

Front Crawl Sprint Performance: A Cluster Analysis of Biomechanics, Energetics, Coordinative, and Anthropometric Determinants in Young Swimmers

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The aim of this study was to evaluate the determinants of front crawl sprint performance of young swimmers using a cluster analysis. 103 swimmers, aged 11- to 13-years old, performed 25-m front crawl swimming at 50-m pace, recorded by two underwater cameras. Swimmers analysis included biomechanics, energetics, coordinative, and anthropometric characteristics. The organization of subjects in meaningful clusters, originated three groups (1.52 ± 0.16 , 1.47 ± 0.17 and 1.40 ± 0.15 m/s, for Clusters 1, 2 and 3, respectively) with differences in velocity between Cluster 1 and 2 compared with Cluster 3 ($p = .003$). Anthropometric variables were the most determinants for clusters solution. Stroke length and stroke index were also considered relevant. In addition, differences between Cluster 1 and the others were also found for critical velocity, stroke rate and intracycle velocity variation ($p < .05$). It can be concluded that anthropometrics, technique and energetics (swimming efficiency) are determinant domains to young swimmers sprint performance.

Keywords: swimming performance, age group, anthropometry, coordination

Swimming performance is dependent on several determinants (Barbosa et al., 2010a; Figueiredo, Pendergast, Vilas-Boas, & Fernandes, 2013), with biomechanics, energetics, electromyography, anthropometry, psychology, medicine, instruments, evaluation, education and training as the main scientific approaches used to understand it (Vilas-Boas, 2010). However, the most important areas to enhance performance and achieve high-standard levels in competitive swimming

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are biomechanics and energetics (Barbosa et al., 2010a; Toussaint & Beek, 1992; Toussaint & Hollander, 1994; Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005). In the last decade, the study of the relationship between these domains on elite swimmers has been of special interest (Barbosa et al., 2010b; Figueiredo et al., 2013). Moreover, swimming coordination, either between the movements of each limb segments or between the movements of two different limbs (or the segments of different limbs), has been explored (Chollet, Chalies, & Chatard, 2000; Schnitzler, Seifert, Alberty, & Chollet, 2010; Seifert, Chollet, & Rouard, 2007). However, the research dedicated to young swimmers is scarce compared with adult/elite swimmers (Barbosa et al., 2010a).

The assessment of sprint performance in young swimmers can lead to a better understanding of performance limitations that may be unique to this age group, leading to more realistic achievement expectations and training goals. On this matter, Kilika & Thorland (1994) reported that stroke efficiency and muscularity index (lean body mass/stature²) significantly accounted for 100 front crawl yards performance differences in male children and young adults. While Hohmann, Dierks, Luehnen-schloss, Seidel, & Wichmann (1998) showed that performance (50-m front crawl) is influenced both by the sprint and pulling strength and also swimming technique and motor coordination for age group swimmers of both genders.

Other studies predicted swimming performance of young swimmers, by examining the influence of the energy cost of exercise, body composition, anthropometry, drag coefficient and technical parameters on swimming performance (e.g., Jurimae et al., 2007; Kilika & Thorland, 1994; Kjendlie, Ingjer, Madsen, Stallman, & Stray-Gundersen, 2004; Lätt et al., 2009; Poujade, Hautier, & Rouard, 2002; Silva et al., 2007). The 100-m front crawl performance in 12- to 14-year-old boys has been predicted using total upper extremity length, horizontal jump and grip strength (Geladas, Nassis, & Pavlicevic, 2005). However, for the same event, Vitor and Böhme (2010) observed that the anaerobic power, swimming index and critical velocity explained 88% of the performance variability, being it predominantly influenced by physiological factors and swimming technique. Recently, a path-flow analysis model based on biomechanical and energetic parameters, using structural equation modeling explained 71% of the 200-m freestyle performance in young male swimmers and where propelling efficiency and critical velocity presented the higher correlations with performance (Barbosa et al., 2010a). A structural equation modeling, using selected kinematic, anthropometric and hydrodynamic variables, showed that the biomechanical domain contributed 50% to overall sample performance at the 100-m freestyle event (Morais et al., 2012). Finally, Barbosa et al. (2014) developed a classification system for young talented swimmers based on kinematical, hydrodynamic, and anthropometrical characteristics where the variable that better discriminated the groups was the intracycle velocity variation. In addition, Barbosa et al. (2013) showed that swimmers achieving a higher velocity had lower intracycle velocity variation. Exploring the interindividual profiles of young swimmers, although poorly studied, will provide new insights on the relationships between influencing performance factors, as there are several solutions to achieve an optimal sprint performance, leading to intersubject variability (Glazier & Davids, 2009).

Variability is inherent to several sports and its analysis is important to determine profiles (Button, Davids, & Schöllhorn, 2006). In addition, cluster analysis is an

increasingly common technique to detect patterns within datasets, being clusters created to organize subjects into groups of relatively homogeneous cases or observations (like anthropometric characteristics, biomechanics or swimming performance). Thus, organizing subjects in meaningful clusters, by maximizing the similarity within each cluster while maximizing the dissimilarity between groups that are initially unknown is extremely valuable. The aim of this study was to evaluate the determinants of front crawl swimming sprint performance by assessing young swimmers profiles using a cluster analysis. It was hypothesized that anthropometric characteristics and efficiency would be the most important determining factors for clustering groups of young swimmers with different performances.

Methods

Subjects

One hundred and three swimmers from the same competitive swimming age group category (51 boys and 52 girls, 11.8 ± 0.8 years-old, 1.55 ± 0.79 m of height, 47.3 ± 7.80 kg of body mass) volunteered for this study. All swimmers participate on regular basis in regional- and national-level competitions and had a training frequency higher than five training sessions per week. All procedures were in accordance to the Declaration of Helsinki in respect to human research. The local Ethics Committee approved the experimental procedures and the swimmer's parents signed a consent form in which the protocol was described.

Procedures

Each swimmer performed 25-m front crawl at a 50-m front crawl race pace, beginning with a push-off start. Each subject swam alone, without opponents, to reduce drafting or pacing effects. To eliminate the possible effects of breathing on the studied variables, swimmers were instructed to avoid breathing while swimming through the midsection of the pool. Afterward, swimmers were informed of their performance time, which was expected to be within $\pm 2.5\%$ of the targeted velocity; if this was not the case, the subject repeated the trial after a 30 min rest interval. Two complete arm stroke cycles were recorded on the sagittal and frontal plane by two video cameras (Sony DCR-HC42E), both under the water inside a sealed housing (SPK—HCB), and synchronized with a flash led. Swimmers were monitored when passing through a specific precalibrated space in the midsection of the pool, using a bidimensional rigid calibration structure (6.30-m^2) with nine control points (Silva et al., 2012). 2D reconstruction was accomplished using DLT algorithm (Abdel-Aziz & Karara, 1971) and a low pass digital filter of 5 Hz. Video analysis was performed in the APASystem software (Ariel Dynamics, Inc., USA). Two consecutive noninspiratory cycles were digitized frame-by-frame (50 Hz), particularly the hip (femoral condyle) and, on both sides of the body, the distal end of the middle finger, the wrist, the elbow and the shoulder (Silva et al., 2012). To determine the accuracy of the digitizing procedure, two-repeated digitization of a randomly selected trial were performed, and the digitize-redigitize reliability was very high (Intraclass correlation coefficient = 0.996). The same researcher conducted the entire digitization process.

Swimming Performance

Sprint swimming velocity (v) was computed as the ratio of the hip displacement to the stroke cycle (entry of the water by one hand until its next entry) duration, during the 25-m front crawl at 50-m race pace.

Anthropometric Variables

The anthropometric measurements followed standardized procedures (Ross & Marfell-Jones, 1982), including body dimensions (height, arm span and body mass), lengths and widths (hand and foot). Sexual maturation was assessed from the development of secondary sex characteristics (Tanner & Whitehouse, 1982), with its evaluation being made by swimmers visualization of images related to the development of secondary sexual characteristics and a self-evaluation rating.

Energetic Variables

The energetics assessment included the analysis of the stroke index (SI) and the propelling efficiency (as a swim efficiency estimator), as well as the critical velocity (as an aerobic capacity estimator). SI was computed as the product of v by stroke length, assuming that at a given velocity, the swimmer that moves the greatest SL has the most efficient technique (Costill, Kovaleski, Porter, Fielding, & King, 1985). The propelling efficiency of the arm stroke (η_p) was computed, considering swimming velocity (v), SF (stroke rate in Hz), and the arm's length (l , computed as the length in the vertical axis between the shoulder and the hand during the insweep phase; $\eta_p = [(v \times 0.9) / (2\pi \times SF \times l)](2/\pi)$, representing the useful mechanical partitioning of the total mechanical work (Martin, Yeater, & White, 1981; Zamparo et al., 2005). Critical velocity (CV) was computed as the slope of the regression line of the distance-time plot (Wakayoshi et al., 1992) established between two test distances (200 and 800 m) and the respective time needed to cover them at maximum intensity (Fernandes, 2011), representing the swimmer's functional aerobic capacity.

Biomechanical Variables

Stroke length (SL), stroke rate (SR) were evaluated as the horizontal distance traveled by the hip during a stroke cycle, the inverse of the stroke cycle duration to complete one stroke cycle (multiplied by 60 to yield units of strokes per min), respectively. It was also computed the ratio SL to arm span (SL/arm span). The intracycle velocity variation (IVV) was computed by the coefficient of variation of the instantaneous velocity-time values of the hip (Barbosa et al., 2005), and represents the accelerations and decelerations of a swimmer's fixed body point within a stroke cycle.

Coordinative Variables

The interarm coordination was assessed using the index of coordination (IdC; Chollet et al., 2000), corresponding to the time lag between interarm propulsive phases and expressed as a percentage of the duration of the complete arm stroke cycle.

IdC assessment required the identification of key points in the stroke cycle (Chollet et al., 2000; Schnitzler et al., 2010; Seifert et al., 2007), particularly the entry and catch of the hand, the pull, the push and the recovery phases. Each phase, within every stroke cycle, was determined from the swimmer's horizontal and vertical displacement of the hand and shoulder, and noting the time corresponding to these displacements. The duration of each phase was also expressed as a percentage of the duration of a complete stroke. The duration of the propulsive and nonpropulsive phases was the sum of pull and push phases, and entry and catch and recovery phases, respectively. The duration of a complete arm stroke was the sum of the propulsive and nonpropulsive phases, and the IdC expressed the time gap between the propulsion of the two arms as a percentage of the duration of the complete arm-stroke cycle. Three different synchronization modes are possible to identify in front crawl (Chollet et al., 2000): (i) opposition (IdC = 0%), i.e., when one arm begins the propulsive phase and the other is finishing it, providing continuous motor action; (ii) catch-up (IdC < 0%), existing a lag time between propulsive phases of the two arms; and (iii) superposition (IdC > 0%), which describes an overlap in the propulsive phases of both arms.

Statistical Procedures

The normality and homocedasticity assumptions were checked with the Shapiro-Wilk and the Levene tests, respectively. The mean and standard deviation (*SD*) were computed for all variables. The cluster analysis was applied to determine performance profiles within the studied swimmers; both hierarchical (Ward's method with squared Euclidian distance) and nonhierarchical cluster (*K*-means clustering) methods were used in the analyses. Hierarchical dendrogram and agglomeration coefficients were also used to determine the optimal number of clusters. The variables used for the cluster analysis were: arm span, height, body mass, hand length, hand width, foot length, foot width, SL, SR, SI, IVV, SL/arm span, IdC, η_p and CV. One-way ANOVA with Games–Howell post hoc comparisons were used to test for differences across the clusters. The effect size was computed with Cohen's *f* for ANOVA. It was considered a: (i) small effect size if $0.1 \leq |f| < 0.25$; (ii) medium effect size if $0.25 \leq |f| < 0.40$, and; (iii) large effect size if $|f| \geq 0.40$ (Cohen, 1988). All tests were conducted with Stata 12.1 (StataCorp LP, USA) with a conventional significance level of $p < .05$. The number of clusters and the classification of their subjects were validated by bootstrapping and the Fisher information used to determine which variables significantly differentiated clusters. This value corresponds to the ratio intercluster to intracluster distances (Breiman, 1996; Rein, Button, Davids, & Summers, 2010). The higher the Fisher information, the more discriminative are the variables. Based on this information, the cluster analysis was repeated several times, removing each variable one by one. A variable was considered significantly discriminative when the composition of the dendrogram (number of cluster and classification of the subject in the cluster) did not change in comparison with the initial result. Following the primary analysis, a multiple linear regression was computed to explain the performance (velocity) using the significantly different variables between the clusters and adjusting for age, sex and maturation.

Results

The composed dendrogram enabled us to classify the swimmers in three different sprint profiles: 15, 23, and 65 subjects composed Clusters 1, 2 and 3, respectively. Eleven variables significantly explained the difference between the three clusters and the number of turnovers in the bagging procedure. Fisher information was used to classify the variables from the most discriminative to the less discriminative ones: arm span, height, hand length, body mass, foot length, foot width, hand width, SL, SI, CV, IVV, SR SL/arm span, IdC and η_p (Table 1).

The analysis of variance revealed significant differences in most of the tested variables (Table 1). Cluster 1 was characterized by high anthropometric values, v and SL, and low IVV. Whereas, Cluster 2 swimmers had moderate anthropometric values, high sprint v and SR. Cluster 3 presented high SR, but low values on the anthropometric variables and v . No differences were observed for the SL/arm span, IdC and η_p parameters between clusters.

The multiple linear regression analysis using the variables arm span, height, hand length, body mass, foot length, foot width, hand width, SI, CV, IVV and adjusting for age, sex and maturation (SL and SR were not included in the model as its product gives the v) significantly predicted v , $F(13, 89) = 20.60$, $p < .001$, $R^2 = .75$, adjusted $R^2 = .71$. From all the variables included in the model, only the SI and hand width were significant ($p < .001$).

Discussion

The aim of this research was to evaluate the determinants of front crawl swimming sprint performance of young swimmers using a cluster analysis. Anthropometric variables were the most determinant for cluster solution, presenting a strong influence on sprint performance in these age group swimmers. Differences between clusters were also found in SL, SR, SI, CV and IVV. Coordination and propelling efficiency were similar between all clusters, not defining specific swimming sprint profiles.

Cluster 1 included swimmers with higher arm span, height, hand length, body mass, foot length, foot width and hand width, but also with fastest sprint and aerobic characteristics. This relation between sprint v and anthropometry was reported before (Geladas et al., 2005; Lätt et al., 2009; Saavedra, Escalante, & Rodríguez, 2010; Vitor & Böhme, 2010) and the link between body height and arm span with v could be explained by the fact that the Froude number is highly dependent on the swimmer's height. In this way, taller swimmers have a decrease in the Froude number and in wave-making resistance (Chatard, Padilla, Cazorla, & Lacour, 1985; Toussaint & Hollander, 1994). Furthermore, lengths and widths of hands and feet could be related to the generation of propulsive force, due to their contribution to the hand surface area. Studies in young swimmers in this field are scarce and inconclusive. Morais et al. (2012) found a bad adjustment on the performance confirmatory model of the hand surface area, and Vitor and Böhme (2010) did not found a significant correlation between hand size and performance. Whereas, in agreement with our results, Huijing et al. (1988) and Geladas et al. (2005) found that lengths of upper extremity and hand were related with propulsive force and performance.

Table 1 Mean (SD) Values Regarding Performance, Anthropometric, Biomechanical, Energetic, and Coordinative Variables for All Clusters

Parameters	Cluster 1 (n = 15)	Cluster 2 (n = 23)	Cluster 3 (n = 65)	F _(2,100)	p-value	f	Fisher Information
Performance							
v (m/s)	1.52 (0.16)	1.47 (0.17)	1.40 (0.15) ^{a,b}	4.64	.003	0.32	0.09
Anthropometric							
body mass (kg)	57.97 (6.52)	50.10 (5.05) ^a	43.88 (6.12) ^{a,b}	37.26	<.001	0.84	0.75
height (cm)	168.30 (4.47)	159.39 (4.89) ^a	150.65 (4.46) ^{a,b}	103.92	<.001	1.41	2.08
arm span (cm)	172.93 (4.61)	162.61 (2.84) ^a	151.06 (5.23) ^{a,b}	153.30	<.001	1.72	3.07
hand length (cm)	18.49 (0.79)	17.49 (0.54) ^a	16.59 (0.70) ^{a,b}	52.55	<.001	1.00	1.05
hand width (cm)	9.20 (0.94)	8.62 (0.66) ^a	8.16 (0.66) ^{a,b}	14.48	<.001	0.51	0.29
foot length (cm)	9.29 (0.64)	8.81 (0.62) ^a	8.29 (0.56) ^{a,b}	35.30	<.001	0.82	0.71
foot width (cm)	25.65 (1.45)	24.18 (1.30) ^a	23.48 (1.67) ^{a,b}	20.16	<.001	0.61	0.40
Biomechanical							
SR (cycles/min)	47.07 (5.94)	50.97 (5.01) ^a	51.00 (6.85) ^a	3.41	.04	0.22	0.05
SL (m)	1.96 (0.27)	1.74 (0.21) ^a	1.67 (0.24) ^a	9.21	<.001	0.40	0.18
IVV	0.13 (0.04)	0.17 (0.09) ^a	0.16 (0.06) ^a	3.16	.046	0.20	0.07
SL/arm span	1.13 (0.16)	1.09 (0.10)	1.10 (0.15)	0.49	.62	0.00	0.02
Energetic							
CV (m/s)	1.21 (0.11)	1.11 (0.12) ^a	1.09 (0.11) ^a	6.69	.002	0.33	0.13
SI (m ² .s ⁻¹)	2.94 (0.62)	2.56 (0.50)	2.37 (0.46) ^a	8.42	<.001	0.38	0.17
η _p	0.32 (0.05)	0.31 (0.03)	0.32 (0.05)	0.70	.50	0.00	0.01
Coordinative							
IdC (%)	-9.39 (3.71)	-8.00 (4.21)	-9.15 (3.65)	0.91	.41	0.00	0.02

Note. Statistical values regarding tests of difference between groups are also displayed. v: swimming velocity; SR: stroke rate; SL: stroke length; IVV: intracycle velocity variation; CV: critical velocity; SI: stroke index; η_p: propelling efficiency; IdC: index of coordination.

^{a,b}Statistically significant differences from Cluster 1, and 2, respectively ($p < .05$).

In spite of the great difference in CV, comparing Cluster 1 with 2 and 3, sprint v was higher for Clusters 1 and 2 compared with Cluster 3. These differences were mostly based on SL, which is in accordance with data from adult and skillful swimmers as they dispose of a larger SL and larger efficiency (Zamparo et al., 2005). Nevertheless, in the current study only the first statement was found to be truthful. The differences found in SL could be related to swimmers anthropometric characteristics, as the analyses of the ratio SL/arm span showed no differences between groups. Seifert et al. (2007) showed that significant differences in the SL/arm span ratio in elite swimmers were due to the greater arm span and longer SL, suggesting that anthropometry explains the variation in SL values. SI was different between clusters, due to its dependence of SL and v , influencing also the clusters solution. Its importance on the performance in young swimmers was already described (Barbosa et al., 2010a; Morais et al., 2012). The capacity to have a higher SL at greater velocity represents an increased swimming efficiency, which reveals the importance of training to enhance technique in young swimmers.

The hp values for this age group are similar to the ones presented by Zamparo (2006) and Zamparo et al. (2008), but higher than those of Barbosa et al. (2010a). However, the latter a different methodology was used to assess their parameters: the fixed angle between the arm and forearm. Despite the lack of differences in hp between clusters, different SL values were observed. In contrast, a strong relationship between these parameters was reported (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011). In addition, based on a 200-m freestyle event Barbosa et al. (2010a) showed that hp had a high capability to predict performance in young swimmers. As indicated by Toussaint, Janssen and Kluft (1991), an increase in propelling surface is related to an increase in arm stroke efficiency. So, the improvements of η_p during growth (Zamparo et al., 2008) can reflect an increase of propelling (hand and arm) surface. However, when taking the ratio SL to arm span the values were similar between clusters, which explains the similar hp.

In spite of the similarities between clusters of the ratio SL to arm span and hp, Cluster 1 presented lower values of IVV. This parameter is also considered a measure of efficiency, as it relates swimming propulsion and drag forces (Vilas-Boas, Barbosa, & Fernandes, 2010), differs between skill levels (Schnitzler et al., 2010; Vilas-Boas, 2010) and is related to energy expenditure (Barbosa et al., 2010b). This could also explain the observed higher absolute v for Cluster 1, which is in accordance with previous data showing that swimmers achieving a higher v had lower IVV (Barbosa et al., 2013). Complementarily, the IVV values were higher than those presented before (Barbosa et al., 2014), but for a mean v substantially lower (1.27 ± 0.19 m/s), and lower than those reported by Kjendlie et al. (2004), who used a different calculation method (difference between maximum and minimum v value) and submaximal efforts.

The lack of difference in v between Clusters 1 and 2 evidence that young swimmers adapt their SL and SR to their anthropometric characteristics to achieve the best swimming v possible, adopting different swimming mechanical strategies, as reported for adult elite swimmers (Figueiredo et al., 2012; Costa et al., 2012). Cluster 1 has an anthropometric advantage that is not so evident in Cluster 2. Thus Cluster 2 swimmers need to compensate the anthropometric disadvantage with improved stroke biomechanics. On the other hand, Cluster 3 is in disadvantage both on their anthropometrics and biomechanics. In practice, there is not an ideal

solution; swimmers should be able to change with the organismic, task and environmental constraints, making the need for SL and SR flexibility. However, regarding interarm coordination, all swimmers presented a catch-up coordination mode that is a surprising result when comparing to older swimmers. This could be justified by the low SR adopted by young swimmers, as they never exceeded 55 cycles/min or 1.7–1.8 m/s, the critical values below which swimmers have several motor solutions when the SR is increased, and the value from which the (wave) drag force greatly increase (Potdevin, Brill, Sidney, & Pelayo, 2006; Seifert et al., 2007; Toussaint & Truijens, 2005). Above both those critical values, the superposition coordination mode is attained (Potdevin et al., 2006; Seifert et al., 2007).

CV has been reported in the literature as one of the variables that best explain performance in young swimmers, even for short distances of 100 and 200 m (Barbosa et al., 2010a; Saavedra et al., 2010; Vitor & Böhme, 2010). This points out that aerobic endurance as an essential factor for this age group, and supporting the notion that aerobic training should be one of the main training goals. Nevertheless, our results showed low influence of this parameter to the sprint performance (Fisher values of 0.13 for CV), as v was similar in Clusters 1 (1.52 ± 0.16 m/s) and 2 (1.47 ± 0.17 m/s), but CV was similar in Clusters 2 (1.11 ± 0.12 m/s) and 3 (1.09 ± 0.11 m/s). The performance distance used could explain this lower influence. Indeed, the aerobic system as a higher contribution on the 100-m compared with the 50-m front crawl (Capelli, Pendergast, & Termin, 1998). The CV values obtained in this study were similar to the literature for age group swimmers, 1.07 ± 0.13 – 1.15 ± 0.07 m/s (Toubekis, Tsami, & Tokmakidis, 2006; Vitor & Böhme, 2010), making the results herein comparable.

Lastly, when taking into consideration the variables that were determinant for the clusters solution only the SI and hand width were significant in the multivariable model, reinforcing that the efficiency is highly important, and linked to technique training and propelling surface.

This research had some limitations, particularly the adoption of indirect measure of the propulsive efficiency, the lack of inclusion of variables related to functional muscular strength or flexibility, which can influence the stroke mechanics (Hohmann et al., 1998). Moreover, the analysis included only two complete midpool stroke cycles (although in a more accurate way, due to the digitization process), and only clean velocity was considered for the sprint performance, without start, turn and finish.

Conclusion

Anthropometric variables have a strong influence on sprint performance in young swimmers. However, the anthropometric disadvantage can be somehow overcome by individual adaptations in the mechanical parameters to achieve the highest v (different combinations of SL and SR). In addition, coordination and propelling efficiency were similar between all clusters, not defining specific swimming sprint profiles.

The comparison between swimmers sprint performance and talent identification, should be carefully done considering the anthropometric influence on the performance. Nevertheless, training to improve technique, aiming to

increase SL, and doing it so at greater velocity (increased swimming efficiency) should be enhance, as well as the management and training of the SL and SR relationship.

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