Biophysical Determinants of Front-Crawl Swimming at Moderate and Severe Intensities


Purpose: To conduct a biophysical analysis of the factors associated with front-crawl performance at moderate and severe swimming intensities, represented by anaerobic-threshold (vAnT) and maximal-oxygen-uptake (v\textsubscript{VO2max}) velocities. Methods: Ten high-level swimmers performed 2 intermittent incremental tests of 7 × 200 and 12 × 25 m (through a system of underwater push-off pads) to assess vAnT, and v\textsubscript{VO2max}, and power output. The 1st protocol was videotaped (3D reconstruction) for kinematic analysis to assess stroke frequency (SF), stroke length (SL), propelling efficiency (\(\eta_p\)), and index of coordination (IdC). VO\textsubscript{2} was measured and capillary blood samples (lactate concentrations) were collected, enabling computation of metabolic power. The 2nd protocol allowed calculating mechanical power and performance efficiency from the ratio of mechanical to metabolic power. Results: Neither vAnT nor v\textsubscript{VO2max} was explained by SF (0.56 ± 0.06 vs 0.68 ± 0.06 Hz), SL (2.29 ± 0.21 vs 2.06 ± 0.20 m), \(\eta_p\) (0.38 ± 0.02 vs 0.36 ± 0.03), IdC (−12.14 ± 5.24 vs −9.61 ± 5.49), or metabolic-power (1063.00 ± 122.90 vs 1338.18 ± 127.40 W) variability. v\textsubscript{VO2max} was explained by power to overcome drag (\(r = .77, P \leq .05\)) and \(\eta_p\) (\(r = .72, P \leq .05\)), in contrast with the nonassociation between these parameters and vAnT; both velocities were well related (\(r = .62, P \leq .05\)). Conclusions: The biomechanical parameters, coordination, and metabolic power seemed not to be performance discriminative at either intensity. However, the increase in power to overcome drag, for the less metabolic input, should be the focus of any intervention that aims to improve performance at severe swimming intensity. This is also true for moderate intensities, as vAnT and v\textsubscript{VO2max} are proportional to each other.

Keywords: kinematics, power, propelling efficiency, coordination, energy expenditure

Swimming velocity is the product of stroke frequency (SF) and stroke length (SL)\textsuperscript{1,2} and is coupled with the qualitative organization (coordination) of upper- and lower-limb movements that determine propelling efficiency (\(\eta_p\)).\textsuperscript{3,4} It is also determined by the useful power to overcome drag forces (\(P_d\)) for a given finite metabolic power (\(\dot{E}\)), whose interrelation generates performance (or drag) efficiency (\(\eta_p\)).\textsuperscript{5,6} This overall idea indicates that the combination of biomechanical (mechanics of swimmers’ movement), energetic, and coordinative factors plays a decisive role in swimming locomotion and that parameters representing each of these areas should be frequently monitored to develop better training processes and, consequently, to enhance performance.

In swim-training programs the moderate- and severe-intensity domains are considered critical once they represent the most-trained bioenergetic areas: the capacity (functional steady state) and power of the aerobic system. The development of these training areas is usually done by assessing the velocity at anaerobic threshold (vAnT) and the minimum velocity that elicits maximal oxygen uptake (v\textsubscript{VO2max}) and, consequently, by developing specific training series to improve oxidative potential.\textsuperscript{7,8} In fact, improvement of these training velocities will shift critical intensity domains to a more favorable performance-enhancement zone and could be the base for the velocity increment in the extreme-intensity domain, where most competitive events take place.

Previous studies have already reported that some biomechanical, energetic, and coordinative parameters show abrupt changes at or after the vAnT,\textsuperscript{9-11} but they have not yet been analyzed for v\textsubscript{VO2max}. Moreover, although the main v\textsubscript{VO2max}-influencing factors have already been determined—energy cost, maximal lactate concentration ([La\textsuperscript{−1}]), and general stroking parameters\textsuperscript{8,12}—no studies have verified which are the determinants of vAnT.

Hence, as swimming performance is biophysically based (ie, established on the confluence of biomechanical and physiological constraints\textsuperscript{1}), and both aerobic capacity and power seem to be relevant for increasing performance in most competitive distances,\textsuperscript{5,7} the purpose of the current study was to conduct a biophysical analysis of the factors associated with front-crawl performance at vAnT and v\textsubscript{VO2max}, representing the moderate and severe intensities.

Materials and Methods

Participants

Ten high-level male swimmers (age 19.8 ± 4.3 y, height 1.81 ± 0.07 m, body mass 71.4 ± 5.7 kg, training background 12.5 ± 3.9 y, training frequency 7.9 ± 0.7 sessions/wk, training volume 38.3 ± 3.6 km/wk, and percentage of the 200-m world record 81.63% ± 2.71%) volunteered to participate in the current study during the
final part of the winter general preparatory training period. Swimmers were familiarized with the test procedures and the equipment used in the experiment (previously approved by the local ethics committee; the study was performed according to the Declaration of Helsinki). Subjects were informed to avoid strenuous exercise and to abstain from smoking and consuming alcohol or caffeine for the 2 days before testing. This was achieved with the coaches’ cooperation and confirmed with swimmers at the testing days.

Experimental Procedure

Each swimmer accomplished 2 testing sessions, separated by at least 24 hours passive rest, in a 25-m indoor pool (1.90 m deep) with a water temperature of 27.5°C and 60% air humidity. In the first session, subjects performed a 7 × 200-m front-crawl intermittent incremental test, with increments of 0.05 m/s and 30-second rest intervals between steps, using in-water starts and open turns.13 Initial velocity was established according to the individual level of fitness and set at the swimmer’s individual performance on the 400-m front-crawl swimming minus 7 increments of velocity. To help maintain the predefined individual velocities, a visual pacer with flashing lights (GBK-pacer, GBK-electronics, Aveiro, Portugal) was placed on the bottom of the swimming pool and the elapsed time taken using a chronometer (Seiko, 140, Tokyo, Japan). In the second session, swimmers performed another intermittent incremental test, but this one consisted of 12 × 25-m front crawl, from slow to maximal velocity (with 3-minute rests between), on the Measuring Active Drag System (MAD system).14 This protocol was used to obtain data in the overall spectrum of swimming intensities.

Metabolic and Energetic Parameters

In the 7 × 200-m test VO2 was directly measured using a telemetric gas analyzer (K4b2, Cosmed, Rome, Italy) connected to a specific respiratory snorkel and valve system (Aquatrainer, Cosmed, Rome, Italy), a breath–by-breath low hydrodynamic resistance device that allows swimming without relevant restrictions.15 Then, during data treatment, occasional VO2 breath values were omitted from the analysis by including only those within 4 SDs of the mean, and the individual breath-by-breath VO2 responses were smoothed using a 3-breath moving average and time-averaged to produce a standard weighted response at 10-second intervals. Heart rate was recorded every 5 seconds using a Polar Vantage NV (Polar Electro Oy, Kempele, Finland) that telemetrically emitted the data to a K4b2 portable unit. Capillary blood samples for \([\text{La}^-]\) analysis were collected from the earlobe at rest in the 30-second rest interval, at the end of exercise, and during the recovery period (1, 3, 5, and 7 min after the end of the protocol) using a portable lactate analyzer (Lactate Pro, Arkray, Inc, Kyoto, Japan). These data allowed assessing the AnT and \(v_{\text{AnT}}\) through the \([\text{La}^-]\)-versus-velocity curve modeling method, assumed to be the interception point of the best fit of a combined linear and exponential pair of regressions used to determine the exact point for the beginning of an exponential rise in \([\text{La}^-]\).13

VO2max was considered to be reached according to primary and secondary traditional physiological criteria,16 with all ventilatory-parameter mean values calculated using the last 60 seconds of exercise of each step, enabling direct detection of \(\nu_{\text{VO2max}}\) or indirectly if a plateau <2.1 mL · kg\(^{-1}\) · min\(^{-1}\) could not be observed.17 \(\hat{E}\) was obtained through the addition of the net VO2 values and those resultant from the transformation of the net \([\text{La}^-]\) into \(\text{O2}\) equivalents, using the proportionality constant of 2.7 mL O2 · kg\(^{-1}\) · mM\(^{-1}\).12,18,19

Biomechanical Parameters

The incremental 7 × 200-m test was recorded with a total of 6 stationary and synchronized video cameras (HDR CX160E, Sony Electronics Inc) operating at a frequency of 50 Hz, with an electronic shutter velocity of 1/250 second. The space recorded was calibrated with a volume with dimensions (6.0 × 2.5 × 2.0 m for \(x, z, y\) directions) with 24 points of calibration, and image synchronization was obtained using a pair of lights observable in the field of view of each camera.20

The video images were digitized using the Ariel Performance Analysis System (Ariel Dynamics, San Diego, CA, USA) at a frequency of 50 Hz, considering 20 anatomical reference points (Zatsiorsky’s model adapted by De Leva21): vertex of the head and ear lobe and right and left acromium, lateral humeral epicondyle, ulnar styloid process, third distal phalanx, prominence of great femoral trochanter external surface, lateral femoral epicondyle, lateral malleolus, calcaneus, and hallux. A 3D reconstruction was accomplished using a direct linear-transformation algorithm and a low-pass digital filter of 5 Hz. The reliability of the digitizing process was calculated from 2 repeated digitizations of a randomly selected trial. The repeatability coefficient with the limits of agreement (95%CI), as described by the Bland-Altman method, was described for horizontal center-of-mass (CM) velocity as 0.00941 m/s (–0.00821 to 0.0193) and horizontal CM displacement as 0.0017 m (–0.0026 to 0.0035).

Kinematic parameters were analyzed through the mean value of 2 consecutive cycles in the midsection of the swimming pool, captured in the penultimate lap of each step of the incremental test (ie, at 175-m lap), defined as the period between 2 consecutive entries of the same hand. The body CM position as a function of time was computed and the mean velocity of swimming cycle calculated by dividing the horizontal displacement of the CM over its total duration. SF was determined from the time needed to complete 1 cycle and SL by the horizontal displacement of the CM.

Hand velocity was computed as the sum of the instantaneous 3D velocity of the right and left hands during the underwater phase, and \(\eta_p\) was estimated from the ratio of CM velocity to 3D mean hand velocity. The computed efficiency represents the Froude/theoretical efficiency (internal work is not considered) of the upper-limb cycle only (cf Zamparo and Swaine6 for a more detailed discussion).

Upper-Limb Coordination

Upper-limb coordination in the 7 × 200-m test was obtained by determining the index of coordination (IdC), with each upper-limb action divided into 4 phases: entry, pull, push, and recovery. The duration of each phase was measured for each upper-limb cycle (with a precision of 0.02 s), and the duration of a complete cycle was the sum of the 4 phases. The \(\text{IdC}\) represented the time gap between the propulsion of the 2 upper limbs as a percentage of the duration of the complete front-crawl swimming cycle, shifting from catch-up (\(\text{IdC} < 0\%\)) to opposition (\(\text{IdC} = 0\%\)) and superposition (\(\text{IdC} > 0\%\)) modes.3,4

All biomechanical, energetic, and coordinate variables were calculated for each of the steps in the 7 × 200-m test. The best individual fitting was drawn for each variable versus corresponding velocity, allowing the \(v_{\text{AnT}}\) and \(v_{\text{VO2max}}\) to be calculated by interpolation.
Power Output

In the MAD-system condition during the 12 × 25-m test, swimmers pushed off from fixed pads attached to a 23-m rod situated 0.8 m below the water surface and with a standard distance of 1.35 m between pads. The rod was instrumented with a force transducer, allowing measurement of momentary push-off force at each pad and calculating the mean force along 1 lap (16 pads in total). Swimmers used their upper limbs only, with the lower limbs elevated and constrained with a pull buoy.

The force signal was acquired by an A/D converter (BIOPAC Systems, Inc) at a sample rate of 1000 Hz and filtered with a low-pass digital filter with a cutoff frequency of 10 Hz. Assuming that swimmers performed at a constant mean swimming velocity, their mean force equals the mean drag force, with the 12 velocity:drag ratio data being least-square fitted according to the equation \( D = Av^n \), where \( D \) is total active drag, \( v \) is swimming velocity, and \( A \) and \( n \) are parameters of the power function. For each subject, \( A \) and \( n \) were estimated using this equation (MATLAB version R2012a, Mathworks, Inc) with a Levenberg-Marquardt algorithm.

\( PD \) was calculated, for both \( v_{AnT} \) and \( v_{VO2max} \) as the product of the corresponding mean velocity and the mean force, and \( \eta_D \) was assessed by the ratio between \( PD \) and \( E\dot{} \).

Statistical Analysis

Mean ± SD computations for descriptive analysis were obtained for all variables, and all data were checked for distribution normality with the Kolmogorov-Smirnov test. Comparison between means of the variables corresponding to each swimming intensity (\( v_{AnT} \) and \( v_{VO2max} \)) was made using a paired-samples t test. Pearson correlation coefficients were used to analyze the relationship between the studied variables and respective moderate and severe intensities. Moreover, the coefficient of variation was applied at \( v_{AnT} \) and \( v_{VO2max} \) to detect the extent of variability in relation to the mean performance. These statistical analyses were performed using SPSS 20.0 (IBM Statistics), and the level of significance was set at 5%.

Results

Data for each swimmer’s individual biomechanical, energetic, and coordinative values obtained at moderate and severe front-crawl intensities, that is, at \( v_{AnT} \) and \( v_{VO2max} \), respectively, are presented in Figure 1.

It was shown that swimmers used distinct intraindividual arrangements among the studied variables at moderate and severe intensities, but low performance variability was observed for both \( v_{AnT} \) (3.7%) and \( v_{VO2max} \) (4.1%). The mean ± SD values of SF, SL, \( PD \), \( \eta_P \), \( IdC \), \( VO2 \), \( [La–] \), \( E \), and \( \eta_D \) at \( v_{AnT} \) and \( v_{VO2max} \) are reported in Table 1. Almost all parameters presented higher values at the most-intense front-crawl effort, with the largest percentage increments observed in \( PD \), \( IdC \), and \( E\dot{} \) (\( VO2 \) plus \( [La–] \)). Similar \( \eta_D \) values were found between swimming intensities, while SL and \( \eta_P \) were lower at \( v_{VO2max} \).

The relationships between \( v_{AnT} \) and \( v_{VO2max} \) and the studied biomechanical, energetic, and coordinative parameters at these intensities are represented in Table 2. A direct relationship was evident between \( v_{VO2max} \) and \( PD \) and \( \eta_D \). On the other hand, no association between these parameters and \( v_{AnT} \) was identified.

Moreover, SR, SL, \( \eta_P \), and \( IdC \) were not associated with \( v_{AnT} \) and \( v_{VO2max} \), while both velocities were directly related to each other.

Discussion

In the current study, biomechanical, energetic, and coordinative factors were measured to identify their influence at moderate and severe swimming intensities, using well-established parameters of \( v_{AnT} \) and \( v_{VO2max} \) (respectively). No significant association was observed between the studied parameters and \( v_{AnT} \), probably due to

![Figure 1](https://example.com/figure1.png) — Values for stroke frequency (SF), stroke length (SL), propelling efficiency (\( \eta_P \)), index of coordination (IdC), power to overcome drag (\( PD \)), metabolic power (\( E \)), and performance efficiency (\( \eta_D \)) obtained at both anaerobic-threshold (\( v_{AnT} \), upper panel) and maximal-oxygen-uptake (\( v_{VO2max} \); lower panel) intensities for each studied swimmer.
Table 1 Velocity (v), Stroke Frequency (SF), Stroke Length (SL), Propelling Efficiency (ηP), Power to Overcome Drag (P0), Index of Coordination (IdC), Oxygen Uptake (VO2), Ventilation (VE), Lactate Concentrations ([La–]), Respiratory Quotient (RQ), Heart Rate (HR), Metabolic Power (E), and Performance Efficiency (ηD) Obtained at Anaerobic Threshold (AnT) and Maximal VO2 (VO2max) Front-Crawl Intensities, Representing the Moderate and Severe Swimming Domains, Mean ± SD

<table>
<thead>
<tr>
<th>Variable</th>
<th>AnT</th>
<th>VO2max</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v (m/s)</td>
<td>1.35 ± 0.05</td>
<td>1.46 ± 0.06*</td>
<td>7.97 ± 1.44</td>
</tr>
<tr>
<td>SF (Hz)</td>
<td>0.56 ± 0.06</td>
<td>0.68 ± 0.06*</td>
<td>17.23 ± 2.87</td>
</tr>
<tr>
<td>SL (m)</td>
<td>2.29 ± 0.21</td>
<td>2.06 ± 0.20*</td>
<td>-10.10 ± 4.89</td>
</tr>
<tr>
<td>ηP</td>
<td>0.38 ± 0.02</td>
<td>0.36 ± 0.03*</td>
<td>-5.18 ± 7.25</td>
</tr>
<tr>
<td>P0 (W)</td>
<td>52.97 ± 7.81</td>
<td>70.69 ± 12.99*</td>
<td>24.53 ± 4.69</td>
</tr>
<tr>
<td>IdC</td>
<td>-12.14 ± 5.24</td>
<td>-9.61 ± 5.49*</td>
<td>22.81 ± 8.27</td>
</tr>
<tr>
<td>VO2</td>
<td>50.72 ± 3.27</td>
<td>59.88 ± 4.07*</td>
<td>15.25 ± 1.95</td>
</tr>
<tr>
<td>VE</td>
<td>82.99 ± 12.07</td>
<td>114.08 ± 13.50*</td>
<td>27.28 ± 6.22</td>
</tr>
<tr>
<td>[La–]</td>
<td>2.92 ± 0.60</td>
<td>8.25 ± 1.67*</td>
<td>35.96 ± 7.30</td>
</tr>
<tr>
<td>RQ</td>
<td>0.94 ± 0.04</td>
<td>1.05 ± 0.06*</td>
<td>10.85 ± 4.72</td>
</tr>
<tr>
<td>HR</td>
<td>169.51 ± 11.25</td>
<td>184.73 ± 9.17*</td>
<td>8.26 ± 3.39</td>
</tr>
<tr>
<td>E (W)</td>
<td>1063.00 ± 122.90</td>
<td>1338.18 ± 127.40*</td>
<td>22.81 ± 8.27</td>
</tr>
<tr>
<td>ηD</td>
<td>5.24 ± 0.78</td>
<td>5.30 ± 0.78</td>
<td>1.13 ± 5.07</td>
</tr>
</tbody>
</table>

*Significant differences between swimming intensities, P ≤ .05.

Table 2 Pearson Correlations (r) Between Velocities at Anaerobic Threshold (vAnT) and Maximal Oxygen Uptake (vVO2max) and Stroke Frequency (SF), Stroke Length (SL), Propelling Efficiency (ηP), Power to Overcome Drag (P0), Index of Coordination (IdC), Metabolic Power (E), and Performance Efficiency (ηD) at Moderate and Severe Intensities

<table>
<thead>
<tr>
<th>Variable</th>
<th>vAnT ρ; r</th>
<th>vVO2max ρ; r</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF</td>
<td>.58; .08</td>
<td>.58; .08</td>
<td></td>
</tr>
<tr>
<td>SL</td>
<td>-.29; .41</td>
<td>-.49; .09</td>
<td></td>
</tr>
<tr>
<td>ηP</td>
<td>-.39; .27</td>
<td>-.26; .46</td>
<td></td>
</tr>
<tr>
<td>P0</td>
<td>.60; .07</td>
<td>.77; .01*</td>
<td></td>
</tr>
<tr>
<td>IdC</td>
<td>.28; .43</td>
<td>.16; .51</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>.45; .20</td>
<td>.03; .90</td>
<td></td>
</tr>
<tr>
<td>ηD</td>
<td>.52; .12</td>
<td>.72; .02*</td>
<td></td>
</tr>
<tr>
<td>vAnT</td>
<td>-</td>
<td>.62; &lt;.01*</td>
<td></td>
</tr>
</tbody>
</table>

*P ≤ .05.

distinct individual performance-determinants combination and low interindivdual performance variability. Although most parameters were not related with vVO2max, P0 and ηD explain most of the variance in swimming performance at this intensity. In addition, vAnT and vVO2max were associated, indicating the interdependence of these prominent aerobic endurance parameters.
mentioned subject homogeneity, indicating that the small discrepancies in swimming velocity were not enough to explain E variability.

The $\eta_0$ values presented by our swimmers revealed that less than 6% of E can be transformed into $P_D$, corroborating previous findings. The $\eta_0$ values' similarity between vAnT and $v\dot{V}O_2_{max}$ seems to be justified by the typical pattern reported for gross efficiency that is characterized by a curvilinear behavior with increasing power, whose plateau is reached at 100% power corresponding to ventilatory threshold (data obtained in cycle-ergometer conditions). This could indicate that our swimmers reached an almost constant $\eta_0$ at vAnT not evidencing differences compared with $v\dot{V}O_2_{max}$.

The absence of association between $\eta_1$ and vAnT, counteracting with the relationship between $\eta_0$ and $v\dot{V}O_2_{max}$, follows exactly the same association between $P_D$ and these 2 swimming intensities, reflecting the dependence of $\eta_0$ on power output. Hence, the relationship between $\eta_0$ and $v\dot{V}O_2_{max}$ might indicate that swimmers who can reach higher $P_D$ are more efficient in transforming the available E to overcome drag; that is, they are able to achieve larger $P_D$ for an almost identical E.

A possible explanation to this assertion could be related to an eventual higher $\eta_0$, but, as previously reported, no relation was found between $\eta_0$ and $v\dot{V}O_2_{max}$. It should be stated, though, that $\eta_0$ estimation is limited to swimming:hand velocity ratio, not considering propulsion-related components (drag, lift, and vortex forces), limiting the attainment of a real measure of $\eta_0$. Another possible explanation is the $\eta_0$ increase due to the rise in muscular efficiency, since the ability to generate muscle power is dependent on the frequency that determines active muscle velocity of contraction. Hence, if an association between SF and $v\dot{V}O_2_{max}$ exists (as observed for $P < .10$), muscular efficiency would be supposed to increase with velocity of contraction until an optimal value (1–1.8 Hz).

Finally, the relationship between vAnT and $v\dot{V}O_2_{max}$ suggests that aerobic capacity is, at a certain point, a necessary component for success when performing at aerobic power intensity and vice versa. This highlights the importance of developing both aerobic capacity and power processes, consisting of 2 independent bioenergetic areas (although based on oxidative pathways), to achieve an optimum level of performance.

Conclusions and Practical Applications

Despite the general stroking parameters, $\eta_0$, IdC, and E are considered relevant for front-crawl locomotion; they were not performance discriminative at either moderate or severe intensity in high-level swimmers. As higher power is required as swimming intensity increases, $P_D$ and $\eta_0$ were identified as $v\dot{V}O_2_{max}$ performance enhancers. Therefore, moderate and severe intensities should be frequently evaluated and the training process focused on aiming to improve $v\dot{V}O_2_{max}$, and indirectly vAnT, as both velocities seem to be proportional to each other.

Acknowledgment

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References


