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

João Ribeiro, Argyris G. Toubekis, Pedro Figueiredo, Kelly de Jesus, Huub M. Toussaint, Francisco Alves, João P. Vilas-Boas, and Ricardo J. Fernandes

Purpose: To conduct a biophysical analysis of the factors associated with front-crawl performance at moderate and severe swimming intensities, represented by anaerobic-threshold (*v*AnT) and maximal-oxygen-uptake ($v\dot{V}O_2max$) 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 *v*AnT, and $v\dot{V}O_2max$, and power output. The 1st protocol was videotaped (3D reconstruction) for kinematic analysis to assess stroke frequency (SF), stroke length (SL), propelling efficiency (η_P), and index of coordination (IdC). $\dot{V}O_2$ 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 *v*AnT nor $v\dot{V}O_2max$ 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), η_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. $v\dot{V}O_2max$ was explained by power to overcome drag (r = .77, $P \leq .05$) and η_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 *v*AnT and $v\dot{V}O_2max$ 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)[1,2] and is coupled with the qualitative organization (coordination) of upper- and lower-limb movements that determine propelling efficiency (η_P).[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 originates performance (or drag) efficiency (η_D).[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 (*v*AnT) and the minimum velocity that elicits maximal oxygen uptake ($v\dot{V}O_2max$) and, consequently, by developing specific training series to improve oxidative potential.[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,[9–11] but they have not yet been analyzed for $v\dot{V}O_2max$. Moreover, although the main $v\dot{V}O_2max$-influencing factors have already been determined—energy cost, maximal lactate concentration ([La$^-$]), and general stroking parameters[8,12]—no studies have verified which are the determinants of *v*AnT.

Hence, as swimming performance is biophysically based (ie, established on the confluence of biomechanical and physiological constraints[1]), and both aerobic capacity and power seem to be relevant for increasing performance in most competitive distances,[5,7] the purpose of the current study was to conduct a biophysical analysis of the factors associated with front-crawl performance at *v*AnT and $v\dot{V}O_2max$, 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

Ribeiro, de Jesus, Vilas-Boas, and Fernandes are with the Ctr of Research, Education, Innovation and Intervention in Sport, University of Porto, Porto, Portugal. Toubekis is with the Dept of Aquatic Sports, Kapodistrian University of Athens, Athens, Greece. Figueiredo is with the School of Physical Education, Federal University of Rio Grande do Sul, Porto Alegre, Brazil. Toussaint is with the School of Sports and Nutrition, Amsterdam University of Applied Sciences, Amsterdam, the Netherlands. Alves is with the Faculty of Human Movement, Technical University of Lisbon, Lisbon, Portugal. Address author correspondence to João Ribeiro at jamribeiro.fadeup@gmail.com.

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 $\dot{V}O_2$ was directly measured using a telemetric portable 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 $\dot{V}O_2$ breath values were omitted from the analysis by including only those within 4 SDs of the mean, and the individual breath-by-breath $\dot{V}O_2$ 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 [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 corresponding *v*AnT through the [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 [La⁻].[13]

$\dot{V}O_2max$ was considered to be reached according to primary and secondary traditional physiological criteria,[8,16] with all ventilatory-parameter mean values calculated using the last 60 seconds of exercise of each step, enabling direct detection of $v\dot{V}O_2max$ or indirectly if a plateau <2.1 $mL \cdot kg^{-1} \cdot min^{-1}$ could not be observed.[17] $\dot{E}$ was obtained through the addition of the net $\dot{V}O_2$ values and those resultant from the transformation of the net [La⁻] into O_2 equivalents, using the proportionality constant of 2.7 $mL\ O_2 \cdot kg^{-1} \cdot mM^{-1}$.[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,* and *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 Leva[21]): vertex of the head and ear lobe and right and left acromion, 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 η_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 Swaine[6] 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 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 (IdC < 0%) to opposition (IdC = 0%) and superposition (IdC > 0%) modes.[3,4]

All biomechanical, energetic, and coordinative 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*AnT and $v\dot{V}O_2max$ 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[14]). Swimmers used their upper limbs only, with the lower limbs elevated and constrained with a pull buoy.[22]

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.[14] 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.[22] P_D was calculated, for both vAnT and $v\dot{V}O_2$max as the product of the correspondent mean velocity and the mean force, and η_D was assessed by the ratio between P_D and $\dot{E}$.[6,23]

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 (vAnT and $v\dot{V}O_2$max) 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 vAnT and $v\dot{V}O_2$max 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 vAnT and $v\dot{V}O_2$max, 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 vAnT (3.7%) and $v\dot{V}O_2$max (4.1%). The mean ± SD values of SF, SL, P_D, η_P, IdC, $\dot{V}O_2$, [La⁻], $\dot{E}$, and η_D at vAnT and $v\dot{V}O_2$max 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 P_D, IdC, and $\dot{E}$ ($\dot{V}O_2$ plus [La⁻]). Similar η_D values were found between swimming intensities, while SL and η_P were lower at $v\dot{V}O_2$max.

The relationships between vAnT and $v\dot{V}O_2$max and the studied biomechanical, energetic, and coordinative parameters at these intensities are represented in Table 2. A direct relationship was evident between $v\dot{V}O_2$max and P_D and η_D. On the other hand, no association between these parameters and vAnT was identified. Moreover, SR, SL, η_P, and IdC were not associated with vAnT and $v\dot{V}O_2$max, 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 vAnT and $v\dot{V}O_2$max (respectively). No significant association was observed between the studied parameters and vAnT, probably due to

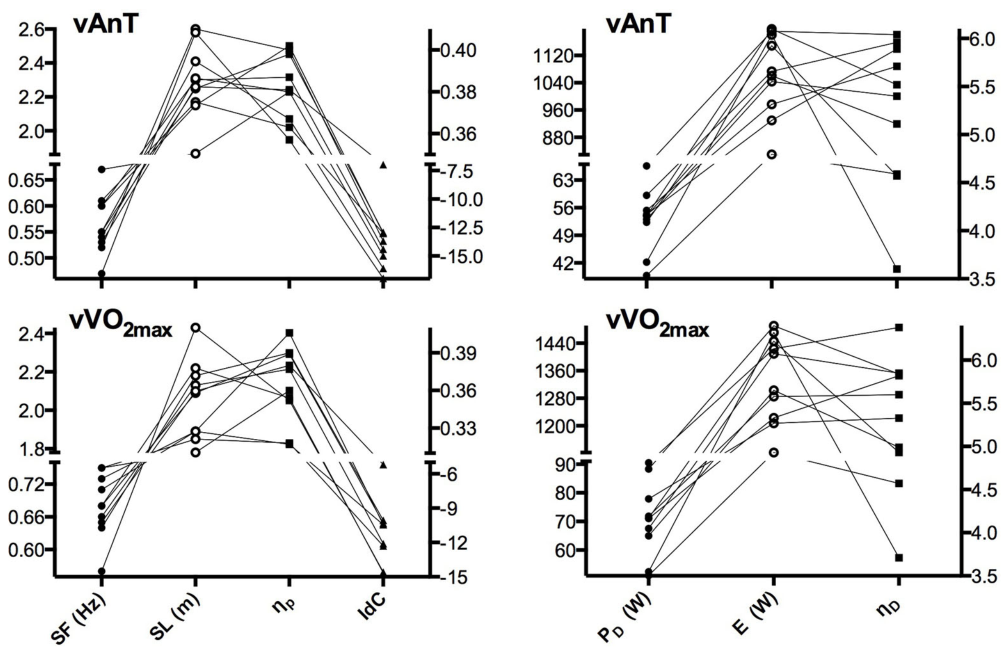

Figure 1 — Values for stroke frequency (SF), stroke length (SL), propelling efficiency (η_P), index of coordination (IdC), power to overcome drag (P_D), metabolic power ($\dot{E}$), and performance efficiency (η_D) obtained at both anaerobic-threshold (vAnT, upper panel) and maximal-oxygen-uptake ($v\dot{V}O_2$max; lower panel) intensities for each studied swimmer.

Table 1 Velocity (v), Stroke Frequency (SF), Stroke Length (SL), Propelling Efficiency (η_P), Power to Overcome Drag (P_D), Index of Coordination (IdC), Oxygen Uptake ($\dot{V}O_2$), Ventilation ($\dot{V}E$), Lactate Concentrations ([La⁻]), Respiratory Quotient (RQ), Heart Rate (HR), Metabolic Power ($\dot{E}$), and Performance Efficiency (η_D) Obtained at Anaerobic Threshold (AnT) and Maximal $\dot{V}O_2$ ($\dot{V}O_2$max) Front-Crawl Intensities, Representing the Moderate and Severe Swimming Domains, Mean ± SD

	AnT	$\dot{V}O_2$max	Difference (%)
v (m/s)	1.35 ± 0.05	1.46 ± 0.06*	7.97 ± 1.44
SF (Hz)	0.56 ± 0.06	0.68 ± 0.06*	17.23 ± 2.87
SL (m)	2.29 ± 0.21	2.06 ± 0.20*	–10.10 ± 4.89
η_P	0.38 ± 0.02	0.36 ± 0.03*	–5.18 ± 7.25
P_D (W)	52.97 ± 7.81	70.69 ± 12.99*	24.53 ± 4.69
IdC	–12.14 ± 5.24	–9.61 ± 5.49*	22.81 ± 8.27
$\dot{V}O_2$	50.72 ± 3.27	59.88 ± 4.07*	15.25 ± 1.95
$\dot{V}E$	82.99 ± 12.07	114.08 ± 13.50*	27.28 ± 6.22
[La⁻]	2.92 ± 0.60	8.25 ± 1.67*	35.96 ± 7.30
RQ	0.94 ± 0.04	1.05 ± 0.06*	10.85 ± 4.72
HR	169.51 ± 11.25	184.73 ± 9.17*	8.26 ± 3.39
$\dot{E}$ (W)	1063.00 ± 122.90	1338.18 ± 127.40*	20.59 ± 4.81
η_D	5.24 ± 0.78	5.30 ± 0.78	1.13 ± 5.07

*Significant differences between swimming intensities, $P \le .05$.

Table 2 Pearson Correlations (r) Between Velocities at Anaerobic Threshold (vAnT) and Maximal Oxygen Uptake ($v\dot{V}O_2$max) and Stroke Frequency (SF), Stroke Length (SL), Propelling Efficiency (η_P), Power to Overcome Drag (P_D), Index of Coordination (IdC), Metabolic Power ($\dot{E}$), and Performance Efficiency (η_D) at Moderate and Severe Intensities

Variable	vAnT r; P	$v\dot{V}O_2$max r; P
SF	.58; .08	.58; .08
SL	–.29; .41	–.49; .09
η_P	–.39; .27	–.26; .46
P_D	.60; .07	.77; .01*
IdC	.28; .43	.16; .51
$\dot{E}$	.45; .20	.03; .90
η_D	.52; .12	.72; .02*
vAnT	—	.62; <.01*

*$P \le .05$.

distinct individual performance-determinants combination and low interindividual performance variability. Although most parameters were not related with $v\dot{V}O_2$max, P_D and η_D explain most of the variance in swimming performance at this intensity. In addition, vAnT and $v\dot{V}O_2$max were associated, indicating the interdependence of these prominent aerobic endurance parameters.

vAnT and $v\dot{V}O_2$max assessment in the current study was conducted in ecological swimming-pool conditions using the 7 × 200-m intermittent incremental test, which is valid for obtaining metabolic and ventilatory data.[13,24] Moreover, taking into consideration that swimming mechanical power output is difficult to assess in ecological swimming conditions, we assumed that P_D evaluated on the MAD system was similar to front-crawl swimming.[22]

Superior SF and lower η_P and SL were observed at $v\dot{V}O_2$max compared with vAnT; it is commonly assumed that higher velocities implying superior SF necessarily compromise η_P and, consequently, SL.[11,25,26] Nevertheless, when analyzing these parameters for each velocity separately, they were not associated with either vAnT or $v\dot{V}O_2$max, likely due to the swimmers' low interindividual performance variability. This assertion can be justified by the fact that the swimmers seemed to present distinct individual SF, SL, and η_P combinations, while attaining a similar vAnT or $v\dot{V}O_2$max, not evidencing a particular profile that could partially explain the variability of these velocities.

Upper-limb coordination evidenced an IdC increase from moderate- to severe-intensity exertion, indicating that swimmers are sufficiently flexible and adaptable to modify their coordination pattern according to velocity-related constraints.[27,28] As confirmed in the current study, this IdC adaptability seems to be more evident at SF lower than 0.75 Hz, a value below which swimmers have several motor solutions.[28] Closely related to the aforementioned findings, given that SF and SL are control parameters of a specific coordination mode,[3] the absence of association of IdC with vAnT and $v\dot{V}O_2$max suggests that it might be a poor predictor of changes at the selected intensities. In fact, there were no differences in IdC when comparing swimmers of similar performance level at velocities lower than 1.5 m/s.[28] This indicates that at intensities analyzed in the current study, minor intervelocity discrepancies among swimmers were not enough to substantially alter drag (which depends on velocity square) and, consequently, modify IdC.[4]

The power values increased from vAnT to $v\dot{V}O_2$max (in accordance with previous findings[29–31]), which could be explained by its dramatic intensification with velocity, usually represented by a cube-power association.[32] However, P_D did not explain vAnT, as, at this specific intensity, the capability of the upper limbs to generate maximum mechanical power might be relatively less important than the ability to sustain a high level of aerobic capacity and economy. This consideration is in accordance with previous findings that revealed a gradual increase in the correlation of power and intensity with decreasing distance, that is, increasing velocity. In fact, we observed a strong relationship between P_D and $v\dot{V}O_2$max, corroborating previous findings (most of them in nonecological conditions) for short, middle, and long swimming distances.[29,33–35]

Ventilatory and metabolic demands increased with swimming intensity, since the moderate domain required lower $\dot{V}O_2$, $\dot{V}E$, [La⁻], and respiratory quotient than the severe exertion. In this sense, the intensification of $\dot{E}$ values (assessed taking into account both aerobic and anaerobic regimens) with the rise of swimming velocity could be explained by their nonlinear relationship, justifying why an ~8% velocity increase led to a substantial increment in $\dot{E}$ (~21%).

However, when analyzing each velocity independently, the nonassociation between $\dot{E}$ and both vAnT and $v\dot{V}O_2$max is not in line with the statement that $\dot{E}$ rises with velocity. This could indicate that $\dot{E}$ per se is neither a discriminative of performance variability at these specific intensities nor a limiting factor in power production that should be, in turn, more dependent on the quantity and quality of propelling muscles.[32] This could also be justified by the previously mentioned subject homogeneity, indicating that the small discrepancies in swimming velocity were not enough to explain $\dot{E}$ variability.

The η_D values presented by our swimmers revealed that less than ~6% of $\dot{E}$ can be transformed into P_D, corroborating previous findings.[23,26] The η_D 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,[30] whose plateau is reached at 100% power corresponding to ventilatory threshold (data obtained in cycle-ergometer conditions[36]). This could indicate that our swimmers reached an almost constant η_D at vAnT not evidencing differences compared with $v\dot{V}O_2$max.

The absence of association between η_D and vAnT, counteracting with the relationship between η_D and $v\dot{V}O_2$max, follows exactly the same association between P_D and these 2 swimming intensities, reflecting the dependence of η_D on power output.[23] Hence, the relationship between η_D and $v\dot{V}O_2$max might indicate that swimmers who can reach higher P_D are more efficient in transforming the available $\dot{E}$ to overcome drag; that is, they are able to achieve larger P_D for an almost identical $\dot{E}$.

A possible explanation to this assertion could be related to an eventual higher η_P, but, as previously reported, no relation was found between η_P and $v\dot{V}O_2$max. It should be stated, though, that η_P estimation is limited to swimming:hand velocity ratio, not considering propulsion-related components (drag, lift, and vortex forces[37]), limiting the obtainment of a real measure of η_P. Another possible explanation is the η_D increase due to the rise in muscular efficiency, since the ability to generate muscle power is dependent on the movement 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[38]).

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.[5,7]

Conclusions and Practical Applications

Despite the general stroking parameters, η_P, IdC, and $\dot{E}$ 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 η_D 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.

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