©Journal of Sports Science and Medicine (2013) **12,** 171-181
http://www.jssm.org

Research article

Analysis of Relationships between the Level of Errors in Leg and Monofin Movement and Stroke Parameters in Monofin Swimming

Marek Rejman
Department of Swimming, University School of Physical Education, Wroclaw, Poland

Abstract
The aim of this study was to analyze the error structure in propulsive movements with regard to its influence on monofin swimming speed. The random cycles performed by six swimmers were filmed during a progressive test (900m). An objective method to estimate errors committed in the area of angular displacement of the feet and monofin segments was employed. The parameters were compared with a previously described model. Mutual dependences between the level of errors, stroke frequency, stroke length and amplitude in relation to swimming velocity were analyzed. The results showed that proper foot movements and the avoidance of errors, arising at the distal part of the fin, ensure the progression of swimming speed. The individual stroke parameters distribution which consists of optimally increasing stroke frequency to the maximal possible level that enables the stabilization of stroke length leads to the minimization of errors. Identification of key elements in the stroke structure based on the analysis of errors committed should aid in improving monofin swimming technique.

Key words: Swimming, monofin, technique, evaluation.

Introduction

The large surface of the monofin is regarded as the main source of a swimmer's propulsion (Rejman et al., 2003). Errors committed in the structure of leg movements are transferred to this surface and result in a meaningful decrease in the ability to generate efficient propulsion. Therefore, the technique of monofin swimming must be very precise. From a biomechanical point of view an error is defined as an execution of movement not in accordance with its pattern (Hay, 1985). From the educational perspective of technical training, it is a movement which is not in accordance with the original intention of the swimmer (Bremer and Sperle, 1984). The interdependence of the above definitions may stem from the fact that an assessment of swimming technique, in the biomechanical sense, is not always sufficient to realize educational aims (Hay, 1985). Therefore, to bridge between scientific knowledge and its application to swimming training, the biomechanical interpretation of technical errors should be objective and fully understandable for coaches and swimmers.

The criteria mentioned may be fulfilled by widely accepted parameters of evaluation of swimming stroke: stroke frequency, stroke length and the amplitude of movement. These parameters are linked, which allows one to relate the technical skill of the swimmer and the effect of the material of the monofin, on the total performance (produced by the "swimmer-fin" system). A high level of technical skill allows the maintaining of stroke parameters at a constant level while swimming over a distance (Alberty et al., 2006; Cappaert, 1999; Chollet et al., 1997; Keskinen et al., 1989; Potdevin et al., 2003; Sidney et al., 1999), increasing the economy of strength (e.g. Toussaint et al., 2006), limiting energy cost (e.g. Keskinen 1989) and reducing the symptoms of fatigue thus leading to the achievement and maintenance of maximal speed (Alberty et al., 2006; Craig et al, 1985; Dekerle et al., 2005; Keskinen et al., 1989; Morrow et al., 2005; Nomura and Shimoyama, 2003; Wakayoshi et al, 1996). The evaluation of monofin swimming technique, through the analyses of stroke parameters, has not been studied to the same extent as in traditional swimming. However, research based on the comparison of efficiency of propulsion while swimming barefoot and with different types of fins (Nicolas and Bideau, 2009; Nicolas et al., 2010; Zamparo et al. 2002; 2006), has allowed to extrapolate most of the depicted dependencies to monofin swimming. A significant relationship was found between amplitude and the forces of monofin strain (Rejman, 1999) and the frequency of movements (Shuping, 1989). Amplitude is determined by the duration of cyclical movement of the fin (Ross, 1995), and as a consequence - influences stroke frequency. Also, vortex parameters, a key component of the propulsion created by the monofin (Arellano and Gavilan, 1999; Collman et al., 1999; Ungerechts et al., 1999), depend on the amplitude and frequency of the movement (Liu et al., 1997). Optimizing frequency also gives the opportunity for the swimmers to conserve energy as a function of race distances (Pendergast et al., 1996; Zamparo et al. 2002; 2006). The optimal schedules of frequency and stroke length for different fin design were also studied (Nicolas et al. 2010). The necessity to control stroke parameters, in the order to gain and maintain maximal swimming speed, is a well known phenomenon. However, the question of how to optimize these parameters has not yet been fully answered, especially in the field of monofin swimming.

In this study, the problem of efficient and economical use of the monofin in order to gain maximal swimming speed, was solved in the quite novel aspect of evaluation of monofin swimming technique through the prism of errors committed in the structure of propulsive movements. An error is understood as a link between objective biomechanical criteria of quality of swimming technique and the realistic possibility of realizing them in order to obtain the educational aim, which is the improvement of technique in the direction of maximizing

Received: 25 May 2012 / Accepted: 09 February 2013 / Published (online): 01 March 2013

swimming speed. The aim of this study was to analyze the error structure in propulsive movements as regards their influence on monofin swimming speed. Moreover, the dependencies between these errors and the parameters of the swimming stroke (stroke frequency, stroke length and amplitude) were analyzed. The main question which this study should answer is how to improve the monofin swimming technique of highly skilled swimmers in accordance with the thesis that cognition, identification and reduction of the errors committed in the structure of propulsive movements, may be a source of resources supporting the progression of swimming speed. The following research questions were asked: (1) How do errors, estimated from the biomechanical evaluation of the structure of propulsive movements of the legs and monofin, influence swimming speed? (2) Is there a link between the number of errors committed in the structure of propulsive movements and the parameters evaluating the swimming stroke (stroke frequency, stroke length and amplitude) and what is their influence on monofin swimming speed? (3) Does the analysis of errors committed allow an objective identification of key elements in monofin swimming technique which will support and improve the process of perfecting technical skills in order to swim faster?

Methods

Six highly-skilled male swimmers, belonging to the Polish National Monofin Swimming Team, voluntarily took part in the research. All the athletes provided written consent for scientific testing. The protocol was reviewed and approved by the local ethics committee according to the principles provided in the Declaration of Helsinki. The characteristics of the participants are presented in Table 1.

The swimmers conducted a test, swimming 900 m on the water's surface at progressively faster speed, so that the last part of the distance was swum at maximal speed. The trial distances were divided into 300 m sections. The swimmers rested for 60s after each section of the trial distance. The test was adapted from a conventional training scheme used in traditional swimming (Hannula and Thornton, 2001; Maglischo, 2003). The test was chosen with the intention of simulating stress conditions and to analyze the biomechanical parameters of swimming technique during increasing fatigue. Swimmers swam individually on the water's surface in a short course pool. They swam with their own monofins meting their individual preferences and used in competitions. This was done to insure the objectification of the procedure of raw data recording and to eliminate the disturbance of swimming technique, arising from swimmers using unknown propulsive equipment (different dimensions, shape and characteristics of the material of monofin's surface) as a factor.

Table 1. Characteristics of monofin swimmers participating in the study.

Subjects	Ages	Body High (m)	Body Mass (kg)
I	15	1.75	70
II	16	1.71	64
III	15	1.63	64
IV	16	1.65	52
V	18	1.80	73
VI	17	1,93	84
CV	.07	.06	.15

CV - coefficient of variation.

All swimmers were filmed underwater in order to collect parameters describing leg and monofin movements. A digital camera (DCR-TRV 22E, Sony, Japan) in a waterproof box was located in a stable position in the middle of the pool. Based on the assumption that the movement of the swimmer and monofin act in a saggital plane (Rejman et al., 2003), the camera was placed and adjusted to visualize in frame the largest possible image of the swimmer performing over more than one entire stroke. A 6m distance from the calibration device was treated as the reference system for further analyses (Rejman and Ochmann, 2009) (Figure 1). The axis of the lens was perpendicular to the objects

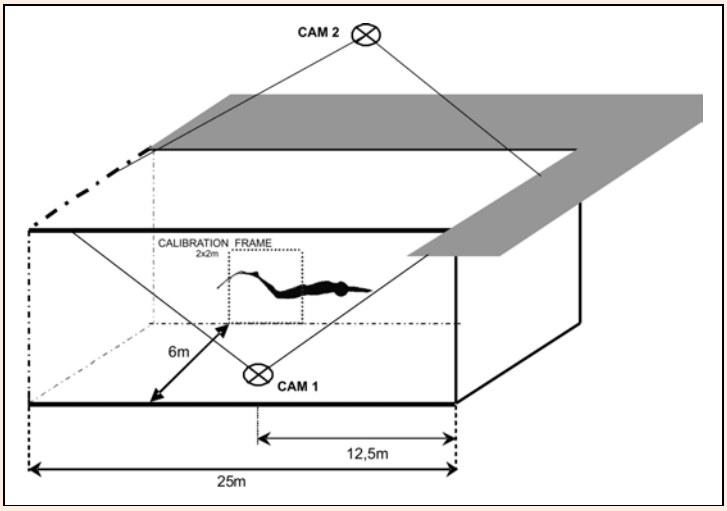


Figure 1. General description of experiment setup.

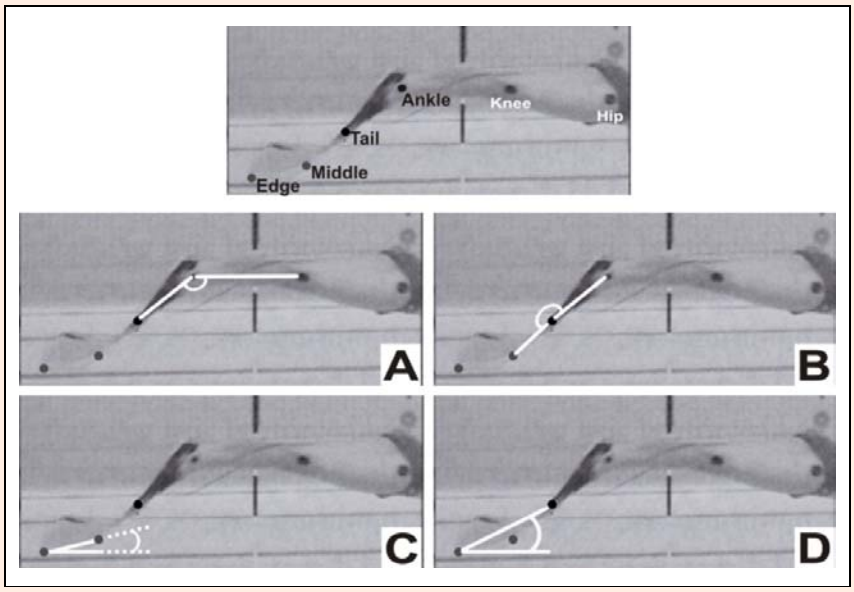


Figure 3. Illustration of procedure employed to define angular parameters studied. The angle of flexion at the foot in relation to the shin (Knee-Ankle-Tail) (A). Angle of bend in the proximal part of the fin in relation to the foot (Ankle-Tail-Middle) (B). Angles of attack were estimated according the generally accepted definition. Between the lines connecting the points marked on the respectively parts of its surface and the lines determining the direction of swimming (parallel to the water surface) - Angle of attack of distal part of monofin (Middle-Edge- Horizontal) (C) even as angle of attack of its entire surface (Tail-Edge-Horizontal) (D) (adapted from Rejman and Ochmann, 2009).

filmed. The recording frequency was 50Hz. Markers allowing the tracking of displacement of the axes of the shoulder, hip, knee and ankle joints (Plagenhoef, 1971) were located on the right side of the swimmers' bodies in order to be visible to the camera placed underwater (Rejman and Ochmann, 2009).

The monofin was also marked at the tail (where the plate is joined to the foot), at the middle and at the edge. The marks served to divide the fin into proximal (between tail and middle) and distal (between middle and edge) parts as well as to monitor displacement and bend of entire surface of the fin (Figure 2).

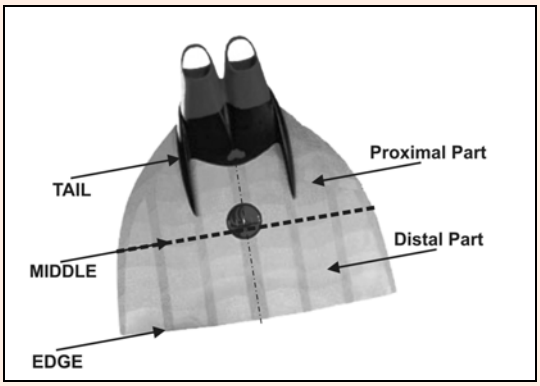


Figure 2. An explanation of monofin marking.

The angles of flexing of feet and bending of the monofin segments were defined for further analyses (Figure 3).

Kinematic analyses of leg and monofin movement were conducted using the SIMI Motion software (Simi Reality Motion Systems GmbH, Germany). One cycle (recorded over the last 25m of all nine of the 100m-intervals of the test distance) was chosen for analysis. The results were obtained in the form of temporal signals (Figure 4A) for the angle of flexion at the foot in relation to the shin (α_{ankle}), bend in the proximal part of the fin in relation to the foot ($\alpha_{proximal}$), the angle of attack of the distal part of the fin (β_{distal}) and the angle of attack of entire surface of the fin (β_{entire}). The procedure for collecting and analyzing the data, which described the amplitude of the legs and monofin segments (AMP - distance between deepest and highest position of the ankle in the cycle), were identical to the procedure previously described. The average horizontal velocity was also estimated. The centre of the swimmer's body mass was computed by the SIMI software with the assumption that the system was composed of the segments of swimmers body and the segments of monofin (Rejman and Ochmann, 2009).

The strokes preformed by each swimmer were filmed from above the water (DCR-TRV 22E, Sony, Japan) (Figure 1) at the same points of distance as during the estimation of errors (the last 25m of all nine 100m intervals). The strokes preformed over a 15m distance (estimated 5m from each wall of the pool by the flagged ropes suspended) were recorded. The number of strokes were directly counted from the digital image by three independent viewers. The head passing the markers was the signal to start the calculation of strokes. This way the mean stroke length (SL), length swum in one movement stroke, being one complete leg action, from the deepest position of the ankle through the highest position to the deepest position, again were estimated. The same procedure, with the use of the SIMI Motion software was

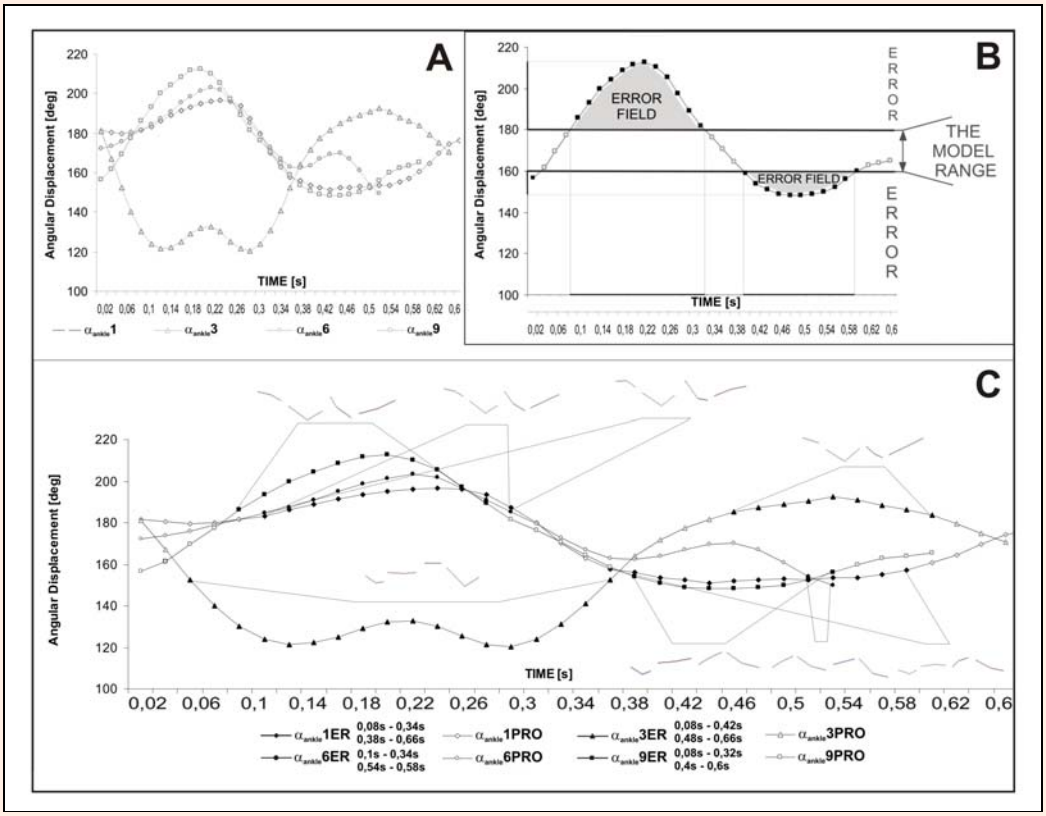


Figure 4. Example of identification, quantification and interpretation of errors registered in angular displacement of the parameters studied, registered at 100m-intervals (1-3-6-9) of the test distance. The division of mentioned errors (ER) is shown in comparison to the proper (PRO) series of registered angular parameters and the movement sequences illustrating the erroneous positioning of the segments of the leg and monofin, in comparison with the established model.

was employed for the estimation of mean stroke frequency (SF) - stroke number per second.

The similarities between the mean values of stroke parameters calculated directly from above the water and the values estimated from underwater filming (stroke length, stroke time/stroke frequency) and average swimming velocity allowed validation of both data collecting procedures.

A functional model of monofin swimming technique was employed for the analysis of error structure in propulsive movement as regards its influence on monofin swimming speed. This model, described in the previous study (Rejman and Ochmann, 2009), was constructed on base of a Neural Network. The kinematic data (angular displacement, angular velocities and accelerations of the all segments of the leg and monofin) were inserted into the network to define model relations with the output variable (horizontal swimming velocity).

The analyses were focused on the network's response graphs and illustrated the ratio of the above-mentioned parameters, describing the flexing of the feet and angular displacement (bending) of the monofin segments and its entire surface, as a function of horizontal swimming velocity. Selection of these parameters was aimed at gathering in one criterion, the most important role parameters can play in the maximization of swimming speed (based on the rank generated by the network sensitivity analysis according to ranking of the standard deviation quotient against output variable - horizontal swimming velocity), and possibilities to interpret these roles within the functional (applicable) aspect of the study. With this in mind, the analyses of other less important parameters, were abandoned.

The average values obtained from the network response graphs were interpreted as the foreseen average values of flexing of the feet and angular displacement of the monofin segments and its entire surface. This allowed the achieving of maximal swimming speed in the group of swimmers tested. The standard deviation values, obtained from the same data, indicated the limits at which the analyzed angular parameters achieve optimal (model) values. In practical terms these values specify the maximal swimming speed that could be achieved by each individual swimmer.

Based on the above mentioned interpretation of the network's response it was established that the optimal (model) range of dorsal flexion in relation to the shin (α_{feet}) is limited to 160° (-20° from the perpendicular location against the shin – 180°). During downward phase the limitation of plantar flexion of the feet was not to exceed 180°. An optimal bending of the proximal part of the monofin, in relation to the feet ($\alpha_{proximal}$), was estimated at 35° in downward movement and -27° in upward movement. The model range of the angles of attack of the distal part of the fin (β_{distal}) and its entire surface (β_{entire}) were located in a range between 37° in

Table 2. The average values of error committed by all swimmers (researched in the sphere of each angular parameter analyzed) on all nine of the 100m-intervals of the test distance. The subjects are ranked in order by average swimming speed.

Parameters Studied	Subjects Ranked						SUM2
	I	II	III	IV	V	VI	[deg]
α_{feet}ER [deg]	58.0	61.5	71.9	77.6	75.0	65.7	409.9
$\alpha_{proximal}$ER [deg]	27.0	33.6	31.4	33.8	41.5	43.0	210.3
β_{distal}ER [deg]	29.8	33.6	35.0	36.6	44.1	47.2	226.3
β_{entire}ER [deg]	22.4	38.9	33.4	33.6	44.5	49.4	222.2
SUM1[deg]	137.2	167.6	171.8	181.7	205.1	205.3	
CV $\alpha_{proximal}$, β_{distal}, β_{entire}	.14	.08	.05	.05	.04	.07	

Note: (α_{feet}ER) – angle of flexion in foot at ankle joint; ($\alpha_{proximal}$ER) – angle of bend in tail of monofin; (β_{distal}ER) – angle of attack of distal part of fin; (β_{entire}ER) – angle of attack of entire surface of fin (SUM1) - sum of errors estimated for each swimmer; (SUM2) - sum of errors estimated for all swimmers researched; (CV) - coefficient of variation.

downward phase and -26° in upward movements. The findings were verified in both theoretical and empirical aspects and corresponded to values previous obtained in the modelling of monofin swimming such as: Wu (1968, 1971) in mathematical modeling, Matsuuchi et al. (2006), Miwa et al. (2006) in the PIV system and Nakashima et al. (2010) in conceptual simulation modeling. Additionally, the possibility for high calculations by the network, in the range of applied analysis for new cases, opens opportunities for current studies in the interpretation of modeling of established parameters; within the practice of technical training of monofin swimming.

In the first stage of analysis of the novel outcome the range of errors committed by swimmers, in relation to the model presented above, were mapped. A basis for estimation of the range mentioned was created by the value of the angular parameters examined in a time function of the cycles analyzed (Figure 4A). The error values were quantified in spatio-temporal dimensions by calculating the definite integral (defined as the area of the region bounded by the graph of the angular parameters analyzed) which exceeded (or did not attain) the range established by the model and vertical line (time axis) limited by the boundary points of the range of the abovementioned model values (Figure 4B). Error values were normalized by estimating the percentage of error ranges (field of errors) in the total value of the fields designated by the courses of the parameters in the entire cycle (the correct range of angular parameters analyzed plus range of errors). The quantified errors, in numerical form, were interpreted as the following: the greater the field of error, the greater the numerical value of its field, and the greater the value of the error committed. Next (Figure 4C), the division of errors mentioned (ER) were estimated in comparison to the proper (PRO) series of registered angular parameters in the entire cycle. The ranges of errors estimated were time synchronized with the movement sequences recorded during swimming, thus allowing the identification of intervals of erroneous positioning of the segments of the leg and monofin (sequences), in comparison with the established model (Figure 4C). This same figure also illustrated that the abovementioned intervals of erroneous positioning are very similar to each other on particular parts of the test distance. On this basis, it was assumed that the quantity analysis of these similarities allows for objective identification and separation of the most crucial fragments (determinant sequences) of leg and monofin movements; due to the possibility of committing the potential errors defined.

The relationship between the values of error committed, stroke parameters and average horizontal swimming velocity were researched. The critical value of Person's correlation coefficient, calculated for n = 9 (p = 0.05), was r = 0.66. In the Friedman's ANOVA test (Six swimmers swam the progressive tests (a total of 900 m consisting of nine separate 100 m distances) which were treated, in the statistical sense, as separate trials during analyses of the parameters researched), significant differences were exhibited between the swimmers for all parameters studied. Kendall's coefficient (0.7963) confirmed the similarities between the groups of parameters studied.

Results

The significant correlation between the mean values of errors committed by the swimmers and the values describing their age and somatic parameters (Table 1), allows an assumption that the individual profiles of the swimmers did not influence the results obtained.

The results suggested that fewer errors were committed by the swimmer who achieved the highest average horizontal swimming velocity (Table 2 - SUM1). The lower the level of errors committed in the angular parameters analyzed, the higher swimming speed (Table 3). The relationships described above confirm that the reduction of errors, in the structure of propulsive movements of the legs and monofin, influenced the progression of swimming speed. It was also found that the majority of errors were committed by subjects within the area of angle of flexion in foot in relation to the shin (α_{feet}ER) (Table 2 -SUM2).

The results presented in Tables 3 and 4 indicate that relationships between the level of errors committed in the structure of propulsive movements and the parameters evaluating the swimming stroke strongly influence monofin swimming speed. In the group of swimmers tested, swimming velocity increases proportionally to stroke frequency (SF), when the relationships with stroke length (SL) were negative (Table 3). Stroke frequency had the greater influence on the increasing of average

Table 3. The values of Pearson's correlation coefficient between the parameters studied and average horizontal monofin swimming velocity, on nine of the 100m-intervals of the test distance estimated.

α_{feet}ER	-.78 *			AMP $_{feet}$	-.56
$\alpha_{proximal}$ER	-.69 *	**SF**	.96 *	AMP $_{tail}$	-.60
β_{distal}ER	-.76 *	**SL**	-.74 *	AMP $_{middle}$	-.53
β_{entire}ER	-.70 *			AMP $_{edge}$	-.40

*Statistically significant correlation coefficients (p = 0.05).
Note: (α_{feet}ER) – error of the angle of flexion in foot at ankle joint; ($\alpha_{proximal}$ER) – error of the angle of bend in tail of monofin; (β_{distal}ER) – error of the angle of attack of distal part of fin; (β_{entire}ER) – error of the angle of attack of entire surface of fin; (SF) mean stroke frequency; (SL) mean stroke length; ($AMP_{feet,}$ $AMP_{tail,}$ $AMP_{middle,}AMP_{edge}$) amplitude of displacement of the segments analyzed.

swimming velocity. The lack of a statistically significant relationship between swimming velocity and the parameters describing the amplitude of movements of feet and monofin indicates a lack of importance for the progression of swimming speed.

Table 4 shows that lower error values (ER) correlated significantly with lower stroke frequency (SF) and the lengthening of stroke length (SL). The strongest relationship was observed between the errors committed in the angle of attack of the distal part of the fin (β_{distal}ER), stroke frequency and stroke length. Only the amplitude of displacement of the distal part of the monofin (amplitude of displacement middle (AMP_{middle})) and of the edge of the fin (AMP_{edge}) were significant and proportionally correlated with the values of error. These results drew attention to the role of the distal part of the monofin in reduction of the errors committed and in the progression of swimming speed.

While analyzing the trials preformed by individual swimmers (Figure 5) attention should be paid to the last 300m sections, when all the swimmers swam fastest. This indicates that the stabilization of stroke parameters, particularly in the case of stroke length (SL), while less so in regards to stroke frequency (SF), may play a significant role in monofin swimming performance. The relationships of stroke parameters to horizontal monofin swimming velocity and to the errors committed in the structure of propulsive movements, were different (Tables 3, 4). These results, taken together with distribution of the stroke frequency and stroke length over the distance (Figure 5), suggest that the optimization of stroke parameters is needed to achieve and maintain maximal swimming speed.

The results, and their mentioned analysis and arguments, strengthen the foundation for an objective identification of determinant sequences in monofin swimming technique (Figure 6). The presented sequences pointed out the elements which are crucial for teaching and improving monofin swimming technique in order to swim faster. The following determinant movement sequences were estimated: (1) The end of the downbeat movement when the legs are straight and the feet are in their lowest downbeat position. The fin tail is at maximum bend at the maximum angle of attack of the entire surface of the fin. (2) The last part of upward movement, when the legs are still straightened, just before flexing at the knees, at the maximum bend of the tail of the fin. (3) The beginning of the downbeat phase at the moment regarded as change of direction (from plantar to dorsal) of flexion of the foot. The legs are maximally flexed in the knee joints and the segments of the fin are more or less parallel. The determinant movement sequences referring to the change of angle of the distal part of the fin and its entire surface are: in downbeat - the second part of the legs straightening at the knees, where the shanks are more or less parallel to the direction of swimming, and the monofin is more or less straight in the maximum angle of attack. During upbeat – the second part of straightening of the lifted legs, at the knee joints, until the legs are placed more or less parallel to the direction of swimming and the monofin is at maximum bend in the middle.

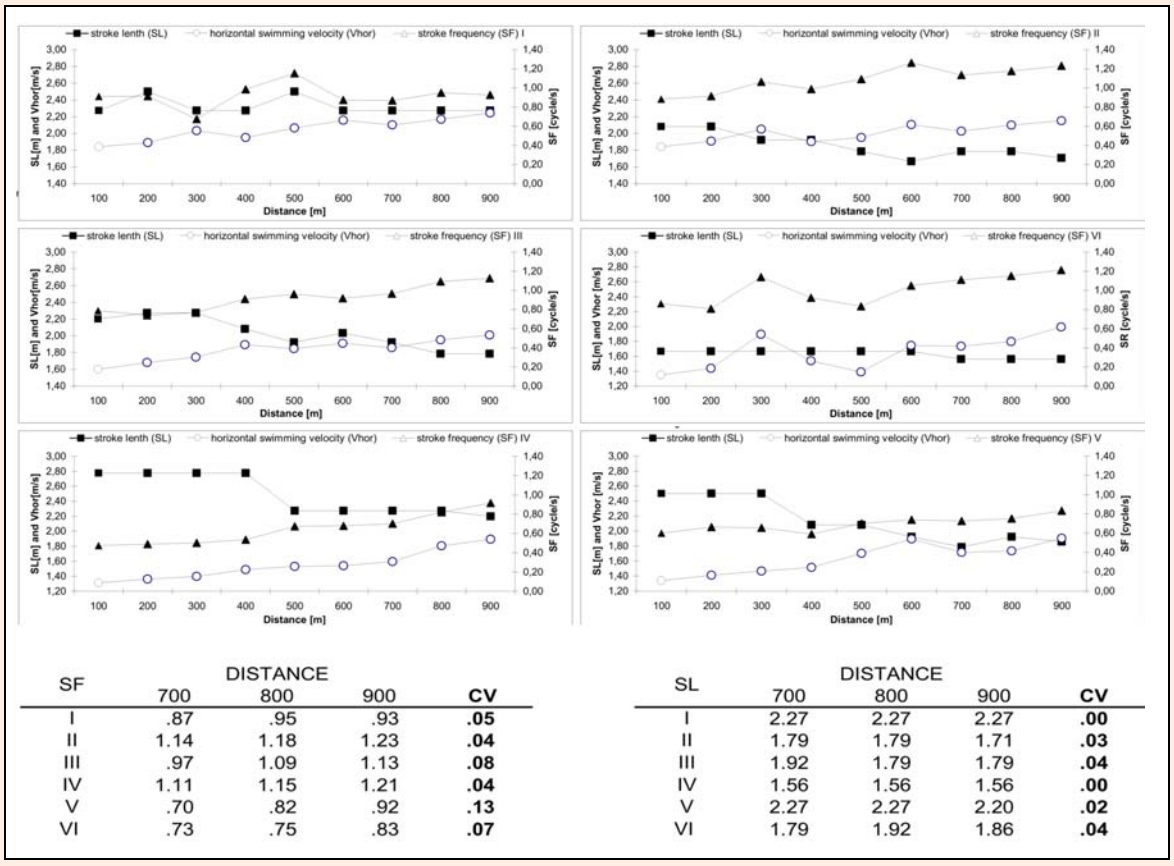
Discussion

An explanation of the advantages and limits of the functional model of monofin swimming technique (Rejman and Ochmann, 2009), which served as a background for the estimation of errors, is needed for

Table 4. The values of Pearson's correlation coefficient between the value of errors committed by all swimmers researched, in the sphere of each angular parameter analyzed, and the stroke parameters on all nine of the 100m-intervals of the test distance.

Parameters	SF	SL	AMP_{feet}	AMP $_{tail}$	AMP_{middle}	AMP_{edge}
α_{feet}ER	.68 *	-.65 *	.30	-.30	-.28	-.34
$\alpha_{proximal}$ER	.66 *	-.64 *	.26	-.46	-.61	-.61
β_{distal}ER	.70 *	-.68 *	.38	.40	.79 *	.79 *
β_{entire}ER	.67 *	-.67 *	.60	.40	.29	.29

*Statistically significant correlation coefficients (p = 0.05).
Note: (α_{feet}ER) – error of the angle of flexion in foot at ankle joint; ($\alpha_{proximal}$ER) – error of the angle of bend in tail of monofin; (β_{distal}ER) – error of the angle of attack of distal part of fin; (β_{entire}ER) – error of the angle of attack of entire surface of fin; (SF) mean stroke frequency; (SL) mean stroke length; ($AMP_{feet,}$ $AMP_{tail,}$ $AMP_{middle,}AMP_{edge}$) amplitude of displacement of the segments analyzed.



SF	DISTANCE 700	800	900	CV
I	.87	.95	.93	**.05**
II	1.14	1.18	1.23	**.04**
III	.97	1.09	1.13	**.08**
IV	1.11	1.15	1.21	**.04**
V	.70	.82	.92	**.13**
VI	.73	.75	.83	**.07**

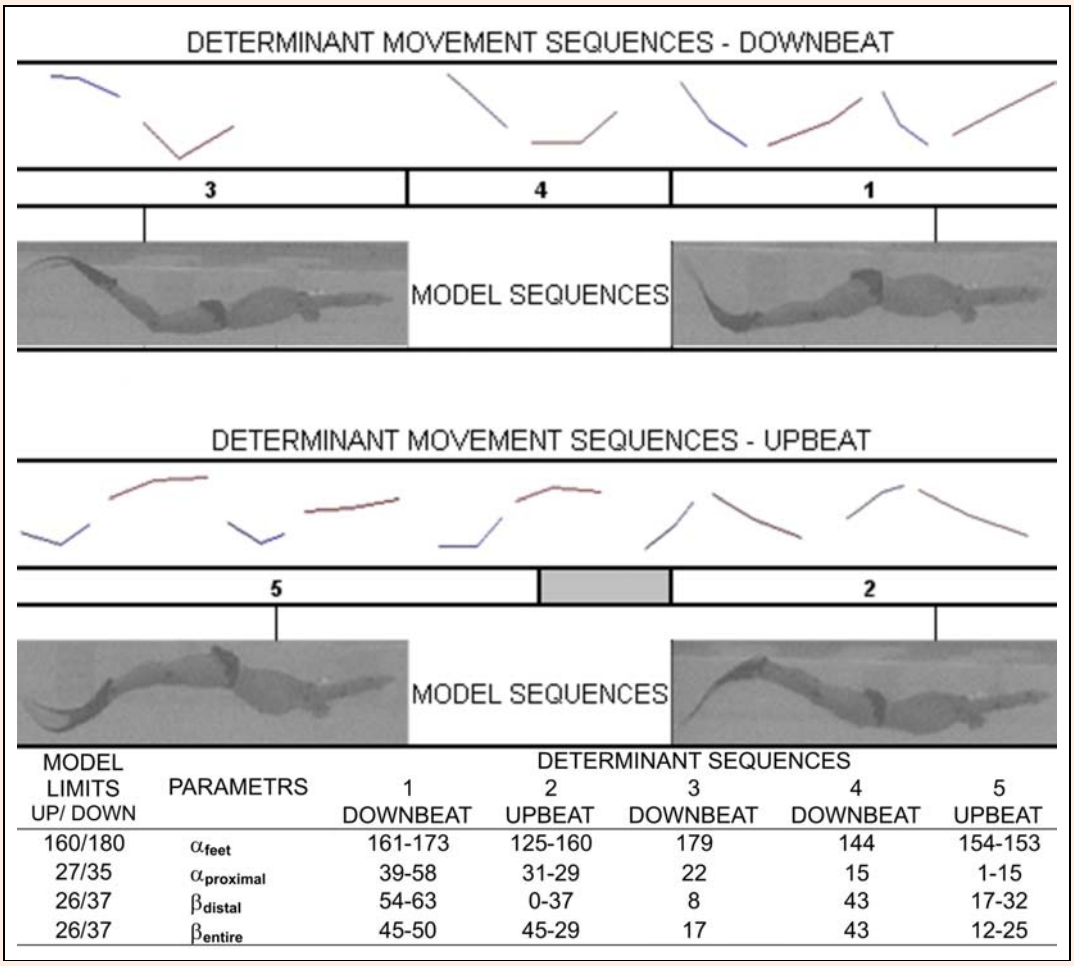
SL	DISTANCE 700	800	900	CV
I	2.27	2.27	2.27	**.00**
II	1.79	1.79	1.71	**.03**
III	1.92	1.79	1.79	**.04**
IV	1.56	1.56	1.56	**.00**
V	2.27	2.27	2.20	**.02**
VI	1.79	1.92	1.86	**.04**

Figure 5. Graphs illustrating the division of stroke frequency (SF) and stroke length (SL) compared with average horizontal swimming velocity (V_{HOR}) registered on all nine of the 100m-intervals of the test distance. A table of values of the stroke parameters registered on the last three 100m-intervals of the test distance is supplemented by the coefficients of variation (CV) estimated. The results are ranked by average swimming velocity achieved by each swimmer.

clear discussion of the results. The standard procedures employed for interpretation of the network model were the first fundamental advantage of them. This way the results of sensitivity analysis and regression statistics became the source of comparative data (Fausett, 1994; Patterson, 1996). A close link between the model and real swimming was confirmed in the teaching and validation tests of the Neural Networks. The empirical (realistic) validation of the model was made through the comparison of the network response graphs, with the movements recorded, along with their kinematic characteristics. The analysis of the sensitivity confirmed that the best network was chosen in terms of accuracy and adequacy to the modeled process. In this manner the high efficiency of the optimizing movements (model) of the leg and monofin were tested. The results of regression statistics of the network employed, confirmed the high quality of the model constructed. It should to be also emphasized that the values estimated in the testing set of the network pointed out the high calculative possibility of the model in the realm of applied analysis for new cases, wherein the starting point for the application of the solutions modeled in assessment of monofin swimming technique are determined.

Nevertheless, the suitability of the model to the analysis of new cases is limited because it was designed for a group of swimmers, homogeneous in terms of their somatic parameters. For that reason other athletes will have to fulfill the same somatic requirements to allow for comparison of their parameters with the data entered into the network. Assuming that the data forming the structural basis of the model could be regarded as typical for the population of the monofin swimmers representing the highest level of proficiency, this limitation seems to not be relevant in terms of realizing the aims of this study (the functional interpretation of the constructed model).

The lack of mechanical characteristics of the monofins used in the research can be read as a limitation of model constructed, in terms of objective estimation of the errors. However, assuming that the swimmers chose the fins according to their individual preferences in order to gain the best results during competitions, it can be extrapolated that the model employed reflected the characteristics of the ”optimal” fin. The density and stiffness of the fin may affect the energy cost and efficiency of swimming (Nicolas et al., 2010; Pendergast et al., 1996; Zamparo et al., 2002; 2006). But the exact influence of fin design on swimming efficiency still needs to be studied. Zamparo et al. (2006) concluded that the characteristics of the monofin’s surface, taken separately, could not totally predict a result of performance. Therefore, the effects of the material of the fin on swimming speed were not taken into consideration in this study.



MODEL LIMITS UP/ DOWN	PARAMETRS	DETERMINANT SEQUENCES 1 DOWNBEAT	2 UPBEAT	3 DOWNBEAT	4 DOWNBEAT	5 UPBEAT
160/180	α_{feet}	161-173	125-160	179	144	154-153
27/35	$\alpha_{proximal}$	39-58	31-29	22	15	1-15
26/37	β_{distal}	54-63	0-37	8	43	17-32
26/37	β_{entire}	45-50	45-29	17	43	12-25

Figure 6. A determinant sequence of leg and monofin movements (1,2,3,4,5), created on the basis of errors objectively estimated from the functional model of monofin swimming technique (Rejman and Ochman, 2009). The values of the angles describing mutual position of the segments of legs and monofin are printed bellow.

Validation of the error estimation procedure in this study was based on a direct interpretation of an error defined as an execution (measurable in spatio-temporal dimensions) of movement not in accordance with its pattern (the functional model) (Hay, 1985). This interpretation has its own source within knowledge from the realm of motor skills education, where there is an obvious axiomatic relation between the value of an error and the assessment of movement technique (Bernstein, 1967; Bremer and Sperle, 1984; Richard et. al., 2005). Given this background, errors in the structure of foot and monofin movement can be interpreted within the category of measures of quality of monofin swimming technique, which possess a broad foundation in biomechanics (i.e Alberty et al., 2006; Keskinen et al., 1989; Rejman, 1999; Toussaint et al., 2006.) and physiology (i.e Dekerle et al., 2005; 2006; Morrow et al., 2005; Potdevin et al., 2003; Zamparo et al., 2002; 2005). Within this context, the objectively quantified errors seem to be a useful tool in support to the process of improving of monofin swimming technique in the direction the increasing speed.

When trying to clarify how to eliminate errors in order to improve the monofin swimming technique of highly-skilled swimmers, the role of angular displacement of the feet and the distal part of the fin for progression of swimming speed should be emphasized. The torque generated by legs, and transferred to the surface of the monofin, must be balanced against the transfer of moments occurring between the monofin and water. In this scope, the feet are treated as the last active segment in the biomechanical chain which (remaining under the total control of the swimmer) steer torque transfer to the monofin's surface (Nicolas et al., 2010; Rejman, 2006). It has been shown that maintaining optimal foot flexion, despite the drag acting in the opposite direction, favors maximum swimming velocity (Rejman and Ochmann, 2009). Such conditions are conducive to the intensification of the balance of propulsive forces in both phases of the stroke - a crucial factor for the stabilization of high intra-cycle velocity (Rejman, 2006). The displacement of the feet generated the largest amount of errors. Thus, foot movement seems to be the most difficult element of swimming technique for swimmers to control. These arguments create a foundation for the statement that cognitive control of foot movement (without errors), through self-correction by the swimmer, seems to improve individual monofin swimming technique in the direction of increasing speed.

The results showed that a lower displacement of the distal parts of monofin facilitate faster swimming. The proper displacement of the distal part of the fin, in relation to the direction of swimming and the direction of water flow over the surface, determines the hydrodynamic conditions for effective propulsion (Rejman 2006, Rejman and Ochmann 2009). It was also discovered that a reduction of errors committed at angular displacement of the distal part of the fin goes hand in hand with a reduction of amplitude of this same part. Arellano et al. (2003) and Nicolas et al. (2007) have demonstrated that greater vertical amplitude leads to a larger effective cross-sectional area and possibly induces more drag. Therefore, a reduction of kick amplitude at optimal level seems to be a factor allowing the achievement the highest monofin swimming velocity. Within this context, avoiding errors through the control of the positioning of the distal part of the monofin (which plays the role of effector of torque generated by the legs) contributes to improvement of monofin swimming technique and so also leads to increased swimming speed.

The biomechanical chain of the segments of the leg and the monofin can be treated as a system which works on the basis of the mutual interactive function of its consecutive units. This is illustrated by the fact that swimming speed depends on the minimization of errors within the realm of the chain: feet – tail – the parts of monofin, and also by similarities in the relationships between average swimming velocity and the value of pairs of errors, which are as follows: error of the angle of flexion at the ankle joint, error of the angle of attack of the distal part of the fin, error of the angle of bend in the tail of the fin and error of the angle of attack of the entire surface of the fin. Additionally, the errors committed within the angles of bend (attack) were almost the same. In this perspective, the mechanism for effective propulsion appears to depend on how much an "exact" (in the model sense) and stable torque generated by the legs will be transferred through the tail, onto the "passive" surface of the fin.

The results discussed indicate that minimizing errors, as well as increasing swimming velocity, depend mainly on the optimization of movement of the feet aimed at controlling the movement within the limits of property, as well as the proper bending of the distal part of the fin within the limits set by the model.

Statistical interpretation of the results suggest that the progression of swimming velocity in each subsequent section of the test trial was obtained through the minimization of errors during realization of a strategy based on increasing the frequency of propulsive movements (stroke frequency) effecting a decrease of the distance swum in one cycle (stroke length). While the relationships between the level of errors and stroke parameters illustrated a reverse relation. Interpretation of these results directs the search for factors in the elimination of errors towards the optimization of stroke parameters. Patterns of fish locomotion (Bainbridge, 1958) hint that the best solution for maintaining maximal swimming speed is keeping movement amplitude (and stroke length) at a constant level while simultaneously increasing stroke rate (Arellano et al., 2003; Nicolas et al., 2007). A comparison of the correlation coefficients outlined allows a formulation of the same generalization. Zamparo et al. (2002; 2006) and Nicolas et al. (2007) have stated that decreased frequency, at a given velocity, leads to lengthened stroke length and therefore should be reduced, depending on the race distance, in order to reduce energy requirements. Other research has reported that insufficient technical skill, or a change in technique resulting from fatigue, are often causes of lengthened stroke rate and shortened stroke length (Nomura and Shimoyama, 2003). This may mean that such an uneconomical strategy is used spontaneously by swimmers, not only by those within the research group. It gives rise to the need to investigate a route for the progression of monofin swimming speed through the reduction of errors and the optimization of stroke parameters, with an eye towards their stabilization. Likewise, the elimination of the factors leading to increased fatigue should be taken into consideration in future research.

The results obtained draw attention to the phenomenon of stabilization of stroke length which occurred more visibly than the stabilization of stroke frequency. Another study has also suggested that an increase in swimming velocity may be achieved by increasing stroke rate, maintaining a stable stroke length (Arellano et al., 2003; Chollet et al., 1997) or with both of these parameters (Sidney et al., 1999). When treating errors committed by the swimmers as an aspect of the improvement of monofin swimming technique, it is worth noting that the influences of stroke rate and stroke length on swimming speed increase along with the increase in intensity of fatigue (Cappaert, 1999; Potdevin et al., 2003; Nomura and Shimoyama, 2003; Toussaint et al., 2006.). The tendency mentioned above (probably being the result of fatigue increased over the final part of the test distance, when swimming efficiency dropped in correspondence with a decrease in quality of technique) was also observed in this study. Within this context, the ability to maintain stable stroke length, regardless of the increasing effects of fatigue, understood as a measure of technical skill (Craig et al, 1985; Keskinen et al., 1989; Wakayoshi et al, 1996), sets directions for the improvement of monofin swimming technique. Swimming with a higher stroke rate and longer stroke length, leading to a stable structure of propulsive movements, supports the ability to achieve maximal swimming speed (Cappaert, 1999; Potdevin et al., 2003; Zamparo, 2006). The arguments presented herein lead to the conviction that the improvement of monofin swimming technique should be steered towards increasing stroke frequency, which itself is regarded as the main factor determining the efficiency of fin swimming (Arellano et al., 2003; Nicolas et al., 2007), towards the optimum and most stable stroke length at the highest level possible.

On other hand, the lack of dependency between the Strouhal Number, amplitude and frequency of propulsive movements (Nicolas et al, 2007) combined with the interpretation of the results presented herein, leads to a reasonable conclusion that a similar monofin swimming speed can be achieved by employing various variants of amplitude, stroke frequency and stroke length. Therefore, the optimization of stroke parameters seems to derive from an

individual level of swimming skills which allows for the maintaining of these parameters at a stable level over the entire distance.

The application value of the results obtained, in terms of technical training in monofin swimming, generally consists of an indication of determinant movement sequences (selected in order to reduce or eliminate errors), which draw the attention of swimmers and coaches to crucial points in swimming technique. In this way, the perception of swimmers could be stimulated by a precise verbal naming of the movement structure actually preformed. It is well known that conscious knowledge of a particular technical skill is the main factor supporting the process of teaching and perfecting the techniques of human movement (Meinel and Schnabel, 2007).

Conclusion

The biomechanical analysis of errors committed confirmed that in the case of the highly-skilled swimmers consciousness identification and reduction of errors in monofin swimming technique can be regarded as the source of reserves supporting the progression of swimming speed. In order to minimize errors, as well as to increase swimming velocity, the technique of highly-skilled swimmers should mainly focus on the optimization of foot movements. It should aim at controlling these movements within the limits of property, as well as the proper bending of the distal part of the monofin. Optimization of the movement structure of the legs and monofin, related to the individual technical skills of the swimmer, should be directed towards increasing stroke frequency to the maximum level possible. This enables the stabilization of stroke length. Objectively defined determinant sequences in monofin swimming technique can draw the attention of swimmers and coaches towards crucial points which allow theavoiding of errors. Thus, they could support the process of technique improvement in order to increase monofin swimming speed across different levels of swimmer proficiency.

References

Alberty M., Sidney M., Huot-Marchand F., Dekerle J., Gorce P., Lensel G., and Pelayo P. (2006) Effects of stroking parameters changes on time to exhaustion. In: *Biomechanics and Medicine in Swimming X.* Eds: Vilas-Boas, J.P., Alves, F. and Marques, A. *Portuguese Journal of Sport Sciences* **6**(Supl.2), 287-290.

Arellano R. and Gavilan P. (1999) Vortices and propulsion. In: *Applied proceedings: Swimming. XVII International Symposium on Biomechanics in Sports.* Eds: Sanders, R. and Listen, J. Perth: Edith Cowan University. 53-65.

Arellano, R., Pardillo, S. and Gavilan, A. (2003) Usefulness of the Strouhal number in evaluating human underwater undulatory swimming. In: *Biomechanics and Medicine in Swimming IX.*. Eds: Chatard, J.C. Saint-Etienne: University of Saint-Etienne, 33-38.

Bainbridge, R. (1958) The speed of swimming of fish as related to size and to frequency and amplitude of the tail beat. *Journal of Experimental Biology* **35**, 109-133.

Bernstein, N.A. (1967) *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Bremer D. and Sperle N. (1984) *Fehler, Mangel, Abweichungen im Sport*. Schriftenreihe des ADH, Sport & Lernen, Wuppertal: Putty- Verlag. (In German)

Cappaert J.M. (1999) Biomechanics of swimming analyzed by three-dimensional techniques. In: *Biomechanics and Medicine in Swimming VIII.* Eds: Keskinen, K.L., Komi, P.V. and Hollander, A.P. Jyvaskyla: Gummerus Printing, 141-145.

Chollet D. Pelayo P., Delaplace C., Tourny and Sidney M. (1997) Stroking characteristic variations in the 100-m Freestyle for male swimmers of differing skill. *Perceptual and Motor Skills* ***85***, 167-177.

Colman V., Persyn U. and Ungerechts B.E. (1999) A mass of water added to the swimmer's mass to estimate the velocity in dolphin-like swimming bellow the water surface. In: *Biomechanics and Medicine in Swimming VIII.* Eds: Keskinen, K.L., Komi, P.V. and Hollander, A.P. Jyvaskyla: Gummerus Printing, 89-94.

Craig A. B., Skehan P. L., Pawelczyk J. A.and Boomer W. L. (1985). Velocity, stroke rate and distance per stroke during elite swimming competition. *Medicine and Science in Sports and Exercise* **17**, 625-634

Dekerle J., Nesi X., Lefevre T., Depretz S., Sidney M., Huot-Marchand F. and Pelayo P. (2005) Stroking parameters in front crawl swimming and maximal lactate steady state speed. *International Journal of Sports Medicine* **26**, 53-58.

Dekerle, J. (2006) The use of critical velocity in swimming. A place for critical stroke rate? In: *Biomechanics and Medicine in Swimming X.* Eds: Vilas-Boas, J.P., Alves, F. and Marques, A. *Portuguese Journal of Sport Sciences* **6**(Supl.2), 201-205.

Fausett, L. (1994) *Fundamentals of Neural Networks.* New York: Prentice-Hall.

Hannula, D. and Thornton N. (2001) *The Swim Coaching Bible*. Champaign: Human Kinetics.

Hay, J.G. (1985) Swimming. In: *The Biomechanics of Sports Techniques*. Engelwood Cliffs: Prentice-hall, Inc.

Keskinen K.L., Tilli L.J. and Komi P.V. (1989) Maximum velocity swimming: interrelationship of stroking characteristics, force production and anthropometrics variables. *Scandinavian Journal of Sports Sciences* **11**(2), 87-92.

Liu R., Wassersug J. and Kawachi J. (1997). CFD Study of Tadpole Swimming. *Journal of Experimental Biology* **200**, 1249-1260.

Maglischo E.W. (2003) *Swimming Fastest*. Champaign, Human Kinetics.

Matsuuchi, K., Hashizume, T., Nakazawa, Y., Nomura, T., Shintani, H. and Miwa, T. (2006) Flow visualization of unsteady flow field around a monofin using PIV. In: *Biomechanics and Medicine in Swimming X.* Eds: Vilas-Boas, J.P., Alves, F. and Marques, A. *Portuguese Journal of Sport Sciences* **6**(Supl.2), 60-62.

Meinel K. and Schnabel G. (2007) *Bewegungslehre Sportmotorik (Abriss einer Theorie der sportlichen Motorik unter pädagogischem Aspekt)*. Köln: Meyer & Meyer. (In German).

Miwa, T., Matsuuchi, K., Shintani, H., Kamata, E. and Nomura, T. (2006) Unsteady flow measurement of dolphin kicking wake in sagittal plane using 2C-PIV. In: *Biomechanics and Medicine in Swimming X.* Eds: Vilas-Boas, J.P., Alves, F. and Marques, A. *Portuguese Journal of Sport Sciences* **6**(Supl.2), 64-66.

Morrow J. Jr., Jackson A., Dissch J. and Mood D. (2005) *Measurement and evaluation in human performance.* 3rd edition. Champaign: Human Kinetics.

Nakashima, M., Suzuki, S. and Nakajima, K. (2010) Development of a simulation model for monofin swimming. *Journal of Biomechanical Science and Engineering* **5**(4), 408-420.

Nicolas G., Bideau B., Colobert B. and Berton E. (2007) How are Strouhal number, drag, and efficiency adjusted in high level underwater monofin-swimming? *Human Movement Science* **26,** 426-442.

Nicolas, G. and Bideau, B. (2009) A kinematic and dynamic comparison of surface and underwater displacement in high level monofin swimming. *Human Movement Science* **28**, 480-493.

Nicolas, G., Bideau, B., Bideau, N., Colobert, B., LeGuerroue, G. and Delamarche, P. (2010) A new system for analyzing swim fin propulsion based on human kinematic data. *Journal of Biomechanics* **43**, 1884-1889.

Nomura, T. and Shimoyama, Y. (2003) The relationship between stroke parameters and physiological responses at various swim speeds. In: *Biomechanics and Medicine in Swimming IX.* Eds: Chatard, J.C. Saint-Etienne: University of Saint-Etienne. 355-360.

Patterson, D. (1996) *Artificial Neural Networks.* Singapore: Prentice-Hall.

Pendergast, D.R., Tedesco, M., Nawrocki, D.M. and Fischer, N.M. (1996) Energetics of underwater swimming with SCUBA. *Medicine and Science in Sports and Exercise* **28**, 573-580.
Plagenhoef, S. (1971) *Patterns of Human Motion - a Cinematographic Analysis*. Englewood Cliffs: Prentice-Hall.
Potdevin, F., Pelayo, P., Delignières, D., Dekerle, J., Alberty, M. and Sidney, M. (2003) Does stroke rate determine swimming velocity values and coordination? In: *Biomechanics and Medicine in Swimming IX.* Eds: Chatard, J.C. Saint-Etienne: University of Saint-Etienne. 163-167.
Rejman, M. and Ochmann, B. (2009) Modelling of monofin swimming technique: optimization of feet displacement and fin strain. *Journal of Applied Biomechanics* **25**, 340-350.
Rejman, M. (2006) Influencing of timing delay on monofin intra-cycle swimming velocity. In: *Biomechanics and Medicine in Swimming X.* Eds: Chatard, J.C. *Portuguese Journal of Sport Sciences* **6**(Supl.2), 85-88.
Rejman, M., Colman, V. and Persyn, U. (2003) The method of assessing the kinematics and dynamics of single fin movements. *Human Movement* **2**(8), 54-62.
Rejman, M. (1999) Dynamic criteria for description of single fin swimming technique. In. *Biomechanics and Medicine in Swimming VIII*. Eds: Keskinen, K.L., Komi, P.V. and Hollander, A.P. Jyvaskyla: Gummerus Printing. 171-176.
Richard, A., Schmidt, R.A. and Lee, T. (2005) *Motor Control and Learning. A Behavioural Emphasis.* 4th Edition. Champaign: Human Kinetics.
Ross, H. (1995) Wave Characteristics of Butterfly swimming. *Journal of Biomechanics* **28**, 9-16.
Shuping, L. (1989) Biomechanical study of Fin-swimming and Fins. In: *Proceedings of the VIIth International Symposium of Biomechanics in Sports.* Ed: Morrison, W.E. Footscray: Institute of Technology. 217-218.
Sidney, M., Delhaye, B., Baillon, M and Pelayo, P. (1999) Stroke frequency evolution during 100-m and 200-m events front crawl swimming. In: *Biomechanics and Medicine in Swimming VIII.* Eds: Keskinen, K.L., Komi, P.V. and Hollander, A.P. Jyvaskyla: Gummerus Printing. 71-75.
Toussaint, H.M., Carol, A., Kranenborg, H. and Trunens, M.J. (2006). Effect of Fatigue on Stroking Characteristics in an Arms-Only 100-m Front-Crawl Race. *Medicine and* Science *in Sports and Exercise* **38**(9), 1635-1642.
Ungerechts, B.E., Persyn, U. and Colman, V. (1999) Application of vortex flow formation to self-propulsion in water. In. *Biomechanics and Medicine in Swimming VIII.* Eds: Keskinen, K.L., Komi, P.V. and Hollander, A.P. Jyvaskyla: Gummerus Printing. 95-100.
Wakayoshi, K., D'Acquisto, J., Cappaert, J.M. and Troup, J.P. (1996) Relationship between metabolic parameters and stroking technique characteristics in front crawl. In: *Biomechanics and medicine in swimming VII.* Eds: Troup, J.P., Hollander, A.P., Strasse, D., Trappe, S.W., Cappaert, J.M. and Trappe, T.A. International Series on Sport Sciences. London: E & FN Spon. 285-293.
Wakayoshi, K., Yoshida, T., Udo, M., Kasai, T., Moritani, T., Mutoh, Y. and Miyashita, M. (1992) A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. *International Journal of Sports Medicine* **13**, 367-371.
Wu Yao-Tsu, T. (1968) Swimming of waving plate. *Journal of Fluid Mechanics* **10,** 321-344.
Wu Yao-Tsu, T. (1971) Hydromechanics of swimming propulsion. part 1. Swimming of a two-dimensional flexible plate at variable forward speeds in an inviscid fluid. *Journal of Fluid Mechanics* **46**(2). 337-355.
Zamparo, P., Pendergast, D.R., Termin, B. and Minetti, A.E. (2002) How fins affect the economy and efficiency of human swimming. *Journal of Experimental Biology* **205**, 2665-2676.
Zamparo, P., Pendergast, D.R., Termin, B. and Minetti, A.E. (2005) Economy and efficiency of swimming at the surface with fins of different size and stiffness. *European Journal of Applied Physiology* **96**, 459-470.
Zamparo P. (2006) Effects of age and gender on the propelling efficiency of the arm stroke. *European Journal of Applied Physiology* **97**, 52-58.

Key points

- The monofin swimming technique was evaluated through the prism of objectively defined errors committed by the swimmers.
- The dependences between the level of errors, stroke rate, stroke length and amplitude in relation to swimming velocity were analyzed.
- Optimally increasing stroke rate to the maximal possible level that enables the stabilization of stroke length leads to the minimization of errors.
- Propriety foot movement and the avoidance of errors arising at the distal part of fin, provide for the progression of swimming speed.
- The key elements improving monofin swimming technique, based on the analysis of errors committed, were designated.

AUTHOR BIOGRAPHY

Marek REJMAN

Employment

Ass. Prof. University School of Physical Education, Wroclaw, Poland.

Degree

PhD

Research interests

Swimming efficiency and its economics is considered in the context of effective employment of fins as a source of propulsion.

E-mail: rejmar@awf.wroc.pl

✉ **Marek Rejman**

Department of Swimming, University School of Physical Education, ul. Paderewskiego 35, 51-612 Wroclaw, Poland