THE POWER OUTPUT AND SPRINTING PERFORMANCE OF YOUNG SWIMMERS

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ABSTRACT

Barbosa, TM, Morais, JE, Marques, MC, Costa, MJ, and Marinho, DA. The power output and sprinting performance of young swimmers. *J Strength Cond Res* 29(2): 440–450, 2015—The aim of this article was to compare swimming power output between boys and girls and to model the relationship between swimming power output and sprinting performance in young swimmers. One hundred young swimmers (49 boys and 51 girls, aged between 11 and 13 years) underwent a test battery including anthropometrics (body mass, height, arm span [AS], and trunk transverse surface area), kinematic and efficiency (velocity, stroke frequency, stroke length, speed fluctuation, normalized speed fluctuation, stroke index, and Froude efficiency), hydrodynamics (active drag and active drag coefficient), and power output (power to overcome drag, power to transfer kinetic energy to water, and external power) assessments and sprinting performance (official 100 freestyle race). All variables but the trunk transverse surface area, stroke length normalize to AS, speed fluctuation, active drag coefficient, and Froude efficiency were significantly higher in boys than in girls with moderate-strong effects. Comparing both sexes but controlling the effect of the sprinting performance, most variables presented a no-significant variation. There was a significant and strong relationship between power output and sprinting performance: $y = 24.179x^{2.9869}$ ($R^2 = 0.426$; standard error of estimation = 0.485; $p < 0.001$). As a conclusion, boys presented better performances than girls because of their higher power output. There is a cubed relationship between power output and sprinting performance in young swimmers.

KEY WORDS front-crawl, power to overcome drag, power to transfer kinetic energy, external power, drag force

INTRODUCTION

Swimming performance depends from propulsion (power) and resistance (drag). In several sports, such as cycling or speed skating, it is a mainstream procedure to assess the power output and learn about the competitive level of sportsmen, monitor their training status, or prescribe a given intensity of exertion. However, in competitive swimming, this is more challenging because of the specific nature of the aquatic environment.

Performance in competitive swimming is measured as the time spent to cover a given distance as fast as possible. Maximal velocity is the balance between the 2 main external forces acting upon the swimmer: propulsion and resistance. So, as happens in other forms of locomotion, speed is related to power and drag:

$$v = \frac{\dot{w}}{D}\ , \tag{1}$$

where v is the velocity (in meter per second), $\dot{w}$ is the power output (in watt), and D is the drag force (in newton). Drag is the resistance force to displace in a fluid environment and can be calculated with Newton's equation:

$$D = \frac{1}{2}\cdot \rho \cdot v^2 \cdot S \cdot C_D, \tag{2}$$

where D is the drag force (in newton), ρ is the fluid density (in kilogram per cubic meter), v is the velocity (in meter per second), S is the projection surface area (in square meter), and C_D is the drag coefficient (dimensionless). Drag force can be assessed with the swimmer being towed or gliding in the hydrodynamic position, with no limb movements (i.e., passive drag) or with the swimmer performing limb action to propel (i.e., active drag). If passive drag is most informative for the starts and the turns, active drag provides more insight about the resistance that subjects are submitted to during stroke swimming. With no surprise, it was verified as a nonlinear relationship between active drag and speed (e.g., Refs. 9,13). Training reduced the drag, increased maximal speed, and therefore performance (20). Yet, most body

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of knowledge about this was gathered with adult/elite swimmers. Only a few articles focused on the hydrodynamics of young swimmers. Indeed, drag force is also linked to performance at early ages (19). It was reported that boys have a higher active drag and power to overcome drag than girls (4). Active drag is also higher in adults than in children (12).

The sum of the power done to move the center of mass of the body with respect to the environment (i.e., external mechanical power) and the power done to move the limbs with respect to the body (i.e., internal mechanical power) provide us the total mechanical power (8). For the case of swimming, we can breakdown further and say that the external mechanical power includes the power done to overcome drag and wasted transferring kinetic energy to water (36):

$$\dot{w}_{tot} = \dot{w}_{int} + \dot{w}_d + \dot{w}_k, \tag{3}$$

where $\dot{w}_{tot}$ is the total mechanical power, $\dot{w}_{int}$ is the internal mechanical power, $\dot{w}_d$ is the mechanical power to overcome drag, and $\dot{w}_k$ is the power to transfer kinetic energy to water. Hence, not all the power (input) will be used to overcome drag (output) and produce body's translation in space. For any form of human locomotion, there is an energy flow, that is, energy will be used for several other purposes besides $\dot{w}_{ext}$, such as thermoregulation, friction force resulting from muscle contraction, isometric postural work, or co-contraction (33). In swimming, as in other techniques for aquatic locomotion, this cascade will consider as well the transfer of kinetic energy to water as reported earlier (17). Therefore, the $\dot{w}_{tot}$ produced by the swimmer that is transformed into useful propulsion (i.e., $\dot{w}_d$) is termed the propelling efficiency (32):

$$\eta_p = \frac{\dot{w}_d}{\dot{w}_{int} + \dot{w}_d + \dot{w}_k}, \tag{4}$$

where η_p is the propelling efficiency, $\dot{w}_{int}$ is the internal mechanical power, $\dot{w}_d$ is the mechanical power to overcome drag, $\dot{w}_k$ is the mechanical power to transfer kinetic energy to water. To be strict, if $\dot{w}_{int}$ is neglected, the $\dot{w}_{ext}$ that is transformed into useful propulsion is termed Froude efficiency, and equation 4 changes to:

$$\eta_F = \frac{\dot{w}_d}{\dot{w}_d + \dot{w}_k}, \tag{5}$$

where η_F is the Froude efficiency, $\dot{w}_d$ is the mechanical power to overcome drag, and $\dot{w}_k$ is the mechanical power to transfer kinetic energy to water ($\dot{w}_{ext} = \dot{w}_d + \dot{w}_k$). Sometimes both η_p and η_F terms are used interchangeably because it has been reported that $\dot{w}_{int}$ can be neglected in some circumstances ($\eta_p \sim \eta_F$). The $\dot{w}_{int}$ is strongly dependent from limbs' frequency (16), which is greatly reduced for leg kicking and even more for arm stroke swim, turning out to be a minor player in swimming (36).

Some time ago, a mathematical model was proposed to estimate in a straightforward fashion the arm's η_F (15). This model is based on the assumption that as suggested by equation 5 η_F is a ratio between the swimming velocity (roughly related to $\dot{w}_d$) and limbs' velocity (related to $\dot{w}_{ext}$). Later on, the model was simplified to a ratio between swimming velocity and limb's frequency (35):

$$\eta_F = \left(\frac{v \cdot 0.9}{2\pi \cdot SF \cdot l}\right) \cdot \frac{2}{\pi}, \tag{6}$$

where η_F is the Froude efficiency (dimensionless), v is the swimming velocity (in meter per second), SF is the stroke frequency (in hertz), and l is the shoulder to hand average distance (in meter). This model seems quite suitable for sprints because the hand's speed is high, showing fewer intracyclic variations and behaving almost as a paddle. Numerator in equation 6 considers that approximately 90% of swim velocity is related to the arm's propulsion (6), whereas the denominator is the basic kinematic calculation of a tangential velocity in periodic motions (i.e., $v = 2 \cdot \pi \cdot r / P = 2 \cdot \pi \cdot r \cdot f$, r being the radius, P the period also known as the period of a full rotation, and f the frequency).

Hence, combining equations 4 and 5 it is possible to estimate the total power output of swimming (or at least the $\dot{w}_{ext}$, which is similar to $\dot{w}_{tot}$ if $\dot{w}_{int}$ is neglected). η_F is estimated after collecting kinematic data with motion capture systems (e.g., video based or infra red based) or mechanical techniques (e.g., speedometer). The $\dot{w}_d$ can be estimated with any active drag method reported in the literature, including the measuring active drag system, velocity perturbation method, assisted towed method or energetic technique. Then, it is possible to calculate the unknown variable, that is, $\dot{w}_{ext}$ and $\dot{w}_k$. As far as we can understand, the power output was never estimated based on this framework before. Literature reports mostly swimming power output collected with the measuring active drag system (e.g., Ref. 27). Despite providing the direct measure of the drag force, practitioners and researchers face some challenges selecting the measuring active drag system: (a) it is a bulky piece of equipment that unable the use of the swim lane for other purposes besides testing, (b) the set-up and pack of the equipment is time-consuming, and (c) the method imposes significant kinematic constrains to the swimming. Even though the Velocity Perturbation Method also has limitations, it is a convenient, straightforward, and quick testing procedure. So it is possible to monitor the swimmers with minimal disruption of the training sessions or other events that are happening at the swimming pool at the same time. This might be another of the reasons why there is scarce evidence about swim power output and on top of that most body of knowledge is related to adult/elite swimmers.

Indeed, only a few articles report power output and how it interplays with performance in adult/elite swimmers. Evidences on this in young counterparts are nonexistent though. Men achieve higher $\dot{w}_{tot}$ than women at a given speed (26). At least for adult swimmers, at a metabolic power of 0.5 kW, $\dot{w}_d$ and $\dot{w}_{tot}$ were on average 40 and 89 W, respectively (21). National swimmers produced more $\dot{w}_d$ to reach higher speeds than regional counterparts (23). Therefore, it seems existing a sex and performance effect in the power output, at least for adult swimmers. Men reach higher power outputs than women; top-level swimmers produce higher power outputs than less competitive counterparts. One might say that hypothetically those who achieve a higher power output, at least for the same propelling efficiency, will be able to reach higher swim speeds and therefore better performances. Hence, improvement in performance is hypothetically related to power output, and furthermore, it changes with training (27). To the best of our knowledge, no research was carried out about this topic with young swimmers before. Therefore, a holistic or at least broader approach including anthropometrics, kinematics, hydrodynamics, efficiency, and power output is needed to have a deeper insight about the performance determinants in age group swimming.

The aim of this article was twofold: (a) to compare swimming power output between boys and girls and (b) to model the relationship between swimming power output and sprinting performance in young swimmers. It was hypothesized that there would be a sex gap and that sprinting performance is strongly related to power output.

METHODS

Experimental Approach to the Problem

One hundred subjects were recruited to compare power output across sexes and its relationship with sprinting performance. A cohort study (boys vs. girls) was designed to analyze the variation between sexes (analysis of variance [ANOVA] and analysis of covariance [ANCOVA]). To learn about the relationships between power output and performance, simple nonlinear regression models were computed, having the power output and sprinting performance as exogenous and endogenous variables, respectively.

Subjects

One hundred young swimmers aged between 11 and 13 years (49 boys and 51 girls aged 12.51 ± 0.77 years and 12.24 ± 0.71 years, respectively; all in Tanner stages 1–2 by self-report) were assessed. The sample included several age group national record holders, age group national champions, and other swimmers who are part of a national talent identification, development, and follow-up scheme.

Written consent was provided by both parents or guardians and the underage swimmers to be part of this study. All procedures were in accordance to the Declaration of Helsinki regarding human research. The University Ethics Board also approved the research design.

Procedures

One day before testing, swimmers underwent a low-intensity training session. There were no reports of overtraining symptoms before any test. Swimmers were part of a national talent identification scheme, being monitored on regular basis, so they were familiar with all the procedures.

Anthropometrics

Body mass (BM) was measured with a digital weighting scale (SECA, 884; Hamburg, Germany) and height with a digital stadiometer (SECA, 242) on the upright position, barefoot, and in swimwear. Arm span (AS) was measured with swimmers in the upright position, arms and fingers fully extended in lateral abduction at a 90° angle with the torso. The distance between the third fingertip of each hand was measured with a flexible anthropometric tape (RossCraft, QuickMedical, Issaquah, WA, USA) (intraclass correlation [ICC] = 0.99). All anthropometric measurements were conducted according to standardized procedures.

The trunk transverse surface area (TTSA) was measured with a photogrammetric technique (18). Swimmers were photographed with a digital camera (DSC-T7; Sony, Tokyo, Japan) in the transverse plane from above. Subjects stood on land, on the upright and streamlined position. This position is characterized by having the arms fully extended above the head, one hand over the other, fingers also extended close together, and head in neutral position. Subjects wear a regular textile swimsuit, cap, and goggles. On the camera shooting field, a calibration frame with 0.945 m length was aside the swimmer at the shoulders level. The TTSA was measured with an area measuring software (Udruler, AVPSoft, USA) after importing the picture (ICC = 0.98).

Kinematics and Efficiency

Kinematics and efficiency were assessed with a mechanical technique. Each swimmer performed 3 maximal 25-m trials at front-crawl stroke with push-off start. The swimmers were advised to reduce gliding during the start. A speedometer cable (Swim Speedo-Meter; Swimsportec, Hildesheim, Germany) was attached to the swimmer's hip (3). The speedometer was placed on the forehead wall of the swimming pool, about 0.2 m above water surface. A customized software's interface in LabVIEW (National Instruments, v. 2009, Austin, TX, USA) was selected to acquire ($f = 50$ Hz), display, and process speed-time data online during the trial. Data were transferred from the speedometer to the software application with a 12-bit resolution acquisition card (USB-6008; National Instruments, Austin, TX, USA).

Thereafter, data were exported to a signal processing software (AcqKnowledge v. 3.9.0; Biopac Systems, Santa Barbara, CA, USA) and filtered with a 5 Hz cut-off low-pass fourth-order Butterworth filter according to the analysis of the residual error vs. cut-off frequency output. The intracyclic variation of the horizontal velocity of the hip (*dv*) was analyzed (2,3):

$$dv = \frac{\sqrt{\frac{\sum_i (v_i - \bar{v})^2 \cdot F_i}{n}}}{\frac{\sum_i v_i \cdot F_i}{n}} \cdot 100, \qquad (7)$$

where dv represents the intracyclic variation of the horizontal velocity of the hip, v represents the mean swimming velocity, v_i represents the instant swimming velocity, F_i represents the acquisition frequency, and n is the number of observations. The dv mean value of 3 consecutive stroke cycles between the 11th and 24th meter from the starting wall in the 3 trials were considered for further analysis (ICC = 0.94). The dv was also normalized to the swimming velocity (dv/v). Comparing hip speed collected with speedometer and a motion capture system, there is a 0.002 ± 0.001 difference (mean ± *SE*, *SD* = 0.012, −0.001; 0.005 for a 95% confidence interval [CI]) at front-crawl and backstroke for swimmers with similar age and competitive level (7). Examination of inter-trial variability (for the 3 trials) revealed a high reproducibility of the stroke kinematics (ICC = 0.941).

Stroke index, as an overall swimming efficiency estimator was calculated (4):

$$SI = SL \cdot v, \tag{8}$$

where SI is the stroke index (in square meter per second), SL is the stroke length (in meter), and v is the swimming velocity (in meter per second). The SL was calculated from the v and stroke frequency (SF) collected with the speedometer:

$$SL = \frac{v}{SF}, \tag{9}$$

where SL is the stroke length (in meter), v is the swimming velocity (in meter per second), and SF is the stroke frequency (in hertz). The SL was also normalized to the AS (SL/AS). The η_F was calculated according to equation 6 as reported earlier in the Introduction section. The l was computed trigonometrically measuring the arm's length and considering the average elbow angles during the in sweep of the arm pull for similar age and sex reported in the literature (34).

Active Drag

The velocity perturbation method was selected to estimate the active drag (13). Active drag was calculated from the difference between the maximal swimming velocities at front-crawl with and without towing a perturbation buoy after push-off start. Swimming velocity was measured after clocking the time trials between the 11th and 24th meters of the starting wall with a stopwatch (Golfinho Sports, MC 815; Aveiro, Portugal) by 2 expert evaluators (ICC = 0.96) and the mean value was used for further analysis (14). Active drag (D_a) was calculated as (13):

$$D_a = \frac{D_b \cdot v_b \cdot v^2}{v^3 - v_b^3}, \tag{10}$$

where D_a is the active drag at maximal velocity, D_b is the resistance of the perturbation buoy provided by the manufacturer, and v_b and v are the swimming velocities with and without the perturbation device, respectively. Active drag coefficient (C_{Da}) was calculated after re-arranging equation 2 to:

$$C_{Da} = \frac{2 \cdot D_a}{\rho \cdot S \cdot v^2}, \tag{11}$$

where ρ is the density of the water (being 1000 $kg \cdot m^{-3}$), D_a is the active drag (in newton), v is the swimming velocity (in meter per second), and S is the swimmer's projected frontal surface area (or TTSA collected with the photogrammetric technique, in square meter).

Power Output

It was estimated the $\dot{w}_{ext}$, $\dot{w}_d$, and $\dot{w}_k$. The $\dot{w}_d$ was computed as:

$$\dot{w}_d = D_a \cdot v, \tag{12}$$

where $\dot{w}_d$ is the power to overcome drag force (in watt), D_a is the active drag (in newton), and v is the swimming velocity (in meter per second). Re-arranging equation 5 and having the $\dot{w}_d$ and η_F as known variables, $\dot{w}_{ext}$ was calculated as:

$$\dot{w}_{\text{ext}} = \frac{\dot{w}_d}{\eta_F}, \tag{13}$$

where $\dot{w}_{ext}$ is the external mechanical power (in watt), $\dot{w}_d$ is the power to overcome drag force (in watt), and η_F is the Froude efficiency (dimensionless). Thereafter, $\dot{w}_k$ was obtained by subtracting $\dot{w}_d$ from $\dot{w}_{ext}$:

$$\dot{w}_k = \dot{w}_{ext} - \dot{w}_d, \tag{14}$$

where $\dot{w}_k$ is the mechanical power to transfer kinetic energy to water, $\dot{w}_{ext}$ is the external mechanical power, and $\dot{w}_d$ is the power to overcome drag force.

Performance

The 100-m freestyle race final time at official regional or national short course meter swimming pool (i.e., 25-m length) was selected to assess the swimming performance. The final time was converted in average racing speed (s@100free, in meter per second). The time gap between data collection and the race took no longer than 2 weeks.

Statistical Analyses

Sample power was calculated for an α error probability of 0.05, effect size of 0.40, and a power $(1 - \beta)$ of 0.95 for 1-way ANOVA, suggesting a total sample size of at least 84 subjects (GPower, v.3.1.7; University of Kiel, Kiel, Germany). The homoscedasticity assumption was checked with the Levene test. Normality [defined as $Y \cap N$ ($\mu_{Y|X1,\ X2,\ \ldots,\ XK}$, σ^2)] was determined with Shapiro-Wilk test. Mean plus 1*SD* are reported for all variables.

Data variation was analyzed with 1-way ANOVA (sex effect) and ANCOVA (controlling the s@100free), including the estimation of the 95% CI of the differences between sexes ($p \leq 0.05$). Total eta square (η^2) was selected as effect

TABLE 1. Comparison of the anthropometrics, kinematics, efficiency, drag force, and power output and performance between boys and girls.*

	Boys	Girls	95 CI		ANOVA			ANCOVA		
	(M ± 1*SD*)	(M ± 1*SD*)	Lower bound	Higher bound	*F*	*p*	η^2	*F*	*p*	η^2
BM (kg)	50.76 ± 8.59	47.02 ± 7.65	−6.96	−0.52	5.310	0.02	0.48	0.307	0.58	0.12
H (m)	1.61 ± 0.08	1.56 ± 0.06	−7.76	−1.71	9.680	<0.001	0.60	0.161	0.69	0.31
AS (m)	1.69 ± 0.09	1.64 ± 0.07	−0.08	−0.01	9.670	<0.001	0.60	0.161	0.69	0.31
TTSA (cm^2)	668.3 ± 103.5	660.6 ± 99.7	−48.01	32.67	0.142	0.70	0.06	1.134	0.29	0.09
SF (Hz)	0.88 ± 0.10	0.82 ± 0.09	−0.10	−0.02	12.116	<0.001	0.64	7.013	0.01	0.01
SL (m)	1.58 ± 0.20	1.53 ± 0.19	−0.12	0.02	1.571	0.21	0.26	0.901	0.35	0.20
SL/AS (dimensionless)	0.933 ± 0.098	0.932 ± 0.102	−0.04	0.03	0.003	0.95	0.02	1.323	0.25	0.07
v ($m \cdot s^{-1}$)	1.38 ± 0.14	1.24 ± 0.12	−0.18	−0.08	28.404	<0.001	0.99	4.616	0.03	0.61
dv (dimensionless)	0.095 ± 0.025	0.091 ± 0.029	−0.01	0.01	0.324	0.57	0.11	0.029	0.87	0.02
dv/*v* (dimensionless)	0.068 ± 0.025	0.077 ± 0.024	0.00	0.02	3.783	0.04	0.37	0.015	0.90	0.13
D_a (N)	59.91 ± 32.54	45.91 ± 24.10	−25.33	−2.67	6.013	0.02	0.44	0.103	0.75	0.19
C_{Da} (dimensionless)	0.42 ± 0.18	0.44 ± 0.23	−0.06	0.10	0.252	0.61	0.15	0.041	0.83	0.01
η_F (dimensionless)	0.298 ± 0.042	0.297 ± 0.036	−1.68	1.45	0.021	0.88	0.01	0.743	0.39	0.05
SI ($m^2 \cdot s^{-1}$)	2.19 ± 0.45	1.92 ± 0.37	−0.42	−0.10	10.497	<0.001	0.63	0.023	0.88	0.47
$\dot{w}_k$ (W)	198.4 ± 115.9	137.5 ± 76.4	−99.69	−22.03	9.677	<0.001	0.59	0.937	0.34	0.19
$\dot{w}_d$ (W)	84.4 ± 51.3	58.4 ± 33.7	−43.23	−8.90	9.086	<0.001	0.56	0.218	0.64	0.27
$\dot{w}_{ext}$ (W)	282.9 ± 164.5	195.9 ± 109.0	−142.1	−31.75	9.773	<0.001	0.58	0.696	0.41	0.22
s@100free ($m \cdot s^{-1}$)	1.44 ± 0.16	1.30 ± 0.12	−0.19	−0.08	23.844	<0.001	0.86	N/A	N/A	N/A

*95 CI = 95% of confidence interval for the difference between sexes having as reference the girls; ANOVA = analysis of variance; ANCOVA = analysis of covariance; M = mean; F = F-ratio; η^2 = total eta squared; BM = body mass; H = height; AS = arm span; TTSA = trunk transverse surface area; SF = stroke frequency; SL = stroke length; SL/AS = ration between SL and AS; *v* = swim velocity during the maximal trial; *dv* = speed fluctuation; *dv*/*v* = ratio between *dv* and *v*; D_a = active drag; C_{Da} = active drag coefficient; η_F = Froude efficiency; SI = stroke index; $\dot{w}_k$ = mechanical power to transfer kinetic energy to water; $\dot{w}_d$ = mechanical power to overcome drag; $\dot{w}_{ext}$ = external mechanical power; N/A = not applicable.

size index and interpreted as: (a) no effect if $0 < \eta^2 \le 0.04$, (b) minimum if $0.04 < \eta^2 \le 0.25$, (c) moderate if $0.25 < \eta^2 \le 0.64$, and (d) strong if $\eta^2 > 0.64$.

The relationship between power output and s@100free was modeled with power functions (described as $y = b_0 \cdot x^{b1} \cdot \varepsilon$, being $b_0 > 0$, $b_1 > 1$, and $x > 0$). It was calculated by the trendline equation, determination coefficient (R^2), and standard error of estimation (SEE). It was considered: (a) small effect size if $0 \le |R| \le 0.2$, (b) moderate effect size if $0.2 < |R| \le 0.5$, and (c) strong effect size if $|R| > 0.5$.

RESULTS

There were significant and strong variations according to sex for the BM, height, AS, SF, *v*, *SI*, $\dot{w}_k$, $\dot{w}_d$, $\dot{w}_{ext}$, and s@100free (Table 1). The mean values of those variables were higher in boys than in girls ($p < 0.001$; $\eta^2 > 0.64$ for all). Body mass, *dv/v*, and D_a showed significant and moderate variations, being higher for the boys once again ($0.02 \le p \le 0.04$; $0.37 \le \eta^2 \le 0.48$). There was no sex effect in the TTSA, *SL/AS*, *dv*, C_{Da}, and η_F. Interestingly, *SL* had a no significant ($p = 0.21$) but moderate effect ($\eta^2 = 0.26$). The 95% CI for the difference between sexes confirmed the trend for the selected parameters being higher in the boys. When comparing both sexes but controlling the effect of the s@100free, most variables presented a no-significant variation, suggesting that the performance is strongly related to these outcomes (Table 1).

Table 2 provides the normative data by each sex and pooled sample for the selected variables (performance, anthropometrics, kinematics, hydrodynamics, efficiency, and power output). Data dispersion was moderate-to-high for most variables selected. For example, s@100free ranged between 1.06 and 1.72 $m \cdot s^{-1}$ (median = 1.44 $m \cdot s^{-1}$) in boys and between 1.05 and 1.51 $m \cdot s^{-1}$ (median = 1.30 $m \cdot s^{-1}$) in girls. Same reasoning can be exercised for remaining outcomes.

Table 2. Normative data for the performance, anthropometrics, kinematics, hydrodynamics, efficiency, and power output.*

	Performance and anthropometrics								
	s@100free			BM			H		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	1.06	1.05	1.05	37.80	30.10	30.10	145.5	141.0	141.0
10	1.20	1.11	1.12	39.10	36.30	38.20	148.0	145.0	148.0
20	1.32	1.15	1.22	43.70	39.70	41.60	153.0	151.5	152.0
30	1.35	1.26	1.29	45.40	43.70	44.50	157.0	153.0	154.0
40	1.38	1.29	1.32	47.50	45.90	46.70	159.0	155.0	157.0
50	1.44	1.30	1.37	49.50	48.10	48.80	162.5	157.0	158.5
60	1.49	1.33	1.40	52.10	50.10	50.40	164.0	158.5	161.5
70	1.53	1.39	1.44	54.60	50.60	52.50	167.0	160.0	164.0
80	1.57	1.41	1.49	56.00	52.60	54.10	168.5	163.5	165.5
90	1.64	1.44	1.57	64.50	54.10	59.90	171.5	165.0	169.0
100	1.72	1.51	1.72	70.50	66.70	70.50	178.0	171.0	178.0

	Performance and anthropometrics								
	AS			TTSA			*v*		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	1.53	1.48	1.48	478.67	471.83	471.83	0.99	0.94	0.94
10	1.55	1.52	1.55	525.01	512.07	525.01	1.20	1.04	1.11
20	1.61	1.59	1.60	563.76	587.12	579.67	1.26	1.13	1.21
30	1.65	1.61	1.62	606.80	616.12	608.86	1.29	1.23	1.26
40	1.67	1.63	1.65	641.52	630.72	630.72	1.35	1.25	1.28
50	1.71	1.65	1.66	667.00	658.72	662.76	1.39	1.27	1.31
60	1.72	1.66	1.70	693.98	687.21	689.05	1.41	1.29	1.34
70	1.75	1.68	1.72	729.30	698.25	707.24	1.45	1.31	1.38
80	1.77	1.72	1.73	750.59	711.11	739.62	1.51	1.34	1.42
90	1.80	1.73	1.77	804.93	759.19	787.69	1.55	1.36	1.51
100	1.87	1.80	1.87	905.85	926.83	926.83	1.63	1.43	1.63

	Kinematics								
	SF			SL			SL/AS		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	0.75	0.54	0.54	1.14	1.16	1.14	0.72	0.73	0.72
10	0.77	0.73	0.75	1.34	1.30	1.32	0.82	0.77	0.80
20	0.80	0.76	0.77	1.44	1.35	1.38	0.85	0.82	0.85
30	0.82	0.77	0.79	1.49	1.41	1.45	0.88	0.88	0.88
40	0.83	0.78	0.81	1.53	1.46	1.50	0.90	0.91	0.90
50	0.87	0.80	0.83	1.57	1.54	1.55	0.92	0.93	0.93
60	0.88	0.82	0.85	1.61	1.60	1.60	0.94	0.96	0.95
70	0.93	0.83	0.88	1.66	1.63	1.65	1.00	0.99	0.99
80	0.96	0.88	0.93	1.73	1.74	1.73	1.02	1.04	1.03
90	1.02	0.94	0.99	1.79	1.79	1.79	1.07	1.06	1.07
100	1.25	1.04	1.25	2.02	1.85	2.02	1.15	1.12	1.15

	Kinematics								
	dv			*dv*/*v*			SI		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	0.05	0.06	0.05	0.04	0.04	0.04	1.23	1.18	1.18
10	0.06	0.06	0.06	0.04	0.05	0.05	1.64	1.45	1.48
20	0.07	0.07	0.07	0.05	0.06	0.05	1.80	1.52	1.70
30	0.08	0.08	0.08	0.05	0.06	0.06	1.89	1.70	1.80
40	0.08	0.08	0.08	0.06	0.07	0.06	2.07	1.81	1.89
50	0.08	0.09	0.09	0.06	0.07	0.07	2.24	1.90	2.03
60	0.09	0.09	0.09	0.06	0.08	0.07	2.33	2.02	2.15
70	0.10	0.10	0.10	0.07	0.09	0.08	2.39	2.12	2.28
80	0.11	0.11	0.11	0.08	0.09	0.09	2.42	2.26	2.39
90	0.13	0.13	0.13	0.10	0.10	0.10	2.68	2.44	2.52
100	0.20	0.18	0.20	0.17	0.15	0.17	3.19	2.61	3.19

	Hydrodynamics and efficiency								
	D_a			C_{Da}			η_F		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	17.65	8.13	8.13	0.12	0.17	0.12	21.40	23.56	21.40
10	30.08	21.07	23.85	0.22	0.19	0.20	24.24	25.15	24.95
20	35.47	25.96	30.08	0.29	0.24	0.27	26.81	27.19	26.89
30	44.00	31.45	35.29	0.31	0.30	0.30	27.37	27.86	27.82
40	46.67	35.29	41.57	0.34	0.37	0.34	28.97	28.19	28.29
50	51.30	40.04	46.96	0.35	0.39	0.37	29.54	29.82	29.69
60	56.12	47.20	52.51	0.41	0.42	0.42	30.91	30.23	30.38
70	65.52	56.64	57.60	0.52	0.50	0.50	31.57	31.85	31.71
80	69.85	59.11	67.94	0.59	0.61	0.60	32.72	32.88	32.86
90	90.95	74.11	87.35	0.66	0.70	0.69	33.77	33.97	33.97
100	167.33	129.80	167.33	0.90	1.36	1.36	44.83	43.02	44.83

	Power output								
	$\dot{w}_k$			$\dot{w}_d$			$\dot{w}_{ext}$		
Percentile	Boys	Girls	Overall	Boys	Girls	Overall	Boys	Girls	Overall
0	48.82	26.38	26.38	24.89	8.13	8.13	77.44	34.51	34.51
10	96.36	52.90	62.77	38.08	21.07	29.33	135.65	74.74	92.84
20	104.35	69.39	91.42	46.93	29.96	38.08	147.00	97.54	134.00
30	132.60	88.61	104.43	58.68	39.94	45.39	193.29	134.00	148.62
40	157.59	104.80	131.23	64.40	45.39	53.63	222.50	148.86	189.92
50	173.22	121.39	147.93	69.70	50.45	61.74	260.00	166.89	213.56
60	197.35	145.78	165.52	78.01	60.96	69.80	276.75	207.52	234.47
70	224.89	160.87	193.93	83.71	74.88	78.01	296.85	231.74	273.27
80	227.58	192.15	224.89	107.57	79.21	89.68	364.86	271.51	300.16
90	281.68	234.79	264.90	137.41	95.99	119.38	417.40	329.44	377.09
100	646.58	378.91	646.58	271.07	185.61	271.07	917.65	564.52	917.65

*BM = body mass; H = height; AS = arm span; TTSA = trunk transverse surface area; *v* = swim velocity during the maximal trial; SF = stroke frequency; SL = stroke length; SL/AS = ration between SL and AS; *dv* = speed fluctuation; *dv*/*v* = ratio between *dv* and *v*; SI = stroke index; D_a = active drag; C_{Da} = active drag coefficient; η_F = Froude efficiency; $\dot{w}_k$ = mechanical power to transfer kinetic energy to water; $\dot{w}_d$ = mechanical power to overcome drag; $\dot{w}_{ext}$ = external mechanical power.

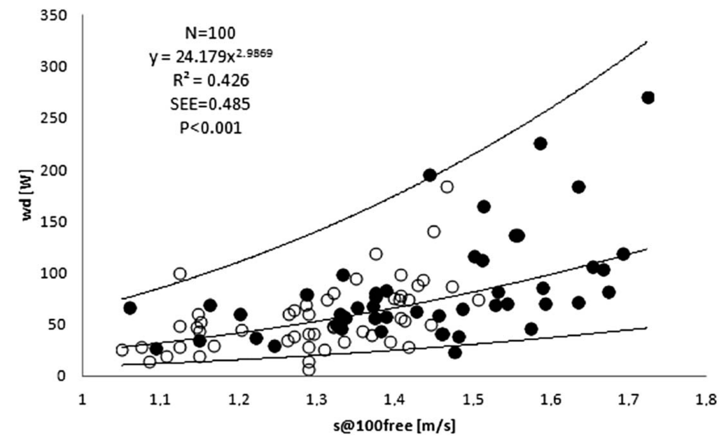

Figure 1. Relationship between mechanical power to overcome drag ($\dot{w}_d$) and sprinting performance (s@100free) in young swimmers. White dots represent the girls and black dots the boys. Lines represent the main trend line, lower and higher bounds for a 95% confidence interval.

There was a significant and strong relationship between power output and sprinting performance ($R = 0.652$; $R^2 = 0.426$; SEE $= 0.485$; $p < 0.001$). Such relationship was modeled with the power equation (Figure 1):

$$\dot{w}_d = 24.179 \cdot \mathrm{s@100free}^{2.9869}. \tag{15}$$

In the final model, b_o was 24.179 and $b_1 \sim 2.99$ (Figure 1, equation 15). So, experimental data showed a cubed relationship between $\dot{w}_d$ and sprinting performance in young swimmers, being the constant value 24.179 at these ages. The models only for boys (equation 16; $R = 0.556$; $R^2 = 0.310$; SEE $= 0.444$; $p < 0.001$) and girls (equation 17; $R = 0.505$; $R^2 = 0.256$; SEE $= 0.524$; $p < 0.001$) were, respectively:

$$\dot{w}_{d_{\mathrm{boys}}} = 30.027 \cdot \mathrm{s@100free}^{2.5046}, \tag{16}$$

$$\dot{w}_{d_{\mathrm{girls}}} = 22.094 \cdot \mathrm{s@100free}^{3.1704}. \tag{17}$$

DISCUSSION

The swimming power output between boys and girls was compared and the relationship between swimming power output and sprinting performance was modeled in young swimmers. Boys presented better performances than girls because of a higher power output. There was a cubed relationship between power output and sprinting performance.

Descriptive statistics for anthropometrics, kinematics, efficiency, and hydrodynamics are within or slightly higher than the range of values reported in literature for subjects with similar age and competitive level (Table 1, descriptive statistics and CIs) (4,12,22,25,31). The analysis of both mean values and the 2*SD* (i.e., ~95% of CI) confirms this fact. This is more obvious in parameters that are reported more often in literature, such as anthropometrics and kinematics (22,31). Yet, there is scarce evidence about the hydrodynamic profile of young swimmers. On top of that, research was conducted with the measuring active drag system (29) or the velocity perturbation method (4,12), making the comparison with literature more challenging. Both measuring active drag system and velocity perturbation method measure the same phenomena but the underlying assumptions explain the differences obtained comparing both procedures (30). For example, while the measuring active drag system does not consider the role of the leg kick because lower limbs are held by a pull-buoy, velocity perturbation method assumes that both trials are performed at maximal power output. Nevertheless, our data seem to be fairly similar to what was reported by previous studies that also selected the velocity perturbation method. To the best of our knowledge, there is no article reporting power output in such early ages. However, compared with data reported in literature for adult swimmers (21,26,35), with no surprise, our young counterparts showed a lower power output no matter the procedure selected to estimate it, considering the metabolic power (i.e., energy expenditure) that would be measured for the s@100free (25):

$$\dot{E} = \frac{\dot{w}_d}{\eta_F \cdot \eta_m}, \tag{18}$$

where E is the metabolic power, $\dot{w}_\mathrm{d}$ the power to overcome drag, η_F the propelling (or Froude) efficiency, and η_m the mechanical efficiency. The η_m was reported as being rather constant and not very sensitive to the competitive level of the swimmer and more related to thermoregulation ($\eta_m \sim 0.1$ in competitive swimming) (21,25). Estimating E from equation 18, boys and girls from our research had 2828.96 ± 1645.15 W and 1959 ± 1090.75 W, respectively.

There were significant and/or strong variations for all anthropometrics parameters but the TTSA, *SF*, *SL*, and v (kinematics), dv/v and *SI* (efficiency), D_a (hydrodynamics), and all power variables between boys and girls (Table 1, ANOVA). The s@100free was also higher for boys than girls. As reported previously, at least for the anthropometrics (22), kinematics (4,22), and hydrodynamics (4), a sex gap exists at these ages. Interestingly, Zamparo (34) reported that girls aged between 10 and 12 years showed higher *v*, *SF*, and *SL* but the same η_F of boys. However, there is a trend in several countries for national age group records and overall performances being better for boys than girls at these ages. So, one might consider that the competitive level of the subjects recruited can explain the mixed findings. Another potential explanation is the sample size. Our research involved the assessment of 100 subjects, all of them regional or national level age group competitive swimmers (including national champions and record holders). Remaining studies had a fairly small sample size and swimmers with a reasonable proficiency. There are in the literature other models to estimate the η_F (28). In such case, the assumption is that the *SF* is scaled to maintain technique and predicts the ratio between v^2 (because it is proportional to the D_a) and average hand speed squared (also proportional to the propulsive force):

$$\eta_p = \frac{\overline{v}^2}{\overline{u}^2}, \tag{19}$$

where *v* is the swimming velocity and *u* the hand's velocity. As happens for remaining mathematical models, averaged angular velocity of the arm depends on the averaged *SF*, according to basic kinematics as explained in equation 6:

$$\overline{\omega} = 2\cdot\pi\cdot SF, \tag{20}$$

where ω is the angular velocity and *SF* the stroke frequency. Knowing the arm length of the swimmer, the average hand speed can be calculated for the underwater phase (i.e., over half a stroke cycle):

$$\overline{u} = \left(2\cdot\pi\cdot SF\cdot l\right)\cdot\frac{2}{\pi}, \tag{21}$$

where *u* is the hand's velocity, *SF* the stroke frequency, and *l* the arm's length. The numerator for equation 19 can be calculated according to equation 9 after being re-arranged. Either way, it is interesting to note that we failed to find significant variations in the η_F and *SL* across sexes, even though the last one presented a moderate effect. This might be consistent to the fact that there is a theoretical relationship between η_F and *SL* (24):

$$SL = \sqrt[3]{\frac{\eta F\cdot\dot{w}}{D_a\cdot SF^2}}, \tag{22}$$

where *SL* is the stroke length, η_F Froude efficiency, $\dot{w}$ mechanical work per stroke cycle, D_a drag force, and *SF* stroke frequency. Data from this research suggest that such relationship is not only theoretical (i.e., mathematical) but empiric evidence support it. Hence, age group coaches can consider paying more care to the *SL* at a given speed because it is a good estimation of the efficiency and power output of their swimmers.

Comparing both sexes and controlling the effect of the s@100free, it was verified a no-significant variation (Table 1, ANCOVA). This suggests that performance differences are related to the selected outcomes. Indeed, there is a solid body of knowledge that these variables are determinant for the swimming performance in young swimmers (2,19). For instance, one of the pathways to excel is to be taller as in this way, *AS* will be higher, increasing *SL*, *v*, *SI*, and therefore performance (in this case the s@100free) (19). Despite being one of the most effective ways to enhance young swimmers performance, other pathways can be found and selected to reach the same final outcome. However, those options might be less effective or efficient than the one reported earlier. Once more, as much as we understand, there is no article comparing the power output between both sexes in age-group swimmers. At least for adult or elite swimmers, power output tends to be higher in men than women (26). Anthropometrics and strength power can explain these findings. Boys and men seem to be taller, heavier, with more lean mass than girls and women, enabling them to reach higher speeds and needing to overcome a higher D_a (equation 2). Considering that there was no significant variations between sexes for the η_F, according to equation 13, the power output likewise will be higher.

For pooled sample and each sex, there was a significant and strong relationship between power output and sprinting performance (equations 15 to 17, Figure 1). Such relationships were modeled as cubed power equations. At constant *v*, the swimmer is submitted to a D_a described by equation 2, which for simplicity's sake can be changed to:

$$D_s = k\cdot v^2, \tag{23}$$

where D_a is the drag force; *k* is the drag factor because the fluid density, the projection surface, and drag coefficient will remain constant ($k = 0.5\cdot\rho\cdot S\cdot C_D$); and *v* is the swimming velocity. Therefore, combining equations 12 and 23:

$$\dot{w}_d = k\cdot v^3, \tag{24}$$

where $\dot{w}_d$ is the power to overcome drag force and *k* is the drag factor. So, the theoretically expected relationship should be cubic, once energy output run in parallel with power, and power is a function of the velocity cubed. Final models reported in equations 15 to 17 confirm such cubed relationships ($2.50 \leq b_1 \leq 3.17$). Even though there is no research on this for young swimmers, same cubed relationships were reported for adult/elite swimmers (25). For the case of young swimmers, the drag factor was $22.094 \leq k \leq 30.027$ (*k* is also known as b_o). The pioneer study by Karpovich (11) found that adult swimmers at that time had a $k = 29$ for passive drag. In young swimmers, active drag is approximately 1.5 times higher than passive drag (3).

Research conducted more recently found that lower values are found with the measuring active drag system ($15.25 \leq k \leq 28.70$), albeit the velocity perturbation method provides even lower k ($k \sim 16$) (30). The lower k of adult/elite swimmers reported in the literature than our young counterparts must be related to the C_D because the S is higher in the first ones. Hydrodynamic dimensionless numbers can play a part on this. Moreover, it was hypothesized that combining equations 5 and 24, it would be possible to predict swimming velocity:

$$v = \sqrt[3]{\frac{\dot{w}_{ext} \cdot \eta F}{k}}, \tag{25}$$

where v is the swimming velocity, $\dot{w}_{ext}$ is the external mechanical power, η_F the Froude efficiency, and k the drag factor. So, it can be concluded that according to equation 25, sprinting performance depends on the power output, efficiency, and the drag factor (that in its turn depends from anthropometrics and hydrodynamics). Age group coaches should consider all these fields when designing training sessions and the periodization plan of young swimmers.

Therefore, sprinting performance depends on anthropometrics, kinematics, hydrodynamics, efficiency, and power output. Power output is also related to dry-land strength. Concurrent dry-land strength and conditioning and aquatic training are a common practice in swimming. Combined strength and endurance training programs tend to inhibit strength and power build-up. However, only a couple of articles aimed to study the effect of concurrent training in competitive swimming. After 11 weeks of a combined strength and endurance program for adult swimmers (approximately 17 years old), dry-land strength, tethered swimming force, and 400-m freestyle performance improved more in the intervention group than in the control group (1). Surprisingly, there were no changes in stroke length, stroke rate, and performance at the 50- and 100-m freestyle sprint. Another research examined the effects of an 8-week program in younger swimmers (approximately 12 years old) on the 25- and 50-m sprint, dry-land strength, and hydrodynamics (10). Sprinting performance and dry-land power did improve but not the hydrodynamics. This moderate transfer of dry-land strength and conditioning to water may be because of several reasons. Dry-land strength does not relate directly with performance. There is a cascade of events linking dry-land strength to aquatic strength, this one to biomechanics (kinematics and kinetics), and finally this to performance (2). There is a challenge transferring dry-land strength to aquatic environment and know how to elicit it in an efficient way while swimming (10). Some of the muscle groups monitored on regular basis are not specific enough for swimming or may not play a major part in such sport. Further EMG studies might help to clear this out. Finally, some tests available are not sensitive or specific enough (maximal strength vs. power).

It can be considered as main limitations of this research: (a) it was neglected the $\dot{w}_{int}$ since it plays a minor part in swimming, (b) the model to estimate power output was applied only to front-crawl swimming, remain to be answered if it is suitable for other stroke techniques, and (c) one might say that middle- and long-distance swimming is determined mainly by swimming economy, so some care should be exercise transferring these findings to those racing distances.

PRACTICAL APPLICATIONS

This novel method to estimate power output based on data collected with the velocity perturbation method and the arm's propelling efficiency is a straightforward, informative, useful, and less time-consuming way to monitor power output. The procedure is easy to carry out by practitioners, with minimal disruption of a training session. This procedure enables to monitor power output on regular basis in swimming as happens in several other sports.

Power output is a well-rounded parameter that should be monitor on regular basis to gather a deeper insight about: (a) the competitive level of the swimmer, (b) his training status, and (c) prescribe a given intensity of exertion. For example, one can benchmark his own swimmers with normative data provided in Table 2. If this procedure is applied over time (e.g., follow-up or intervention program), it is possible to understand the variations in the interplay between the swimming performance, anthropometrics, kinematics, hydrodynamics, efficiency, and power output.

This research provides evidence that power output is related to the swimmer's performance, hydrodynamic profile, anthropometrics, strength & conditioning, and technique. Hence, practitioners, such as swim and S&C coaches, should take on board this information to develop an evidence-based practice. Even though very challenging, dry-land strength and conditioning should be transferable to water so that it can properly elicit and therefore maximize the swim power output. To do so, priority should be given to the build-up of power than maximal strength besides. Moreover, drills and routines selected should mimic as much as possible swimming actions.

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