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RESEARCH ARTICLE

50 m freestyle in 21, 22 and 23 s: What differentiates the speed curve of world-class and elite male swimmers?

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ABSTRACT

We examined the association between 50 m freestyle performance (50FS) and average speed (AS), peak speed (PS), minimum speed (MS) and intracyclic speed variation (ISV) and compared the speed curves from swimmers with different performance levels using functional analysis of variance (FANOVA). Fourteen male swimmers (50FS: 22.50 ± 0.58 s) performed a maximal sprint with a speedometer and AS, PS, MS, and IVV were assessed for correlational analysis. 50FS were obtained in official competitions. Swimmers were assigned to three groups based on actual 50FS: G21 (n = 2, 21.99 ± 0.04 s), G22 (n = 6, 22.82 ± 0.10 s) or G23 (n = 6, 23.55 ± 0.18 s). FANOVA compared the average curves. 50FS correlated to AS (r = –0.781, p = 0.001) and PS (ρ = –0.766, p = 0.001), but not to MS (r = –0.185, p = 0.527) or IVV (r = –0.323, p = 0.259). FANOVA showed that faster swimmers achieved higher PS and stayed longer at the upper part of the curve. 50FS performance is related to average and peak speed assessed with the speedometer. Swimmers should seek techniques to maintain the speed at the upper part of the curve as long as possible.

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1. Introduction

Men's 50 m freestyle is the fastest race in competitive swimming and is typically completed between 23 and 21 seconds in national-to-international competitions. Performance in this race requires a complex interaction among physiological, biomechanical, and psychological factors, so that even marginal improvements are considered challenging. To better understand these factors and identify improvement opportunities, coaches and sports scientists search for assessments that capture relevant information during training and competition routines.

The intracyclic speed fluctuation analysed with a speedometer is an approach for monitoring physical and technical progression in swimming (Barbosa et al., 2021, 2019; Seifert et al., 2007). The device measures instantaneous speed as a function of time and

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consists of a set of reels and a linear encoder connected to the swimmer's hip by a non-stretchable line (Craig et al., 2006). The speed fluctuations represent the net result of resistive and propulsive forces acting on the swimmer's body (Alberty et al., 2005). In other words, the speed increases when the propulsive force exceeds drag, and decreases when drag is greater than the propulsive force (Termin & Pendergast, 1998). The speed curve then reflects the swimmers' ability to coordinate the propulsive actions of the arms and legs while minimising sources of resistive forces (Alberty et al., 2005).

Several parameters can be derived from the speed curve, such as average speed, peak speed, minimum speed and the intracyclic speed variation (ISV) (Alberty et al., 2005; Barbosa et al., 2021, 2019). For instance, Barbosa et al. (2019) analysed the long-term changes of an Olympic sprinter and verified that 50 m freestyle time was associated with average and peak speeds, but not with the minimum speed. Although these findings indicated relevant speed parameters to monitor training effects and potential limiting factors of sprint performance, the study analysed only one swimmer, and the relationship between the speed curve parameters with sprint performance has to be confirmed in a larger sample of high-level swimmers.

Additionally, considering that the propulsive actions of arms and legs affect speed and that individuals coordinate these actions differently (Chollet et al., 2000), the speed curve is expected to differentiate swimmers from distinct performance levels. From a practical perspective, males who perform the 50 m freestyle in 21, 22, and 23 s represent different competitive levels. While 23 and 22 s are typical times for qualifying to national and international competitions, respectively, the 21-s mark has become essential to achieve finals in major international competitions (Barbosa et al., 2019).

Although discrete parameters can be quickly extracted from the speed curve and enable prompt feedback, they neglect the temporal and dynamic information contained in the waveforms. A method that compares the entire cycle rather than isolated speed points (Andrade et al., 2014) could shed more light on the differences between international- and national-level sprinters. The functional analysis of variance (FANOVA) combines the functional data analysis with the analysis of variance so that the whole speed curve is represented by a mathematical function that can be statistically compared with others (Andrade et al., 2014).

Therefore, the aims of this study were twofold: 1) to examine the association between the 50 m freestyle performance and average speed, peak speed, minimum speed, and ISV in elite swimmers; and 2) to compare the speed curves of 23-, 22- and 21-s swimmers using FANOVA and to identify which parts of the stroke cycle differ across performance levels. We hypothesised that average speed and peak speed but not minimum speed correlate with 50 m freestyle performance and also that faster sprinters adopt a technique that favours higher peak speeds and longer periods at the upper part of the speed curve, as well as higher and less prolonged low-speed moments.

2. Materials and methods

2.1. Participants

Fourteen male swimmers (age: 25.7 ± 6.4 years; body mass: 80.8 ± 5.8 kg; height: 1.87 ± 0.06 m) who were national-to-international competitors in the 50 m freestyle (personal best time in long course pool: 22.50 ± 0.58 s) participated in this study. To be included, swimmers had to be tested with the speedometer from a push-off start in maximal intensity and performed the 50 m freestyle in long-course within 30 days of the speed measurement (9.4 ± 7.7, min-max: 1–29 days) under 23.99 s (23.01 ± 0.58, min-max: 21.96–23.77 s). They provided verbal and written informed consent to participate, and the University's Ethics Committee approved all procedures (Process: 74.965.917.5.0000.5404).

2.2. Study design

This retrospective cross-sectional study was conducted from 2014 to 2021. Competitive performance and the speed curve from all swimmers were assessed and used in the correlation analysis. The participants were also assigned into three groups based on their actual 50 m freestyle performance: G21 (n = 2, 21.96 and 22.01 s), G22 (n = 6, 22.66 to 22.96 s) and G23 (n = 6, from 23.34 to 23.77 s). The average speed curve from each group was compared with FANOVA.

2.3. Competitive performance

Actual 50 m freestyle performances were obtained from official timing in long course pools within 30 days of the speed measurement. The best time from either the heat, semi-final or final was retained.

2.4. Testing procedures

After a ~20-min warm-up with low-to-moderate swimming intensity, swimmers performed one ~25 m maximal sprint with no breathing and self-selected stroke rate from an in-water push-off. A speedometer attached to the swimmer's hip at the central point of the lumbar region measured the instantaneous speed during the trial. Two devices of the same manufacturer (CEFISE, Nova Odessa, Brazil) were used throughout the procedures. The speed curves from both devices presented a very large cross-correlation (from 0.75 ± 0.13 to 0.79 ± 0.08) and a low pointwise coefficient of variation (5.8 ± 2.2% to 5.9 ± 2.8%), indicating high reliability. We were unable to evaluate the between-device error, so the number of swimmers assessed with each device was balanced across each group. The sampling frequency varied from 150 to 250 Hz due to improvements of the system over time. An underwater cabled camera was attached to either a trolley or to a monopod and recorded the trial at 30 Hz. The trolley was pulled alongside the pool at the same speed as the swimmer, whereas the monopod was positioned at the 15-m mark and was rotated by the operator to record the swimmer's motion. A customised software (Forward®, Meazure Sport Sciences, Brazil) triggered both the camera and speedometer nd synchronised their signals, which allowed the assessment of the speed curve together with the stroke movements. The raw data were smoothed by a fourth-order Butterworth low-pass digital filter with a cut-off frequency of 12 Hz determined through residual analysis (Winter, 1990).

After the break-out, two to three strokes were omitted to attenuate the push-off and underwater kicking effects. The data selection started from the stroke with the highest peak speed. Average speed, stroke rate ([3 · 60]/time of the three stroke cycles), stroke length (average speed/stroke rate), and ISV (i.e. the coefficient of variation of hip speed) were calculated from the next three stroke cycles. Minimum (the minimum speed value found after hand's entry in the water) and peak speeds (the highest speed value between two consecutive minimum speeds) were also obtained in every stroke, and the average was retained for analysis.

Speed curves were time normalised for FANOVA. Time values were assigned from 0 to 100, which corresponded to the start and end of the stroke cycle, respectively. An average curve was generated for each group by taking the mean of the speed curve at each percentile time point using 6, 18 and 18 signals for G21, G22, G23, respectively (number of participants of the group x 3 stroke cycles per trial).

2.5. Statistical analysis

Parameters derived from the speed curve were presented as mean ± standard deviation. Shapiro-Wilk test verified data normality, whereas the outlier labelling rule identified possible outliers (Hoaglin et al., 1986). Pearson or Spearman (for peak speed) correlation coefficients assessed the relationships between variables, and when significant, were interpreted as: >0.30: small, 0.31–0.49: moderate, 0.50–0.69: large, 0.70–0.89: very large, and 0.90–1.00: nearly perfect (Hopkins et al., 2009). The Cohen's d effect size was used for between-group comparisons and was interpreted as: <0.2: trivial; >0.2–0.6: small; >0.6–1.2: moderate; 1.2–2.0: large; >2.0–4.0: very large; >4.0: extremely large (Hopkins et al., 2009). The significance level was set at $p \leq 0.05$.

A one-way FANOVA determined differences between the speed curves of the groups. First, data was converted into a functional form, i.e. the raw data for observation *I* defined the *xi* function, which could be evaluated at all *F* values over some intervals. Four B-splines with a least-square fitting technique were applied to obtain a smooth and accurate representation of the data (Ramsay & Silverman, 2005). B-spline functions are more appropriate for noncyclical data values observed at distinct points on a finite interval (Melo et al., 2020; Ramsay & Silverman, 2005). As the time series of different trials can vary in phase or amplitude, the curves were aligned to reduce phase variability while preserving the curves' shape and amplitude. This procedure was performed before generating the average curve for each condition. An identifiable point in all curves was defined as a reference (e.g. a crossover of minimums, maximums, or zero) to orient the alignment, so the average curve could faithfully represent the trial performed (Crane et al., 2011). Finally, a one-way ANOVA was used in functional contexts according to the equation:

$$\mathrm{Speed}_{\mathrm{kc}}(\mathrm{t}) = \mu(\mathrm{t}) + \alpha_{\mathrm{c}}(\mathrm{t}) + \varepsilon_{\mathrm{kc}}(\mathrm{t})$$

Table 1. Between-group comparisons with effect size for 50 m freestyle performance (50 FS) average speed (AS), minimum speed (MS), peak speed (PS), stroke rate (SR), stroke length (SL), intracyclic speed variation (ISV).

	G21 (n = 2)	G22 (n = 6)	G23 (n = 6)	Effect size		
				G21 x G22	G21 x G23	G22 x G23
50 FS (s)	21.99 ± 0.04	22.82 ± 0.10	23.55 ± 0.18	−12.16 (Extremely Large)	−14.28 (Extremely Large)	−5.16 (Extremely Large)
AS (m/s)	2.05 ± 0.01	1.94 ± 0.06	1.89 ± 0.05	3.00 (Very Large)	5.72 (Extremely Large)	1.06 (Moderate)
MS (m/s)	1.54 ± 0.01	1.46 ± 0.19	1.47 ± 0.08	0.77 (Moderate)	1.54 (Large)	−0.07 (Trivial)
PS (m/s)	2.71 ± 0.13	2.40 ± 0.05	2.33 ± 0.06	3.45 (Very Large)	3.95 (Very Large)	1.09 (Moderate)
SR (c/min)	60.3 ± 3.9	56.6 ± 3.0	58.9 ± 4.1	1.08 (Moderate)	0.35 (Small)	−0.65 (Moderate)
SL (m)	2.04 ± 0.12	2.06 ± 0.08	1.93 ± 0.10	−0.25 (Small)	0.97 (Moderate)	1.49 (Large)
ISV (%)	16.7 ± 0.6	14.1 ± 2.6	13.6 ± 2.3	1.64 (Large)	2.19 (Very Large)	0.21 (Small)

G21: group of 21-s swimmers in the 50 m freestyle; G22: group of 22-s swimmers in the 50 m freestyle; G23: group of 23-s swimmers in the 50 m freestyle; c/min = stroke cycles per minute

"μ" indicates the average speed profile in all conditions, "α_c" refers to the specific speed profile of a "c" condition with three levels (G21, G22, and G23). The residual functional ε_{kc} is the variation not explained by the model. The analysis resulted in curves of the estimated average effects with 95% confidence intervals throughout the stroke cycle. The pairwise comparison indicated significant differences in specific phases of the average speed curves if the CI values did not include the zero line (Røislien et al., 2009). FANOVA was implemented in Matlab (MathWorks, USA 2017a) as described elsewhere (Ramsay et al., 2009).

3. Results

Descriptive data and between-group comparisons of all variables are shown in Table 1. The 50 m freestyle performance correlated with the average speed ($r = -0.781$, $p = 0.001$, very large) and peak speed ($\rho = -0.766$, $p = 0.001$, very large), but not with minimum speed ($r = -0.185$, $p = 0.527$) or ISV ($r = -0.323$, $p = 0.259$).

FANOVA showed a main effect of group on the time-series speed data. Pairwise comparisons are presented in Figure 1. There were differences between G21 and G22 from ~26 to 32%, ~48 to 52%, 68 to 73%, 75 to 82% and 89 to 98% of the speed curve (average speeds: 2.60 vs. 2.16 m/s, 1.57 vs. 1.79 m/s, 1.76 vs. 1.97 m/s, 2.38 vs. 2.12 m/s, and 2.22 vs. 1.96 m/s, respectively). The comparison between G21 and G23 indicated differences from 0 to 14%, ~25 to 49%, and ~75 to 93% (average speeds: 1.98 vs. 1.77 m/s, 2.20 vs. 1.93 m/s, and 2.31 vs. 1.96 m/s, respectively). There were differences between G22 and G23 from 6 to 11% and 30 to 35% (average speeds: 2.11 vs. 1.91 m/s, and 2.05 vs. 1.89 m/s, respectively).

4. Discussion

We examined the relationship between world-class (21 s), international (22 s) and national (23 s) level 50-m freestylers with the speed curve using FANOVA and discrete parameters derived from the speed curve. Our main findings were: 1) 50 m freestyle

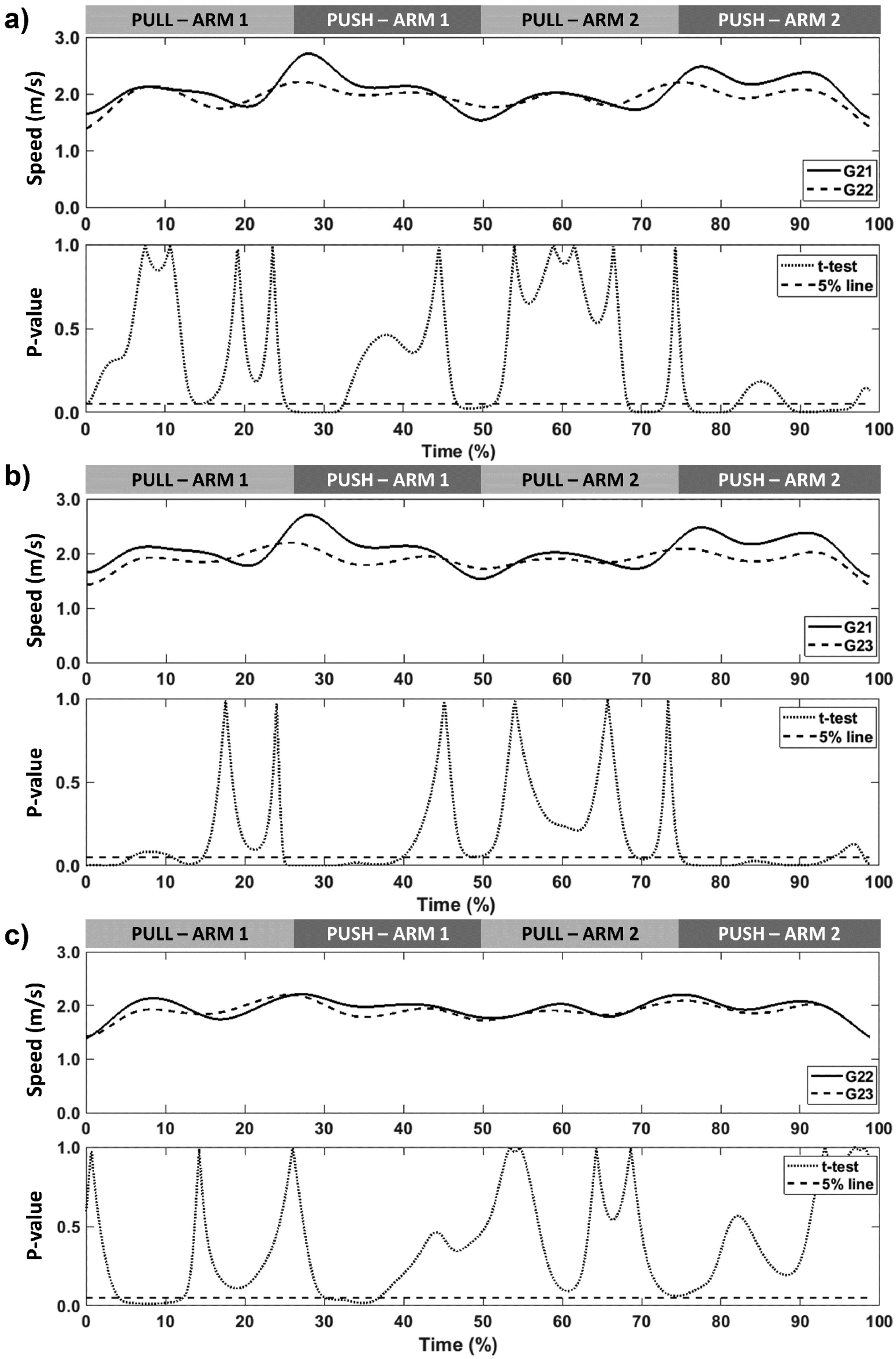

Figure 1. Results from FANOVA pairwise comparisons: (a) G21 and G22, (b) G21 and G23, and (c) G22 and G23.

performance was very largely associated with average speed and peak speed, but not with minimum speed and ISV; (2) faster swimmers achieved higher peak speeds and stayed longer at the upper part of the speed curve.

The average speed differed across the groups. As swimming speed is the product of stroke rate and stroke length (Craig et al., 1985), swimmers should find the optimal combination of these parameters to improve performance. Comparing G22 to G21, a slightly shorter stroke length (1%) but a 6.5% higher stroke rate was observed, which resulted in a 5.7% higher swimming speed for G21. Conversely, a 5.5 to 6.3% shorter stroke length (whereas the numerical difference in stroke rate was smaller; 2.3 to 4.0%) explains the speed difference between G23 and the other groups and indicates that this should be a point to improve for these swimmers. Increasing distance per stroke while maintaining a similar stroke rate was one of the training effects experienced by one Olympic swimmer who evolved to 21 s in the 50 m freestyle (Barbosa et al., 2019).

The ISV increased from G23 to G21. ISV is associated with swimming efficiency because of its inverse relationship with the energy cost (Barbosa et al., 2008, 2005, 2006; Figueiredo et al., 2012). However, since the 50 m is a short-duration race, swimmers do not experience a high level of acidosis (Rodrigues & Mader, 2010) and may focus on generating and sustaining the highest possible speed rather than being more economical (i.e. having low ISV). Herein, the high ISV was likely induced by a larger amplitude of the speed curve in faster than slower groups. Similarly, in the literature, elite breaststrokers also presented higher ISV than non-experts because of a combination of higher peak speeds with similar minimum speeds (Leblanc et al., 2007).

The correlation analysis indicated that the 50 m freestyle time decreases as the average and peak speed increase. Similar correlations were reported previously for one Olympic freestyle sprinter (Barbosa et al., 2019). Average swimming speed is acknowledged as the most important performance metric in competitive swimming (i.e. to cover a given distance in the shortest time possible), so its relationship with performance was expected. The later result is novel though. While Barbosa et al. (2019) reported that the peak speed is related to a long-term performance change in a world-class swimmer, the present study confirmed that the same knowledge can be applied for swimmers of distinct performance levels.

FANOVA also highlighted the importance of the peak speed. We found that faster swimmers achieved higher peak speeds and stayed longer at the upper part of the speed curve, especially G21. Also, the video footage showed that the peak timing corresponded to the push phase. Higher peaks depend on a large net impulse, which is produced when propulsion is greater than drag over the period that contains peak speed. This may indicate that the G21 swimmers produced a large propulsive force and maintained it from the end of the pull phase to the push phase, which seems a key factor to reach the world-class level.

Propulsive force is related to mechanical power and Froude efficiency (Gatta et al., 2018; Toussaint, 1990). Mechanical power results from the muscle contractions that occur in the kinetic chains of the upper and lower limbs (Vorontsov & Rumyantsev, 2004) and is typically developed through resistance training. Froude efficiency is the amount of the mechanical power used beneficially to overcome drag (Toussaint & Truijens, 2005), which relates to technique (Toussaint, 1990) and the ability to coordinate arms and legs (Silveira et al., 2017). Barbosa et al. (2019) analysed the long-term changes of one Olympic sprinter and suggested that the peak speed improvements could relate to increases in maximum dry-land strength levels. Swimmers are then encouraged to improve their strength and power abilities (mechanical power) as well as their technique and coordination (Froude efficiency) to reach higher peak speeds.

Given the present findings and suggestions in the literature, coaches and sports scientists are also encouraged to investigate what training strategies could improve swimmer's ability to produce a large propulsive force and maintain it over a period of time, especially during the push phase. This suggestion is in agreement with Koga et al. (2020) who investigated the effect of increasing stroke rate on propulsive hand force. They have indicated that swimmers should be able to maintain a proper angle of attack of the hand during the push phase; otherwise, the propulsion decreases despite the increase in stroke rate. This phenomenon is likely related to both the sufficient strength to maintain a proper hand angle and Froude efficiency (minimising the energy waste).

Swimmers should also seek techniques to maintain the speed at the upper portion of the curve as long as possible. For instance, after reaching the two peak speeds at ~28 and ~78% (one for each arm), G21 sustained the speed higher than 2.10 m/s until 43 and 96%, respectively, that is 32% of the entire cycle. Differently, the G22 remained higher than the "threshold" from 28 to 31% and 76 to 79%, whereas G23 surpassed it only in the first stroke from 26 to 29%. These intervals represent 6 and 3% of the entire cycle for G22 and G23, respectively. Given that the peak timing corresponded to the push motion, it is likely that G21 swimmers minimised the deceleration after the push motion (e.g. during the entry and down-sweep motion of the other arm). Although the present study did not contain any qualitative analysis to link detailed kinematic factors and the speed curve, it is possible that faster swimmers present a more streamlined body position resulting in lower drag which allows speed to be higher for a longer period of time.

The minimum speed does not seem to differentiate swimmers from different levels. The instants near 0 and 50% correspond to the entry-catch phase of the arms, when the speed typically reaches the lowest values. Although some propulsion is generated during this phase (Koga, Homoto et al., 2020), drag is higher and causes body deceleration (Termin & Pendergast, 1998). The between-group comparisons demonstrated that G21 was faster than the other groups at 0%, but not at 50%, whereas there was no difference between G22 and G23. The average lowest speed for all groups was ~1.50 m/s when considering the curves of both arm strokes. It is suggested that the low part of the speed curve may have less influence on defining competitive level after reaching ~1.50 m/s.

Finally, some limitations may be raised. In FANOVA, the three cycles that generated the average curve were analysed as independent samples despite being dependent. Also, as G21 only comprised two swimmers, the individual curve pattern has a greater effect on the final average speed curve and the differences observed in FANOVA might have been overestimated from a statistical perspective. However, it seemed reasonable to treat the data with this approach since only 30 and 17 swimmers performed the 50 m freestyle under 22.01 s in 2019 and 2020, according to the FINA world ranking. Our sample then represents 6.7–11.8% of the whole <22.0 s population worldwide.

5. Conclusions

The 50 m freestyle performance correlated to average and peak speeds, but not to minimum speed and intracyclic speed variation. Additionally, faster swimmers achieved higher peak speeds and stayed longer at the upper part of the curve, while the low-speed moments and ISV do not seem to differentiate athletes from different performance levels.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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