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Human Kinetics
ORIGINAL INVESTIGATION

Determinant Factors of Long-Term Performance Development in Young Swimmers

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Purpose: To develop a performance predictor model based on swimmers' biomechanical profile, relate the partial contribution of the main predictors with the training program, and analyze the time effect, sex effect, and time × sex interaction. ***Methods:*** 91 swimmers (44 boys, 12.04 ± 0.81 y; 47 girls, 11.22 ± 0.98 y) evaluated during a 3-y period. The decimal age and anthropometric, kinematic, and efficiency features were collected 10 different times over 3 seasons (ie, 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]). Decimal age (estimate [EST] –2.05, $P < .001$), arm span (EST –0.59, $P < .001$), stroke length (EST 3.82; $P = .002$), and propelling efficiency (EST –0.17, $P = .001$) were entered in the final model. ***Conclusion:*** Over 3 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 identification and development program.

Keywords: kinematics, anthropometrics, biomechanical predictors, contribution, talent identification, talent development

These days, talent identification and development is a main topic in sports performance for both researchers and practitioners. Identifying a potential elite athlete at an early age is challenging.[1] The talent identification and development process in swimming should hold 3 main components, as in other sports: identification—identifying athletes with the potential to reach the highest performance in adulthood and the main traits related to it,[2] development—understand the changes in the performance and determinant factors according to training program,[3] 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 happen. Hence, talent development and follow-up depend on genetics and environmental conditions, as well as their interactions.[5] The former is mainly related to genetic profiling and/or anthropometric assessment.[6] The latter can be monitored by control tests. A well-designed training plan can build up physiological parameters and/or enhance 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 has been gathered about these partial contributions in swimming or, for that matter, in any other sport. Cross-sectional studies report that, at least for young swimmers, biomechanics and physiology may explain up to 80% of performance.[8] Moreover, 1 study reports that biomechanics alone (including anthropometrics, hydrodynamics, and kinematics) explains 60% and seems to be the main determinant field.[9] However, during a season, the training program (ie, external training load) relies on different parameters that have an effect on the swimmers' response (ie, internal training load).[7] The performance can depend on 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 the fact that in competitive swimming, the vast majority of studies use cross-sectional designs. Regarding the few papers reporting changes over time in young swimmers, there are a few concerns[10–12]:

- The sample (ie, small and underpowered samples. The subjects recruited are not always talented swimmers.)
- The modeling procedures and the data analysis (ie, most researchers still run classic null-hypothesis statistics, with no predictions and interactions being made by more cutting-edge and comprehensive modeling procedures)
- The time frame (ie, short time frames from a few weeks up to 1 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.)
- Follow-up studies with little insight on the dose response (ie, the studies 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 any

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longitudinal research reporting the relationships between talent development and training programs in a large sample of subjects over a long period of time.

The aims of this study were to test a performance-predictor model based on swimmers' biomechanical profile over 3 consecutive seasons, relate the partial contribution of the main predictors with the training program over time, and analyze the time effect, sex effect, and time × sex interaction. We hypothesized that the partial contribution of each determinant factor might be related to the training program. A time and sex effect and a time × sex interaction should be verified.

Methods

Subjects

Ninety-one young swimmers (44 boys, 217.7 ± 69.5 FINA points at short-course 100-m freestyle; 47 girls, 277.7 ± 68.7 FINA points at short-course freestyle) racing on regular basis at regional and national competitions were evaluated during 3 full seasons (3 y). The swimmers were under a talent identification, development, and follow-up scheme, including age-group national record holders, age-group national champions, and others. At baseline, boys were 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) and 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; and 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 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 informed consent/assent to participate in this study. All procedures were in accordance with the Helsinki Declaration regarding human research. The University of Trás-os-Montes and Alto Douro ethics committee also approved the study design (ethics review UTAD-2011-219).

Study Design

Repeated measures of anthropometrics, kinematics, and efficiency parameters over 10 different moments over 3 seasons were performed (Figure 2). The evaluation moments were different in each season according to coaches' advice. Evaluation moments were set according to the training program and the competitive calendar in each season.

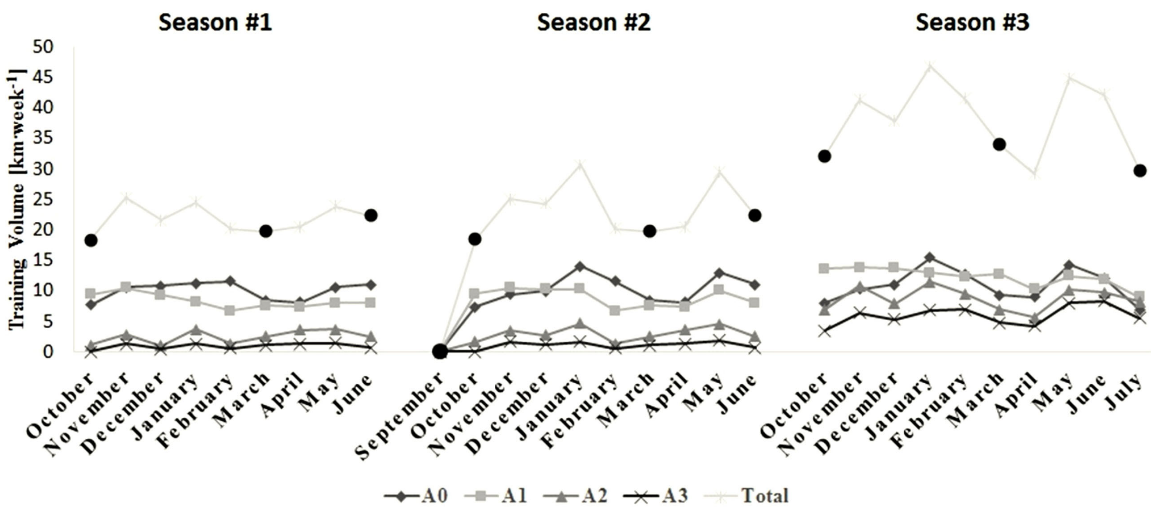

Figure 1 — Training volume per week (km) in each season and the performance variation. Black circles indicate evaluation moments; A0, warm-up and recovery pace; A1, slow pace; A2, moderate pace (aerobic capacity); A3, intense pace (aerobic power). For each training zone, the coefficient of variation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

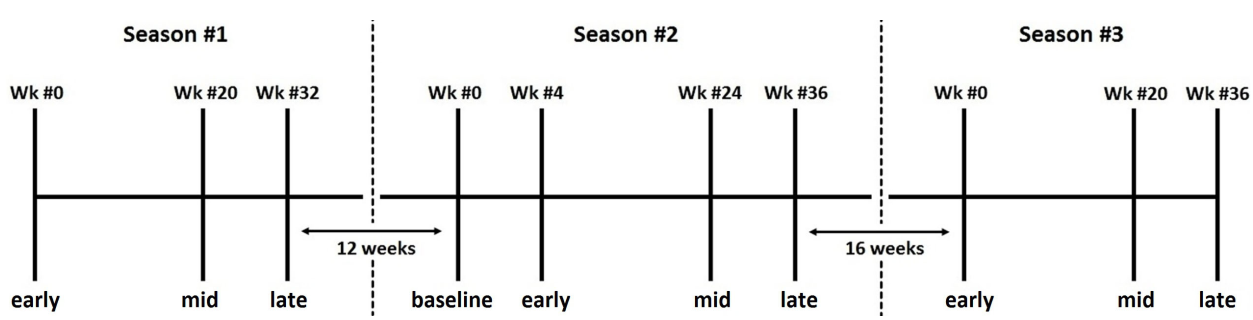

Figure 2 — Timeline for the data collection over the 3 seasons (10 evaluation moments). All moments included the performance, kinematics, efficiency, and anthropometrics assessment.

Performance-Data Collection

The 100-m freestyle event was selected as the main outcome (official race time at regional or national short-course events). The time gap between data collection and the race was no more than 2 weeks.

Kinematic-Data Collection

The swimmers were instructed to perform 3 maximal freestyle swim trials of 25 m with a push-off start. Between trials, they had 30 minutes rest to ensure full recovery. For further analysis the average value of the 3 trials was calculated.

Kinematic data were collected with a mechanical technique (Swim speedo-meter, Swimsportec, Hildesheim, Germany) (ICC = .95). A 12-bit resolution acquisition card (USB-6008, National Instruments, Austin, TX, USA) transferred data ($f = 50$ Hz) to software customized by our group (LabVIEW interface, version 2009).[15] Data were exported to signal-processing software (AcqKnowledge version 3.9.0, Biopac Systems, Santa Barbara, CA, USA) and filtered with a 5-Hz-cutoff low-pass fourth-order Butterworth filter. The swimming speed (v; in m/s) was calculated as $v = d/t$ in the middle 15 m (ie, between 5 and 20 m). Two expert evaluators measured stroke frequency (SF; cycles/min; ICC = .98) with a stroke counter (base 3) and then converted to SI units (Hz). Stroke length (SL; m) was calculated as SL = v/SF.[16] The intracyclic variation of the horizontal velocity of the center of mass (dv; dimensionless) was calculated as[15]

$$dv = \frac{\sqrt{\sum_i (v_i - \overline{v})^2 F_i / \mathrm{n}}}{\sum_i v_i F_i / \mathrm{n}}$$

where dv is the intracyclic variation of the horizontal velocity of the center of mass (dimensionless), v is the mean velocity (m/s), v_i is the instant velocity (m/s), F_i is the absolute frequency, and n is the number of observations. The dv is a feasible way to analyze swimmers' overall stroke mechanics, as it measures the ratio of acceleration to deceleration within each stroke cycle, allowing one to identify critical points in the different phases of each cycle and collect relevant data for practitioners and coaches.[15]

Efficiency-Data Collection

Propelling efficiency (η_p, in %) was estimated as[17]

$$\eta_p = \left[\left(\frac{v \cdot 0.9}{2\pi \cdot \mathrm{SF} \cdot 1}\right) \cdot \frac{2}{\pi}\right] \cdot 100$$

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/s), SF is stroke frequency (Hz), and the term l is the average shoulder-to-hand distance (m, ie, this distance was measured on dry land, while the swimmer was simulating a stroke cycle between the acromion and the olecranon and between the olecranon and the tip of the third finger, with a measuring tape [RossCraft, Canada]; ICC = .99). The stroke index (SI; in m^2/s) was calculated as SI = $v \times$ SL.[18]

Anthropometric-Data Collection

All measurements were carried out with the swimmers' wearing a regular textile swimsuit, cap, and goggles. Body mass was measured with the swimmers in the upright position with a digital scale (SECA, 884, Hamburg, Germany). Height was measured in the anthropometrical position from vertex to the floor with a digital stadiometer (SECA, 242, Hamburg, Germany). Arm span (AS) was measured with swimmers standing in the upright position, arms and fingers fully extended in lateral abduction at a 90° angle with the trunk. The distance between the third fingertips of both hands was measured with a flexible anthropometric measuring tape (RossCraft, Canada) (ICC = .99).

Statistical Analysis

Linearity, normality, and homoscedasticity assumptions were checked beforehand. Descriptive statistics included the mean, 1 SD, the difference between first and last evaluation moments (delta), and 95% confidence interval. For the assessment of mean stability, after running ANOVA repeated measures, a Bonferroni test ($P \leq .05$) was used to test pairwise between the first and last evaluation moments.[19] Normative stability was analyzed with Pearson autocorrelation coefficient ($P < .05$). As rule of thumb, for qualitative assessment, it was set that stability was high if $r \geq .60$, moderate if $.30 \leq r < .60$, and low if $r < .30$.[19] The longitudinal data analysis was performed by hierarchical linear modeling (HLM). Two models were computed. The first model included the time effect, the sex effect, and the time × sex interaction, to see if there were any changes over time, differences between sexes, and 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 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) (Tables 1 and 2). Both boys ($\Delta = 26.9\%$, 95CI 20.88;32.96, $P < .001$) and girls ($\Delta = 16.1\%$, 95CI 10.34;22.54, $P = .002$) enhanced their performance (Table 2). Both sexes increased their body mass and height. Body mass was the variable with the highest difference between season 1 early and season 3 late (boys 21.1%, 95CI 15.24;26.99, $P < .001$; girls 16.7%, 95CI 12.43;21.45, $P < .001$) (Table 1). Overall, kinematics improved in both sexes. For the boys, v was the variable with the best improvement ($\Delta = 17.8\%$, 95CI 9.00;26.60, $P = .05$), while girls presented a meaningful, but not significant, decrease in dv ($\Delta = -40.8\%$, 95CI –69.96;–10.75, $P = .64$), the latter suggesting high variability (Table 2). Regarding swimming efficiency, boys and girls presented higher improvement in SI (boys 24.9%, 95CI 12.75;38.75, $P = .03$; girls 32.7%, 21.04;45.83, $P = .001$). The performance revealed moderate to high normative stability for the boys ($r = .51$, $P = .09$ at season 1 midseason and season 3 midseason; $r = .74$, $P < .001$ at season 2 midseason and season 2 late) and low to high for the girls ($r = .20$, $P = .46$ at season 1 early and season 3 late; $r = .95$, $P < .001$ at season 2 midseason and season 2 late). As for the boys and girls pooled together, moderate to high normative stability was observed ($r = .38$, $P = .04$ at season 1 early and season 3, late; $r = .98$, $P < .001$ at season 3 midseason and season 3 late). Hence, the wider the time lag between evaluation moments, the lower the stability.

The HLM procedure included 2 stages: assessing hypothetical effects/interactions in the performance with time and sex (Table 3, model 1) and assessing hypothetical relationships between changes in 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 differed significantly at baseline (Table

Table 1 Descriptive Statistics and Variation (%; 95% CI) of the Anthropometrics Between Season 1 Early and Season 3 Late, Mean ± SD

		Season 1			Season 2				Season 3			Season 1 early v season 3 late, Δ [95% CI]
		Early	Mid	Late	Base	Early	Mid	Late	Early	Mid	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, Mean ± SD

		Season 1			Season 2				Season 3			Season 1 early v season 3 late, Δ [95% CI]
		Early	Mid	Late	Base	Early	Mid	Late	Early	Mid	Late	
Stroke frequency (Hz)	M	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]
	F	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)	M	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]
	F	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]
Swim velocity (m/s)	M	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]
	F	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]
Intracyclic velocity[a]	M	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]
	F	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)	M	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]
	F	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 (%)	M	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]
	F	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)	M	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]
	F	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]

Abbreviations: M, male; F, female.

[a] Dimensionless.

Table 3 Parameters of the 2 Models Computed With Standard Errors (SE) and 95% Confidence Intervals (CI)

Parameter fixed effect	Estimate (SE)	95% CI	*P*
Model 1			
intercept	83.47 (1.62)	86.67–80.28	<.001
time	–1.32 (0.16)	–1.00 to –1.64	<.001
sex	–5.72 (2.23)	–1.34 to –10.10	.01
time × sex	–0.50 (0.23)	–0.03 to –0.97	.035
Model 2			
intercept	73.65 (0.85)	75.33–71.97	<.001
decimal age	–2.05 (0.32)	–1.42 to –2.68	<.001
arm span	–0.59 (0.04)	–0.50 to –0.68	<.001
stroke length	3.82 (1.22)	6.23–1.42	.002
propelling efficiency	–0.17 (0.05)	–0.06 to –0.27	.001

Note: Model 1—first model computed, including only the time effect, sex effect, and time × sex interaction; Model 2—final model, retaining the final performance predictors.

3, model 1). Girls' performance at the 100-m freestyle event was estimated as being 83.47 seconds, and boys, 77.75 seconds. Performance improved significantly over the 3 seasons (ie, time effect). Between evaluation moments performance improved by 1.32 seconds. The performance enhancement was significantly higher in the boys (ie, time × sex interaction effect). Between moments, performance was estimated to be higher for the boys (ie, less 0.50 s to cover the distance in comparison with girls). Therefore, time and sex have significant effects on swimming performance.

Because there were significant effects/interactions, in the second model these predictors were retained and added to the decimal-age, anthropometric, kinematic, and efficiency variables selected. The second model (ie, final model) retained as final predictors of performance decimal age, AS, SL, and η_p (Table 3, model 2). In this second stage, there were no sex and time effects or time × sex interaction. Thus, boys and girls could be pooled together, having an overall estimation of 73.75 seconds at the 100-m freestyle (Table 3, model 2). Decimal age, AS, and η_p had positive effects on performance. By increasing 1 unit in decimal age (y), performance improved by 2.05 seconds. For each unit increase in AS (cm), performance improved 0.59 seconds. The same trend was observed for η_p; for each unit increase (%), performance improved 0.17 seconds. SL was estimated as having an inverse relationship with performance. Increasing the SL by 1 unit (m), performance was predicted as decreasing by 3.82 seconds (ie, more time to cover the distance) (Table 3, model 2). Hence, age, anthropometric 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 3 seasons in young swimmers and to learn about the partial contribution of each predictor. The main finding was that performance relates to age (decimal age), anthropometrics (AS), kinematics (SL), and efficiency (η_p).

Performance improved over the 3 seasons (3 y), and the main determinants presented an overall increase. Previous studies tracking young swimmers' performance and its determinant factors reported an increase over 3 evaluation moments.[21,22] In this study, the performance showed the same trend, with an overall moderate to 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 a model linear. This variance seems to be coupled with the training program (Figure 1). For instance, as reported earlier for a single season, it seems that for 3 consecutive seasons, building up aerobic capacity and improving technique also have an effect on kinematics and efficiency and hence on performance.[7]

Over the 3 years, there was an increase in total volume and an improvement in performance (Figure 1). Doing the breakdown of the volume into energetic bands, there is also an obvious 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). This is when there is the highest improvement in performance (season 1, 6.41%; season 2, 4.71%; season 3, 1.68%). In the middle of each season (between the intermediate and last moments), there is an increase in training volume at higher regimens, 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 periods of time. Some of these energetic regimens are coupled with enhancement of technique. Coaches tend to spend a lot of time with technical drills and delivering cues on swimmers' technique, which also has a positive effect on performance.[7,23] Therefore, it seems that there is a clear relationship between the designed training program, the external training load, and the performance enhancement within each season and over consecutive seasons.

The final hierarchical model included decimal age, AS, SL, and η_p. The swimmers were evaluated over a 3-year period. As the swimmers aged, there was a shift in biological maturation (seasons 1 and 2, Tanner 1–2; season 3, Tanner 2–3). Because we did not measure biological maturation, decimal age was chosen as a surrogate variable. An increase in 1 unit in decimal age (y) was related to a 2.05-second improvement in performance. Age and anthropometrics seem to be major determinants. However, these are intrinsic factors that a practitioner cannot change but should be aware of. SL and η_p, also included in the model, are not genetically predicted, so coaches can play a role in helping swimmers improve them. Silva et al[24] compared the kinematics and efficiency between prepubertal and postpubertal swimmers with similar training background. The main findings were that postpubertal swimmers had significantly higher v, SL, and SI than their 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 better performance. During the 3-year assessment, a 1-unit increment (cm) in AS led to a 0.59-second improvement in performance. Surprisingly, the SL increase over time had a negative impact on performance. Literature reports that a higher SL provides better performance, and some of that is due to a higher AS (r = .55; P < .05),[9] (r = .91; P < .01).[25] However, these studies are cross-sectional designs or evaluate swimmers during a shorter time frame. Added to that, the swimmers were not evaluated during the transition from a prepubertal to postpubertal maturational stages when significant motor control changes happen.[26] During childhood, swimmers, as any other children, undergo 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, coaches should 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 nonlinear pedagogy framework.[27,29] The latter suggests that there is more than 1 way to reach the same goal. Indeed, Strzala and Tyka[12] suggested that an SL decrease may occur and that the swimming performance is enhanced with an SF increase. However, in our study, SL showed a high coefficient of variation in comparison with 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. Performance enhancement is a multifactorial phenomenon and relies on different features throughout a time frame,[7] and not only on SL. Besides that, there is a significant and inverse relationship between SL and SF,[31] suggesting therefore that the increase in the latter parameter took place to increase the speed and ultimately to excel. Aside from these considerations, from season 3 early onward, SL improved and became more stable. One might consider that those adjustments were probably acquired. However with only 2 measurements such a trend remains to be completely clear. As for η_p, a 1-unit increase (%) led to a 0.17-second improvement in performance. In training programs, more attention should be given to 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 on the interaction among several.[5] Based on the final model, intrinsic factors, more related to "nature" (such as 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 at such early ages in swimming. Besides that, there is evidence that the changes of the determinant factors over time happen in a nonlinear fashion (there are slight improvements and impairments along the way). Talent identification and development programs should rely on identifying the performance determinant features in several moments of the season and 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 a regular basis (within and between seasons).

So far, to the best of our understanding, no study has provided deep insight on the relationship between the development of these determinants and the training program. However, some might consider that training level and other environmental factors (nurture) are ignored in detriment of natural growth and maturation processes (genetics).[32] Our data show that the training program also has a meaningful influence on 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 performance's main determinants in young talented athletes, under different talent identification and development schemes of different sports.

The main limitations of this study are as follows:

- Decimal age is a surrogate variable of sexual maturation. Lately there are increasing ethical 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 maturation by self-report and undisclosed identity as we carried out suggests that there is no effect, at least for this time frame of 3 years.
- The kinematic and efficiency variables were collected over 25-m trials and not a 100-m freestyle race. One might consider that to ensure a more real evolution of the kinematic and efficiency features with 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 to very high correlation with 100-m performance in pilot studies. For example, for the data collected in this research the correlation between 25-m and 100-m performance was $r = .71$ ($P < .001$). This allows us to select straightforward, less time-consuming and insightful procedures (eg, mechanical speedo-meter rather than motion-capture systems) that are feasible to carry out in such a large sample size over 3 consecutive years.
- 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.

Conclusion

In conclusion, over 3 consecutive seasons 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 identification and development programs should rely not only on the identification but also on the development of the main predictors according to a well-designed training program planned on a long-term basis.

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