerical forms to certain technique parameters. The precise determination of optimal foot displacement and monofin strain points toward a model aspect for increasing swimming speed. Eleven professional swimmers were filmed underwater. The kinematic data were then used as entry variable for an artificial neural network, which itself created the foundation for a model of monofin swimming technique. The resulting network response graphs indicate a division set of standard deviation values in which the examined angular parameters of foot and monofin displacement achieve optimal values in terms of gaining maximal swimming speed. During the upward movement, it is essential to limit dorsal foot flexion (–20°) from the parallel position toward the shin (180°). During the downward movement, plantar flexion should not exceed 180°. The optimal scope of the proximal part of the fin strain is 35° in the downward movement and (–)27° in the upward; the angles of attack of the distal part of the fin and its entire surface are limited to 37° in the downward movement and (–)26° in the upward. Optimization criteria allowed for movement modification to gain and maintain maximal velocity during both cycle phases and to limit cycle velocity decrease.

**Keywords:** kinematics, leg and monofin movements, neural network

This study is an attempt to solve the problem of the efficient and economical use of a monofin to gain maximum swimming speed.

The essence of monofin propulsion has been explained with the use of kinematics (Arellano & Gavilan, 1999a; Arellano et al., 1999b; Colman et al., 1999; Rejman et al., 2003a; Ungerechts, 1982a, 1982b) and dynamic (Rejman et al., 2003b) analyses. The kinematic (Shuping, 1989, 2000a; Shuping & Sanders, 2002; Szilagyi et al., 1999; Tze et al., 1999) and dynamic (Rejman 1999; Rejman et al., 2004) criteria of monofin swimming technique have been specified. Modeling of the technique under analysis was improved in several directions: by Wu (1968, 1971; mathematical modeling); Matsuuchi et al. (2006), Miwa et al. (2006; PIV system); and Nakashima (2006; conceptual simulation modeling). Yet the partial applicability of this research created the need to construct a functional model of monofin swimming technique.

The first construction of a functional model of monofin swimming was based on results generated by an artificial neural network (Rejman & Ochmann, 2007). The utility of the neural network as a modeling method is based on the correlation between describing and described variables in dynamic processes of a probabilistic nature. This makes it a useful tool in sport research. Neural networks have been used in modeling traditional swimming technique (Edelmann-Nusser et al., 2001; Mujika et al., 1986). The two-dimensional structure of propulsive movements where the monofin is the only source of propulsion (Rejman, 1999) has facilitated the modeling of monofin swimming technique. Construction of a functional model of monofin swimming technique required a regard for traditional patterns. The model was represented by physical formulas. These formulas, according to suggestions by Hay (1985) and Reischle and Spikermann (1992), describe the physical parameters and their combinations that determine maximal monofin swimming speed. Results of the network response allowed the parameters to be ordered as to form an understandable mechanism for achieving maximum swimming speed. The fundamental feature of
the model created was its functionality in terms of the real possibility of using its conclusions in the practice of monofin swimming training.

The aim of the study is to develop a functional model of monofin swimming by assigning numerical form to certain technique parameters. The precise determination of optimal foot displacement and monofin strain indicates a model whose aspects increase swimming speed. Optimization criteria are to be connected with the modification of propulsive movement to gain and maintain maximal speed during both phases of movement cycle and to limit decrease in velocity during the movement cycle. The stabilization of intracycle velocity at a high level will create the basis for achieving maximal monofin swimming speed.

Methods

The study was realized in two stages. The result of the first stage was the construction of a functional model of monofin swimming technique (Rejman & Ochmann, 2007). In the second stage, after a 1-year break, the aims of this study were realized.

The same group of 11 male swimmers volunteered to take part in the study for both stages of the research. They were 15–18 years old at the beginning of research and they were comparable in terms of body composition and level of monofin swimming skill. As members of the Polish Monofin Swimming Team, all the swimmers displayed a high level of monofin swimming proficiency. During the first research session, they covered a distance of 25 m underwater, at maximum speed, while holding their breath. All swimmers used the same monofin equipped with strain gauges (Rejman & Ochmann, 2007). For the second session, the participants swam a 50-m distance using their own monofin.

To record the kinematic data of leg and monofin movement, the swimmers were filmed underwater in both experimental sessions. A digital camera was placed in the middle of the swimming pool. It was assumed that the swimmers and the monofin move only on a lateral dimension. Monofin swimmers, as with most fish, attempt to minimize active drag by limiting the degrees of freedom of motion and by making rigid the body segments that do not contribute to propulsion generation (Rejman, 2006). All divergences in the mentioned segments, from the plane of active movement, disturb laminar flow and cause uncontrolled induction and dislocation of the vortices (Daniel, 1984), as well as increasing active drag. The changes of monofin shape in the transversal plane, in reaction to water resistance, were omitted, as there was no influence on the aim of this study, in terms of realizing the functionality of the model created. The following reference points were marked on each swimmer’s body: shoulder, hip, knee, and ankle (Plagenhoef, 1971), along with the tail, middle, and edge of the fin. A kinematic analysis of the movements was carried out using the SIMI Analysis System. During analysis, a division of the cycle into an upward movement phase and a downward movement phase was accepted. Movement directions in the phases mentioned were described based on the axis of shin–ankle joint displacement. The results of this analysis represented angular leg displacement, monofin angles of strain, and angles of attack of the monofin’s surface parts (and their derivations) (Figure 1). The horizontal velocity of the swimmers’ center of body mass, in a randomly separated cycle, was also calculated by the system.

After the first experimental session, the raw data mentioned were used as entry variables for the development of an artificial neural network, which was the chosen source of information for modeling monofin swimming technique. In this part of the research, 23 input variables were used to define model relations against the output variable (horizontal velocity of the swimmer’s center of body mass). The functional model showed that the factors, which influenced monofin swimming speed, can be attributed to the following 16 parameters, in order: 1) the angular acceleration and angular velocity of attack for the proximal part of the fin; 2) the angular acceleration, angular velocity of attack, and angle of attack for the distal part of the fin; 3) the angle of attack, angular acceleration, and angular velocity for the entire surface of the fin; 4) the angle of strain, angular acceleration, and angular velocity of the proximal part of the fin toward the foot; 5) the angular velocity of knee flexion; 6) the angle and angular velocity of foot flexion toward the shin. The remaining elements flexing the monofin were forces straining the middle and the tail.

After the second experimental session, the same neural network was used for itemizing the functional model of monofin swimming technique constructed in the first stage. The numbers of input variables were reduced to 14 parameters indicated in the network in the first step of the research (variables describing forces

Figure 1 — Examples illustrating procedure of defining angles of monofin and body segment flexion based on points marked in the axes of joints and tail, in the middle, and on the edge of the monofin. A—foot flexion angle toward shin (α_{ank}); B—proximal fin part strain angle toward foot (α_{tail}); C—angle of attack of the distal part (β_{distal}); D—angle of attack of entire surface of the monofin (β_{surface}).
straining the monofin—in the tail and in the middle—were passed over because they were not registered in the second stage of the experiment. The elimination of the two variables mentioned above did not entail any interference on the construction of the network. Through such criteria, the collation of results obtained in both stages of the experiment were saved. As a consequence the network selected all inputted parameters. The following parameters were chosen for further analysis, owing to the significance of their influence on swimming speed and the convenience of their measurement and interpretation, during the process of monofin swimming training: foot flexion angle toward the shin (\( \alpha_{\text{ankle}} \)), strain angle on the proximal part of the fin toward the foot (\( \alpha_{\text{tail}} \)), angle of attack of the distal part (\( \beta_{\text{distal}} \)), and angle of attack of entire surface of the monofin (\( \beta_{\text{surface}} \)).

The same procedures were employed for the construction of artificial neural networks in both stages of modeling monofin swimming technique. In the selection of a genetic algorithm (verified stepwise backward and forward), other neural nets (such as generalized regression neural networks and probabilistic neural network [Specht, 1990, 1991]) were used, after which the features were selected and attributed to particular groups of the network. The best model, with the lowest number of mistakes, was chosen from several models tested. The model’s development was based on a multilayer perception (Bishop, 1995), using a postsynaptic potential linear activation function, with a nonlinear activation function and a logistic (sigmoid) function. The network’s training process was based on a back-propagation algorithm (Haykin, 1994; Fausett, 1994; Patterson, 1996). The data were distributed into training, validation, and testing sets. The neural net model was constructed based on the training set. The validation set was a foundation for the network’s “learning” to check results. The testing set enabled an independent assessment of network quality. Cases to be used in particular sets were chosen at random, maintaining similar mean values and standard deviations.

For the preliminary interpretation of network response, sensitivity analyses and regression statistics were used. An analysis of sensitivity (Table 1) provides additional information concerning the influence of particular variables on the output parameter. Sensitivity parameters were calculated for each variable shown in the model and were described on the basis of a rank of values, error and quotient. Error shows the network’s quality with the lack of a given variable (important variables are given a higher rank). Quotient is the result of dividing an error by an error obtained with the use of all variables. The higher the value of a quotient, the greater the importance of a parameter in the process reproduced by the model. Rank was used to put variables in order.

All outcomes have been depicted as numbers in the regression statistics tables (Table 2) and have the following features: average error for output variables (a module of difference between a given value and value at

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Results of network sensitivity analysis according to ranking of the standard deviation quotient against output variable (horizontal swimming velocity)</th>
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<tbody>
<tr>
<td>Rank</td>
<td>( e_M )</td>
</tr>
<tr>
<td>Error</td>
<td>0.532</td>
</tr>
<tr>
<td>Quotient</td>
<td>1.821</td>
</tr>
</tbody>
</table>

| Rank    | \( \alpha_K \) | \( \omega_T \) | \( \omega_A \) | \( \epsilon_{\text{EH}} \) | \( \beta_{\text{surface}} \) | \( \omega_{\text{EH}} \) | \( \alpha_{\text{ankle}} \) |
| Error   | 0.425 | 0.423 | 0.419 | 0.413 | \textbf{0.395} | 0.361 | \textbf{0.328} |
| Quotient| 1.454 | 1.447 | 1.432 | 1.411 | \textbf{1.351} | 1.236 | \textbf{1.122} |

Note. The parameters chosen for the second step of the experiment (modeling of feet displacement and fin strain) are indicated with boldface. Angles of flexion: on the monofin tail—(\( \alpha_{\text{tail}} \)), shin–ankle joints—(\( \alpha_{\text{ankle}} \)). Angular velocities of monofin tail strain—(\( \omega_T \)); shin–ankle joints—(\( \omega_A \)) and knee joints (\( \omega_K \)). Angular accelerations of monofin tail strain—(\( \epsilon_T \)); monofin’s middle—(\( \epsilon_M \)). Angles of attack of the monofin: entire surface—(\( \beta_{\text{surface}} \)); distal part—(\( \beta_{\text{distal}} \)). Angular velocities of attack: entire surface—(\( \omega_{\text{EH}} \)); proximal part (\( \omega_{PH} \)); distal part (\( \omega_{DH} \)). Angular accelerations of attack: entire surface—(\( \omega_{\text{EH}} \)); and distal part (\( \omega_{DH} \)).

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Regression statistics table</th>
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<tbody>
<tr>
<td></td>
<td>Teaching Set</td>
</tr>
<tr>
<td>Arithmetical average</td>
<td>2.548</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.450</td>
</tr>
<tr>
<td>Average error</td>
<td>0.004</td>
</tr>
<tr>
<td>Average error deviation</td>
<td>0.242</td>
</tr>
<tr>
<td>Average absolute error</td>
<td>0.153</td>
</tr>
<tr>
<td>Standard deviation quotient</td>
<td>0.538</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.843</td>
</tr>
</tbody>
</table>
output), average absolute error for output variables (the difference between a given value and value at output), Pearson’s standard correlation ratio for a given value and value at output, standard deviation of error for output variable, and finally, standard deviation quotient for errors and data. Response graphs were used to display the particular correlations between input and output variables.

**Results**

As was foreseen, the average values obtained from data forming the network’s response graphs confirm the average values of leg segment and monofin strain, thus making possible the achievement of maximum swimming speed in the group of swimmers tested (Figure 2). The values on the network response graphs oscillate around 180°, meaning that foot and monofin surfaces are placed in a line, according to swimming direction. This type of segment positioning can be interpreted as a stipulated neutral setting, the consequence of which are propulsive upward and downward movements. The standard deviation values obtained from the response graph data indicate the limits to which the angular parameters of leg segment displacement and the monofin strain analyzed achieve optimal (model) values in terms of the possibility to achieve, by a particular swimmer, maximal swimming speed. It needs to be emphasized that the limits mentioned are not a mathematical calculation of unreal swimming activity, but rather a representation of movement structures possible to execute during monofin swimming. This is a key fact in the functional understanding of the model.

Optimal angular changes, which were acknowledged as a model, go beyond the limit of the 180° value, except flexion at the angle of the feet toward the shin (α_{ankle}; Table 3). Only in this parameter was a direct proportional dependence in relation to horizontal swimming velocity recorded (Figure 2). The results explain the fact that the scope of foot movements is limited in plantar and dorsal flexion, whereas parts of the monofin’s surface can freely move up and down in relation to horizontal position (180°).

The optimum foot displacement range in relation to the shin (α_{ankle}) is shown in the limitation of movement to around 160° (–20°) in downward movement. The optimal range of foot displacement in downward movement is greater than 20° compared with the range of foot displacement in the upward phase. The optimal strain on the proximal part of the fin is limited by section to 145°–156° (35°–24°) in the downward phase and to 204°–207°, (–)24° to (–)27°, in the upward (Table 3). The maximum values in the range described are greater than 8° for downward movement. In the case of angular displacement at the proximal part of the fin (α_{tail}), a difference between maximum values of standard deviation (marked as optimal [model] range of fin strain at distances of 25 m and 50 m) was recorded. The difference was 11° (Figure 2, Table 3). The optimal angle of attack of the distal part of fin (β_{distal}) and its entire surface are limited in the downward phase to 143° (37°) and also in the upward, to around 206° (–26°) (Table 3). The difference among the angle of attack values considered amounts to approximately 11° of downward phase advantage. The view of optimum angular displacement of feet and monofin segment strain confirms the true analysis of propulsive movement (Figure 3). The results suggest a larger optimal range of foot displacement and monofin segment strain in downward movement compared with the upward phase.

Table 3 shows the percentage values illustrating how large a role the change of the range of angle, establishing foot displacement and monofin segment strain (on response graphs), plays in determining the ranges acknowledged as optimal (model). Results show that the optimum degree of angular displacement of the foot and monofin segment strain, to get maximum swimming speed, is based on the utilization of only part of the performed movements mentioned in the segment ranges.

The inclination of the network response graphs demonstrates the foreseen dynamics of monofin swimming velocity, in terms of changes in movement cycle, etc.

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**Table 3** Maximal and minimal standard deviation values as the borderlines within which angle changes of the analyzed leg segments displacement and monofin strain take optimal (model) values in terms of possibility to gain maximal swimming speed

<table>
<thead>
<tr>
<th>Values of the Angles in Optimal Range</th>
<th>Percentage of Angle Optimal Range Into Entire Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 m</td>
</tr>
<tr>
<td>SD_{max}</td>
<td>SD_{min}</td>
</tr>
<tr>
<td>180.36</td>
<td>160.53</td>
</tr>
<tr>
<td>156.54</td>
<td>207.07</td>
</tr>
<tr>
<td>143.94</td>
<td>207.31</td>
</tr>
<tr>
<td>143.64</td>
<td>204.00</td>
</tr>
</tbody>
</table>

*Note: Foot flexion angle toward shin (α_{ankle}); proximal fin part strain angle toward foot (α_{tail}); angle of attack of the distal part (β_{distal}); and angle of attack of entire surface of the monofin (β_{surface}).*
Figure 2 — Network response diagrams illustrating borderlines (marked by the standard deviation values) in which the analyzed angular parameters of leg segment displacement and monofin strain take optimal (model) values in terms of possibilities to gain maximal swimming speed.

- $\alpha_{\text{ankle}}$ - Foot flexion angle towards shin (Knee-Ankle-Tail(fin))
- $\alpha_{\text{tail}}$ - Proximal fin part strain angle towards foot (Ankle-Tail(fin)-Middle(fin))
- $\beta_{\text{dist}}$ - Angle of attack of distal part of fin (Middle(fin)-Edge(fin)-HOR)
- $\beta_{\text{surface}}$ - Angle of attack of entire fin surface (Tail(fin)-Edge(fin)-HOR)

- Average values obtained from the data composing the network response graphs regarding foreseen average values of leg segments and monofin’s strain, which make achieving maximum swimming speed possible.
- Standard deviation values obtained from the data composing the response graphs, indicate limits, in which the analysed angular parameters of leg segment displacement and monofin strain take optimal (model).
Figure 3 — Real swimmer’s movement illustration recorded during the research and corresponding characteristics of the analyzed angle leg displacements and monofin strain in the fragments of movement cycle essential in terms of swimming velocity.
as a result of angular changes of leg displacement and monofin strain (Figure 2). Table 4 illustrates the dimensions of the increase in velocity of the movement cycle, in the area of optimal (model) angular changes of analyzed parameters. Interpretation of aspects of the model’s results allows us to accept that the range of foot displacement in relation to the shin ($\alpha_{\text{ankle}}$), has a greater influence on the optimal swimming velocity obtained. Whereas with strain on the proximal part of the monofin ($\alpha_{\text{tail}}$), the influence on swimming velocity is smaller and comparable to the influence of the optimal dimension of the angle of attack of the distal part ($\beta_{\text{distal}}$). The least important aspect of efficient propulsion generation is the strain (attack angle) on the entire monofin surface ($\beta_{\text{surface}}$).

Maximum swimming velocity in the optimal ranges of foot displacement and monofin strain limits (established by standard deviation values) does not vary much from the maximum velocity indicated on the network response graphs (Table 4). The high percentage values of the above-mentioned specifications testify to the high efficiency of the optimizing movements (model) of the leg segments and monofin.

Analysis of the average values of distribution and standard deviation in the response graphs confirms a certain regularity as a result of the optimal degree of angular foot displacement and the segments of monofin under consideration (Figure 2). Considering all examined parameters, the optimal angular changes are situated in the $64^\circ$ section. This type of section seems to be justified by the variety of movement structures connected with the displacement of the segments examined during swimming. A similar analysis in the area of intracycle swimming velocity points to an increase of around 0.8 m/s within a range of 2.0 to 2.8 m/s. This result suggests that the optimal degree of change to the range of angle of the parameters examined corresponds to the maximal and submaximal velocities obtained in a monofin movement cycle.

### Discussion

The same group of swimmers was examined in both stages of the experiment, in the same conditions, with the use of the same research tools—i.e., a neural network of identical construction. The networks created in the first step of the experiment were verified in the theoretical aspect (Rejman & Ochmann, 2007). The same neural network used in the current study generated very similar results, indicating the same parameters as in the first version. Results of sensitivity analyses (Table 1) and regression statistics (Table 2) confirm the high quality of the network used.

The results of network response (Figure 2) corresponded to the swimmer’s movements recorded and their kinematic characteristics (Figure 3). This fact validates the results within the empirical (realistic) aspect. Therefore, there is now a basis for interpretation of the model of established parameters of monofin swimming, whereas the high calculation possibility of the network in the range of applied analysis for new cases (Table 2; testing set) determines the starting point for the application of the solutions modeled in the practice of assessment of monofin swimming technique.

Results specifying the optimal scope of foot displacement ($\alpha_{\text{ankle}}$) indicate that to gain maximal velocity during the upward movement, it is essential to limit dorsal foot flexion ($-20^\circ$) from the parallel position toward the shin ($180^\circ$). Whereas during downward movement, plantar flexion should not exceed $180^\circ$. Standard deviation values point to the following optimal monofin segment strains: the proximal part of the fin ($\alpha_{\text{tail}}$) at $35^\circ$ in the downward movement and ($-27^\circ$ in the upward; in angles of attack of the distal part of the fin, and its entire surface ($\beta_{\text{distal}}$, $\beta_{\text{surface}}$), $37^\circ$ in the downward movement and ($-26^\circ$ in the upward. In both movement phases, maximal swimming velocity corresponds to the angle of foot displacement and to the positioning of the monofin segments in one line at the optimal angle of attack (Figure 3, panels A, C, D). Thus, it

<table>
<thead>
<tr>
<th>Values of Velocity in Optimal Range of the Angles</th>
<th>Velocity Increasing in Optimal Range</th>
<th>Percentage of Maximal Velocity Increasing in Optimal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>V&lt;sub&gt;max&lt;/sub&gt;</td>
<td>V&lt;sub&gt;min&lt;/sub&gt;</td>
<td>V&lt;sub&gt;max&lt;/sub&gt;</td>
</tr>
<tr>
<td>2.78</td>
<td>2.08</td>
<td>2.8</td>
</tr>
<tr>
<td>2.6</td>
<td>2.12</td>
<td>2.75</td>
</tr>
<tr>
<td>2.36</td>
<td>1.98</td>
<td>2.36</td>
</tr>
<tr>
<td>2.36</td>
<td>2.16</td>
<td>2.36</td>
</tr>
</tbody>
</table>

Note: Foot flexion angle toward shin ($\alpha_{\text{ankle}}$); proximal fin part strain angle toward foot ($\alpha_{\text{tail}}$); angle of attack of the distal part ($\beta_{\text{distal}}$) and angle of attack of entire surface of the monofin ($\beta_{\text{surface}}$).
seems that the optimal scope of foot flexion and the maximization of monofin surface positioning at optimal attack angle, in both movement directions, might be interpreted as factors deciding the highest monofin swimming speed in the sense of the model.

Results suggest that swimming velocity obtained as a result of downward movements is slightly greater than that obtained in upward movements (Tables 3 and 4). In addition, analysis of response graphs together with graphs registering horizontal intracycle velocity (Figures 1 and 2), confirm the argument that decreases of intracycle velocity during monofin swimming are inevitable (Rejman et al., 2003b). The interpretation of the results in terms of maintaining maximal speed in both movement phases suggests that, during downward movement, swimmers are obligated to make an earlier initiation of the upward movement of the feet (with knees straightened, just before the end of downward motion) to avoid swimming parallel to the direction of the monofin’s position. The only way to maintain maximal velocity in the upward phase is through the optimal extension of leg lift time (with knees straightened) at optimal dorsal flexion of the feet.

Swimming speed is the result of positioning the monofin at a proper angle of attack to make use of the horizontal components of the reaction acting in opposition to the swimming direction (Schleichauf, 1979; Yi-Chung & Hay, 1998; Rejman et al., 2003a). Comparisons between the propulsive movements of monofin swimming and those of fish confirm the importance of lift and thrust in effective propulsion (Daniel, 1984; Wolfgang & Anderson, 1999). In this area of the propulsion generation process, the angle of attack of the entire surface of the monofin seems to play a more important role than the angle of attack of the distal part of its surface. The reverse relationship takes place when the angle of attack of the monofin is considered as an important factor in determining the direction of movement of added water mass. When the additional water mass is pushed out by the monofin in a perpendicular direction to the rear, it becomes an additional source of propulsion (Colman et al., 1999). The maximum value of energy gained from the rotating water mass appears when water breaks from the fin. The horizontal velocity of the swimmer decreases in this phase of cycle (Colman et al., 1999; Rejman et al., 2003b). In this context, the role of the angle of attack (and additional water mass) is extended in terms of maintaining the highest swimming speed possible for a longer period of time.

The minimal velocity of subsequent cycle phases appears when the tail and the edge are connected in a straight line parallel with the direction of swimming (Figure 3B, E). There is no basis for generating propulsion in such conditions. The least favorable monofin position from the point of view of propulsion efficiency takes place during the transition from upward to downward movement and vice versa (Colman et al., 1999). The minimal velocity in the upward movement is also the lowest velocity in the cycle. The unfavorable monofin position in this phase is accompanied by flexion at the knee joint, which facilitates laminar water flow over the monofin. When water slides off the monofin’s surface, no hydrodynamic sources of propulsion can arise. In addition, upward shin movement (in the direction of swimming) produces resistance. The forward movement of the swimmer is a result of the activity of inertial force in the preceding effective phase of the cycle.

The suggestions formulated as to the decreased velocity limit in the movement cycle are confirmed by Gavilan et al. (2006). They proved that as a result of undulatory movements accompanied by wave resistance, the shape of the fin’s surface changes, causing a negative phenomenon. To minimize this, it is necessary to minimize the amplitude of monofin movements while increasing stroke length. In unsteady flow, the trajectory and shape (strain) of the monofin play a dominant role in inducing vortices (Ungerechts et al., 1999). Propulsive movements with unstable velocity result in the creation of unsteady vortices and their uncontrolled distribution has a negative impact on the structure of propulsive forces (Arellano & Gavilan, 1999a). Therefore, the constant rotation of the vortex is a measure of advanced monofin swimming technique. This constant rotation (rhythm) results from a linear increase of velocity until the vortex breaks away from the monofin’s surface (Wu, 1968, 1971; Vilder, 1993). The minimizing of movement amplitude also results in reducing the time for positioning the monofin in a streamlined position. Delay in beginning knee flexion helps to minimize the decrease in swimming velocity in the upward movement (Rejman, 2006). The suggestion mentioned could be used in an interpretation of the modeling aspect in terms of optimization of monofin movements to limit velocity decrease in the cycle.

Foot displacement and monofin strain to generate propulsion can be interpreted as analogous to fish movement. Eel-like movements are characterized by the sinusoidal trajectory of all body segment displacement (Vilder, 1993). In a model sense, equal proportions of propulsive forces are maintained during both cycle phases (Rejman, 1999). The “perfect” ability of fish to swim is a credit to an optimized kinematic propulsive movement structure resulting in a high intracycle velocity, which is a condition for gaining maximal swimming speed.

Monofin swimming skills based on limited (model) foot displacement and monofin segment strain do not limit the actual possibility of obtaining maximum swimming speed. As mentioned above, an analysis of changes of swimming velocity in the movement cycle (Figure 2) suggests that the optimal degree of angle change in the parameters scale examined corresponds with the maximal and submaximal speeds obtained in the monofin movement cycle. This opinion confirms the high efficiency of optimal movements, in relation to their full scale, as illustrated in the response graphs (Table 2 and 3). As concerns shin–ankle joint movements (αankle)
almost half of the range of angular displacement determined by the network is outside of optimum limits. Thus, it does not have a direct influence on swimming speed. Likewise, the existing tendency among swimmers to engage in excessive dorsal flexion of the feet (down movement phase), does result as an infracycle velocity increase, and should be limited. On the response graphs, the proximal part of fin strain (\(\alpha_{\text{tail}}\)) is more than nearly 50% above optimal values. The fact that there is a difference between maximum standard deviation values, determined for this parameter over distances of 25 m and 50 m, suggests that optimization of the structure of propulsive movement can lead to the emergence of reserves concerning maximum speed over a determined distance.

During a swim of 50 m, the potential possibilities of optimal strain (in tail) maintenance in the proximal part of the monofin, as determined over a distance of 25 m, create the possibilities for an approximate increase of 0.14 m/s in swimming speed (Figure 2). This illustrates the essential time of distance beating improvement (0.35 s). In terms of the distal part of the fin, and its entire surface (\(\beta_{\text{distal}}, \beta_{\text{surface}}\)), angles of attack of over 45% of registered changes in range are outside of the determined optimum. The results presented confirm the suggestion, already formulated, that an excessive amplitude of propulsive movements (strain on tail and proximal part of fin and its entire surface) does not stimulate an increase in swimming speed. It seems that effective propulsion is not a direct consequence of characteristic changes in the fin to stiffen its surface (Figure 3B, C). The results obtained allow us to propose that optimal dorsal flexion of the feet during downward movement limits the strain on the monofin’s tail and results in a decrease of the angle of attack of the proximal part of the monofin. Optimal dorsal flexion of the feet during upward movement with greater tail strain favors an increase of the angle mentioned during the upward phase. As a consequence, angles of attack of the distal part of the fin, and its entire surface, also assume optimal values securing similar monofin strain in both phases of the movement cycle. The mechanism described produces an equal proportion of propulsive force generation during both phases, which favors the maintenance of a constant monofin swimming speed and is an essential criterion of monofin swimming quality (Rejman, 1999). Consequently, it can be suggested that in monofin selection for each swimmer, the flexibility of the fin’s tail as a source of consciously generated torque transfer over a passive monofin surface should be considered. The stiffness of the fin’s surface should be greater than the stiffness of the tail but flexible enough to assume a shape supplying a source of additional propulsive forces—spinning motion and additional water mass—when possible.

With the above generalizations in mind, it is necessary to turn our attention to the need for a range of foot displacement in both phases of the movement cycle, as they work under considerable load occurring from water resistance. It is essential to eliminate the tendency to amplify the movement of the monofin. There are no grounds for using fins with greater stiffness during training and competition. Ignoring the suggestions formulated above may lead to excessive burden on the shin–ankle joints, injury, and pathological overload conditions (Rejman & Frackiewicz, 2008). The optimal degree of angular foot and fin segment displacement while training seems to result in a certain degree of success. In this context, considering the optimal degree of angular displacement of the feet and monofin segments in training seems to be an element in achieving success.

Regularities visible on the response graphs of the network correspond with the records of actual swimmer movements, and their kinematics characteristics. The credibility of the results in a practical sense is seen in the results obtained, which were the tools for interpretation of the model of the defined parameters of monofin swimming technique. All important, from the point of view of maximizing swimming speed, seems to be the need for leg movement in the shin–ankle joints during limited propulsive movements. The tail of the fin plays an important role in the efficient generation of propulsion and mobility, which stems from the quality of torque produced with the legs in monofin surface transfer. The quality of the transfer increases mentioned, together with the limitation of amplitude in propulsive movement (reduction of monofin segment strain during downward movements and the increase of the monofin’s upward movement scale with straight shin–ankle joints) suggests conditions forming a basis for intracycle velocity stabilization on a high level, leading to the achievement of maximal monofin swimming speed.

**References**


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