©Journal of Sports Science and Medicine (2007) **6**, 193-203
http://www.jssm.org

Research article

Functional model of monofin swimming technique based on the construction of neural networks

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Abstract
In this study we employed an Artificial Neuronal Network to analyze the forces flexing the monofin in reaction to water resistance. In addition we selected and characterized key kinematic parameters of leg and monofin movements that define how to use a monofin efficiently and economically to achieve maximum swimming speed. By collecting the data recorded by strain gauges placed throughout the monofin, we were able to demonstrate the distribution of forces flexing the monofin in a single movement cycle. Kinematic and dynamic data were synchronized and used as entry variable to build up a Multi-Layer Perception Network. The horizontal velocity of the swimmer's center of body mass was used as an output variable. The network response graphs indicated the criteria for achieving maximum swimming speed. Our results pointed out the need to intensify the angular velocity of thigh extension and dorsal flexion of the feet, to strengthen velocity of attack of the tail and to accelerate the attack of the distal part of the fin. The other two parameters which should be taken into account are dynamics of tail flexion change in downbeat and dynamics of the change in angle of attack in upbeat.

Key words: Kinematics, dynamics, leg and fin movements, modeling.

Introduction

The information flow between swimmer and coach must be objective and of a precisely determined quality. Such criteria may be assessed by applying biomechanical methods, including modeling. Modeling is a process related to the description of a technique, which based on physical or mathematical correlations, reflects the subject of the study and thus creates the possibility to optimize the technique. The concept of the functional model of swimming is based on the development of a deterministic model, i.e. the correlation between measurable performance and the features determining the outcome (Hay, 1985; Reischle and Spikermann, 1992).

The utility of the Artificial Neural Network as a modeling method is based on the correlation between describing variables and described variables in dynamic processes of a probabilistic nature. This makes it a useful tool in sports - including swimming. In this method of modeling the logical set of physical correlations determines the mechanism for achieving maximum swimming speed. Modeling based on Neural Networks, with respect to traditional swimming (Edelmann-Nusser et al., 2001; Mujika et al., 1986), is an example of this.

The one-dimensional structure of monofin swimming is much easier to analyze than that of "traditional" swimming. The detailed biomechanical structure of monofin movements were described earlier: (Arelano and Gavilan, 1999a; 1999b; Colman et al., 1999; Rejman et al., 2003a; 2003b; Ungerechts, 1982a; 1982b) and to the present kinematic (Shuping, 1989; 2000a; Shuping et al., 2000b; 2002; Szilagyi et al., 1999; Tze Chung Luk et al., 1999) and dynamic (Rejman 1999; Rejman et al., 2004) criteria of efficient monofin swimming have been defined as well. Physical and mathematical modeling of monofin movements were preformed earlier by Wu (1968; 1971). However, our study is the first trial in the construction of a functional (applicable to practice) model of monofin swimming.

The aim of the study was to select, by means of Artificial Neural Networks, the kinematic parameters of leg and monofin movements and to compare them with the forces flexing the monofin in reaction to water resistance. The analysis of these parameters further allowed us to construct a functional model the of monofin swimming technique. Thanks to this model we were able to define how to use a monofin efficiently and economically to achieve maximum swimming speed.

Methods

Eleven male swimmers, 15-18 years old, volunteered for the study. As members of the Polish Monofin Swimming Team all of them displayed a high level of swimming proficiency. The body composition of all the swimmers was comparable. They covered a distance of 25 m underwater at a maximum speed while holding their breath.

One handmade monofin (standard size and medium flexibility) was used for all the trials. Pairs of strain gauges were attached to the monofin at the tail and in the middle, in the symmetry axis of its surface (Figure 1A).

The raw data collected by the gauges was expressed as voltage change time series, which are defined as changes in the forces flexing the monofin in reaction to water resistance (Rejman, 1999, Rejman, et al., 2003a). Impulses from the gauges (sagging fin) were amplified, converted and recorded by a computer at a frequency of 50Hz.

The scaling of the monofin involved exposing its surface to different weights, which mass had been predetermined at 1 kG and recording the degree of flexion in a selected frame of reference (Figure 1B). Five measuring points were marked on the symmetry axis. The first on

Received: 26 July 2006 / Accepted: 20 February 2007 / Published (online): 01 June 2007

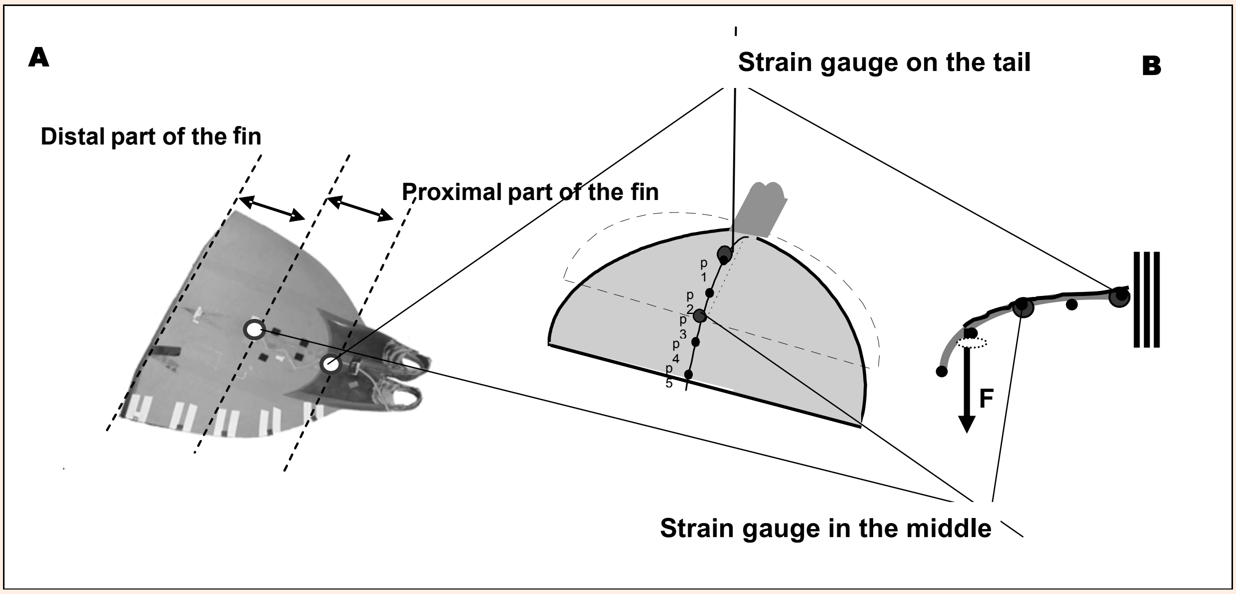

Figure. 1. The monofin used in the research with the strain gauges marked, dividing the monofin into front and end parts (A). Illustration of the monofin scaling concept consisting of simulating balanced load on its surface at each point where flexing force was applied (B).

the tail and the last one on the edge, with distances between them equal. Thin lines were fixed at the front of the fin, then weights, bending the monofin, were hung on this line and put into holes placed in each of the marked points. In this way we created conditions simulating fluids imparting a distribution of loads overall surface of the monofin. The average value of voltage, with the same value of force applied, was calculated. This served to determine the scalability coefficient. The scaling procedures confirmed that the relationship between registered forces and degree of the bending of the fin is not linear (Rejman et al., 2003b).

In order to record the kinematic data of leg and monofin movement, all of the swimmers were filmed underwater. A digital camera was placed in the middle of the swimming pool, assuming that the swimmers and the monofin move only on a lateral plane and without insweep, upsweep or rotation movements (Rejman et al., 2003a). Reference points were the following: middle finger, wrist, elbow, shoulder, hip, knee, ankle and tail, middle and edge of the fin. Kinematic analysis of the movements was carried out using the SIMI® Analysis System. The results were expressed as time dependent series representing the angles of flexion of the leg and monofin and the angles of attack of the monofin surface parts (Figure2). Force sampling, synchronization and recording of the images were performed using SIMI® for a single cycle of each swimmer (upward and downward movement of the monofin edge).

Horizontal velocity of the swimmer's centre of body mass in a randomly chosen movement cycle was selected as the output variable of the network, while 23 input variables were used to define model relations against the output variable (Table 1).

To select a genetic algorithm, verified stepwise backwards and forwards, other neural nets, such as Generalized Regression Neural Networks and Probabilistic Neural Network (Speckt, 1990; 1991), were used. Subsequently, the features were selected and attributed to particular groups of networks. The best model, with the lowest number of errors, was selected from several tested models. The model's development 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 three sets: training, validation and testing. Based on the training set the neural net model was constructed. The validation set

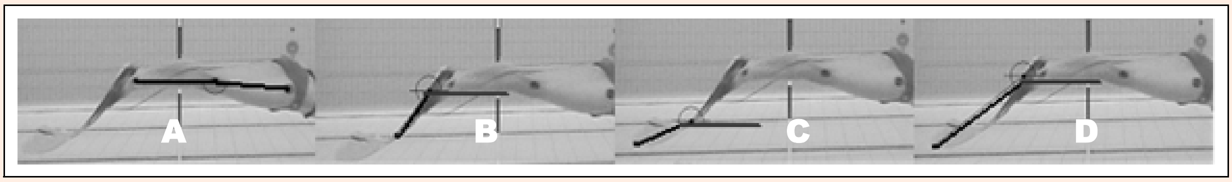

Figure 2. Examples illustrating procedure for defining angles of flexing of body segments and monofin and based on points marked in the axes of joints and tail, in the middle and on the edge of the monofin. A – Angle of flexion in knee joints, B – angle of attack of the monofin's front part, C- angle of attack of the end part of the monofin, D - angle of attack of the entire surface of the fin.

Table 1. The input variables generated by artificial neural network which were used to define functional model of monofin swimming relations (classification, names and symbols of the parameters calculated by the network).

			PARAMETERS AND SYMBOLS		
	Part of the monofin/ lower limb	**Points marked on the monofin /body surface**	**ANGLES OF FLEXION ON THE MONOFIN'S**	**ANGULAR VELOCITIES OF THE MONOFIN FLEXION**	**ANGULAR ACCELERATIONS OF THE MONOFIN FLEXION**
MONOFIN	Tail	(Ankle-Tail-Middle)	(α_T)	(ω_T)	(ε_T),
	Middle	(Tail-Middle-Edge)	(α_M)	(ω_M),	(ε_M)
			ANGLES OF ATTACK OF THE MONOFIN	**ANGULAR VELOCITIES OF THE MONOFIN ATTACK**	**ANGULAR ACCELERATIONS OF THE MONOFIN ATTACK**
	The entire surface	**(Tail-Edge-Horizontal)**	(β_{EH})	(ω_{EH})	(ω_{EH})
	Proximal part	**(Tail-Middle-Horizontal)**	(β_{PH})	(ω_{PH})	(ε_{PH})
	The distal part	**(Middle-Edge-Horizontal)**	(β_{DH})	(ω_{DH})	(ω_{DH})
	Water resistance forces		**FORCES FLEXING THE TAIL**		**FORCES FLEXING THE MIDDLE**
			(F_T)		(F_M)
LOWER LIMBS			**ANGLES OF FLEXION ON THE LEGS**	**ANGULAR VELOCITIES OF THE LES FLEXION**	**ANGULAR ACCELERATIONS OF THE LEGS FLEXION**
	Knee joints	**(Ankle-Knee-Hip)**	(α_K)	(ω_K)	(ε_K)
	Shin-ankle joints	**(Knee-Ankle-Tail)**	(α_A)	(ω_K)	(ω_K)

was the basis for checking the network's "learning" results (this was not done while constructing the model). The testing set enabled an independent assessment of network quality. Data used in particular sets was chosen randomly, maintaining similar mean values and standard deviations.

For the preliminary interpretation of the network model, sensitivity analysis and regression statistics were applied. The analysis of sensitivity provides additional information concerning the influence of particular variables on the output parameter. Sensitivity parameters were calculated for each variable shown in the model, separately for the training set and the validation set. Sensitivity was described on the basis of the values of rank, error and quotient. Error shows the network's quality with the lack of a given variable (important variables give higher rank). Quotient is a result of dividing error by error obtained with the use of all variables. The value of a quotient lower than one shows a parameter, which disturbs the network's quality. Such values have been eliminated from the model. 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 regression statistics tables and set out independently for the training, the validation or the testing sets. They have the following attributes: an average error for output variables (difference between a given value and the output value); an average absolute error for output variables (difference between a given value and the output value); a Pearson's standard correlation ratio for a given value and the output value; a standard deviation of error for output variable and standard deviation quotient for errors and data. Response graphs were used to display graphically particular correlations between input and output variables.

Results

In the first step we sorted out the parameters, which in the ranking of Neural Network sensitivity showed the highest relation to horizontal velocity of the swimmer's centre of body mass. Sixteen parameters were selected out of twenty three. Next, these parameters were grouped to select techniques influencing swimming speed. (Figure 3).

The groups served to construct a functional model (Figure 4). Three levels of generalization were set to build up the model. The first level contained the elements of the monofin swimming technique, which determined the swimming speed. The highest diagnostic role of parameters placed on this level resulted from features, which were on the top of the ranking of parameters created by Neural Network. The second level was created on the basis of direct correlations between features and achieved speed (Table 2). For that reason the parameters on this level were specified as directly influencing swimming speed. The parameters indirectly influencing swimming speed were placed on the third level. These parameters reflect the existence of a correlation between the swimmer's horizontal velocity and the forces flexing the monofin (Rejman, et al., 2003b).

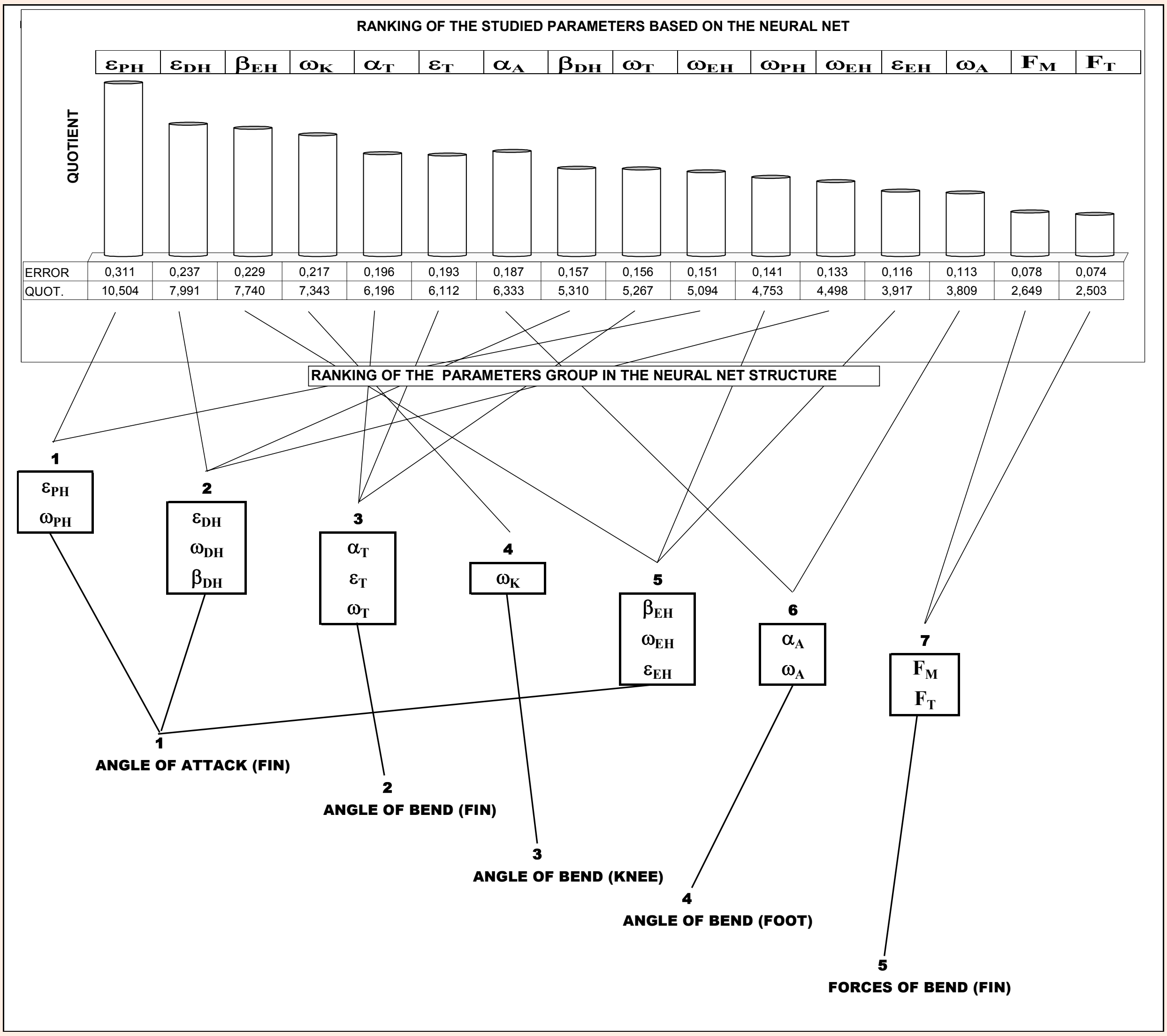

Figure 3. Results of the network sensitivity analysis according to ranking of the standard deviation quotient against output variable (horizontal swimming velocity) which allow ordering of the parameters together into groups of features, techniques of monofin and the leg movements. These parameters were used for constructing a functonal model of monofin swimming technique. Angles of flexion: on the monofin's tail – (α_T); monofin's middle – (α_M); knee joints – (α_K); shin-ankle joints – (α_A). Angular velocities of flexion monofin's tail – (ω_T); monofin's middle - (ω_M); knee joints (ω_K) and shin-ankle joints - (ω_A) Angular accelerations of flexion monofin's tail – (ε_T); monofin's middle - (ε_M); knee joints - (ε_K) and shin-ankle joints (ε_A). Angles of attack of the monofin: entire surface – (β_{EH}); proximal part – (β_{PH}); and distal part – (β_{DH}). Angular velocities of attack: entire surface - (ω_{EH}); proximal part - (ω_{PH}); distal part (ω_{DH}) Angular accelerations of attack: entire surface - (ε_{EH}); proximal part- (ε_{PH}); and distal part (ε_{DH}). Water resistance forces reacting on the monofin: forces flexing the tail (F_T); forces flexing the middle (F_M).

The model (Figure 4, 5) shows that the factors, which directly influence swimming speed can be attributed to the following 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 the angle of attack for the distal part of the fin;
3. The angle of attack, angular acceleration and angular velocity for the entire fin surface.

The parameters indirectly influencing swimming speed are related to:

1. The angle of flexion, angular acceleration and angular velocity of fin's tail;
2. The angular velocity of knee flexion;
3. The angle and angular velocity in shin-ankle joints.

The remaining elements flexing the monofin were the forces flexing in the middle and in the tail.

The model emerged from response graphs and interpreted on the basis of empirical background represented by the sequences of real movements (Figure 5, 6) pointed out some important correlations, which might be used to optimize leg and monofin movements in order to achieve maximum speed.

The model demonstrates that the increase in horizontal velocity of the swimmer's centre of body mass correlates with the velocity of leg flexion in the downbeat.

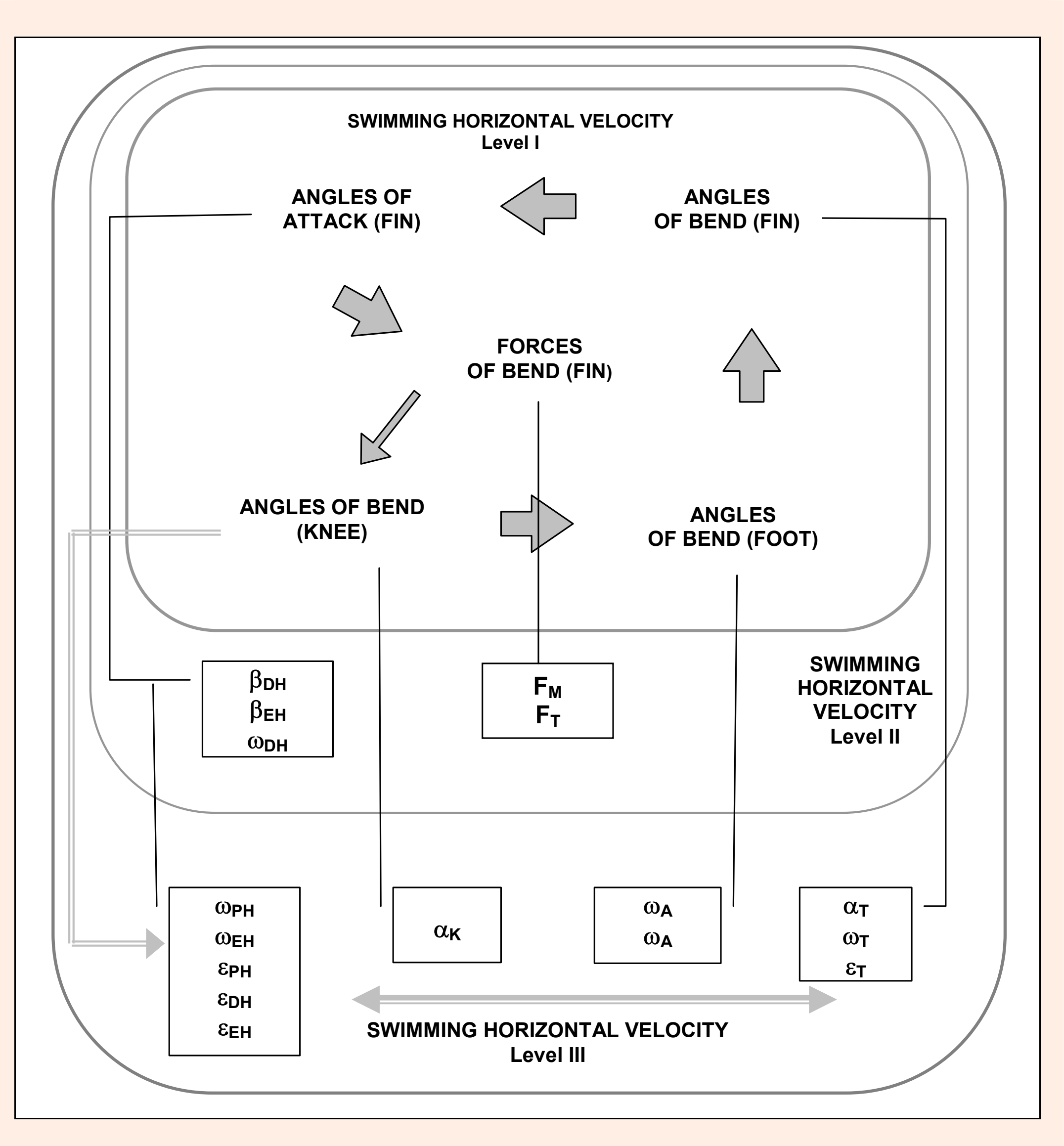

Figure. 4. Functional model of leg and monofin movements based on the mutual relations between horizontal swimming speed and the groups of features, techniques of monofin and leg movements (level I) and the parameters which directly (level II) and indirectly (level III) influence swimming speed. Arrows illustrate relations between elements of the model, lines indicate the parameters describing the elements of the model on its various levels, depending on the relations from the influence on swimming speed.

Moreover, the horizontal velocity of the swimmer's centre of body mass increases along with dorsal flexion of the feet in the same phase. Parameters of tail flexion also increase horizontal velocity relative to the downbeat. The high horizontal velocity of the swimmer's centre of body mass is achieved by high angular velocity in the upbeat. The movement of the proximal part of the fin increases the swimmer's velocity, only when done together with high angular acceleration in the upbeat and with high angular velocity in the downbeat. The higher is the angle of attack of the monofin's distal part in the downbeat phase, the higher is the swimming speed. Similarly, the movement of the entire surface increases horizontal velocity of the swimmer's centre of body mass when moving at a high angular acceleration in the downbeat, at high velocity in both phases and with a high angle of attack in the upbeat.

Results of the dynamics of the monofin indicate a correlation between the swimmer's horizontal velocity and the forces recorded in the fin's tail and in the middle of its surface in the downbeat. The resulting influence on velocity recorded in the middle of the monofin is significantly higher in comparison with forces flexing the tail. It seems that the kinematics and dynamics of the movement of the distal part of the fin affect the trajectory of the movement of its entire surface creating conditions for achieving maximum speed.

The role of forces flexing the monofin in increasing horizontal velocity of the swimmer is confirmed by the values of the correlation coefficient (Table 2). The forces generated in the middle of the fin depend on the changes in the angular velocities of the leg and monofin segments. Conversely, the forces flexing the tail are a consequence of the accelerated movements of the leg and monofin segments.

Table 2. Values of the significance of correlation coefficients between model parameters and the horizontal swimming velocity (A) and the forces flexing the monofin (B) used for classification of the role of parameters in levels I and II of the model (the ranking of the parameters pointed by neural networks are in brackets).

CORRELATION COEFFICIENTS			
PARAMETERS AND RANK	HORIZONTAL VELOCITY	FORCE MIDDLE	FORCE TAIL
(ω_{DH}) (2)	.55	.73	.86
(β_{DH}) (12)	.51	.80	.80
(β_{EH}) (3)	.48	.82	.75
(F_M) (15)	.50		
(F_T) (16)	.46		

A

CORRELATION COEFFICIENTS			
FORCE TAIL	PARAMETERS AND RANK		FORCE MIDDLE
.86	(ω_K) (4)	(ω_K) (4)	.86
.80	(ω_{EH}) (11)	(ε_{EH}) (13)	.79
.79	(ω_{PH}) (10)	(ε_T) (6)	.75
.78	(ω_T) (5)	(ε_{DH}) (2)	.73
.78	(ε_{PH}) (1)	(ε_{PH}) (1)	.70
.71	(ω_A) (9)	(ε_A) (14)	.67
.60	(α_T) (5)	(ω_T) (5)	.66
.59	(ε_{EH}) (11)	(α_A) (7)	.65
		(ω_{EH}) (11)	.64
		(α_T) (5)	.63
		(ω_{PH}) (10)	.54

B

An analysis of the results implies that in order to achieve maximal speed the swimmer should intensify:

1. The velocity of thighs and dorsal flexion of the feet in the downbeat.
2. The tail's angular velocity in the upbeat.
3. The velocity of the angle of attack in the distal part of the fin in the upbeat and the downbeat.
4. The forces generated on the monofin's surface in downbeat.

The other two parameters which should be taken into account are:

1. The dynamics of tail flexion change in downbeat.
2. The dynamics of the change in angle of attack in upbeat.

Discussion

The high value of the standard deviation quotient (Table 3) is the main indicator of the quality of the monofin swimming model created by the network. The similarity between the values of quotients and errors in the teaching and validation tests are also apparent. This indicates the importance of the constructed model to real life swimming conditions. The diagnostic value of the parameters indicated by the Artificial Neural Networks can also be interpreted through the error values.

On this basis one can conclude that if the most significant parameters, which described the angular accelerations of the proximal and distal parts of the fin as well as the entire monofin's surface attack, are not taken into account, the diagnostic value of the model decreases by 22%-31%. This argument implies that the network was chosen properly for the process analyzed, and that the model may be used to assess the monofin swimming technique.

Among the parameters defined by the network the angle of attack and the angles of monofin flexion are crucial for achieving maximal swimming speed. The angle of monofin flexing at a given point is defined by angles of attack of its parts in relation to this point. Positioning of the monofin in relation to the feet was interpreted in a similar way. The angle of attack was classified as a factor determining position in relation to swimming direction (movement trajectory) and the direction of the water flow around the surface (monofin shape). The optimum range of the angle of attack ensures the effective use of the propulsive force components (Schleichauf, 1979; YI-Chung and Hay, 1998). In unsteady flow, the trajectory and the shape of the monofin play a dominant role in inducing surface vortex (Ungerechts et al., 1999). Within the proportional correlation between the angle of attack and the vorticity of the vortex - the Magnus Effect and Bernoulli's Theorem explain the development of an additional lift force component. In certain parts of the cycle (Figure.5, sequences 2, 3, 4) this acts in opposition to the swimming direction, thus creating propulsion.

Swimming speed is the result of positioning the monofin at a proper angle of attack and angle of flex in order to make use of the horizontal components of the reaction acting in opposition to the swimming direction (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 and Anderson, 1999). When interpreting the propulsion of the monofin based on

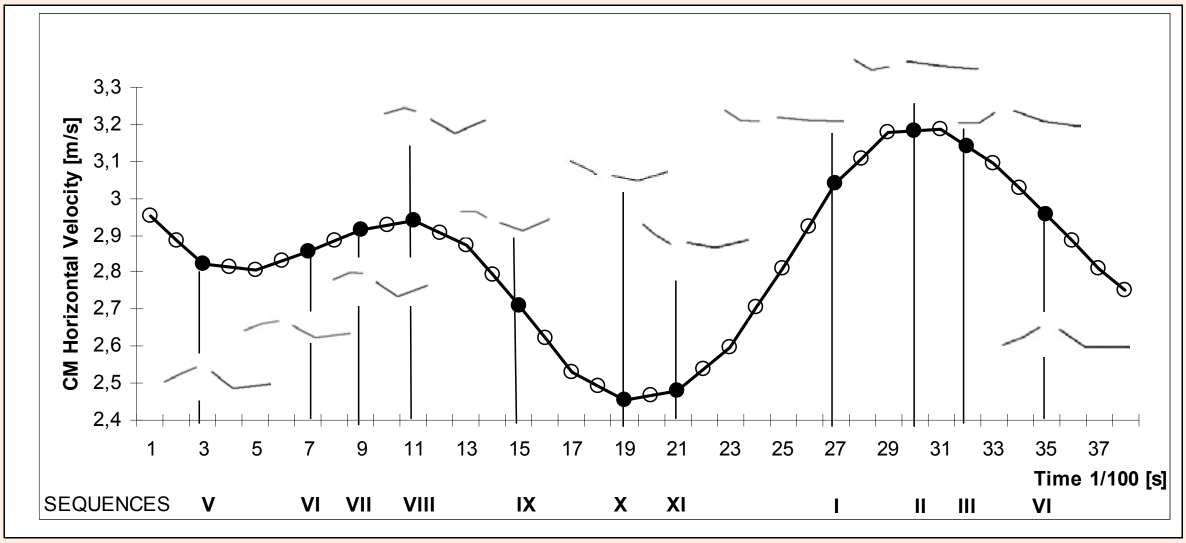

Figure 5. **Changes in horizontal swimming velocity with matching sequences of recorded leg segment movements and monofin movements – in one movement cycle.**

mechanism action – reaction is not limited to the use of thrust and lift - the angle of attack and the angle of flex determine the direction of movement of added water mass. When pushed backwards (Figure.5, sequences 2, 3, 4) this creates an additional source of propulsion (Colman et al., 1999).

Equating the velocities of points on the monofin with force recorded in those points is the result of the relation between drag and velocity (Rejman et al., 2003b). Therefore, the moment of force bending the monofin is a product of the force of reaction (measured in selected points on the monofin's surface) and its arm (the length of the parts of the monofin). The model can be represented by formulas describing dependencies between the momentum of the bending forces and the examined parameters, i.e. angle of attack, angle of flex (Equations1, 2), angular velocity (Equation 4), angular acceleration of attack and flexing (Equations 3, 4), and momentum of reaction force recorded in the tail and in the middle of the monofin (Equations 2, 3, 4).

In conditions of unsteady flow:

$$L = 2\pi\alpha\rho\frac{V^2}{2}\Phi(\tau) \Rightarrow [N] \qquad (1)$$

where: L – lift, ρ – water density, α – angle of attack, V – monofin's velocity, Φ(τ) Wagner's function.

$$M = F_R r_i = C\,\rho\,\frac{V^2}{2} S r_i \Rightarrow [Nm] \qquad (2)$$

$$C = 2\pi\alpha$$

where: F_r - drag; r_i – arm of the force bending the monofin in a given point (i), (tail and middle); α - angle of attack; V – monofin's velocity; S – cross-section of the monofin; C – ratio of the monofin's streaming.

$$M = I\frac{(\varpi_k - \varpi_p)^2}{2(\varepsilon_k - \varepsilon_p)\Delta t^2} \Rightarrow [Nm] \qquad (3)$$

where: M.- momentum of force; I- moment of inertia; ε- angular acceleration.

$$M = I\varepsilon \Rightarrow [Nm] \qquad (4)$$

where: M.- momentum of bending; I- moment of inertia; ϖk- final angular velocity; ϖp- initial angular velocity; εk- final angular acceleration; εp- initial angular acceleration; Δt- time change; Δγ- angle of turn.

The results (Figure 5, 6) support the mechanism arising from interpretation of the model at level I. In the first part of the downbeat (Figure.5, sequences 11-1), horizontal velocity of the swimmer increases. In the second part, the increase of this velocity is lower (Figure 5, sequences 1-2). Flexion increases the angular velocity of leg and foot movement when the legs are extended and "extends" the scope of force transferred to the monofin. In effect, the angular velocity of the legs increases together with the force of tail flexing. The dynamics of tail flexing stimulate swimming speed changing the shape of the monofin at the point of transfer of force, generated by the legs, to the monofin. Dorsal flexion of the feet affects the changes in the angle of attack. The resulting angle of attack positions the remaining part perpendicular to the swimming direction. Acceleration increases the mass of water circulating backwards and pushes the monofin back (Colman, et al., 1999). This complements the lift component. Part of the energy expended on accelerating the water mass is recovered thanks to the shortening of the time needed to generate propulsion.

The first phase of the upbeat is similar (Figure.5, sequences 6-8). The increase of the swimmer's horizontal velocity is lower than in the downbeat due to knee flexion. The monofin moves in line with the movement and does not generate propulsion. In this situation the intensification of acceleration of thigh movements does not flex the tail, ensuring proper positioning, as the proximal part of the monofin does not allow for positioning the distal part of the fin perpendicular to the swimming direction. Part of the energy expended is through decreased water resistance closest to the fin resulting from water circulation at the surface of the monofin. Additionally, upbeat acceleration "pushes" the swimmer forwards (Colman et al., 1999).

Table 3. Regression statistics table.

	SETS		
	TEACHING	VALIDATION	TESTING
ARITHMETICAL AVERAGE	2.84758	2.78802	2.89208
STANDARD DEVIATION	.36506	.33382	.37626
AVERAGE ERROR	-.00010	.00344	.00111
AVERAGE ERROR DEVIATION	.01956	.02956	.03442
AVERAGE ABSOLUTE ERROR	.01496	.02387	.02587
STANDARD DEVIATION QUOTIENT	.05357	.08854	.09149
CORRELATION	.99856	.99613	.99591

In sequences 3-4, horizontal velocity of the swimmer (v_H) drops. Because of knee flexion, the mass of water slides off the monofin. The drop in the swimmer's horizontal velocity is limited by the monofin's flexible energy (the thighs start to move upwards at the end of the downbeat phase). A drop in horizontal velocity also occurs in sequence 8-10. This results from the adjustment of the monofin shape to the direction of water flow. The added mass of water slides from under the monofin as it is no longer being accelerated (Colman et al., 1999).

Transition from the downbeat to the upbeat phase, results in a drop in horizontal velocity of the swimmer which is lower than the downbeat.

At the end of the downbeat, part of the energy expended on pushing may be recovered when the mass of water near the edge of the monofin circulates in a direction opposite to the movement and "pushes" it additionally from behind (Colman et al., 1999) (Figure.5, sequences 4-5). The minimum horizontal velocity of the swimmer was recorded in the last sequence of the upbeat (Figure.5, sequence 10,11) when the parallel positioning of both segments and the change of direction in movement do not constitute a basis for propulsion.

Diagnostic checking of the model at levels II and III was based on the correlation between horizontal velocity of the swimmer and the model's parameters directly influencing swimming speed (Table 2): angle of attack of the monofin's entire surface, angular velocity and angle of the monofin's distal part attack. The indirect influence of most parameters on speed is confirmed by the confrontation of model results with the significance of the correlation with forces flexing the monofin, presented in the Table 2.

Theoretical and empirical proof of the results provides a basis for the search for practical solutions aimed at optimization of leg and monofin movement technique to achieve maximum speed.

Adverse hydrodynamic conditions in the upbeat tend to minimize loss caused by adverse horizontal velocity of the swimmer changes due to this phase. Therefore, the upbeat seems to be an extra source of propulsion. The results suggest that the proximal and distal parts form reserves in the acceleration of attack. This is supported by the fact that the horizontal velocity of the swimmer depends on the dynamics of the upbeat (Rejman and Ochmann, 2005). Forces flexing the monofin are correlated with the acceleration parameters defined in the model. There are reasons to believe that the upbeat propulsion effect is dependent on constant angular acceleration. This is confirmed by the shorter time of increase in horizontal velocity in the upbeat than the downbeat phase. These generalizations are supported by the results of other studies. The power of leg movements in dolphin swimming drops proportionally to the change in velocity of those movements (Holmer, 1982). Avoiding sudden changes in the velocity of monofin affects the constant swimming velocity (Rejman, 1999). Propulsive movements with unstable velocity result in the creation of unsteady vortices and their uncontrolled distribution has a negative affect on the structure of propulsive forces (Arelano and Gavilan, 1999a). Therefore, the constant rotation of the vortex is a measure of advanced monofin swimming technique. This constant rotation (rhythm) results from the linear acceleration of velocity until the vortex breaks away from the monofin's surface. (Wu, 1968; Vilder, 1993).

Reserves in the upbeat may also be used in the reduction of the degrees of freedom of the legs (the limitation of the movements in knee joints and shin-ankle joints) and the controlling of the monofin's flexibility, which fulfils a certain function in the process of propulsion. This thesis is confirmed by the analogy between monofin swimming and Tuna fish swimming (Colman et al., 1999). As a result of undulatory movements accompanied by wave resistance, the shape of the fin surface changes, causing a negative phenomenon. In order to minimize this, it is necessary to minimize the amplitude of monofin movements while increasing stroke length. Consequently, the delay in the transfer of moments of force generated by the leg muscles and the forces flexing the monofin, normally characteristic in this phase, does not occur (Rejman et al., 2004).

At the current level of generalization, the optimization of leg and monofin movement technique is demonstrated in the extending of knee joints as quickly as possible in order to immediately flex the distal part of the monofin and therefore to position it perpendicular to the swimming direction. The continuation of the movement with maximum leg extension will allow extension of the amount of time a monofin of a given shape will move in the optimum trajectory, thus generating the maximum propulsion necessary to achieve maximum swimming speed.

The theoretical and empirical (realistic) verification created by the parameters indicate by Artificial Neural Networks, paves the way to creating a more detailed deterministic model, and requires the application of its elements to other groups of swimmers.

Conclusion

The analysis of the collected data confirmed the diagnostic value of the parameters indicated by Artificial

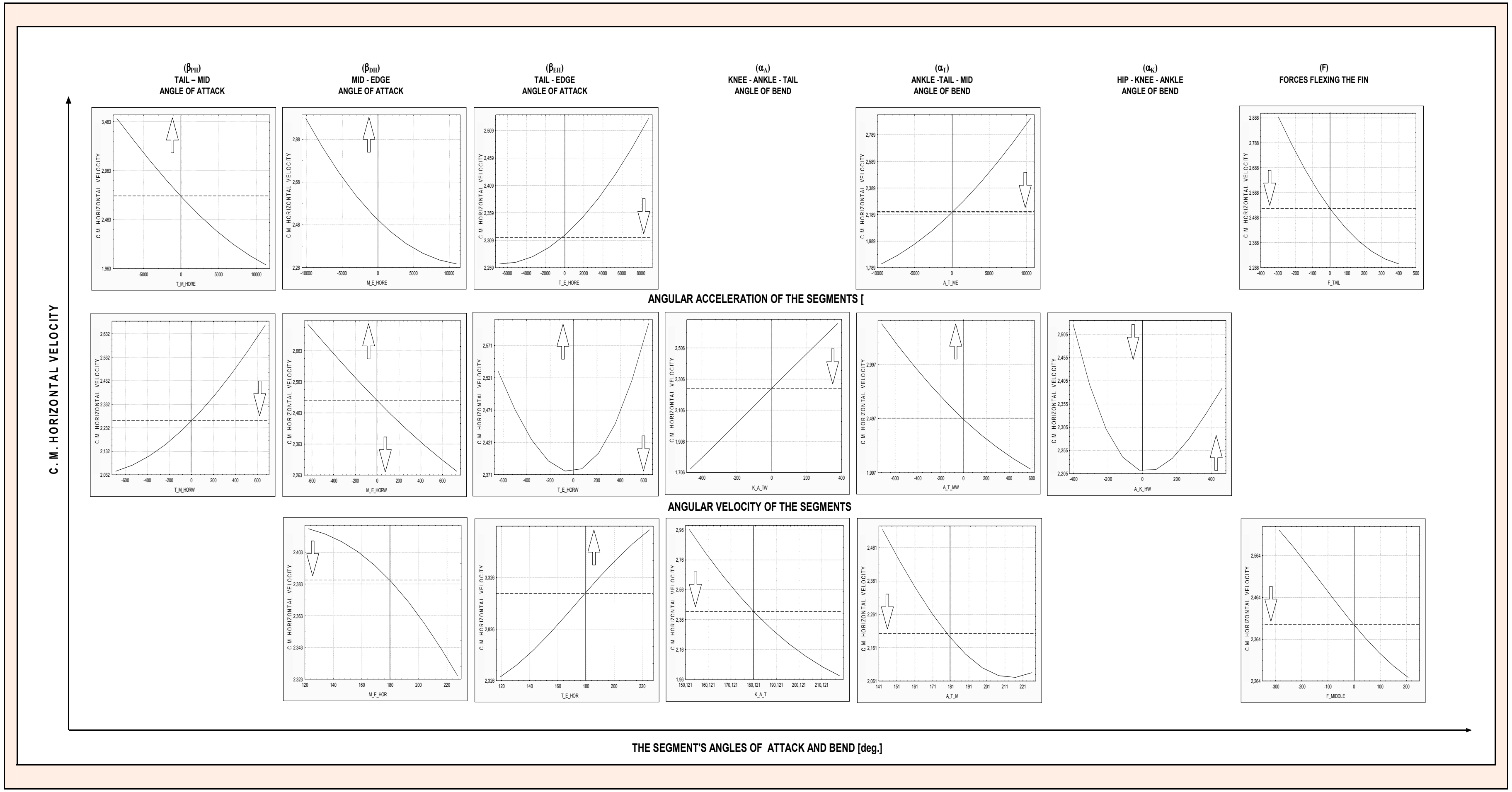

Figure 6. ANN response graphs illustrating the relations between swimming speed and parameters indicate by ANN which describe how the legs and monofin movement structure in down-beat and upbeat phases (direction of arrows) influenced on the infra-cycle swimming speed.

Neuronal Networks indicating that the model constructed on its basis may be used to assess the monofin swimming technique. The parameters defined by the network pointed out the need to intensify the angular velocity of thigh extension and dorsal flexion of the feet, to strengthen angular velocity of attack of the tail and to accelerate the attack of the distal part of the fin.

The other two parameters which should be taken into account are dynamics of tail flexion change in downbeat and dynamics of the change in angle of attack in upbeat.

Thanks to the model we were able to define how to use a monofin efficiently and economically. To achieve maximum speed a swimmer should utilize the reserves in the upbeat phases by the reduction of the degrees of freedom of the legs leading to controlling of the monofin's flexibility.

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Key points

- The one-dimensional structure of the monofin swimming creates favorable conditions to study the swimming technique.
- Monofin swimming modeling allows unequivocal interpretation of the propulsion structure. This further permits to define the mechanisms, which determine efficient propulsion.
- This study is the very first one in which the Neuronal Networks was applied to construct a functional/applicable to practice model of monofin swimming.
- The objective suggestions lead to formulating the criteria of monofin swimming technique, which plays the crucial role in achieving maximal swimming speed.
- Theoretical and empirical (realistic) verification created by parameters indicate by neural networks, paves the way for creating suitable models, which could be employed for other sports.

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