Acta of Bioengineering and Biomechanics
Vol. 15, No. 3, 2013

Original paper
DOI: 10.5277/abb130316

Tracking young talented swimmers: follow-up of performance and its biomechanical determinant factors

JORGE E. MORAIS[1,5], JOSE M. SAAVEDRA[2], MÁRIO J. COSTA[5], ANTÓNIO J. SILVA[1,5], DANIEL A. MARINHO[3,5], TIAGO M. BARBOSA[4,5]*

[1] Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal.
[2] Facultad de Ciencias del Deporte, AFIDES Reseach Group, Universidad of Extremadura, Cáceres, Spain.
[3] Department of Sport Sciences, University of Beira Interior, Covilhã, Portugal.
[4] National Institute of Education, Nanyang Technological University, Singapore.
[5] Research Centre in Sports, Health and Human Development, Vila Real, Portugal.

The aim of the study was to follow-up the stability of young talented swimmers' performance and its biomechanical determinant factors (i.e., anthropometrics, kinematics, hydrodynamics and efficiency) during a competitive season. Thirty three (15 boys and 18 girls) young swimmers (overall: 11.81 ± 0.75 years old and Tanner stages 1–2 by self-evaluation) were evaluated. Performance, anthropometrics, hydrodynamics, kinematics and efficiency variables were assessed at three moments during a competitive season. Performance had a significant improvement (with minimum effect size) and a moderate-very high stability throughout the season. In the anthropometrics domain all variables increased significantly (ranging from without to minimum effect size) between moments and had a moderate-very high stability. Hydrodynamics presented no variations between all moments and had a low-very high stability throughout the season. In the kinematics domain, there were no variations between moment one and three, except for an increase in stroke frequency (without size effect). Speed fluctuation remained constant, with no significant variations. All kinematic variables had a low-very high stability. Efficiency variables did not present variations between moment one and three and had a low-moderate stability. Overall, young swimmers showed a minimum improvement in performance and in anthropometric factors; and a moderate stability of performance and its determinant factors (i.e., anthropometrics, hydrodynamics, kinematics and efficiency) during the competitive season.

Key words: *prepubescent swimmers, longitudinal assessment, kinematics, drag force, anthropometrics, efficiency*

1. Introduction

Talent identification represents a complex interaction of interdisciplinary factors about future performance levels based on the individual data follow-up [1]. Most of the times, research concerning young swimmers is based on cross-sectional designs. When applied to talent identification, this research design is likely to exclude features as it is the multidimensional nature of the athletes' progression [2]. For a deeper understanding of the changes that occur throughout a time-frame, it is suggested to follow-up the swimmers' performance and its determinant factors with longitudinal or training-intervention designs [3]. However, there is scarce evidence of these changes throughout a given time-frame.

Longitudinal assessment gives a deeper and more reliable insight into the athletes' performance and its stability. Stability analysis is a concept based on tracking individual skills or abilities and see how they change over time. Tracking is focused on the stability of inter-individual differences in intra-individual changes [4]. It measures the maintenance of relative position of an individual within a group longitudinally assessed. In training-intervention, it allows practitio-

* Corresponding author: Tiago Barbosa, Physical Education & Sports Science Academic Group, National Institute of Education, Nanyang Technological University, NIE5-03-32, 1 Nanyang Walk, Singapore 637616. Tel: (65) 6219-6213, fax: (65) 6896-9260, e-mail: tiago.barbosa@nie.edu.sg
Received: April 17nd, 2013
Accepted for publication: May 23rd, 2013

ners to track down talented swimmers' performance and its determinant factors, defining realistic goals and training methods during a full competitive season, as it happens in swimming [5].

Swimming performance is a multi-factorial phenomenon, where recent research trends suggest a deterministic relationship between several scientific domains to explain it. For example, young swimmers' performance depends on energetics, kinematics and efficiency [6], while kinematics is influenced by anthropometrics and hydrodynamics/hydrostatic [7], [8]. So, the follow-up of talented swimmers should consider all these scientific fields and how they interact. Some longitudinal studies have assessed exclusively young swimmers' anthropometric [9]–[11] or kinematic [9]–[11] or hydrodynamic [12] or energetic [13] changes. It seems there is an absence of studies analyzing all these domains in one single study. This interdisciplinary approach allows a broader and more complete understanding of the relationships established among all determinant factors. Since this has never been attempted before, the interdisciplinary approach is a true breakthrough for a broader understanding of the mechanisms related to talented athlete's performance and notably the one from young swimmers.

The purpose of the study was to follow-up the stability of young talented swimmers' performance and its determinant factors (i.e., anthropometrics, kinematics, hydrodynamics and efficiency) during a competitive season. An enhancement of the performance and its determinant variables with moderate stability was hypothesized.

2. Materials and methods

2.1. Sample

Thirty-three young talented swimmers (overall: 11.81 ± 0.75-y, Tanner stages 1–2 by self-evaluation; N = 15 boys: 12.30 ± 0.63-y; N = 18 girls: 11.77 ± 0.92-y,) participating on regular basis in regional and national level competitions were assessed. The sample includes age-group national record holders and champions. The swimmers are part of the national talent identification follow-up project. At the beginning of data collection, swimmers had 3.18 ± 0.52-y of training experience. Swimmers had a total volume of 991.9 training sessions, 5.59 ± 0.92 training sessions per week (range = 3–8 in the season) that included warm-up, recovery, slow, medium, intense pace, technical drills, dry-land strength and stretching exercises.

Coaches, parents and/or guardians and also the athletes gave their consent for participation in this study. All procedures were in accordance with the Helsinki Declaration regarding Human research. The University Institutional Review Board also approved the study design.

2.2. Study design

A longitudinal research design with three-dimensional or axis box plot was carried out

$$Y_{ijt} \ (i = 1, 2, 3, ..., N; \ \ j = 1, 2, 3, ..., X; \ \ t = 1, 2, 3, ..., \mathrm{M}) \qquad (1)$$

where Y is the longitudinal co-variation, i is the sample size (N) variation, j the variables (X) variations and t the evaluation moment (M) variation. So, a longitudinal research design with repeated measures (within subject) of selected outcomes at three different moments (i.e., M) of the season was selected. Swimmers were evaluated in: (i) October (M1) corresponding to the season's first competition; (ii) March (M2) corresponding to the winter peak competition and; (iii): June (M3) corresponding to the summer peak competition.

2.3. Data collection

2.3.1. Performance data collection

Swimming performance was assessed as the official race time of the 100-m freestyle event of an official short course (i.e., 25-m swimming pool) competition on regional or national level. The time gap between data collection and swimming performance was less than 2-wks [6].

2.3.2. Anthropometric data collection

For anthropometrical assessment swimmers wear a textile swimsuit and a cap. Body mass (BM) was measured with a digital scale (SECA, 884, Hamburg, Germany) and height (H) with the swimmer in the upright anthropometrical position from vertex to the ground with a digital stadiometer (SECA, 242, Hamburg, Germany). Arm span (AS) was measured with swimmers in the upright position, arms and fingers fully extended in lateral abduction at a 90º angle with the trunk. The distance between the third fingertip of each hand was measured with a flexible anthropometric tape (RossCraft, Canada) (ICC = 0.98). Chest perimeter (CP) assessment was made with a flexible anthropometric tape (RossCraft, Canada) being the swimmer upright position simulating the hydrodynamic position (i.e., upright orthostatic position with arms fully extended upwards) (ICC = 0.99).

Hand (HSA), foot (FSA) and trunk (TTSA) areas were computed by digital photogrammetry [14]. For HSA and FSA, swimmers put their dominant hand and foot, respectively, on the scan surface of a copy machine (Xerox 4110, Norwalk, Connecticut, USA), near to a 2D calibration frame [8]. The perimeter of the HSA and FSA was digitized in the Xerox machine and files were converted to *.pdf. For TTSA measurement, swimmers were photographed with a digital camera (DSC-T7, Sony, Tokyo, Japan) in the transverse plane from above simulating the hydrodynamic position [15]. Afterwards the three surface areas were computed with specific software (Universal Desktop Ruler, v3.3.3268, AVPSoft, USA) [8] (ICC: HAS = 0.99; FSA = 0.97; TTSA = 0.97).

2.3.3. Hydrodynamic data collection

Active drag (D_a) and active drag coefficient (CD_a) were computed using the velocity perturbation method [16]. Each swimmer performed two maximal 25-m trials of freestyle swim with push-off start (with and without carrying the perturbation device) [12]. Active drag was computed as [16]

$$D_a = \frac{D_b v_b v^2}{v^3 - v_b^3} \quad (2)$$

where D_a represents the swimmers' active drag at maximal velocity (in N), D_b is the resistance of the perturbation buoy computed from the manufacturer's calibration of the buoy-drag characteristics and its velocity (in N), v_b and v are the swimming velocities with and without the perturbation device (in m·s^{-1}), respectively, measured by two expert evaluators with stop watches between the 11th and 24th meters (ICC = 0.96). The coefficient of active drag was computed as [16]

$$C_{Da} = \frac{2D_a}{\rho S v^2} \quad (3)$$

where C_{Da} is the active drag coefficient (dimensionless), D_a is the active drag (in N), ρ is the water density (assumed to be 1000 kg·m^{-3}), v is the velocity (in m·s^{-1}) and S (or TTSA as reported in the anthropometrics sub-section) is the swimmers' projected frontal surface area (in cm^2).

2.3.4. Kinematic data collection

Each swimmer performed three maximal freestyle swim trials of 25-m with push-off start. Trials were performed alone, with no other swimmers in the lane and were advised to reduce gliding during start to avoid higher acceleration with the push-off start help [17]. For further analysis the average value of the three trials was calculated.

A speedo-meter cable (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the swimmers' hip. A 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA) was used to transfer data (sampling rate at 50Hz) from the speedo-meter to a software interface in LabVIEW® (v.2009) [17]. Data were exported to signal processing software (AcqKnowledge v.3.5, Biopac Systems, Santa Barbara, USA) and filtered with a 5Hz cut-off low-pass 4th order Butterworth filter. Swimming velocity (v) was computed in the middle 15-m as

$$v = \frac{d}{t} \quad (4)$$

where v is the mean swimming velocity (in m·s^{-1}), d is the distance (in m) and t is the time (in s). Stroke frequency (SF, in cycles·min^{-1}) was measured with a chrono-frequency counter during three consecutive strokes by two expert evaluators (ICC = 0.97). Stroke length (SL) was computed as [18]

$$\mathrm{SL} = \frac{v}{\mathrm{SF}} \quad (5)$$

where SL represents stroke length (in m), v represents the mean velocity (in m·s^{-1}) and SF represents the stroke frequency (in Hz). Speed fluctuation (dv) was computed as [19]

$$\mathrm{d}v = \frac{\sqrt{\Sigma_i (v_i - \bar{v})^2 F_i / n}}{\Sigma_i v_i F_i / n} \quad (6)$$

where dv represents speed fluctuation (dimensionless), v represents the mean velocity (in m·s^{-1}), v_i represents the instant velocity (in m·s^{-1}), F_i represents the absolute frequency and n represents the number of observations.

2.3.5. Efficiency data collection

Efficiency variables (representing overall technical ability) were calculated from kinematical data. Stroke index (SI) was computed as [20]

$$\mathrm{SI} = \mathrm{SL} \cdot v \quad (7)$$

where SI represents stroke index (in $m^2 \cdot s^{-1}$), SL represents stroke length (in m) and v is the mean swimming velocity (in $m \cdot s^{-1}$). The propelling efficiency (η_p) was computed as [21]

$$\eta_p = \left[\left(\frac{v \cdot 0.9}{2\pi \cdot \mathrm{SF} \cdot l} \right) \cdot \frac{2}{\pi} \right] \cdot 100 \quad (8)$$

where η_p represents propelling efficiency (in %), v represents the velocity (in $m \cdot s^{-1}$), SF represents the stroke frequency (in Hz), and l is the distance between the shoulder and the tip of the 3rd finger during the insweep (in m).

2.4. Statistical analysis

The Kolmogorov–Smirnov and the Levene tests were used to analyze normality and homocedasticity assumptions, respectively. Longitudinal assessment was made based on two approaches [5]: (i) mean stability and (ii) normative stability. For mean stability, mean ± one standard deviation were calculated for each moment. Data variation was assessed with ANOVA repeated measures followed by the Bonferroni post-hoc test to verify differences between moments ($p < 0.05$). Total eta square (η^2) was selected as effect size index and interpreted as [22]: (i) without effect if $0 < \eta^2 \leq 0.04$; (ii) minimum if $0.04 < \eta^2 \leq 0.25$; (iii) moderate if $0.25 < \eta^2 < 0.64$ and; (iv) strong if $\eta^2 > 0.64$.

Normative stability was analyzed with Pearson's correlation coefficient ($p < 0.05$) and Cohen's Kappa. Pearson's correlation coefficient was computed for each selected variable between moments. As a rule of thumb, for qualitative assessment, it was defined that the stability was [23]: (i) very weak if $r < 0.04$; weak if $0.04 \leq r < 0.16$; moderate if $0.16 \leq r < 0.49$; high if $0.49 \leq r < 0.81$, and very high if $0.81 \leq r < 1.0$. Cohen's Kappa (K) was used to detect inter-individual differences over the season. The K was computed based on three channels ("tracks") delimited by the percentiles 33, 66 and 100. The number of times each swimmer goes out of a specific track reflects the inter-individual stability in a certain characteristic. K was computed with the Longitudinal Data Analysis software (v.3.2, Dallas, USA) with a confidence interval of 95%. The qualitative interpretation was made as [24]: excellent if $K \geq 0.75$; (ii) moderate if $0.40 \leq K < 0.75$ and; (iii) low if $K < 0.40$.

3. Results

3.1. Mean stability

The Bonferroni post-hoc test revealed significant differences in the performance between all three moments for overall, boys and girls (Fig. 1). So, an improvement in the swimming performance was verified throughout the season.

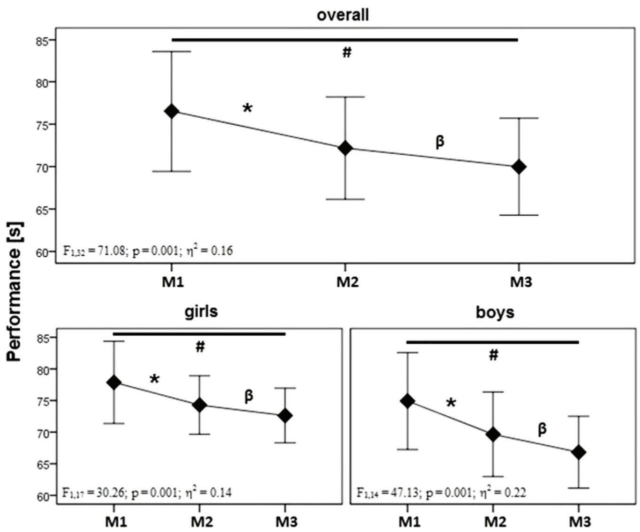

Fig. 1. Performance variation during the competitive season; * $p < 0.05$ M1 vs M2; # $p < 0.05$ M1 vs M3; β $p < 0.05$ M2 vs M3; F – F test value; η^2 – effect size value; p – significance value

There were significant variations in all anthropometrical variables (Fig. 2). For BM, post-hoc test showed significant increases in all three moments, except between M1-vs-M2 for the girls. For H, AS and CP (overall, boys and girls) there were significant increases in all three moments. For HSA (overall) there were significant increases in all moments. For boys and girls, there were no-significant increases between M2-vs-M3. For FSA there were significant increases in all moments for overall and girls. For boys there were only no-significant differences between M2-vs-M3. For TTSA (overall) there were significant increases between M1-vs-M2 and M1-vs-M3, but not between M2-vs-M3. As for boys and girls there were no-significant differences in all moments. Active drag and C_{Da} presented no-significant variations (Fig. 2).

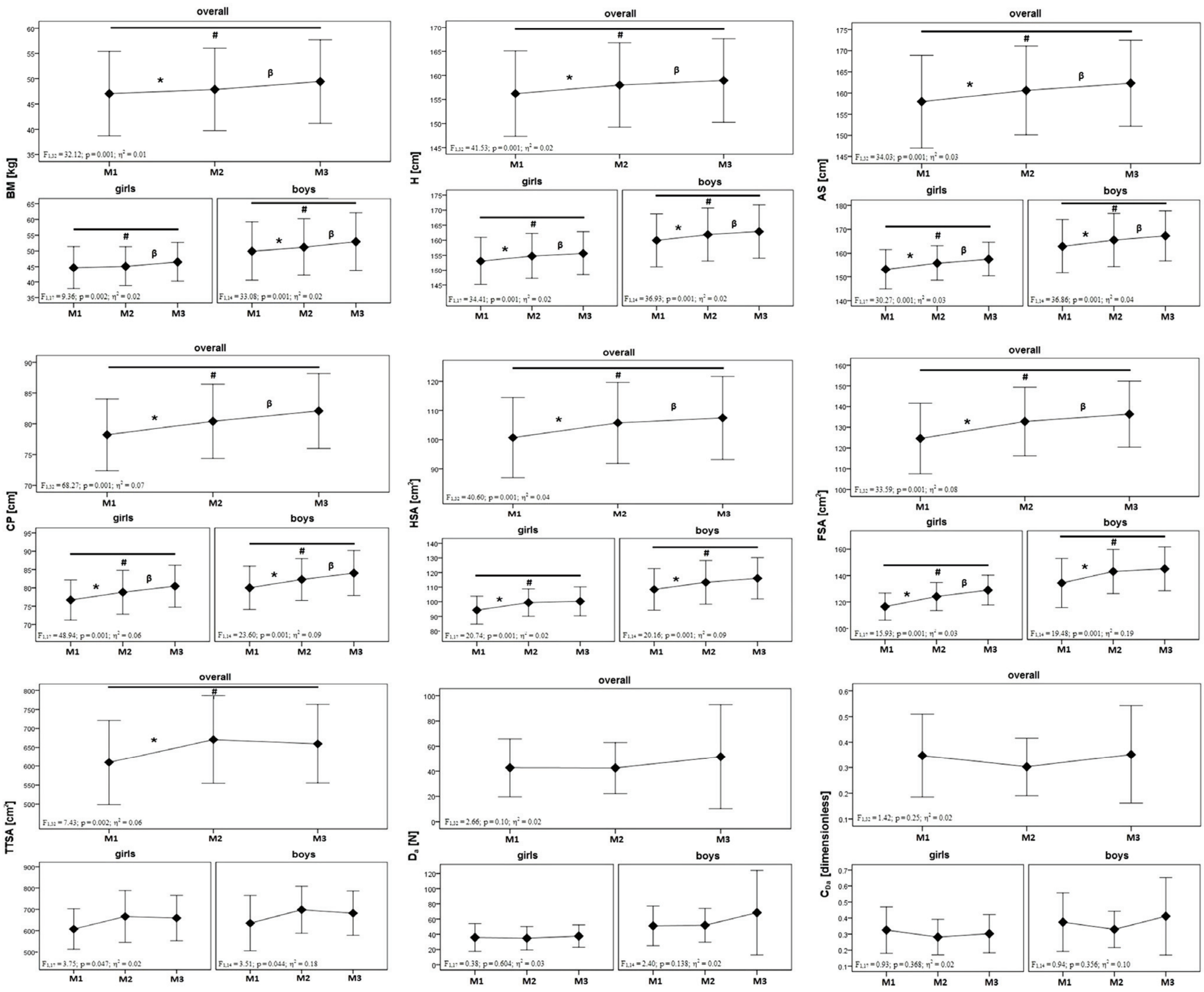

Fig. 2. Anthropometrics and hydrodynamics variation throughout the competitive season.
BM – body mass; H – height; AS – arm span; CP – chest perimeter; HSA – hand surface area;
FSA – foot surface area; TTSA – trunk transverse surface area;
D_a – active drag; C_{Da} – active drag coefficient; * $p < 0.05$ M1 vs M2; # $p < 0.05$ M1 vs M3;
β $p < 0.05$ M2 vs M3; F – F test value; η^2 – effect size value; p – significance value

SL and v revealed significant variations during the competitive season but for SF there were no-significant one in the two groups (overall and girls) and a significant one in the group of boys' (Fig. 3). As for dv, there was a no-significant variation. Regarding the pairwise differences between moments, for SL as well for v, there were significant differences between M1-vs-M2 and M2-vs-M3, but not between M1-vs-M3. For SF there was a significant difference in the group of boys between M1-vs-M3. Regarding the efficiency variables, both SI and η_p revealed significant variations (Fig. 3). Post-hoc test showed, for both SI and η_p, significant differences between M1-vs-M2 and M2-vs-M3, but not between M1-vs-M3.

3.2. Normative stability

The performance (Table 1) presented a very high stability throughout the season for overall ($0.82 \leq r \leq 0.91$), boys ($0.84 \leq r \leq 0.94$) and girls ($0.86 \leq r \leq 0.96$). The anthropometric domain had the highest number of variables with a very high stability. For example, H (overall: $0.87 \leq r \leq 0.99$; boys: $0.98 \leq r \leq 0.99$; girls: $0.98 \leq r \leq 0.99$) and AS (overall: $0.95 \leq r \leq 0.99$; boys: $0.98 \leq r \leq 0.99$; girls: $0.93 \leq r \leq 0.98$) are two of those cases. Variables related to swim efficiency, notably the η_p, showed a weak-moderate stability (overall: $0.09 \leq r \leq 0.30$; boys: $0.15 \leq r \leq 0.32$; girls: $0.004 \leq r \leq 0.39$).

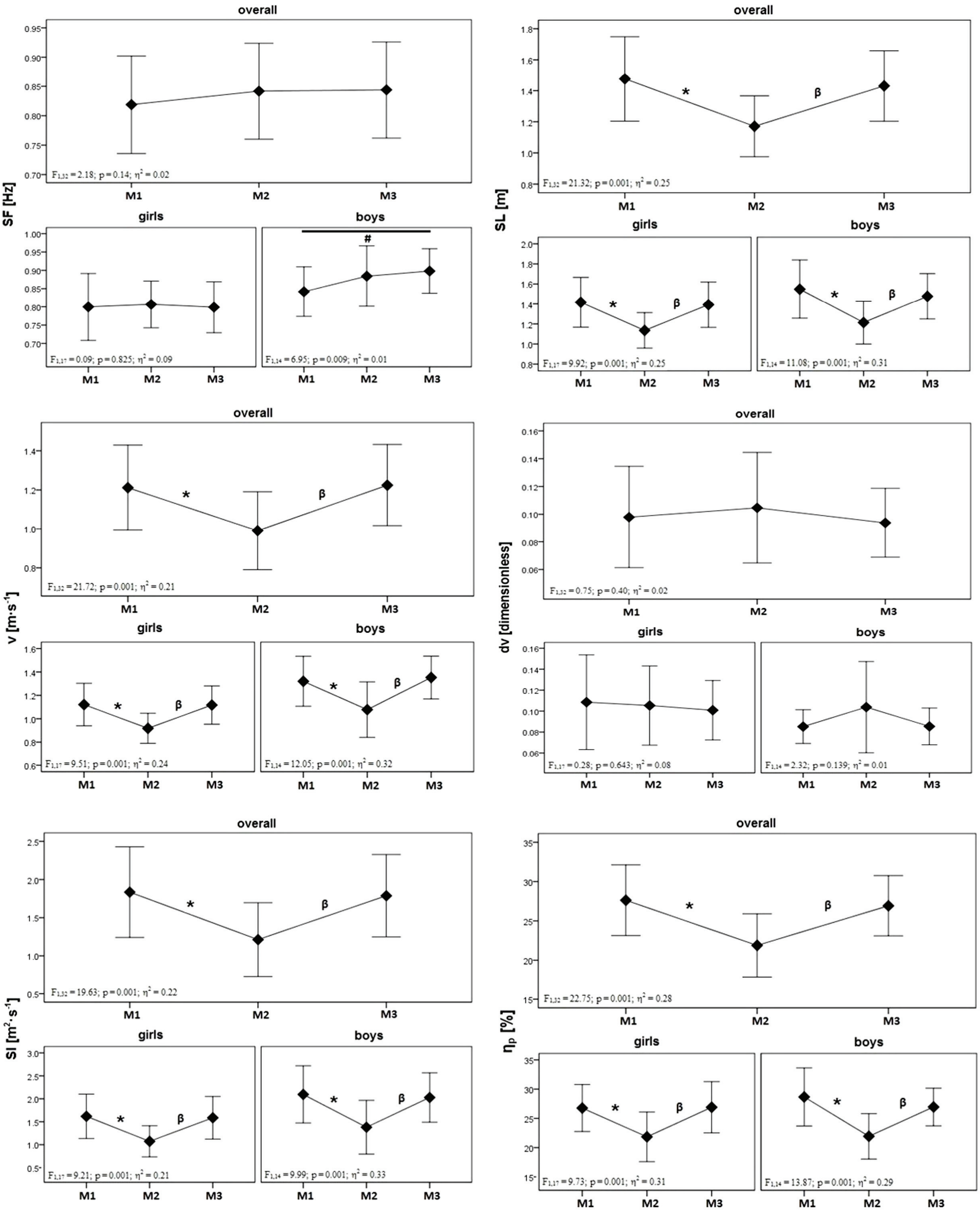

Fig. 3. Kinematics and efficiency variation throughout the competitive season.
SF – stroke frequency; SL – stroke length; v – swimming velocity; dv – speed fluctuation;
SI – stroke index; η_p – propelling efficiency; * $p < 0.05$ M1 vs M2; # $p < 0.05$ M1 vs M3;
β $p < 0.05$ M2 vs M3; F – F test value; η^2 – effect size value; p – significance value

Performance had a moderate stability (overall: K = 0.59; boys: K = 0.73; girls: K = 0.63) when assessed with Cohen's Kappa (Table 2). For overall, H (K = 0.92) and HSA (K = 0.92) were the variables with the highest stability; for the boys there were the AS (K = 0.91) and CP (K = 0.90); and for the girls the H (K = 1.00) and BM (K = 0.85).

Table 1. Pearson's correlation coefficients between the three data collection moments (M) for performance and its determinant factors (i.e., anthropometrics, kinematics, hydrodynamics and energetics)

		Overall			Boys			Girls		
		M1 vs M2	M2 vs M3	M1 vs M3	M1 vs M2	M2 vs M3	M1 vs M3	M1 vs M2	M2 vs M3	M1 vs M3
Anthropometrics	BM [kg]	0.98*	0.99*	0.96*	0.99*	0.99*	0.98*	0.97*	0.97*	0.94*
	H [cm]	0.99*	0.99*	0.97*	0.99*	0.99*	0.98*	0.99*	0.99*	0.98*
	AS [cm]	0.97*	0.95*	0.93*	0.99*	0.99*	0.98*	0.97*	0.98*	0.93*
	CP [cm]	0.94*	0.96*	0.94*	0.90*	0.95*	0.94*	0.97*	0.97*	0.94*
	HSA [cm^2]	0.96*	0.96*	0.92*	0.95*	0.96*	0.93*	0.93*	0.94*	0.83*
	FSA [cm^2]	0.87*	0.96*	0.78*	0.91*	0.98*	0.88*	0.60**	0.90*	0.33
	TTSA [cm^2]	0.57*	0.79*	0.49**	0.69**	0.73**	0.57***	0.46	0.83*	0.41
Hydrodynamics	D_a [N]	0.80*	0.79*	0.64*	0.84*	0.80*	0.67**	0.67**	0.83*	0.42
	C_{Da} [dimensionless]	0.66*	0.48**	0.07	0.85*	0.30	–0.02	0.44	0.76*	0.14
Kinematics	SF [Hz]	0.53*	0.83*	0.34	0.54***	0.88*	0.51	0.48***	0.72**	0.09
	SL [m]	0.12	0.36***	0.25	0.16	0.36	0.44	–0.02	0.33	0.002
	v [$m \cdot s^{-1}$]	0.28	0.50***	0.43**	0.31	0.41	0.47	–0.23	0.30	–0.03
	dv [dimensionless]	0.96*	–0.08	–0.07	–0.04	0.30	0.17	0.87*	0.12	–0.14
Efficiency	SI [$m^2 \cdot s^{-1}$]	0.16	0.39***	0.39***	0.16	0.32	0.48	–0.20	0.29	0.02
	η_p [%]	0.09	0.30	0.14	0.18	0.15	0.32	–0.004	0.39	0.01
	Perf@100free [s]	0.91*	0.93*	0.82*	0.92*	0.94*	0.84*	0.92*	0.90*	0.86*

BM – body mass; H – height; AS – arm span; CP – chest perimeter; HSA – hand surface area; FSA – foot surface area; TTSA – trunk transverse area; D_a – active drag; C_{Da} – active drag coefficient; SF – stroke frequency; SL – stroke length; v – swimming velocity; dv – speed fluctuation; SI – stroke index; η_p – propelling efficiency; Perf@100free – performance at the 100-m freestyle event; *$p < 0.001$; ** $p < 0.01$; ***$p < 0.05$.

Table 2. Cohen's Kappa (K) and 95 % confidence interval for performance and its determinant factors (i.e., anthropometrics, kinematics, hydrodynamics and energetics)

		Overall			Boys			Girls		
			95% Confidence Interval			95% Confidence Interval			95% Confidence Interval	
		K	Lower bound	Upper bound	K	Lower bound	Upper bound	K	Lower bound	Upper bound
Anthropometrics	BM [kg]	0.75	0.55	0.95	0.82	0.52	1.12	0.85	0.57	1.12
	H [cm]	0.92	0.71	1.12	0.82	0.52	1.12	1.00	0.72	1.27
	AS [cm]	0.79	0.59	0.99	0.91	0.61	1.20	0.70	0.43	0.97
	CP [cm]	0.63	0.43	0.83	0.90	0.61	1.20	0.70	0.43	0.97
	HSA [cm^2]	0.92	0.71	1.12	0.64	0.34	0.94	0.70	0.43	0.97
	FSA [cm^2]	0.63	0.43	0.83	0.64	0.34	0.94	0.48	0.21	0.75
	TTSA [cm^2]	0.51	0.31	0.71	0.55	0.25	0.85	0.33	0.06	0.60
Hydrodynamics	D_a [N]	0.43	0.23	0.63	0.37	0.07	0.67	0.40	0.13	0.68
	C_{Da} [dimensionless]	0.27	0.07	0.47	0.37	0.07	0.67	0.40	0.13	0.68
Kinematics	SF [Hz]	0.51	0.30	0.71	0.63	0.33	0.92	0.33	0.06	0.60
	SL [m]	0.06	–0.13	0.26	0.19	–0.10	0.49	0.03	-0.23	0.31
	v [$m \cdot s^{-1}$]	0.31	0.11	0.51	0.46	0.16	0.76	–0.03	-0.31	0.23
	dv [dimensionless]	0.34	0.14	0.54	0.36	0.06	0.66	0.22	-0.05	0.49
Efficiency	SI [$m^2 \cdot s^{-1}$]	0.23	0.03	0.43	0.19	–0.10	0.48	–0.18	-0.45	0.08
	η_p [%]	0.03	–0.17	0.23	0.10	–0.19	0.40	0.03	-0.23	0.31
	Perf@100free [s]	0.59	0.39	0.79	0.73	0.43	1.03	0.63	0.35	0.90

BM – body mass; H – height; AS – arm span; CP – chest perimeter; HSA – hand surface area; FSA – foot surface area; TTSA – trunk transverse area; D_a – active drag; C_{Da} – active drag coefficient; SF – stroke frequency; SL – stroke length; v – swimming velocity; dv – speed fluctuation; SI – stroke index; η_p – propelling efficiency; Perf@100free – performance at the 100-m freestyle event

4. Discussion

The purpose of the study was to follow-up the stability of young talented swimmers' performance and its biomechanical determinant factors throughout a competitive season. Performance (overall, boys and girls data) showed a significant improvement during the competitive season with a moderate-very high stability. Overall, most of the performance determinant variables increased with a moderate stability.

Mean stability

The performance showed an improvement between all the moments (overall, boys and girls). The same trend was reported in a couple of papers [9], [10]. Confirmatory research reports that young swimmers' performance is a multi-factorial phenomenon [6]. Biomechanics explained 50–60% of the performance [8]. On one hand, the state of the art as regards this subject is supported in cross-sectional studies [25]; on the other, the influence of each one of the main subdisciplines of biomechanics (i.e., kinematics, kinetics/hydrodynamics, efficiency and even anthropometrics) on performance throughout a time-frame has never been investigated before.

Most anthropometrical variables (weight, lengths and areas) increased throughout the season. Growth and maturation processes during these ages are well known phenomenon [26]. One paper observed similar results in young male swimmers for a 2-y assessment [10]. Despite scarce evidence about young swimmers follow-up, it seems that anthropometrics increases significantly in a shorter time-frame than reported in the previous study [10]; as our data shows, significant anthropometric changes happen in less than 2-y. In the hydrodynamics there were no-significant changes in both D_a and C_{Da}. After 8-wks of training, there was verified no-significant decrease in both D_a and C_{Da} [12]. However, one study found a significant decrease in pubescent swimmers' C_{Da} after 1-wk of intervention (focused on technique drills, feedback with specific visual and kinesthetic cues) [27]. Also, in computational fluid dynamics [28] and experimental methods but in a "flume" [29], the head and shoulders, and also overall body position (i.e., technical training) seem to have a substantial role in drag. So, hydrodynamic improvement in young swimmers might be strongly related to a training design focused more on drills and technical improvement (i.e., biomechanics).

For kinematics, SL and v presented no-significant variations between M1 and M3. However, a significant decrease of the v happened in M2. Coaches design the training process to elicit performance improvements throughout the season, but especially at the main peak performance moment (i.e., at M3, end of the season). As happens in other locomotion technics, including gait [30]–[32] or fin swimming [33], kinematic improvements also presented a no-linear (i.e., "sine wave") change throughout a time-frame. As reported in the literature [9], no changes were verified for SF. Speed fluctuation increased from M1 to M2 and decreased from M2 to M3, which coincided with the v changes. This confirms that there is a negative association between dv and v [17]. SI and η_p presented significant variations. Two papers found that SI increases from the beginning till the end of the season, in both genders [9], [10]. SI and η_p also changed in a nonlinear fashion, since both are estimations based on kinematical outcomes.

Normative stability

Performance stability (overall, boys and girls data) was moderate-very high. Anthropometrics also had a moderate-very high stability. Others also found a high stability for the anthropometrics but assessed only with auto-correlation [9], [10]. Kinematics and hydrodynamics had a low-very high stability and efficiency had a low-moderate stability. Although in two papers a high stability for the kinematics was found [9], [10]. It might be speculated that physical development (i.e., growth and maturation) led young swimmers to change their motor control strategies affecting the stroke mechanics and efficiency [34]. Each swimmer has their own sensitive or critical development periods that are not coincident with each other. It seems that young swimmers might have to acquire, learn and consolidate a new motor control strategy whenever a quick growth and maturation change happens (e.g. mid-grow spurt). This leads to a momentary decrease in the efficiency and kinematic behavior. Furthermore, since growth and maturation processes happen in a very unique fashion in each swimmer, this leads to consecutive changes in the stability outcomes.

The performance and anthropometrics presented a significant increase and moderate-very high stability. Then it might be suggested that anthropometrics was the most determinant domain for young swimmers' performance improvement and stability. A cross-sectional multivariate analysis reported a good performance prediction based on anthropometrics, notably for the boys [35]. As swimming is a sport of multi-factorial nature, performance improvement does not only occur in response to one single domain (i.e., anthropometrics).

As a conclusion, performance showed a minimum but significant improvement throughout the competitive season with a moderate-very high stability. On overall, most of the performance determinant variables increased (and ranged from without to moderate effect size) with a moderate stability. Anthropometrics was the domain that showed the highest increase (but also ranging from without to minimum effect size), though with a very high stability. Hence, anthropometrics was the domain that played the major role in the performance improvement and its stability; while kinematics, hydrodynamics and efficiency played a minor role.

Acknowledgments

Thanks are due to Marc Moreira (CIDESD) for his useful help during data collection. Jorge E. Morais acknowledges the Portuguese Science and Technology Foundation (FCT) for the PhD scholarship (SFRH/BD/76287/2011).

References

[1] FORD P., DE STE CROIX M., LLOYD R., MEYERS R., MOOSAVI M., OLIVER J., TILL K., CRAIG W., *The long-term athlete development model: physiological evidence and application*, J. Sports Sci., 2011, Vol. 29, 389–402.

[2] VAEYENS R., LENOIR M., WILLIAMS A.M., PHILIPPAERTS R.M., *Talent identification and development programmes in sport: current models and future directions*, Sports Med., 2008, Vol. 38, 703–714.

[3] HOHMANN A., SEIDEL I., *Talent prognosis in young swimmers*, [in:] P. Kjendlie, R.K. Stallman, J. Cabri (eds.), *Biomechanics and Medicine in Swimming XI*, Oslo, Norwegian School of Sport Sciences, 2010, 262–264.

[4] KOWALSKI C.J., SCHNEIDERMAN E.D., *Tracking: concepts, methods and tools*, Int. J. Anthrop., 1992, Vol. 7, 33–50.

[5] COSTA M.J., BRAGADA J.A., MEJIAS J.E., LOURO H., MARINHO D.A., SILVA A.J., BARBOSA T.M., *Tracking the performance, energetics and biomechanics of international versus national level swimmers during a competitive season*, Eur. J. Appl. Physiol., 2012, Vol. 112, 811–820.

[6] BARBOSA T.M., COSTA M.J., MARINHO D.A., COELHO J., MOREIRA M., SILVA A.J., *Modeling the links between young swimmers' performance: energetic and biomechanical profiles*, Ped. Exerc. Sci., 2010a, Vol. 22, 379–391.

[7] BARBOSA T.M., COSTA M.J., MORAIS J.E., MOREIRA M., SILVA A.J., MARINHO D.A., *How informative are the vertical buoyancy and the prone gliding tests to assess young swimmers hydrostatic and hydrodynamic profiles?*, J. Hum Kinetics, 2012, Vol. 32, 21–32.

[8] MORAIS J.M., JESUS S., LOPES V., GARRIDO N.D., SILVA A.J., MARINHO D.A., BARBOSA T.M., *Linking selected kinematic, anthropometric and hydrodynamic variables to young swimmer performance*, Ped. Exerc. Sci., 2012, Vol. 24, 649–664.

[9] LÄTT E., JÜRIMÄE J., HALJASTE K., CICCHELL A., PURGE P., JÜRIMÄE T., *Physical development and swimming performance during biological maturation in young female swimmers*, Coll. Antropol., 2009a, Vol. 33, 117–122.

[10] LÄTT E., JÜRIMÄE J., HALJASTE K., *Longitudinal development of physical and performance parameters during biological maturation of young male swimmers*, Percep. Motor Skills, 2009, Vol. 108, 297–307.

[11] TELLA V., LLANA S., MADERA J., NAVARRO F., *Evolution of anthropometrical and kinematic parameters in young swimmers: a longitudinal study*, [in:] K.E. Gianikellis (ed.), Proceedings of The XX International Symposium on Biomechanics in Sports, Cáceres, University of Extremadura, 2002, 64–67.

[12] MARINHO D.A., BARBOSA T.M., COSTA M.J., FIGUEIREDO C., REIS V.M., SILVA A.J., MARQUES M.C., *Can 8 weeks of training affect active drag in young swimmers?*, J. Sports Sci Med., 2010, Vol. 9, 71–78.

[13] MARINHO D.A., SILVA A.J., REIS V.M., COSTA A.M., BRITO J.P., FERRAZ R., MARQUES M.C., *Changes in critical velocity and critical stroke rate during a 12 week swimming training period: a case study*, J. Hum. Sport Exerc., 2009, Vol. 4, 48–56.

[14] TAÏAR R., LODINI A., *Estimation of swimmers anthropometrics parameters and surface areas in real swimming conditions*, Acta Bioeng. Biomech., 2005, Vol. 7, 85–95.

[15] CASPERSEN C., BERTHELSEN P.A., EIK M., PÂKOZDI C., KJENDLIE P.L., *Added mass in human swimmers: age and gender differences*, J. Biomech., 2010, Vol. 43, 2369–2373.

[16] KOLMOGOROV S., DUPLISHCHEVA O., *Active drag, useful mechanical power output and hydrodynamic force in different swimming strokes at maximal velocity*, J. Biomech., 1992, Vol. 25, 311–318.

[17] BARBOSA T.M., MOROUÇO P.G., JESUS S., FEITOSA W.G., COSTA M.J., MARINHO D.A., SILVA A.J., GARRIDO N.D., *The interaction between intra-cyclic variation of the velocity and mean swimming velocity in young competitive swimmers*, Int. J. Sports. Med., 2013, Vol. 34, 123–130.

[18] CRAIG A., PENDERGAST D., *Relationships of stroke rate, distance per stroke and velocity in competitive swimming*, Med. Sci. Sports Exerc., 1979, Vol. 11, 278–283.

[19] BARBOSA T.M., BRAGADA J.A., REIS V.M., MARINHO D.A., CARVALHO C., SILVA A.J., *Energetics and biomechanics as determining factors of swimming performance: updating the state of the art*, J. Sci. Sports Med., 2010, Vol. 13, 262–269.

[20] COSTILL D.L., KOVALESKI J., PORTER D., KIRWAN J., FIELDING R., KING D., *Energy expenditure during front crawl swimming: predicting success in middle-distance events*, Int. J. Sports. Med., 1985, Vol. 6, 266–270.

[21] ZAMPARO P., PENDERGAST D.R., MOLLENDORF J., TERMIN A., MINETTI A.E., *An energy balance of front crawl*, Eur. J. Appl. Phnysiol., 2005, Vol. 94, 134–144.

[22] FERGUSON C.J., *An Effect Size Primer: A Guide for Clinicians and Researchers*, Professional Psychology: Research and Practice, 2009, Vol. 40, 532–538.

[23] COSTA M.J., OLIVEIRA C., TEIXEIRA G., MARINHO D.A., SILVA A.J., BARBOSA T.M., *The influence of musical cadence into aquatic jumping jacks kinematics*, J. Sport Sci. Med., 2011, Vol. 10, 607–615.

[24] LANDIS J., KOCH G., *The measurement of observer agreement for categorical data*, Biometrics, 1977, Vol. 33, 159–174.

[25] TAÏAR R., TOSHEV Y., LODINI A., ROUARD A., *Performance modeling of butterfly swimmers: links between morphometric, kinematic and hydrodynamic variables*, Acta Bioeng. Biomech., 2004, Vol. 6, 77–88.

[26] PISZCZATOWSKI S., *Geometrical aspects of growth plate modeling using Carter's and Stokes's approaches*, Acta Bioeng. Biomech., 2012, Vol. 14, 93–106.

[27] HAVRILUK R., *Magnitude of the effect of an instructional intervention on swimming technique and performance*, [in:] J.P. Vilas-Boas, F. Alves, A. Marques (eds.), X International Symposium of Biomechanics and Medicine in Swimming, Porto, Portuguese Journal of Sport Sciences, 2006, 218–220.

[28] POPA C.V., ZAIDI H., ARFAOUNI A., POLIDORI G., TAIAR R., FOHANNO S., *Analysis of wall shear stress around a competitive swimmer using 3D Navier–Stokes equations in CFD*, Acta Bioeng. Biomech., 2011, Vol. 13, 3–11.

[29] TAÏAR R., BERTUCCI W., LETELLIER TH., BENKEMIS I., *Experimental assessment of the drag coefficient during butterfly swimming in hydraulic flume*, Acta Bioeng. Biomech., 2005, Vol. 7, 97–108.

[30] COSTA M.J., MARINHO D.A., BRAGADA J.A., SILVA A.J., BARBOSA T.M., *Stability of elite freestyle performance from childhood to adulthood*, J. Sports Sci., 2011, Vol. 29, 1183–1189.

[31] STASZKIEWICZ R., CHWALA W., FORCZEK W., LASKA J., *Influence of surface on kinematic gait parameters and lower extremity joints mobility*, Acta Bioeng. Biomech., 2012, Vol. 14, 75–82.

[32] STASZKIEWICZ R., RUCHLEWICZ T., FORCZEK W., LASKA J., *The impact of changes in gait speed and step frequency on the extent of the center of mass displacements*, Acta Bioeng. Biomech., 2010, Vol. 12, 13–20.

[33] REJMAN M., *The dynamic and timing criteria for assessing the single fin swimming technique*, Acta Bioeng. Biomech., 2011, Vol. 3, 67–79.

[34] SEIFERT L., CHOLLET D., BARDY B.G., *Effect of swimming velocity on arm coordination in the front crawl: a dynamic analysis*, J. Sports Sci., 2004, Vol. 22, 651–660.

[35] SAAVEDRA J.M., ESCALANTE Y., RODRÍGUEZ F.A., *A multivariate analysis of performance in young swimmers*, Ped. Exerc. Sci., 2010, Vol. 22, 135–151.