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Hydrodynamic profile of young swimmers: Changes over a competitive season

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The aim of this study was to analyze the changes in the hydrodynamic profile of young swimmers over a competitive season and to compare the variations according to a well-designed training periodization. Twenty-five swimmers (13 boys and 12 girls) were evaluated in (a) October (M1); (b) March (M2); and (c) June (M3). Inertial and anthropometrical measures included body mass, swimmer's added water mass, height, and trunk transverse surface area. Swimming efficiency was estimated by the speed fluctuation, stroke index, and approximate entropy. Active drag was estimated with the velocity perturbation method and the passive drag with the gliding decay method. Hydrodynamic dimensionless numbers (Froude and Reynolds numbers) and hull velocity (i.e., speed at Froude number = 0.42) were also calculated. No variable presented a significant gender effect. Anthropometrics and inertial parameters plus dimensionless numbers increased over time. Swimming efficiency improved between M1 and M3. There was a trend for both passive and active drag increase from M1 to M2, but being lower at M3 than at M1. Intra-individual changes between evaluation moments suggest high between- and within-subject variations. Therefore, hydrodynamic changes over a season occur in a non-linear fashion way, where the interplay between growth and training periodization explain the unique path flow selected by each young swimmer.

Swimming is a locomotion technique to travel in water. As a land species, humans are not completely adapted to aquatic environments, or at least to the same extent as others. Swimming can be used for purposes of survival, leisure and recreation, health and fitness, and sports and exercise. Performance in swimming is measured by the time spent to cover a given distance. Swimming proficiency and performance will depend greatly on the hydrodynamic profile of the subject. The hydrodynamic profile involves analysis of the drag force (passive and active drag), dimensionless numbers (e.g., Reynolds and Froude numbers), and mechanical power and its relationships with anthropometrics, swimming kinematics, and efficiency.

A profile is a collection of features that might characterize someone. Sports performance profiling can include anthropometrical, biomechanical, physiological, or psychological variables, among others. Profiling provides athletes with an awareness of their strongest and weak points. Profiling enables a swimmer to excel, as long as the determinant factors of performance are assessed. Swimming performance is a multifactorial phenomenon in which several domains, including hydrodynamics (Barbosa et al., 2010), play a part. Theoretical and empirical studies (experimental or numerical simulations) have shown that several hydrodynamic variables are related to performance and/or the competitive level. Hydrodynamic profiling may include analysis of the two main streamwise external forces that act upon the swimmer: thrust and drag. Theoretically, swimming velocity is the balance between both forces. To be stricter, the balance between the power output and the drag should provide us the velocity (in m/s):

$$v = \frac{P}{D} \quad [1]$$

where v is the velocity (in m/s), P is the power output (in W), and D is the drag, i.e., the resistive force (in N). Confirming theoretical models with empirical data is more challenging. Nevertheless, it has been reported that the three most propulsive phases of the butterfly stroke cycle are the outsweep, the insweep, and the upsweep (Taiar et al., 1999). Improvement in performance is related to power output. Furthermore, hydrodynamic profile shows dramatic changes with training (Toussaint

& Beek, 1992). It has been suggested that, to maximize velocity, drag has to be minimized by tailoring the resistance type (friction, pressure, or wave) according to the form of locomotion (e.g., fins swimming vs front crawl stroke) and swim pace (Pendergast et al., 2005). For instance, at speeds below 1 m/s, pressure drag dominates, whereas friction drag dominates up to 3 m/s (Pendergast et al., 2005). Swimmers who have recorded the fastest speed also showed the smallest difference in net drag force fluctuations, at least for backstroke (Formosa et al., 2013). Overall, both thrust and drag affect swimming performance.

Thrust is produced from steady and unsteady flows. Steady-flow propulsion is related to the effective propulsive force (Schleihauf et al., 1988):

$$F_{\mathrm{p}} = D_{\mathrm{prop}} + L \cdot \cos\alpha \quad [2]$$

where F_{p} is the effective propulsive force, D_{prop} is the propulsive drag, L is the lift force, and α is the absolute angle of the resultant vector in the displacement direction (i.e., horizontal axis). Unsteady-flow propulsion is related to vortex or intermittent jet-flow:

$$\Gamma = \int \omega \cdot ds \quad [3]$$

where Γ is the vortex circulation, ω is the angular velocity, and ds is the area. The velocity induced by a vortex ring is calculated using Biot–Savart's law, which can also be applied to hydrodynamics:

$$v_0 = \frac{\Gamma}{2 \cdot R} \quad [4]$$

where v_0 is the instantaneous induced velocity, Γ is the circulation of vortex ring, and R is the vortex ring radius at a given moment. On the other side, resistance or drag can be calculated with Newton's equation:

$$D = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S \cdot C_{\mathrm{D}} \quad [5]$$

where D is the drag force, ρ is the fluid density, v is the velocity, S is the projection surface, and C_{D} is the drag coefficient. Total drag force includes three components:

$$D = D_{\mathrm{f}} + D_{\mathrm{pr}} + D_{\mathrm{w}} \quad [6]$$

where D is the total drag force, D_{f} is the friction drag, D_{pr} is the pressure drag, and D_{w} is the wave drag. The total drag or each one of its components can be measured when the swimmer glides or is towed with no segmental action (i.e., passive drag) or he propels himself (i.e., active drag). D_{f} is attributed to tangential forces that slow down the water flowing around the body surface. D_{pr} is caused by the pressure differential between the front and the rear parts of the body. Both D_{f} and D_{pr} are strongly related to the fluid flow around the body. The Reynolds number (*Re*) is a dimensionless variable expressing the ratio between inertial and viscous forces, hence quantifying the flow conditions. D_{w} is due to the displacement of the body at surface, which catches and compresses fluid, setting up a wave system. With increasing depth the effect of D_{w} decreases meaningfully, i.e., there is a significant and moderate/large effect size, hence making it a relevant phenomenon for swimming (Vorontsov & Rumyantsev, 2000). Experimental evidence suggests that D_{w} can be neglected when a swimmer is fully submerged (Naemi et al., 2010). Froude number (*Fr*) and hull velocity (v_{hull}) can be used complimentarily to assess wave resistance (Kjendlie & Stallman, 2008). The Froude number represents the ratio of inertial to gravitational forces experienced by a body moving at or close to a fluid/fluid interface (Webb, 1975). Therefore, wave-making resistance is related to *Fr*, whereas v_{hull} is the critical velocity where upon the wave wake length is equal to hull length. The D_{w} increase is less sharp above $Fr = 0.45$ (Vennell et al., 2006). At $Fr = 0.42$, the body is trapped in the hull, moving along with the wave system, i.e., the v_{hull} (Vogel, 1994), and therefore is more economic and efficient. Comparing adults and children, the former present a higher maximal swim speed, but also *Fr* and *Re* (Kjendlie & Stallman, 2008). Besides that, performance enhancement was coupled with increases in *Fr* and *Re* (Toussaint et al., 1990).

Because it is so challenging to directly measure swimming efficiency, researchers tend to select a few estimators. These estimators are based on the reasoning that, according to Newton's laws, resistance to any change in a body motion will increase the energy demand. Higher variations in the state of the motion (i.e., velocity changes) likewise will increase the energy cost of transportation. Speed fluctuation and stroke index are two variables most cited in the swimming literature (Barbosa et al., 2010). In young swimmers, it was reported that as speed increases, speed fluctuation tends to decrease (Barbosa et al., 2012) and stroke index tends to increase (Latt et al., 2009). However, claims that both parameters are not sensitive or informative enough have been increasing. This might be due to the fact that both parameters assess intra-cyclic variations, i.e., changes in a very short period of time. There is always a delay between the start of a physical effort and the neuromuscular, kinematic, and kinetic and energetic acute responses. Whereas kinematic changes take no longer than a few tenths of a second to happen, the kinetic and energetic response to such changes might need some seconds or minutes. Hence, a parameter that allows assessment of the speed inter-cyclic changes throughout several stroke cycles can be a true novelty and deliver more insightful details.

Approximate entropy (*ApEn*; Pincus, 1991) is one non-linear technique used to quantify the regularity of fluctuations over time series data. In this regard, *ApEn* might allow us to learn about the inter-cyclic variations of the horizontal velocity. According to the published literature, this measure has not been used previously to assess competitive swimming or any other competitive technique. However, it has been used in other fields, for instance, to assess body sway (e.g., Kee et al., 2012), gait analysis of patients (e.g., Arif et al., 2004), and notational analysis in team sports (Sampaio & Maçãs, 2012).

Several methods have been reported for hydrodynamic testing. Active drag can be assessed using energetic procedures, the velocity perturbation method (VPM), the assisted towing method (ATM), the measuring active drag system (MAD), and computer fluid dynamics (CFD) (Havriluk, 2007; Barbosa et al., 2013; Formosa et al., 2013). Passive drag can be assessed using the glide decay method, the isokinetic engine or strain gauge while being towed, the ATM, and computational fluid dynamics (Havriluk, 2007; Barbosa et al., 2013). Some of these methods involve the measurement beforehand of inertial and kinematic data. After anthropometric [i.e., inertial parameters, such as body mass (BM) or added water mass] and kinematic (i.e., speed and accelerations) data are collected, drag force is calculated according to Newton's law of motion and Newton's law of resistance. To estimate efficiency, kinematic data may be collected using mechanical speedometers, motion capture systems, and, more recently, inertial measurement units tracking the head, hip, or center of mass (Barbosa et al., 2012). Because of the large variety of procedures available, comparison of data across different papers is very challenging, as all methods have advantages and disadvantages. Not one procedure is considered by the scientific community as a true gold standard, at least for hydrodynamic testing.

Evidence on hydrodynamic changes over time in young and even adult swimmers is scarce. After an 8-week preparation to build up aerobic capacity and aerobic power and to enhance swimming technique of young swimmers, there were no significant changes in active drag or coefficient of active drag assessed with the VPM (Marinho et al., 2010). Surprisingly, 1 week of instructional intervention (including swim drills with specific visual and kinesthetic cues) was enough to decrease the coefficient of active drag, measured with a barometric technique, in pubescent counterparts (Havriluk, 2006). Training programs focused on energetic buildup might probably not affect hydrodynamics; however, if the objective is to improve technique, such programs might have an effect, even in a short time frame. Nevertheless, further research should be carried out to clarify the relationship between different training programs and the hydrodynamic profile. Indeed, it is suggested that a complex process takes place in the interplay between growth, technique, and hydrodynamics, which for this case was measured on the MAD system (Toussaint et al., 1990), even though some care should be exercised in interpreting these findings, as the MAD system imposes a few constraints compared with free swimming, especially in children. A broad and holistic approach, reporting both passive and active drag plus swimming efficiency, has never been done before, as much as we are aware of. Indeed most of the scarce literature focuses on active drag (i.e., clean swimming). However, top performance in major international competitions suggests that starts and turns are key moments of a race. As such, a renewed interest has emerged for the passive drag (i.e., gliding after the start and each turn). On top of that, new trends in sports science and coaching strongly suggest that longitudinal designs should monitor training loads, as this might be a confounding factor (Mujika, 2013). Unfortunately, the literature available does not provide detailed reports of the training loads.

The current study aimed to analyze the changes in the hydrodynamic profile of young swimmers over a competitive season and compare the variations of this profile according to training periodization. It was hypothesized that if training planning is designed with two major macro-cycles (one general preparation cycle to build up energetic and the other more specific on the road to the main competition), the hydrodynamic profile would be impaired in the first macro-cycle and enhanced in the second.

Methods

Subjects

Twenty-five talented swimmers were assessed (13 boys: 12.64 ± 0.81 years old and 68.02 ± 5.49 s personal best in short-course swimming pool at freestyle; 12 girls: 12.43 ± 0.78 years old and 71.23 ± 5.45 s personal best; both genders in Tanner stages 1–2 by self-report at the beginning of the research). The sample included age group national record holders, age group national champions, and other swimmers who are part of a national talent identification and follow-up project.

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

Study design

A longitudinal research design was selected, including repeated measures of several hydrodynamic variables in three different moments (M_i) over one season. Swimmers were evaluated in the following periods: (a) October (M1, the season's first competition); (b) March (M2, the winter's peak competition); and (c) June (M3, the summer's peak competition). Between October and February, the training program had, as its major goal, to build up energetics, being characterized by a fairly high volume (Table 1). Between March and June the main goal was to fine-tune technique and build up energetics at race pace on the road to the major competition of the season (Table 1). Data collection procedures were carried out under the same testing conditions at all times (e.g., the same swimming pool, time of day, lane, no other swimmer was in the lane or nearby lanes to reduce drafting and pacing effects, affecting the drag force).

A potential confounding factor for the analysis of the changes over time was the intra-subject variability within a testing session and between testing sessions. True/meaningful changes do occur

Table 1. Total external training loads

	October–February (M1–M2)	March–June (M2–M3)
Volume (km)	497	481
Training sessions	117	114
A0 (km)	209.5	197.5
A1 (km)	189.1	156.7
A2 (km)	55.7	58.7
A3 (km)	20.6	21.7
LT (km)	4.3	4.4
LP (km)	2.7	2.5
RP (km)	1.5	3.8
Sprint (km)	9.1	8.4

A0, warm-up and cool-down; A1, low aerobic capacity; A2, anaerobic threshold; A3, aerobic power; LP, lactate power; LT, lactate tolerance; RP, race pace.

when intra-subject variability over time (i.e., between testing sessions) is higher than that verified in a single moment (i.e., within a testing session, performing several trials of the same task). Vantorre et al. (2010) analyzed the variability of front crawl starts in elite (89.3% ± 3.0% of the 100 freestyle World Record) and trained swimmers (79.9% ± 8.0% of the World Record). The start was split into several phases, including the "swimming phase" (i.e., the time from the beginning of the first arm stroke to the instant the head reached the 15-m mark), which can be selected to learn about the intra-subject variability. Examination of intertrial variability revealed high reproducibility for the swimming phase (ICC = 0.951 for trained; ICC = 0.981 for elite swimmers). Earlier data not published from our research group suggest an intra-subject variability of 11% for passive drag and 9% for stroke kinematics in young swimmers. Therefore, a true/meaningful change over time if variability is higher than 10% is expected.

Anthropometrics and inertial parameters

BM was measured with a digital weight scale (SECA, 884, Hamburg, Germany) (ICC = 0.99). The swimmer's added water mass (m_a) was estimated as being approximately 27% [26.8% ± 2.3%, mean ± standard error (SE)] for a subject with similar age (Caspersen et al., 2010). Height was measured with a digital stadiometer (SECA, 242, Hamburg, Germany) on the upright position, barefoot, and in swimwear (ICC = 0.99). All anthropometric measurements were collected according to standardized procedures.

The trunk transverse surface area (TTSA) was measured with a photogrammetric technique (Morais et al., 2011). Swimmers were photographed with a digital camera (DSC-T7, Sony, Tokyo, Japan) in the transverse plane from above (Caspersen et al., 2010). Subjects stood on land, on the upright, and streamlined position. This position is characterized by having the arms fully extended above the head, one hand over the other, fingers also extended close together, and head in neutral position. Subjects wore a regular textile swim suit, cap, and goggles. On the camera shooting field, a calibration frame with 0.945 m in length was aside the swimmer at the shoulders level. The TTSA was measured with an area measuring software (Udruler, AVPSoft, USA) after importing the digital picture (ICC = 0.97).

Kinematics and non-linear parameter

Each swimmer performed a maximal 25-m front crawl trial with a push-off start. Because data were collected in a short-course swimming pool, subjects were advised to reduce gliding during the start so that it would be possible to collect data between the 11th and the 24th meter. A speedometer cable (Swim speedometer, Swimsportec, Hildesheim, Germany) was attached to the swimmer's hip (Barbosa et al., 2012). The speedometer was placed on the forehead wall of the swimming pool, about 0.2 m above water surface. A software's interface in LabVIEW® (v. 2009, National Instruments, Austin, TX, USA) was used to acquire ($f = 50$Hz), display, and process speed– time data online during the trial. Data were transferred from the speedometer to the software application with a 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA). Although the speedometer is a "coach-friendly" piece of equipment (it is affordable, easy to operate, and it allows immediate feedback for swimmer), the hip's *dv* does not represent with total accuracy the center of the mass's *dv*. Two major sources of error should be acknowledged: (a) speedometer measures the speed of a fixed point and (b) inertial effects might act upon the system. A 0.1-s time delay (i.e., ~10% of the stroke cycle duration), a 0.2 m/s higher speed range (i.e., less than 10% of the maximal speed for young swimmers), and a moderate root mean square (RMS) error ($0.16 \le RMS_{error} \le 0.3$) comparing hip and center of mass kinematics at front crawl (Figueiredo et al., 2009; Psycharakis & Sanders, 2009) have been reported. Comparing hip speed collected with speedometer and a motion capture system, there is a 0.002 ± 0.001 difference [mean ± SE, standard deviation (SD) = 0.012, –0.001; 0.005 for a 95% confidence interval] at front crawl and backstroke for swimmers with similar age and competitive level of our subject (Feitosa et al., 2013). Whenever any problems were identified through visual observation/inspection of curves, the swimmers were asked to repeat the trial. This was by no means expected to eliminate every problem that might have occurred through testing (e.g., bumping feet on the cable). Rather, it was used as an extra precaution to exclude problematic trials.

Thereafter, data were exported to a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, California, USA) and filtered with a 5-Hz, cut-off, low-pass fourth-order Butterworth filter according to the analysis of the residual error vs cut-off frequency output. The intra-cyclic variation of the horizontal velocity of the hip (*dv*) was analyzed (Barbosa et al., 2010):

$$dv = \frac{\sqrt{\dfrac{\sum_i (v_i - \bar{v})^2 . F_i}{n}}}{\dfrac{\sum_i v_i . F_i}{n}} \cdot 100 \qquad [7]$$

where *dv* represents the intra-cyclic variation of the horizontal velocity of the hip, *v* represents the mean swimming velocity, v_i represents the instant swimming velocity, F_i represents the acquisition frequency, and *n* is the number speed–time pairs. For further analysis, the *dv* mean values of three consecutive stroke cycles between the 11th and 24th meter from the starting wall were considered (Fig. 1(a)).

The stroke index, as an overall swimming efficiency estimator, was calculated (Costill et al., 1985):

$$SI = SL \cdot v \qquad [8]$$

where *SI* is the stroke index, *SL* is the stroke length, and *v* is the swimming velocity. The *SL* was calculated from the *v* and *SF* collected with the speedometer:

$$SL = \frac{v}{SF} \qquad [9]$$

where *SL* is the stroke length, *v* is the swimming velocity, and *SF* is the stroke frequency.

The *ApEn* is a non-linear technique to quantify the temporal structure of (un)predictability in its fluctuations over a given time

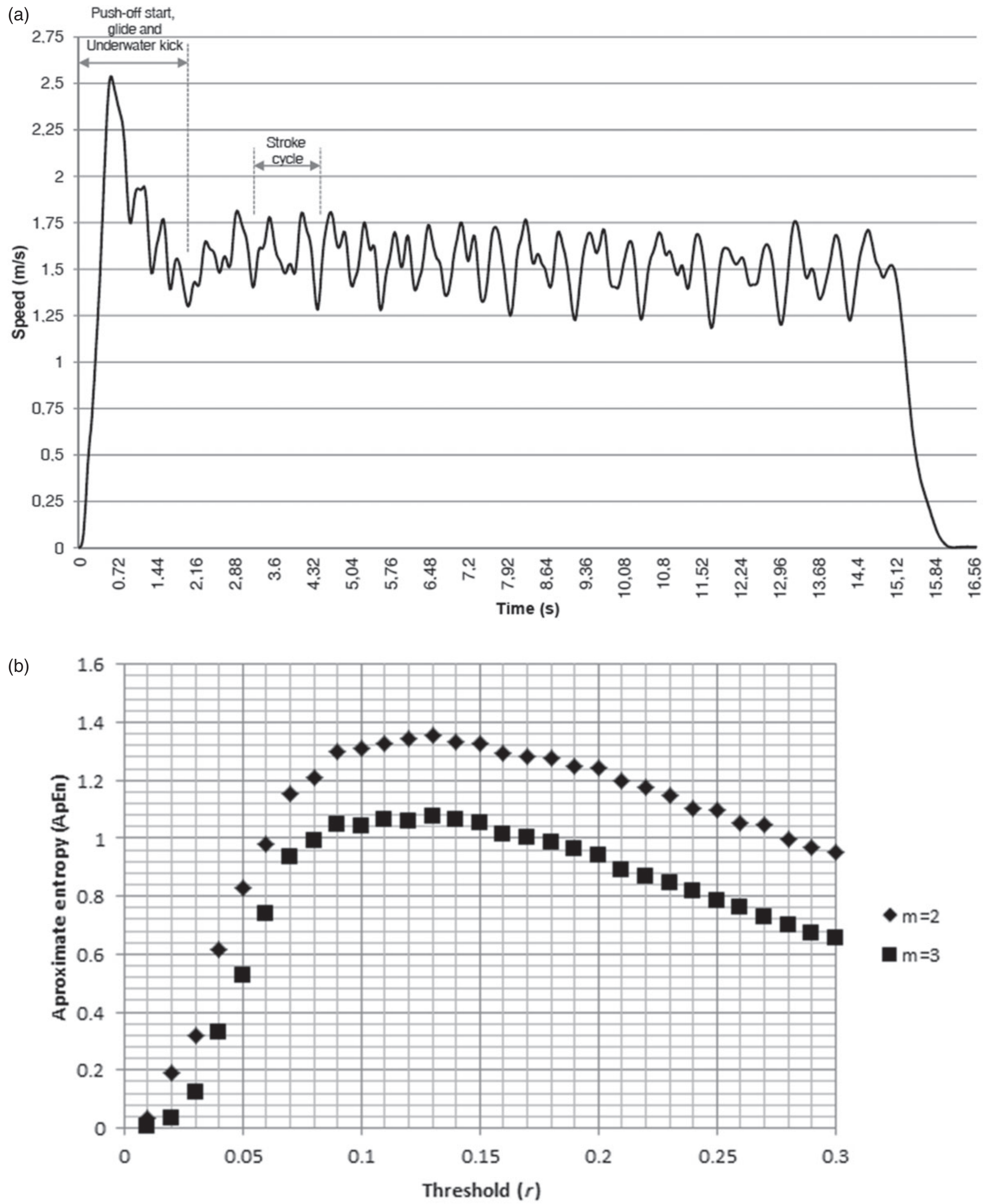

Fig. 1. Example of the speed fluctuation during one trial (a) and approximate entropy (*ApEn*) variations for a range of tolerance values (r) and embedding dimensions (m) for one young swimmer (b).

series data. Hence, it can be used to assess the inter-cyclic variation of the horizontal velocity of the hip. It ranges from 0 to 2. A low *ApEn* value indicates that the time series is deterministic, and a high value indicates randomness. The *ApEn* is derived based on the following algorithm (Pincus, 1991; Pincus & Goldberger, 1994):

$$ApEn(N, m, r) = \ln\left[\frac{C_{m}(r)}{C_{m+1}(r)}\right] \quad [10]$$

where *ApEn* is the approximate entropy, N is the data length ($N = 700$ speed–time pairs, according to the suggestion of Yentes et al., 2013), m is the embedding dimension ($m = 2$, because two consecutive cycles contributing to two data points were considered for each mobile window), r is the tolerance value or similarity criterion ($r = 0.1$, determined beforehand as the maximum *ApEn* for a wide range of r values between 0.01 and 0.3 as suggested by Chon et al., 2009 and Yentes et al., 2013), and

$$C_{im}(r) = \frac{n_{im}}{N - m + 1} \quad [11]$$

where C_{im} is the fraction of patterns of length, n_{im} is the number of patterns that are similar between two sets (given the similarity criterion, r), N is the data length, and m is the embedding dimension. It should be highlighted that the selection of different input values can be a potential source of error. Changes in the m and/or r have an influence on the *ApEn* (Fig. 1(b)).

Active drag

The VPM was used to estimate active drag (Kolmogorov & Duplischeva, 1992). Active drag was calculated from the difference between the swimming velocities with and without towing a perturbation buoy. To ensure similar maximal power output of both sprints, the subjects were instructed to swim front crawl at maximal pace after a push-off start. Swimming velocity (vertex as reference) was measured for 13 m (between 11th and 24th of the starting wall) with a stopwatch (Golfinho Sports MC-815, Aveiro, Portugal) by two expert evaluators, and the mean value was used for further analysis (ICC = 0.96). Active drag (D_a) was calculated as (Kolmogorov & Duplischeva, 1992):

$$D_a = \frac{D_b \cdot v_b \cdot v^2}{v^3 - v_b^3} \qquad [12]$$

where D_a represents the swimmer's active drag at maximal velocity, D_b is the resistance of the perturbation buoy provided by the manufacturer, and v_b and v are the swimming velocities with and without the perturbation device, respectively. The active drag coefficient (C_{Da}) was calculated as:

$$C_{Da} = \frac{2 \cdot D_a}{\rho \cdot S \cdot v^2} \qquad [13]$$

where ρ is the density of the water (being 1000 kg/m^3), D_a is the active drag, v is the swimming velocity, and S is the swimmer's projected frontal surface area (or TTSA; see "Anthropometrics and inertial parameters" subsection). The power needed to overcome the drag force (P_D) was computed as:

$$P_D = D_a \cdot v \qquad [14]$$

where P_D is the power to overcome drag force, D_a is the active drag, and v is the swimming velocity.

Passive drag

The passive drag was assessed with inverse dynamics of the gliding decay speed (Klauck & Daniel, 1976). Swimmers were instructed to perform a maximal push-off on the wall fully immersed, at a self-selected depth, ranging approximately between 0.5 and 1.0 m to avoid D_w (Vorontsov & Rumyantsev, 2000). Gliding was performed in the streamlined gliding position (head in neutral position, looking at the bottom of the swimming pool, legs fully extended and close together, arms fully extended at the front, and with one hand over the other) with no segmental actions. Testing ended when swimmers broke the surface and/or were not able to make any further horizontal displacement gliding and/or started any limbs' actions.

A speedometer cable (Swim speedometer, Swimsportec) was attached to the swimmer's hip, and the gliding velocity decay was acquired online ($f = 50$ Hz) (Barbosa et al., 2013). Data were exported to a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems) and filtered with a 5-Hz, cut-off, low-pass fourth-order Butterworth filter.

The gliding mean velocity and the corresponding mean acceleration based on the acceleration to time were calculated with moving time frame windows. The acceleration to time curve was obtained by numerical differentiation of the filtered speed–time curve, using the fifth-order centered equation (Vilas-Boas et al., 2010):

$$a_i = \frac{2v_{i-2} - 16v_{i-1} + 16v_{i+1} - 2v_{i+2}}{24\Delta t} \qquad [15]$$

where a_i is the hip's instantaneous acceleration, v_i is the hip's instantaneous velocity, and t is the time. Passive drag (D_p) force was calculated as:

$$D_p = (BM + m_a) \cdot a \qquad [16]$$

where D_p is the passive drag, BM is the swimmers on-the-day BM, m_a is the swimmer's added water mass, and a is the acceleration. The passive drag coefficient (C_{Dp}) was calculated as:

$$C_{Dp} = \frac{2 \cdot D_p}{\rho \cdot S \cdot v^2} \qquad [17]$$

where ρ is the density of the water (being 1000 kg/m^3), D_p is the passive drag, v is the gliding velocity, and S is the projected frontal surface area. The total drag index (*TDI*) was assessed as a hydrodynamic efficiency estimation (Kjendlie & Stallman, 2008). To learn if the swimmer relies more on the D_a or D_p (Kolmogorov & Duplischeva, 1992):

$$TDI = \frac{D_a}{D_p} \qquad [18]$$

where *TDI* is the drag technique index, D_a is the active drag, and D_p is the passive drag.

Froude number, hull speed, and Reynolds number

The Froude number is a dimensionless parameter that is considered as a wave-making resistance index (Kjendlie & Stallman, 2008):

$$Fr = \frac{v}{\sqrt{g \cdot H}} \qquad [19]$$

where v is the swimming velocity (collected with the speedometer), g is the gravitational acceleration, and H the swimmer's height. Hull velocity, i.e., the speed at a Froude number equal to 0.42 (Vogel, 1994), was also selected:

$$v_h = \sqrt{\frac{g \cdot H}{2 \cdot \pi}} \qquad [20]$$

where g is the gravitational acceleration and H is the height. The Reynolds number was used to assess the water flow status surrounding the swimmer:

$$\mathrm{Re} = \frac{v \cdot H}{\upsilon} \qquad [21]$$

where v is the swimming velocity, H is the height, and υ is the water kinematic viscosity (being 8.97×10^{-7} m^2/s at 26 °C).

Statistical procedures

The homoscedasticity assumption was checked with the Levene test. Normality [defined as $Y \cap N(\mu_{Y|X1,X2,\ldots,XK}, \sigma^2)$] was determined with the Shapiro–Wilk test. Mean ± 1 SD is reported for all variables.

Data variation was analyzed with two-way analysis of variance (ANOVA) (time effect, gender effect, time × gender interaction) followed by the Bonferroni post-hoc test ($P \leq 0.05$), whenever suitable. Total eta square (η^2) was selected as effect size index and interpreted as (a) no effect if $0 < \eta^2 \leq 0.04$; (b) minimum if $0.04 < \eta^2 \leq 0.25$; (c) moderate if $0.25 < \eta^2 \leq 0.64$; and (d) strong if $\eta^2 > 0.64$.

For each evaluation moment, after the diagnosis of multicolinearity effects (including independence of the measures), correlation coefficients were calculated ($P \leq 0.05$). As rule of thumb the following were considered: (a) small effect size if $0 \leq |R| \leq 0.2$; (b) moderate effect size if $0.2 < |R| \leq 0.5$; and (c) strong effect size if $|R| > 0.5$.

Results

No variables presented a significant gender effect (Table 2). All selected variables but *dv*, D_p, and C_{Dp} presented a time effect (Table 2; Figs. 1–4). Anthropometrics and inertial parameters increased over time (Table 2; Fig. 2). *ApEn* and *SI* suggest that swimming efficiency improved (Table 1; Fig. 3). D_a, C_{Da}, P_D, and *TDI* increased at M2 but then decreased at M3 to values lower than observed at baseline (Table 2; Fig. 4). There was a non-significant decrease of C_{Dp} over time. Dimensionless numbers increased from M1 to M3 (Table 2; Fig. 5). Overall, it seems that the changes occurred in a non-linear fashion way. The effect size index suggests a minimum-to-strong effect size for the variables with significant effects ($0.21 \leq \eta^2 \leq 0.75$). Nine of the 11 variables are within the "moderate" band though. Only the height and the v_{hull} showed significant time × gender interactions but with no effect (Table 2).

Intra-individual changes between evaluation moments suggest a high between- and within-subject variation (Table 3). The variables related to drag, such as D_a, D_p, and therefore, C_{Da}, C_{Dp}, P_D, and *TDI*, have the highest within-subject changes. Between-subject changes can be analyzed with the SD. Once again, variables related to passive and active drag plus *dv* have the highest variations. Variables related to anthropometrics and inertia, swimming efficiency, and dimensionless numbers had a lower intra-individual change.

For a set of computed correlations, the odds of some being significant will be only by chance. With significance accepted at $P < 0.05$, for every 20 correlations performed, on average one might be significant by chance. Correlations were computed between all variables in the three evaluation moments (3 moments × 15 variables × 15 variables). To minimize the odds of type I

Table 2. Data variation (two-way ANOVA) for the selected variables over one season (time effect) for boys and girls (gender effect)

	Time effect d.f. (2,46)		Eta²	Gender effect d.f. (1,23)		Eta²	Time × gender interaction d.f. (2,46)		Eta²
	F	*P*		*F*	*P*		*F*	*P*	
BM (kg)	70.768	< 0.001	0.49	0.781	0.39	0.03	2.221	0.48	0.02
H (cm)	61.778	< 0.001	0.69	1.959	0.18	0.08	5.220	0.01	0.06
TTSA (m²)	6.267	0.01	0.21	0.545	0.47	0.02	0.082	0.92	0.01
dv (dimensionless)	2.366	0.10	0.07	0.167	0.69	0.01	0.518	0.60	0.01
ApEn (dimensionless)	10.893	< 0.001	0.31	0.166	0.69	0.01	1.674	0.19	0.04
D_a (N)	15.296	< 0.001	0.39	0.563	0.46	0.02	0.511	0.60	0.01
C_{Da} (dimensionless)	12.688	0.47	0.28	1.150	0.30	0.05	0.782	0.46	0.02
D_p (N)	0.773	0.47	0.03	0.447	0.51	0.02	0.703	0.50	0.03
C_{Dp} (dimensionless)	0.763	< 0.001	0.03	0.186	0.67	0.01	0.155	0.84	0.01
P_D (W)	15.884	< 0.001	0.40	0.967	0.34	0.04	0.744	0.48	0.02
TDI (dimensionless)	10.042	< 0.001	0.30	0.060	0.70	0.01	0.935	0.41	0.03
SI (m²/s)	15.501	< 0.001	0.38	0.162	0.69	0.01	2.342	0.11	0.06
Fr (dimensionless)	13.382	< 0.001	0.38	2.392	0.14	0.11	0.915	0.41	0.01
v_{hull} (m/s)	49.177	< 0.001	0.75	1.643	0.21	0.07	5.017	0.01	0.01
Re (dimensionless)	39.236	< 0.001	0.60	3.231	0.08	0.12	3.174	0.06	0.05

ANOVA, analysis of variance; *ApEn*, approximate entropy; BM, body mass; C_{Da}, coefficient of active drag; C_{Dp}, coefficient of passive drag coefficient; D_a, active drag; d.f., degrees of freedom; D_p, passive drag; *dv*, speed fluctuation; *Fr*, Froude number; *H*, height; P_D, mechanical power to overcome drag; *Re*, Reynolds number; *SI*, stroke index; *TDI*, total drag index; TTSA, trunk transverse surface area; v_{hull}, hull velocity.

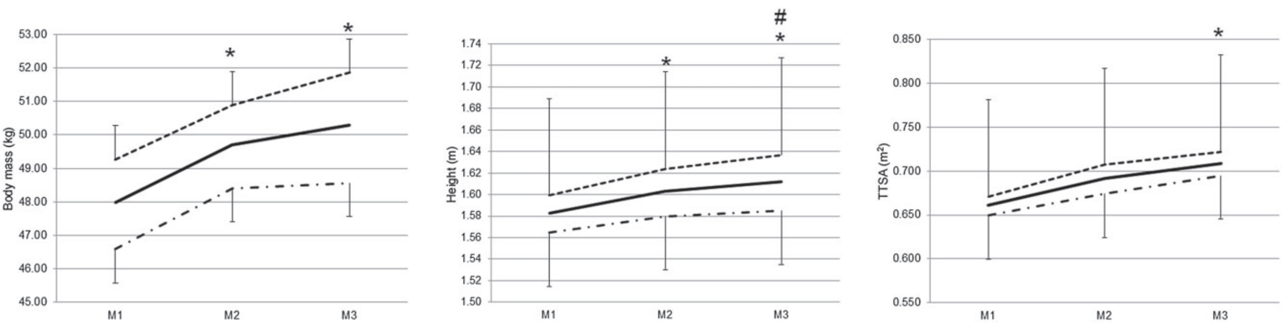

Fig. 2. Changes in anthropometrics and inertial parameters. Solid line (—) overall sample; dash line (- - -) boys; dash and dotted line (-·-·-) girls; *Post-hoc test between M1 and M2 or M1 and M3 ($P \leq 0.05$); #Post-hoc test between M2 and M3 ($P \leq 0.05$). TTSA, trunk transverse surface area.

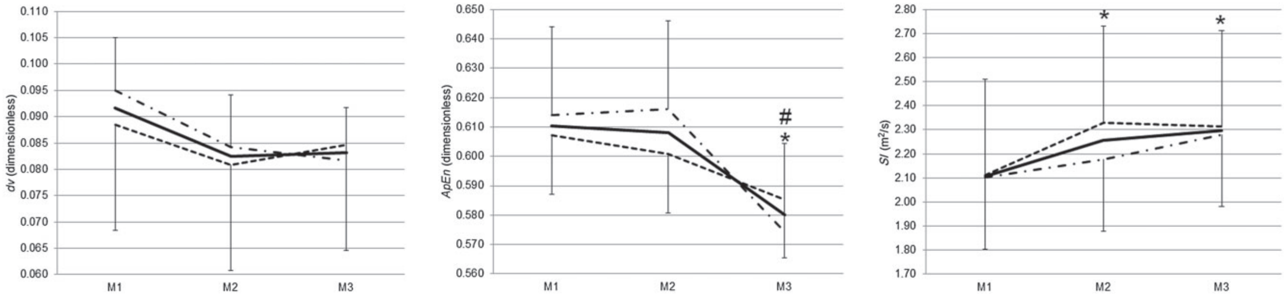

Fig. 3. Changes in kinematic and non-linear parameters. Solid line (—) overall sample; dash line (- - -) boys; dash and dotted line (-·-·-) girls; *Post-hoc test between M1 and M2 or M1 and M3 ($P \leq 0.05$); #Post-hoc test between M2 and M3 ($P \leq 0.05$). *ApEn*, approximate entropy; *dv*, speed fluctuation; *SI*, stroke index.

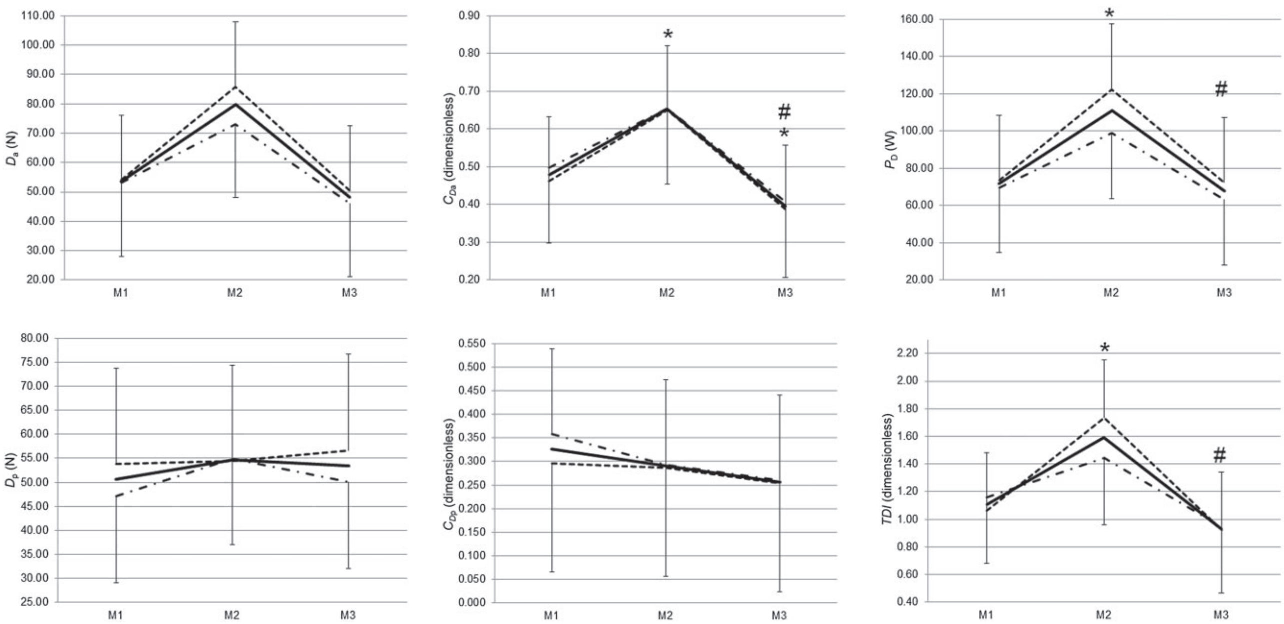

Fig. 4. Changes in drag force. Solid line (—) overall sample; dash line (- - -) boys; dash and dotted line (-·-·-) girls; *Post-hoc test between M1 and M2 or M1 and M3 ($P \leq 0.05$); #Post-hoc test between M2 and M3 ($P \leq 0.05$). C_{Da}, coefficient of active drag; C_{Dp}, coefficient of passive drag coefficient; D_a, active drag; D_p, passive drag; P_D, Mechanical power to overcome drag; *TDI*, total drag index.

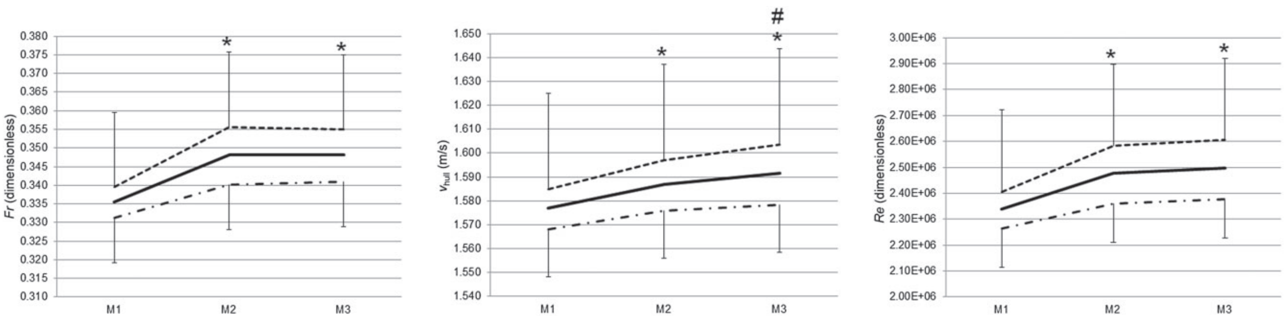

Fig. 5. Changes in Froude number, hull speed, and Reynolds number. Solid line (—) overall sample; dash line (- - -) boys; dash and dotted line (-·-·-) girls; *Post-hoc test between M1 and M2 or M1 and M3 ($P \leq 0.05$); #Post-hoc test between M2 and M3 ($P \leq 0.05$). *Fr*, Froude number; *Re*, Reynolds number; v_{hull}, hull velocity.

error, only the correlation between independent variables is reported. On top of that, an effect size index was selected (cf. "Statistical procedures" subsection). At M1, D_a and P_D had significant and moderate correlations with *Fr* ($R = 0.41$, $P = 0.02$; $R = 0.50$, $P = 0.01$), v_{hull} ($R = 0.35$, $P = 0.04$; $R = 0.42$, $P = 0.02$), and *Re* ($R = 0.41$, $P = 0.02$; $R = 0.52$, $P = 0.01$). *SI* was strongly associated with *Fr* ($R = 0.65$, $P < 0.001$), v_{hull} ($R = 0.62$,

Table 3. Intra-individual changes (%) between evaluation moments

	M1 vs M2 (%)	M1 vs M3 (%)	M2 vs M3 (%)
BM	3.72 ± 3.81	5.05 ± 3.90	1.34 ± 3.73
H	1.28 ± 0.95	1.86 ± 1.04	0.58 ± 0.67
TTSA	4.85 ± 9.76	7.80 ± 13.08	2.79 ± 7.83
dv	−5.74 ± 22.05	−2.67 ± 32.12	4.55 ± 26.90
ApEn	−0.14 ± 6.81	−4.79 ± 5.20	−4.38 ± 6.56
D_a	64.62 ± 79.60	−4.37 ± 39.36	−32.30 ± 32.84
C_{Da}	49.44 ± 78.70	−14.03 ± 27.67	−31.61 ± 31.46
D_p	13.59 ± 37.56	10.41 ± 34.89	−1.42 ± 15.90
C_{Dp}	22.86 ± 96.30	23.13 ± 53.04	39.86 ± 54.32
P_D	71.53 ± 81.29	0.73 ± 43.21	−32.07 ± 32.71
TDI	73.67 ± 58.93	−1.94 ± 58.27	−28.68 ± 39.41
SI	7.07 ± 10.61	9.59 ± 9.44	2.86 ± 8.68
Fr	3.78 ± 4.69	3.83 ± 3.92	0.17 ± 4.05
v_{hull}	0.63 ± 0.47	0.92 ± 0.51	0.28 ± 0.33
Re	5.76 ± 4.53	6.74 ± 4.15	1.02 ± 3.90

ApEn, approximate entropy; BM, body mass; C_{Da}, coefficient of active drag; C_{Dp}, coefficient of passive drag coefficient; D_a, active drag; D_p, passive drag; *dv*, speed fluctuation; *Fr*, Froude number; *H*, height; P_D, mechanical power to overcome drag; *Re*, Reynolds number; *SI*, stroke index; *TDI*, total drag index; TTSA, trunk transverse surface area; v_{hull}, hull velocity.

$P < 0.001$), and *Re* ($R = 0.75$, $P < 0.001$). TTSA was strongly associated with *SI* ($R = 0.58$, $P < 0.001$), v_{hull} ($R = 0.72$, $P < 0.001$), and *Re* ($R = 0.61$, $P < 0.001$).

At M2, P_D was correlated with *SI* ($R = 0.48$, $P = 0.01$), *Fr* ($R = 0.42$, $P = 0.02$), v_{hull} ($R = 0.52$, $P = 0.01$), and *Re* ($R = 0.59$, $P < 0.001$). D_p had a moderate association with v_{hull} ($R = 0.38$, $P = 0.03$) and *Re* ($R = 0.36$, $P = 0.04$), *dv* with *TDI* ($R = -0.35$, $P = 0.04$), but *SI* correlated strongly with v_{hull} ($R = 0.68$, $P < 0.001$) and *Re* ($R = 0.85$, $P < 0.001$).

Finally, at M3 D_a was related to D_p ($R = 0.62$, $P < 0.001$), *Fr* ($R = 0.60$, $P < 0.001$), v_{hull} ($R = 0.39$, $P = 0.02$), and *Re* ($R = 0.57$, $P = 0.01$). A similar trend was observed for the relationships between P_D and D_p ($R = 0.63$, $P < 0.001$), *SI* ($R = 0.35$, $P = 0.04$), *Fr* ($R = 0.66$, $P < 0.001$), v_{hull} ($R = 0.45$, $P = 0.01$), and *Re* ($R = 0.63$, $P < 0.001$). Besides that, D_p was correlated with *SI* ($R = 0.47$, $P = 0.01$), *Fr* ($R = 0.47$, $P = 0.01$), v_{hull} ($R = 0.50$, $P < 0.001$), and *Re* ($R = 0.56$, $P < 0.001$).

Discussion

This study aimed (a) to analyze the changes in the hydrodynamic profile of young swimmers over a season and (b) to assess the changes in the hydrodynamic profile according to the periodization designed. Hydrodynamic changes occurred in a non-linear fashion way. Some of the individual changes observed were affected by factors such as growth and periodization. The general preparation cycle, at the beginning of the season, had a higher focus on the energetic buildup, and the hydrodynamics profile was impaired. Meanwhile, the hydrodynamics profile was enhanced significantly after the specific preparation cycle (aiming to fine-tune technique and build up energetics at race pace) on the road to the major competition of the season.

No variables presented a significant gender effect, and a couple had a significant time × gender interactions but with no effect (Table 2). There is a very solid body of knowledge that no gender gap exists before puberty. This was already reported by several empirical papers on swimming kinematics, efficiency, anthropometrics, and performance, as reviewed elsewhere (Seifert et al., 2010). In this sense, data might be analyzed either by gender or pooled sample. As for hydrodynamics, one paper revealed significant differences in D_a, D_p, and related outcomes, but for pubertal boys and girls (Barbosa et al., 2013). To the best of our knowledge, no study compares the hydrodynamics between genders at such earlier ages and/or maturational state. Even so, however, hydrodynamics depends mostly on anthropometrics and kinematics. Because there is no gender gap before puberty in both domains, it is expected that the same would happen for hydrodynamic outcomes.

It is no surprise that anthropometrics and inertial parameters increased over time (Table 2; Fig. 1). Children experience physical changes as part of their biological development (Malina & Bouchard, 1991), including young swimmers that others have reported as having similar percentage of change to the ones verified in this research (Toussaint et al., 1990; Latt et al., 2009). The three swimming efficiency estimators suggest that there is an improvement in such outcomes over time, notably between M2 and M3 (i.e., the cycle with a higher focus on technique enhancement) (Fig. 2). *ApEn* and *SI* showed a significant improvement between M1 and M3. However, *dv* presented a non-significant decrease. For the changes over time smaller than 10%, the variation might as well be related to intra-swimmer variability as explained earlier in the Methods section (cf. "Study design" subsection).

SI is a classical outcome to roughly estimate overall swimming efficiency. The pioneering paper by Costill et al. (1985), which describes and validates *SI*, is among the highest cited papers in "swimming science." The bibliometric data reveal how much the swimming community recognizes *SI* as a good approximation of overall swimming efficiency. The *SI* of at least adult national- and international-level swimmers increases slightly throughout a season (Costa et al., 2012). Over two consecutive seasons, sub-elite swimmers might increase *SI* around 4% (Costa et al., 2013). Latt et al. (2009) reported an improvement of *SI* over time for young swimmers as well. Others did not report *SI* directly, but based on *SL* and *v*, one might consider that *SI* also increased throughout time (e.g., Wakayoshi et al., 1993; Anderson et al., 2006), although it is a rough estimator that does not provide insight about detailed energy path flow from input (as metabolic energy) all the way up to output (as external mechanical work).

The *dv* was first introduced as an estimation of swimming efficiency for butterfly and breaststroke (e.g., Barbosa et al., 2005). The main assumption is that intra-cyclic changes will impose a higher energy demand and therefore a lower efficiency. There are some claims that intra-cyclic variations might not be sensitive enough to small changes in the swim pace or given swimming strokes where *dv* has a fairly low range (e.g., front crawl and backstroke). For instance, unless an incremental and maximal protocol is implemented it seems that the changes in *dv* are quite low. Even so, most of the time the protocols include a very narrow pace range (Greco et al., 2013). A second explanation for the lower sensitivity is that, according to some determinist models, *dv* is an intermediate variable between the energetic and biomechanical fields, depending on third-party variables. A few papers have reported that the *dv* is consistent within adult swimmers for different velocities (e.g., Schnitzler et al., 2008; Psycharakis et al., 2010). It seems, however, that there is no paper reporting the change of *dv* over time for either young or adult swimmers. In this sense, *dv* is the balance of several determinant factors, and each one can play a major or minor role in *dv* depending on the imposed constrains (task, environment, and organismic) at each moment.

The second explanation leads us to address movement variability. For a long time a lower variability was considered as noise that should be minimized or eradicated to enable high performance levels (Davids et al., 2004). However, research in ecological dynamics suggested that movement variability should not necessarily be construed as noise, which is detrimental to performance (Davids et al., 2004). Evidence on this was also obtained for swimming (e.g., Komar et al., 2013). To this end, we explored the use of *ApEn* in assessing the inter-cycle changes, given its potential utility for quantifying the structure of temporal variability. Indeed, the selection of non-linear parameters, such as *ApEn*, is a step forward in this research field. *ApEn* has been used in the analysis of time series data in biomechanics, most notably in postural balance (e.g., Kee et al., 2012) and gait analysis (e.g., Arif et al., 2004). Conceptually, *ApEn* quantifies the probability of predetermined length of consecutive data segments repeating with other segments of the same length within the same time series data. *ApEn* is a dimensionless measure that ranges from 0 (signifying repeatability) to 2 (signifying randomness) (Pincus, 1991; Cavanaugh et al., 2007). *ApEn* quantifies the temporal structure of predictability of time series data. Based on the dynamical systems perspective of motor control, heightened systems complexity is indicative of adaptive control of degrees of freedom in the movement system. Because *ApEn* has never been used before in the analysis of competitive swimming, and the algorithm is presumably suited for small data sets of between 50 and 5000 data points (Stergiou et al., 2004), the use of *ApEn* could allow us to learn about the inter-cyclic variations of the horizontal velocity from a fresh perspective. *ApEn* decreased over time, being more notorious at the end of the season. One might consider that a higher predictability means a lower submission of the swimmer to inertial forces and therefore to lower energy expenditures (Barbosa et al., 2010). Moreover, a lower *ApEn* and therefore a higher predictability would be expected for the most efficient swimmers. However, further studies should be carried out to explore this and other non-linear parameters in swimming and gather a better insight.

Most variables related to drag had a non-linear change over time (Table 2; Fig. 3). An increase between M1 and M2 and then a decrease between M2 and M3 (significant for C_{Da}, P_D, and *TDI*; non-significant for D_a, D_p, C_{Dp}) were verified. The season was split into two main cycles (one to build up energetics between M1 and M2 and the other to enhance technique and fine-tune for the main competition of the season between M2 and M3). The first 8 weeks of a season aimed at building up aerobic capacity and aerobic power and at enhancing swimming technique showed no significant effects in active drag parameters (Marinho et al., 2010). These findings seem to be in accordance to our data for the first cycle of the season (i.e., M1–M2). Therefore, the energetic buildup (that is not concurrent with technique enhancement) tends to impair the hydrodynamic profile with a moderate effect. It may be considered that swimmers throughout the training sessions and the sets to be performed are less aware or put less effort in keeping a good technique. Technique intervention programs that include swim drills with specific visual and kinesthetic cues can decrease significantly the coefficient of active drag from 1.0 to 0.9 (Havriluk, 2006). Once more this is in accordance with our data for the second main cycle of the season (i.e., M2–M3) that was designed to fine-tune technique on the road to the main competition. To the best of our knowledge, the literature does not provide evidence about the changes over time of passive drag. Nevertheless, gliding is strongly related to starts and turns, and most times these race segments are improved in the specific preparation period, close to a main competition.

It is interesting to note that at M1 and M2 D_a was higher than D_p (11% and 59%; *TDI* at M1 and M2 was 1.11 and 1.59, respectively). Surprisingly at M3, D_a was lower than D_p (*TDI* at M3 was 0.93). The TDI is based on the reasoning that if two swimmers with similar D_p are compared, the one with lower D_a could be considered as having a better technique (Kjendlie & Stallman, 2008). Poorer swimmers will have a higher *TDI* in comparison with proficient counterparts as a result of a lower hydrodynamic efficiency. Because this is the first time that such concept seems to be applied in a longitudinal design, it can be stated that the hydrodynamic efficiency improved between M1 and M3 but not between M1 and M2. All these findings are clearly coupled with training periodization. However, growth should not be disregarded, because it also plays a role in the hydrodynamics of young swimmers (Toussaint et al., 1990). Growth is the main explanation for changes in dimensionless numbers. It is quite easy to follow that the variations in hydrodynamic numbers (Fig. 4) present the same shape or profile of the anthropometric variables (Fig. 1). Interestingly, comparing the biomechanics of talented swimmers after a 10-week summer break, it was found that swim kinematics and efficiency improved mainly due to growth, with no changes in the active drag (Moreira et al., 2014).

The hydrodynamic profile of a swimmer and therefore performance is a multifactorial phenomenon, where several variables and domains determine the final outcome. In such early ages, growth (i.e., intrinsic factor) and training (i.e., extrinsic factor) are the main determinants. Short-duration research designs are most convenient to assess the effect of an intervention program, because there will be no significant changes in growth or maturational state, such as the cases of the works by Havriluk (2006) and Marinho et al. (2010). Long-term longitudinal studies, such as that reported by Toussaint et al. (1990), can be useful to gather insight about the effect of growth and biological state. Even so, growth for short-term programs and training periodization for long-term programs can be confounding factors. Until now, there has been no report on the concurrent effect of both training and growth, providing a more holistic and ecological insight. The scarce literature does not report hypothetical relationships between anthropometrics, drag (active and passive), swimming efficiency, and dimensionless hydrodynamics over a season. Although both growth and training are important, intra-individual changes (Table 3) suggest that drag parameters had a higher variation than remaining outcomes. Thus, there is no clear couple between growth and resistance, meaning that the intervention program (i.e., training periodization split in two cycles) might explain the biggest share of the drag changes. On top of that, the correlation coefficient suggests that if colinearity effects are removed, most drag parameters are more related with dimensionless variables and less with anthropometrics (cf. correlations reported in the main text of the Results section). Hence, growth is indeed one factor affecting hydrodynamics and, even more so, the dimensionless numbers. As far as a coach or sports analysis is concerned, this insight can be used to control the growth effect on technique changes over time. Moreover, it should also take into account the moment of the season that swimmers are being assessed, as hydrodynamic changes are also related to the preparation phases they are going through.

The following can be addressed as main limitations: (a) there is no technique to assess drag force that might be considered as gold standard. Some care should be exercised when comparing data collected with different procedures (e.g., for active drag – VPM vs ATM vs MAD system vs CFD; for passive drag – glide decay vs strain gauge vs ATM vs CFD) (e.g., Sacilotto et al., 2014). (b) This is the first time that non-linear parameters, such as *ApEn*, are reported in competitive swimming. *ApEn* is very sensitive to input data (Yentes et al., 2013). Hence, future studies reporting this variable should acknowledge such fact in comparing data. (c) The changes over time reported with young swimmers might not be representative of what happens in pubertal or adult counterparts. (d) Intra-subject variability within testing sessions must be considered to have an accurate understanding of the true/meaningful changes over time.

As a conclusion, hydrodynamic changes over a season occurs in a non-linear fashion way, where the interplay between growth and training periodization explains the unique path flow selected by each young swimmer on the road to the season's main competition.

Perspectives

The aim of this research was to analyze the changes in the hydrodynamic profile of young swimmers over a competitive season and compare its variations according to a well-designed training periodization (two major macro-cycles: one general preparation cycle to build up energetics and one specific cycle preparing to main competition). Hydrodynamic changes over a season occur in a non-linear fashion way, where the interplay between growth and training periodization explain the unique path flow selected by each young swimmer on the road to the season's main competition. However, main trend was that the general preparation cycle (characterized by a high focus on energetics buildup) tends to impair the hydrodynamics profile. On the other hand, the specific cycle of preparation to the main competition (including technique fine-tuning with high number of cues, plus energetics workout at race pace) enables to enhance hydrodynamics and swim efficiency. In this sense, age group coaches should on regular basis deliver customized cues and feedbacks about the technique of each and every swimmers. This is even more relevant in heavy macro-cycles (i.e., with a high volume or density) where swimmers tend to neglect technique. Furthermore, because growth plays a role, this should be considered as a covariable, which should be controlled comparing parameters over time.

Key words: Swimming, active and passive drag, Reynolds number, Froude number, approximate entropy, speed fluctuation.

Nomenclature

a_i	hip's instantaneous acceleration
ApEn	approximate entropy
BM	body mass
C_D	drag coefficient
C_{Da}	active drag coefficient
C_{Dp}	passive drag coefficient
ds	area
dv	intra-cyclic variation of the horizontal velocity of the hip
D	drag force
D_a	active drag
D_b	resistance of the perturbation buoy
D_f	friction drag
D_p	passive drag
D_{pr}	pressure drag
D_{prop}	propulsive drag
D_w	wave drag
F_p	effective propulsive force
Fr	Froude number
H	height
L	lift force
m	embedding dimension
N	data length
n_{im}	number of patterns that are similar between two sets
P	mechanical power
P_D	power to overcome drag force
R	vortex ring
r	tolerance value or similarity criterion
Re	Reynolds number
S	projection surface (cf. TTSA)
SF	stroke frequency
SL	stroke length
SI	stroke index
t	time
TDI	total drag index
TTSA	trunk transverse surface area
v	velocity
v_i	hip's instantaneous velocity
v_{hull}	hull velocity
Γ	vortex circulation
ω	angular velocity
ρ	fluid density

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