Section: Original Investigation

Article Title: Determinant Factors of Long-Term Performance Development in Young Swimmers

Authors: Jorge E Morais[1,5], António J Silva[2,5], Daniel A Marinho[3,5], Vítor P Lopes[1,5], and Tiago M Barbosa[4,5]

Affiliations: [1]Polytechnic Institute of Bragança, Bragança, Portugal. [2]Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal. [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.

Journal: *International Journal of Sports Physiology and Performance*

Acceptance Date: April 22, 2016

DOI: http://dx.doi.org/10.1123/ijspp.2015-0420

"Determinant Factors of Long-Term Performance Development in Young Swimmers" by Morais JE et al.
International Journal of Sports Physiology and Performance

Determinant factors of long-term performance development in young swimmers

Original investigation

Jorge E Morais[1,5], António J Silva[2,5], Daniel A Marinho[3,5], Vítor P Lopes[1,5], Tiago M Barbosa[4,5]

[1]Polytechnic Institute of Bragança, Bragança, Portugal
[2]Department of Sport Sciences, Exercise and Health, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal
[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

Contact author:
Jorge E Morais
Department of Sport Sciences, Polytechnic Institute of Bragança
Campus Sta. Apolónia, Apartado 1101, 5301-856, Bragança, Portugal
Tel: (351) 273 303 000
Fax: (351) 273 303 135
E-mail: morais.jorgestrela@gmail.com

Preferred Running head: Young swimmers' longitudinal modeling

Abstract Word Count: 201
Text-only Word Count: 3898
Number of Figures and Tables: 5

Abstract

Purpose: The aims of this study were: (i) develop a performance predictor model based on the swimmers’ biomechanical profile; (ii) relate the partial contribution of the main predictors with the training program and; (iii) analyze the time effect, sex effect and time X sex interaction. **Methods**: Ninety one swimmers (44 boys: 12.04 ± 0.81 years-old, 47 girls: 11.22 ± 0.98 years-old) were evaluated during a 3-year period. The decimal age, anthropometric, kinematic and efficiency features were collected in ten different moments over three seasons (i.e. longitudinal research). Hierarchical linear modeling was the procedure used to estimate the performance predictors. **Results**: Performance improved between season #1 - early and season #3 - late for both sexes (boys: 26.9% [20.88;32.96]; girls: 16.1% [10.34;22.54]). The decimal age (Estimate: -2.05; $P < 0.001$), arm span (Estimate: -0.59; $P < 0.001$), stroke length (Estimate: 3.82; $P = 0.002$) and propelling efficiency (Estimate: -0.17; $P = 0.001$) entered in the final model. **Conclusion**: Our results showed that over three consecutive seasons young swimmers’ performance improved. Performance is a multifactorial phenomenon where anthropometrics, kinematics and efficiency were the main determinants. The change of these factors over time was coupled with the training plans of this talent ID program.

Key Words: kinematics, anthropometrics, biomechanical predictors, contribution, talent ID

Introduction

These days, talent identification and development (ID) is one of the main topics in sports performance for both researchers and practitioners. Identifying a potential elite sportsman at an early age is challenging.[1] The talent ID process in swimming should hold three main components, as in other sports: (i) identification - identifying the athletes with the potential to reach the highest performance in adulthood and the main traits related to it;[2] (ii) development - understand the changes in the performance and determinant factors according to training program;[3] (iii) and follow-up - learn about the changes in the performance and determinant factors during a time-frame.[4]

Swimming is a multifactorial sport, where interactions between several scientific factors from different fields of science do happen. Hence, talent development and follow-up depends on genetics and environmental conditions, as well as its interactions.[5] The former is mainly related to genetic profiling and/or anthropometric assessment.[6] The later can be monitored by control tests. A well-designed training plan can build-up physiological parameters and/or enhance the technique with a positive effect on the performance.[7] However, evidence on this with youth is scarce. It is claimed that several determinant factors have different partial contributions to performance.[7] However, so far little insight was gathered about these partial contributions in swimming or even in any other sport. Cross-sectional studies report that, at least for young swimmers, the biomechanics and physiology may explain up to 80% of the performance.[8] Moreover one study reports that biomechanics alone (including anthropometrics, hydrodynamics and kinematics) explain 60% and seems to be the main determinant field.[9] However, during a season, the training program (i.e. external training load) relies on different parameters, that have an effect on the swimmers' response (i.e. internal training load).[7] The performance can depend upon different anthropometric, kinematic or efficiency features over a full season. Moreover, this might be a dynamic relationship with systematic shifts in the interplay among these factors. Nevertheless, little is known about such hypothetical relationships between internal and external training loads in young athletes.

The best way to gather insight on such relationships is based on longitudinal studies, despite in competitive swimming the vast majority are cross-sectional designs. Regarding the few papers reporting changes over time in young swimmers, there are a few concerns:[10,11,12] (i) the sample (i.e. small and underpowered samples; the subjects recruited are not always talented swimmers); (ii) the modelling procedures and the data analysis (i.e. most researchers run yet classic null-hypothesis stats, with no predictions and interactions being made by more cutting-edge and comprehensive modelling procedures); (iii) the time-frame (i.e. short time-frames from few weeks up to one full season, and few evaluation moments over time. Young swimmers, as other athletes, are sensitive to changes within and between seasons. This means that more evaluation moments are needed to have a deeper understanding on the changes over time); (iv) follow-up studies with little insight on the dose-response (i.e. do not share details on the external training load and hence, do not attempt to understand the interplay or at least the coupling between internal and external training load over time). Indeed, it was suggested earlier that longitudinal studies in competitive swimming should adopt the best practices of other scientific fields.[13] Having said that, we failed to find in the literature a longitudinal research reporting the relationships between talent development and training program in a large sample of subjects over a long period of time.

The aims of this study were to: (i) test a performance predictor model based on the swimmers' biomechanical profile, over three consecutive seasons; (ii) relate the partial contribution of the main predictors with the training program over time and; (iii) analyze the time effect, sex effect and time X sex interaction. It was hypothesized that the partial contribution of each determinant factor might be related to the training program. A time and sex effect, and a time X sex interaction should be verified.

Methods

Subjects

Ninety one young swimmers (44 boys: 217.7±69.5 FINA points at short-course meters 100-m freestyle; and 47 girls: 277.7±68.7 FINA points at short-course meters freestyle) racing on regular basis at regional and national competitions were evaluated during 3 full seasons (3 years). The swimmers were under a talent identification, development & follow-up scheme, including age-group national record holders, age-group national champions, besides others. At the baseline, boys had 12.04±0.81 years-old and girls 11.22±0.98 years-old, and they had 3.18±0.62 years of training experience. Between the first and third seasons, they had 5.10±1.08, 5.5±1.26 (ranging from 3 to 7 in the season), 7.1±1.11 (ranging from 6 to 9 in the season) weekly training sessions, respectively. Sessions included warm-up, recovery, slow, medium and intense pace, technical drills, as well as dry-land strength and conditioning sessions (twice per week) according to the training program (Figure 1). Different practitioners and researchers name the energetic zones or bands differently. Coaches often classify the zones from A0 to A3, depending on the energetic pathways to be elicited. Another mainstream terminology is reported by Maglisho,[14] naming the zones from En 1 all the way to En 3. The A1, A2 and A3 zones reported here are also known as En1, En2 and En3, respectively.

Coaches, parents and/or guardians and the swimmers gave the informed consent/assent to participate on this study. All procedures were in accordance to the Helsinki Declaration regarding Human research. The University of Trás-os-Montes and Alto Douro Ethic committee also approved the study design (ethic review: UTAD-2011-219).

Study design

Repeated measures of anthropometrics, kinematics and efficiency parameters over ten different moments (M), along three seasons, were performed (Figure 2). The evaluation moments were different in each season according to coaches' advices. Evaluation moments were set according to the training program and the competitive calendar in each season.

Performance data collection

The 100-m freestyle event was selected as the main outcome (official race time at regional or national short course meter event). The time gap between data collection and the race was no more than two weeks.

Kinematic data collection

The swimmers were instructed to perform three maximal freestyle swim trials of 25-m with push-off start. Between each trial, they had a 30 minutes rest to ensure a full recovery. For further analysis the average value of the three trials were calculated.

Kinematic data was collected with a mechanical technique (Swim speedo-meter, Swimsportec, Hildesheim, Germany) (ICC=0.95). A 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, Texas, USA) transferred data (f = 50Hz) to a software customized by our group (LabVIEW® interface, v.2009).[15] Data was exported to a signal processing software (AcqKnowledge v.3.9.0, Biopac Systems, Santa Barbara, USA) and filtered with a 5Hz cut-off low-pass 4th order Butterworth filter. The swimming speed (v; in $m \cdot s^{-1}$) was calculated as v=d/t in the middle 15-m (i.e. between the 5th and the 20th meter). Two experts evaluators measured the stroke frequency (SF; $cycles \cdot min^{-1}$; ICC=0.98) with a stroke counter (base 3) and then converted to SI units (Hz). The stroke length (SL; in m) was calculated as SL=v/SF.[16] The intra-cyclic variation of the horizontal velocity of the center of mass (dv; dimensionless) was calculated as:[15]

$$dv = \frac{\sqrt{\sum_i (v_i - \bar{v})^2 F_i / n}}{\sum_i v_i F_i / n} \quad (1)$$

Where dv is the intra-cyclic variation of the horizontal velocity of the center of mass (dimensionless), v is the mean velocity ($m \cdot s^{-1}$), v_i is the instant velocity ($m \cdot s^{-1}$), F_i is the absolute frequency and n is the number of observations. The dv is a feasible way to analyze the swimmers' overall stroke mechanics, as it measures the ratio between the acceleration and deceleration within each stroke cycle, allowing to: identify critical points in the different phases of each cycle, and collect relevant data for practitioners and coaches.[15]

Efficiency data collection

The propelling efficiency (η_p; in %) was estimated as:[17]

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

Where η_p is the arm's propelling efficiency (%), v is the average speed of the swimmer (multiplied by 0.9 to take into account that, in the front crawl, about 10% of forward propulsion is produced by the legs) ($m \cdot s^{-1}$), SF is the stroke frequency (Hz) and the term l is the average shoulder-to-hand distance (m, i.e. this distance was measured on dry-land, while the swimmer was simulating a stroke cycle: (i) between the acromion and the olecranon; (ii) and between the olecranon and the tip of the 3rd finger, with a measuring tape (RossCraft, Canada); ICC=0.99). The stroke index (SI; in $m^2 \cdot s^{-1}$) was calculated as SI=v·SL.[18]

Anthropometrics data collection

All measurements were carried-out in a regular textile swimsuit, wearing cap and goggles. The body mass (BM) was measured with the swimmers in the upright position with a digital weighting scale (SECA, 884, Hamburg, Germany). The height (H) was measured in the anthropometrical position from vertex to the floor with a digital stadiometer (SECA, 242, Hamburg, Germany). The arm span (AS) was measured with swimmers standing 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 measuring tape (RossCraft, Canada) (ICC=0.99).

Statistical analysis

The linearity, normality and homoscedasticity assumptions were checked beforehand. Descriptive statistics included the mean, one standard deviation and the difference between first and last evaluation moment (delta), and 95% confidence interval. For the assessment of the mean stability, after running ANOVA repeated measures, Bonferroni test ($P \leq 0.05$) was used to test the pairwise between the first and last evaluation moment.[19] Normative stability was analyzed with Pearson's auto-correlation coefficient ($P<0.05$). As rule of thumb, for qualitative assessment, it was set that the stability was: (i) high if $r \geq 0.60$; (ii) moderate if $0.30 \leq r < 0.60$ and; (iii) low if $r<0.30$.[19] The longitudinal data analysis was performed by the hierarchical linear modeling (HLM). Two models were computed. The first model included the time effect, the sex effect and the time X sex interaction, to understand if: (i) there were any changes over time; (ii) differences between sexes and; (iii) differences in the changes between sexes, respectively. In the second model, decimal age, anthropometrics, kinematics and efficiency variables were tested as potential predictors. The final model only included significant predictors. Maximum likelihood estimation was calculated with the HLM5 software.[20]

Results

Overall all variables showed an improvement between the first evaluation moment (season #1 - early) and the last moment (season #3 - late) (Table 1 and 2). Both boys (Δ=26.9%, 95CI: 20.88;32.96, $P<0.001$) and girls (Δ=16.1%, 95CI: 10.34;22.54, $P=0.002$) enhanced their performance (Table 2). Both sexes increased their BM and H. The BM was the variable with the highest difference between season #1 - early and season #3 - late (boys:

21.1%, 95CI: 15.24;26.99, P<0.001; girls: 16.7%, 95CI: 12.43;21.45, P<0.001) (Table 1). Overall, the kinematics improved in both sexes. For the boys, the v was the variable with the best improvement (Δ=17.8%, 95CI: 9.00;26.60, P=0.05), while girls presented a meaningful, but not significant decrease in their dv (Δ=-40.8%, 95CI: -69.96;-10.75, P=0.64), the later one suggesting a high variability (Table 2). Regarding swimming efficiency, boys and girls presented a higher improvement in the SI (boys: 24.9%, 95CI: 12.75;38.75, P=0.03; girls: 32.7%, 21.04;45.83, P=0.001). The performance revealed a moderate-high normative stability for the boys (r=0.51, P=0.09 at season #1 - midvseason #3 - mid; r=0.74, P<0.001 at season #2 - midvseason #2 - late) and low-high for the girls (r=0.20, P=0.46 at season #1 - earlyvseason #3 - late; r=0.95, P<0.001 at season #2 - midvseason #2 - late). As for the boys and girls pooled together, a moderate-high normative stability was observed (r=0.38, P=0.04 at season #1 - earlyvseason #3 - late; r=0.98, P<0.001 at season #3 - midvseason #3 - late). Hence, wider the time-lag between evaluation moments, lower the stability is.

The HLM procedure included two stages: (1st) assess hypothetical effects/interactions in the performance with time and sex (Table 3-Model 1); (2nd) assess hypothetical relationships between changes in the performance over time with potential determinant factors (Table 3-Model 2). The results of the first hierarchical linear model tested showed that boys and girls differ significantly at the baseline (Table 3-Model 1). Girls’ performance at the 100-m freestyle event was estimated as being 83.47s and boys 77.75s. The performance improved significantly over the 3 seasons (i.e. time effect). Between evaluation moments the performance improved by 1.32s. The performance enhancement was significantly higher in the boys (i.e. time X sex interaction effect). Between each moment, the performance was estimated to be higher for the boys (i.e. less 0.50s to cover the distance in comparison to girls). Therefore, time and sex have significant effects on the swimming performance.

Because there were significant effects/interactions, in the second model, these predictors were retained and added to the decimal age, anthropometrics, kinematics and efficiency variables selected. The second model (i.e. final model) retained as final predictors of performance the decimal age, AS, SL and η_p (Table 3-Model 2). In this second stage, there were no sex and time effects or time X sex interaction. So, boys and girls could be pooled together having an overall estimation of 73.75s at the 100m freestyle (Table 3-Model 2). The decimal age, AS and η_p had positive effects on the performance. By increasing one unit in the decimal age (in years), performance enhanced 2.05s. For each unit increase in AS (in cm) performance improve 0.59s. Same trend for the η_p, for each unit increase (in %) the performance improve 0.17s. The SL was estimated as having an inverse relationship with performance. Increasing the SL in one unit (in m) the performance was predicted as decreasing by 3.82s (i.e. more time to cover the distance) (Table 3-Model 2). Hence, age, anthropometrics variables, kinematics and swim efficiency are determinant factors to enhance the performance over 3 seasons.

Discussion

The aims of this study were to test a model to predict swimming performance over three seasons in young swimmers and to learn about the partial contribution of each predictor. Main finding was that performance relates to the age (decimal age), anthropometrics (AS), kinematics (SL) and efficiency (η_p).

Performance improved over the 3 seasons (3 years), and the main determinants presented an overall increase. Previous studies tracking young swimmers' performance and its determinant factors reported an increase over three evaluation moments.[21,22] In this study, the performance showed the same trend, with an overall moderate-high stability. However, if one includes more intermediate evaluations (as this study), some of the determinant factors (kinematic and efficiency) may present slight and circumstantial increases and decreases between evaluation moments (Table 2). Overall, these changes are not significant, being the model linear. This variance seems to be coupled with the training program (Figure 1). For instance, as reported earlier for one single season, it seems that for three consecutive seasons building-up aerobic capacity and technique improvement also has an effect on the kinematics and efficiency and hence on the performance.[7]

Over the three years, there is an increase in the total volume and an improvement in the performance (Figure 1). Doing the breakdown of the volume into energetic bands, it is also obvious such increase in the external training load. At the beginning of each season (between the first and intermediate moments) the training program is based on high training volumes (mainly A0: warm-up and recovery pace; and A1: slow pace). It is when there is the highest improvement in the performance (season one: 6.41%; season two: 4.71%; season three: 1.68%). In the middle of each season (between the intermediate and last moments), there is an increase in the training volume at higher regimes such as aerobic capacity and power (A2 and A3, respectively). Swimmers improved their performances by 2.48% (season #1), 1.51% (season #2) and 0.70% (season #3) in such period of time. Some of these energetic regimes are coupled with the enhancement of the technique. Coaches tend to spend a lot of time with technical drills and delivering cues on the swimmers' technique, having as well a positive effect on the performance.[7,23] Therefore, it seems that there is a clear relationship between the training program designed, the external training load and the performance enhancement within each season and over consecutive seasons.

The final hierarchical model included the decimal age, AS, SL and the η_p. The swimmers were evaluated in a three-year period. As the swimmer gets old, happens a shift in biological maturation (season #1 and #2: Tanner 1-2; season #3: Tanner 2-3). Because we did not measure the biological maturation, the decimal age was chosen as a surrogate variable. The increase in one unit in the decimal age (in years) was related to a 2.05s improvement in the performance. The age and anthropometrics seem to be major determinants. However these are intrinsic factors that one practitioner hardly can change but should be aware and acknowledge. The SL and η_p also included in the model are not genetically predicted, so coaches can play a role helping swimmers to improve it. Silva and co-workers[24] compared the kinematics and efficiency between pre-pubertal and post-pubertal swimmers with similar training background. Main findings were that post-pubertal swimmers had significantly higher v, SL and SI than younger counterparts.

Anthropometric features are highly associated with young swimmers' performance.[1,21,22] The AS presents a high contribution to performance.[9,24] A higher AS leads to a higher v and hence to a better performance. During the three-year assessment, one unit increment (in cm) in the AS imposed a 0.59s improvement in the performance. Surprisingly, the SL increase over time but had a negative impact on the performance. Estimations showed that for the swimmers assessed, an increase in the SL impaired the performance. Literature reports that a higher SL provides better performances, and some of that is due to a higher AS($r=0.55$; $P<0.05$)[9], ($r=0.91$; $P<0.01$).[25] However, these studies are cross-sectional designs or evaluate the swimmers during a shorter time-frame. Added to that, the swimmers were not evaluated during the transition from a pre-pubertal to post-pubertal maturational stages when significant motor control changes do happen.[26] During childhood, swimmers as any other children suffer changes in kinematics and motor control patterns. Motor learning is a process of acquiring movement patterns, which satisfy the key constraints on each individual.[14,27] So it seems that during the maturation stage, the swimmers "relearn" some technical features associated to motor control aspects. Wilson and Hyde[28] pointed out an age-related variation on kinematic measures, suggesting a continual refinement of these parameters between older childhood and early adulthood. In opposition to the conventional demonstration, the constraint-led approach provides a framework, combining a balanced interaction between individual, environmental and task constraints.[27,29] In teaching and/or swimming training, the coaches should put the focus on individual task goals instead of relying on a standard coordination pattern.[30] The need to explore different strategies to reach a given outcome in motor control lead eventually to the non-linear pedagogy framework.[27,29] The later one suggests that there is more than one way to reach the same goal. Indeed, Strzala and Tyka[12] suggested that a SL decrease may occur, and that the swimming performance enhances throughout a SF increase. However, in our study, the SL showed a high coefficient of variation in comparison to the remaining predictors and can be explained under the constraint-led framework as reported earlier. It can be speculated that this higher variability concurrent with the maximum likelihood estimation explains the final outcome in the model. The performance enhancement is a multi-factorial phenomenon and relies on different features throughout a time-frame[7] and not only on the SL. Besides that, there is a significant and inverse relationship between SL and SF[31] suggesting therefore that the increase of the later parameter took place to increase the speed and ultimately to excel. Albeit these considerations, from season #3 - early onwards, the SL improved and became more stable. One might consider that probably those adjustments were acquired. However with only two measurements remains to be complete clear such trend. As for the η_p, one unit increase (in %) lead to a 0.17s improvement in the performance. In the training programs, a higher attention should be given to the efficiency and not only to training volume and intensity.

Practical Implications

The HLM is a comprehensive and straightforward way to model young swimmers' performance. Swimming performance does not depend on isolated features but from the interaction among several.[5] Based on the final model, intrinsic factors, more related to "nature" (such as the decimal age and anthropometrics, in this case, arm span) and extrinsic ones linked to "nurture" (including stroke length and propelling efficiency) are determinant to excel in such early ages in swimming. Besides that, there is evidence that the changes of the determinant factors over time happen in a non-linear fashion way (there are slight improvements and impairments along the way). .Talent ID programs should rely on identifying the performance determinant features in several moments of the season, how these change over time and interact. Hence, evidence-based information, about the partial contribution of each determinant factor, should be provided to coaches on regular basis (within and between seasons).

So far, to the best of our understanding no study provided a deep insight on the relationship between the development of these determinants and the training program. However, some might consider that the training level and other environmental factors (nurture) are ignored in detriment of a natural growth and maturation processes (genetics).[32] Our data shows that the training program also has a meaningful influence on the performance and its main extrinsic determinants. The same procedure and reasoning can be applied to other sports, so that one can gather insight over time on the performance's main determinants, in young talented athletes, under different talent ID schemes of different sports.

It can be addressed as main limitations: (i) the decimal age is a surrogate variable of sexual maturation. Lately there are increasing ethic concerns regarding the direct assessment of sexual maturation by Tanner stages due to some misconduct between practitioners and athletes. Despite that, the low variability in the maturation by the self-report and undisclosed identify as we carried out suggests that there is no effect at least for this time-frame of 3 years; (ii) the kinematics and efficiency variables were collected over 25-m trials and not the 100-m freestyle race. One might consider that to ensure a more real evolution of the kinematic and efficiency features with the performance, these parameters should have been assessed during the official race or a simulated event. However, kinematics and efficiency measured during the 25-m trial, showed an overall high-very high correlation with the 100-m performance in pilot studies. E.g., for the data collected in this research the correlation between the 25m and 100m performance was r=0.71 (P<0.001). This allow us selecting straightforward, less time-consuming and insightful procedures (e.g. mechanical speedometer rather than motion-capture systems) that are feasible to carry out in such a large sample size over three consecutive years; (iii) encompassed by these findings, follow-up research may aim to model over time the relationship between performance and each feature of the external training load in a more comprehensive fashion-way.

Conclusion

As a conclusion, over three consecutive seasons the performance and its determinant factors improved. Young swimmers’ performance is a multifactorial phenomenon where different factors play meaningful roles. Anthropometric, kinematic and efficiency features entered in the final model as main predictors. The change of these factors over time was coupled with the training program. Therefore, talent ID programs should rely not only on the identification but also on the development of the main predictors according to a well-designed training program plan in a long-term basis.

Acknowledgments

Jorge E. Morais gratefully acknowledges the PhD scholarship granted by the Portuguese Science and Technology Foundation (FCT) (SFRH/BD/76287/2011).

This project was supported by national funds granted by the Portuguese Science and Technology Foundation (FCT) (UID/DTP/04045/2013) and European Union fund for regional development (FEDER) under the COMPETE 2020 Programme for Competitiveness and internationalization (POCI) (POCI-01-0145-FEDER-006969).

References

1. Morais JE, Silva AJ, Marinho DA, Seifert L, Barbosa TM. cluster stability as a new method to assess changes in performance and its determinant factors over a season in young swimmers. *Int J Sports Physiol Perform*. 2015;10(2):261-168.

2. Delextrat A, Grosgeorge B, Bieuzen F. Determinants of performance in a new test of planned agility for young elite basketball players. *Int J Sports Physiol Perform*. 2015;10(2):160-165.

3. Matthys SP, Vaeyens R, Fransen J, Deprez D, Pion J, Vandendriessche J, Vandorpe B Lenoir M, Philippaerts R. A longitudinal study of multidimensional performance characteristics related to physical capacities in youth handball. *J Sports Sci*. 2013;31(3):325-334.

4. Mara JK, Thompson KG, Pumpa KL, Ball NB. Periodization and physical performance in elite female soccer players. *Int J Sports Physiol Perform*. 2015;10(5):664-669.

5. Barbosa TM, Bragada JA, Reis VM, Marinho DA, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. *J Sci Med Sport*. 2010;13(2):262-269.

6. Costa AM, Silva AJ, Garrido ND, Louro H, de Oliveira RJ, Breitenfeld L. Association between ACE D allele and elite short distance swimming. *Eur J Appl Physiol*. 2009;106(6):785-790.

7. Morais JE, Marques MC, Marinho Da, Silva AJ, Barbosa TM. Longitudinal modeling in sports: young swimmers' performance and biomechanics profile. *Hum Mov Sci*. 2014;37:111-122.

8. Barbosa TM, Costa MJ, Marinho DA, Coelho J, Moreira M, Silva AJ. Modeling the links between young swimmers' performance: energetic and biomechanic profiles. *Pediatr Exerc Sci*. 2010;22(3):379-391.

9. Morais JE, Jesus S, Lopes V, Garrido N, Silva AJ, Marinho DA, Barbosa TM. Linking selected kinematic, anthropometric and hydrodynamic variables to young swimmer performance. *Pediatr Exerc Sci*. 2012;24(4):649-664.

10. Batalha NM, Raimundo AM, Tomas-Carus P, Barbosa TM, Silva AJ. Shoulder rotator cuff balance, strength, and endurance in young swimmers during a competitive season. *J Strength Cond Res*. 2013;27(9):2562-2568.

11. Toubekis AG, Vasilaki A, Douda H, Gourgoulis V, Tokmakidis S. Physiological responses during interval training at relative to critical velocity intensity in young swimmers. *J Sci Med Sport*. 2011;14(4):363-368.

12. Strzala M, Tyka A. Shaping of physical endurance and front crawl swimming technique indices in swimmers after half-year training period. *Med Sportiva*. 2007;11(4): 88-96.

13. Costa MJ, Bragada JA, Marinho DA, Silva AJ, Barbosa TM. Longitudinal interventions in elite swimming: a systematic review based on energetics, biomechanics, and performance. *J Strength Cond Res*. 2012;26(7):2006-2016.

14. Maglisho E. *Swimming fastest*. Champaign, IL: Human Kinetics; 2003.

15. Barbosa TM, Morais JE, Marques MC, Silva AJ, Marinho DA, Kee YH. Hydrodynamic profile of young swimmers: changes over a competitive season. *Scan J Med Sci Sports*. 2015;25:184-196.

16. Craig A, Pendergast D. Relationships of stroke rate, distance per stroke and velocity in competitive swimming. *Med Sci Sports*. 1979;11:278-283.

17. Zamparo P. Effects of age and gender on the propelling efficiency of the arm stroke. *Eur J Appl Physiol*. 2006;97(1):52-58.

18. Costill DL, Kovaleski J, Porter D, Kirwan R, Fielding R, King D. Energy expenditure during front crawl swimming: predicting success in middle-distance events. *Int J Sports Med*. 1985;6:266–270.

19. Costa MJ, Marinho DA, Bragada JA, Silva AJ, Barbosa TM. Stability of elite Freestyle performance from childhood to adulthood. *J Sports Sci*. 2011;29(11):1183-1189.

20. Raudenbush S, Bryk A, Cheong YF, Congdon R. *HLM 5: hierarchical linear and nonlinear modeling*. Lincolnwood, IL: Scientific Software International Inc; 2001.

21. Lätt E, Jürimae J, Haljaste K, Cicchella A, Purge P, Jürimae T. Physical development and swimming performance during biological maturation in young female swimmers. *Coll Antropol*. 2009;33:117–122.

22. Lätt E, Jürimäe J, Haljaste K, Cicchella A, Purge P, Jürimäe T. Longitudinal development of physical and performance parameters during biological maturation of young male swimmers. *Percept Mot Skills*. 2009;108:297–307.

23. Barroso R, Salgueiro DF, do Carmo EC, Nakamura FY. Training volume and repetition distance affect session rating of perceived exertion and internal load in swimmers. *Int J Sports Physiol Perform*. 2015;[Epub ahead of print].

24. Silva AF, Figueiredo P, Seifert L, Soares S, Vilas-Boas JP, Fernandes RJ. Backstroke technical characterization of 11-13 year old swimmers. *J Sports Sci Med*. 2013;12(4):623-629.

25. Saavedra JM, Escalante Y, Ferran AR. A multivariate analysis of performance in young swimmers. *Pediatr Exerc Sci*. 2010;22:135-151.

26. Barnett LM, Van Beurden E, Morgan PJ, Brooks LO, Beard JR. Does childhood motor skill proficiency predict adolescent fitness? *Med Sci Sports Exerc*. 2008;40(12):2137-2144.

27. Davids K, Button C, Bennett SJ. *Dynamics of skill acquisition: a constraint-led approach*. Champaign, IL: Human Kinetics; 2008.

28. Wilson PH, Hyde C. The development of rapid online control in children aged 6-12 years: reaching performance. *Hum Mov Sci*. 2013;32(5):1138-1150.

29. Chow JY, Koh M, Davids K, Button C, Rein R. Effects of different instructional constraints on task performance and emergence of coordination in children. *Eur J Sports Sci*. 2014;14(3):224-232.

30. Seifert L, Komar J, Barbosa TM, Toussaint H, Millet G, Davids K. Coordination pattern variability provides functional adaptations to constraints in swimming performance. *Sports Med*. 2014;44:1333-1345.

31. Barden JM, Kell RT, Kobsar D. The effect of critical speed and exercise intensity on stroke phase duration and bilateral asymmetry in 200-m front crawl swimming. *J Sports Sci*. 2011;29(5):517-526.

32. Brutsaert TD, Parra EJ. Nature versus nurture in determining athletic ability. *Med Sport Sci*. 2009;54:11-27.

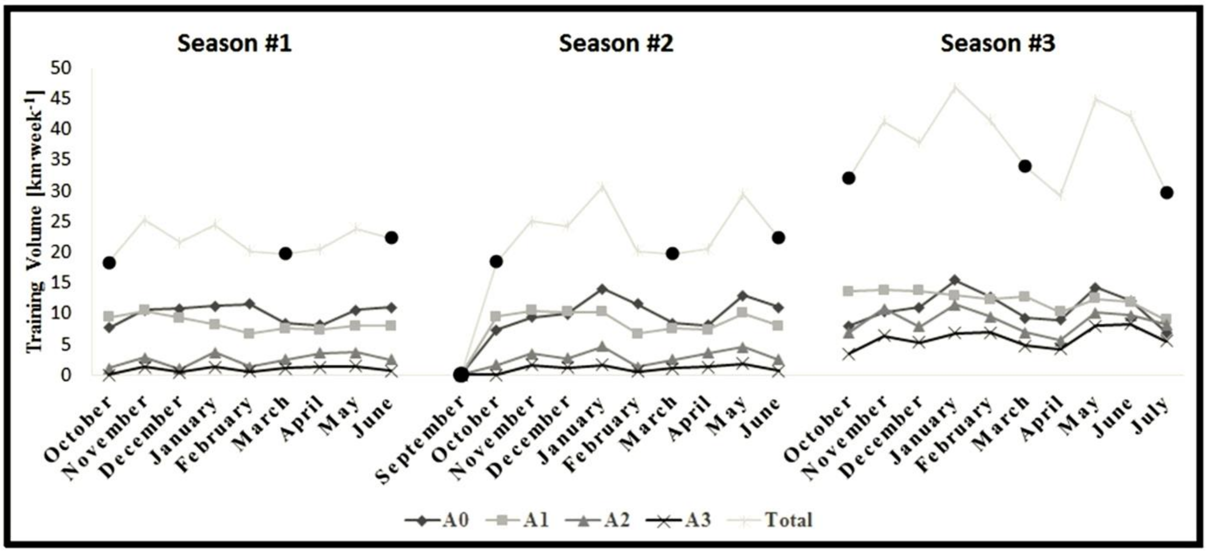

Figure 1. Training volume per week (in km) in each season, and the performance variation. ● – evaluation moments (Mi); A0 – warm-up and recovery pace; A1 – slow pace; A2 – moderate pace (aerobic capacity); A3 – intense pace (aerobic power). For each training zone, the coefficient of variation was in season #1: 15% (A0), 14% (A1), 44% (A2), 54% (A3); season #2: 22% (A0), 16% (A1), 39% (A2), 53% (A3) and; season #3: 25% (A0), 13% (A1), 25% (A2), 26% (A3), respectively.

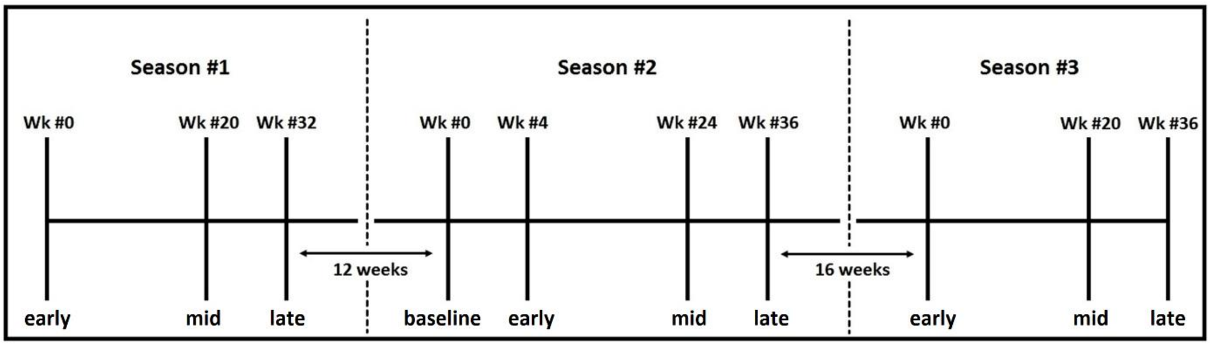

Figure 2. The timeline for the data collection over the three seasons (10 evaluation moments). All moments included the performance, kinematics, efficiency and anthropometrics assessment; #Wk – week number in each season; ↔ number of weeks break between seasons.

Table 1. Descriptive statistics and variation (%; 95% CI) of the anthropometrics between season #1 - early and season #3 - late.

		Season #1			**Season #2**				**Season #3**			
		early (#1)	**mid (#1)**	**late (#1)**	**base (#2)**	**early (#2)**	**mid (#2)**	**late (#2)**	**early (#3)**	**mid (#3)**	**late (#3)**	**Δ [95% CI]**
		Mean±SD	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Mean±SD**	**Season #1 – early v season #3 - late**
Body mass [kg]	**Boys**	47.2±10.1	48.4±9.6	50.1±10.0	49.7±8.5	50.5±8.4	52.1±8.0	53.1±7.6	57.9±8.3	60.0±7.9	59.5±7.5	21.1% [15.24;26.99]
	Girls	44.9±7.6	45.5±7.8	47.2±7.8	46.0±7.8	46.9±7.8	48.2±7.9	49.0±7.8	52.7±6.5	53.8±6.4	54.0±6.6	16.7% [12.43;21.45]
Height [cm]	**Boys**	156.9±11.0	158.8±10.9	159.7±10.6	160.3±8.5	161.6±8.2	163.5±8.2	164.6±8.1	168.6±8.2	171.0±7.4	171.7±7.1	8.6% [6.18;11.15]
	Girls	153.9±8.4	155.0±7.6	155.4±7.8	156.2±6.9	156.9±6.9	157.3±6.7	158.2±6.6	161.2±6.1	162.3±5.6	163.5±5.5	5.8% [4.28;7.46]
Arm span [cm]	**Boys**	161.4±14.0	163.6±9.2	163.8±14.0	165.3±12.7	165.4±8.8	168.0±9.0	169.4±9.3	174.9±9.3	176.5±8.9	177.4±8.4	9.0% [6.05;12.22]
	Girls	154.1±10.0	156.2±7.8	156.7±8.97	157.8±7.42	158.3±8.3	159.4±7.3	160.3±7.1	164.3±6.4	164.8±6.6	165.7±7.1	6.9% [4.97;9.05]

Table 2. Descriptive statistics and variation (%; 95% CI) of the technical and performance data between season #1 - early and season #3 - late.

		Season #1			**Season #2**				**Season #3**			
		early (#1)	mid (#1)	late (#1)	base (#2)	early (#2)	mid (#2)	late (#2)	early (#3)	mid (#3)	late (#3)	Δ [95% CI]
		Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Mean±SD	Season #1 – early v season #3 - late
Stroke frequency [Hz]	Boys	0.83±0.06	0.86±0.07	0.88±0.06	0.88±0.09	0.88±0.10	0.91±0.09	0.90±0.10	0.87±0.06	0.88±0.06	0.90±0.08	7.6% [3.57;11.01]
	Girls	0.82±0.13	0.82±0.09	0.80±0.07	0.82±0.11	0.82±0.10	0.80±0.08	0.81±0.08	0.78±0.06	0.81±0.07	0.82±0.08	-0.28% [-8.20;7.63]
Stroke length [m]	Boys	1.55±0.31	1.10±0.18	1.45±0.26	1.55±0.19	1.58±0.20	1.60±0.21	1.64±0.21	1.76±0.15	1.76±0.14	1.75±0.17	11.1% [3.04;20.23]
	Girls	1.40±0.34	1.12±0.27	1.38±0.24	1.51±0.21	1.54±0.20	1.66±0.17	1.66±0.17	1.74±0.13	1.70±0.14	1.73±0.15	18.7% [9.30;28.95]
Swimming velocity [m·s^{-1}]	Boys	1.29±0.22	0.95±0.14	1.28±0.19	1.35±0.14	1.37±0.13	1.44±0.14	1.47±0.13	1.52±0.09	1.55±0.07	1.56±0.08	17.8% [9.00;26.60]
	Girls	1.18±0.21	0.90±0.16	1.11±0.19	1.23±0.12	1.25±0.11	1.33±0.11	1.33±0.10	1.35±0.08	1.37±0.06	1.41±0.07	15.7% [7.03;24.24]
intra-cyclic velocity [dimensionless]	Boys	0.08±0.01	0.11±0.05	0.08±0.01	0.09±0.03	0.09±0.03	0.09±0.01	0.09±0.01	0.09±0.02	0.09±0.01	0.08±0.02	2.1% [-20.74;15.08]
	Girls	0.11±0.05	0.10±0.04	0.10±0.03	0.10±0.03	0.09±0.03	0.08±0.02	0.08±0.02	0.10±0.04	0.09±0.02	0.08±0.02	-40.8% [-69.96;-10.75]
Stroke index [m^2·s^{-1}]	Boys	2.06±0.66	1.07±0.36	1.90±0.61	2.11±0.44	2.18±0.44	2.35±0.48	2.43±0.46	2.68±0.36	2.74±0.29	2.74±0.37	24.9% [12.75;38.75]
	Girls	1.63±0.58	1.05±0.50	1.56±0.51	1.87±0.38	1.93±0.37	2.20±0.34	2.22±0.34	2.36±0.2	2.33±0.26	2.43±0.27	32.7% [21.04;45.83]
Propelling efficiency [%]	Boys	28±5	20±3	26±4	28±3	29.±3	32±6	30±4	30±2	30±2	29±2	2% [-7.34;11.56]
	Girls	26±7	21±5	26±5	30±4	28±3	35±5	32±5	31±3	31±2	31±3	15% [4.71;25.56]
Performance [s]	Boys	76.26±7.00	71.73±7.29	68.88±6.66	73.48±8.10	69.93±7.86	67.15±6.94	66.33±6.36	62.00±3.14	60.55±3.23	60.08±3.22	26.9% [20.88;32.96]
	Girls	79.06±6.77	74.30±4.55	72.50±4.11	80.32±8.60	77.66±8.01	74.16±6.82	73.05±5.72	69.70±3.98	68.54±3.75	68.06±4.40	16.1% [10.34;22.54]

Table 3. Parameters of the two models computed with standard errors (SE) and 95% confidence intervals (CI).

Parameter Fixed Effect	Estimate (SE)	95% CI	P value
Model 1			
Intercept	83.47(1.62)	86.67 – 80.28	<0.001
Time	-1.32(0.16)	-1.00 – -1.64	<0.001
Sex	-5.72(2.23)	-1.34 – -10.10	0.01
Time X Sex	-0.50(0.23)	-0.03 – -0.97	0.035
Model 2			
Intercept	73.65(0.85)	75.33 – 71.97	<0.001
Decimal Age	-2.05(0.32)	-1.42 – -2.68	<0.001
Arm span	-0.59(0.04)	-0.50 – -0.68	<0.001
Stroke length	3.82(1.22)	6.23 – 1.42	0.002
Propelling efficiency	-0.17(0.05)	-0.06 – -0.27	0.001

Model 1 – first model computed, including only the time effect, sex effect and time X sex interaction; Model 2 – final model, retaining the final performance predictors.