Full title:

MECHANICAL POWER, THRUST POWER AND PROPELLING EFFICIENCY: RELATIONSHIPS WITH ELITE SPRINT SWIMMING PERFORMANCE

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Abstract

The purpose of this study was to explore the relationships between mechanical power, thrust power, propelling efficiency and sprint performance in elite swimmers. Mechanical power was measured in 12 elite sprint male swimmers: i) in the laboratory, by using a whole body swimming ergometer (W'_{TOT}); and ii) in the pool, by measuring full tethered swimming force (F_T) and maximal swimming velocity (V_{max}): $W'_T = F_T \cdot V_{max}$. Propelling efficiency (η_P) was estimated based on the “paddle wheel model“ at V_{max}. V_{max} was 2.17 ± 0.06 $m \cdot s^{-1}$, η_P was 0.39 ± 0.02, W'_T was 374 ± 62 W and W'_{TOT} was 941 ± 92 W. V_{max} was better related to W'_T (useful power output: $R=0.943$, $P<0.001$) than to W'_{TOT} (total power output: $R=0.744$, $P<0.01$) and this confirms the use of the full tethered test as a valid test to assess power propulsion in sprinters and to estimate swimming performance. The ratio W'_T/ W'_{TOT} (0.40 ± 0.04) represents the fraction of total mechanical power that can be utilized in water (e.g. η_P) and was indeed the same as that estimated based on the “paddle wheel model”; this supports the use of this model to estimate η_P in swimming.

Keywords: propelling efficiency, hydrodynamic resistance, sprint swimming, power output

Introduction

Maximal swimming velocity (v) depends on three biomechanical factors: the total mechanical power (W'_{TOT}) that a swimmer can generate (via the action of the upper and lower limbs), propelling efficiency (η_P) which represents the fraction of W'_{TOT} that can be utilized to overcome external forces in water and hydrodynamic resistance (drag, $F_D = k\ v^2$). The relationship between these parameters is described by:

$$v^3 = 1/k \cdot \eta_P \cdot W'_{TOT} \quad (1)$$

(e.g. Toussaint, Carol, Kranenborg, & Truijens, 2006; Zamparo, Turri, Peterson Silveira, & Poli, 2014)), where k is speed specific drag ($k = F_D / v^2$) This equation can be algebraically derived by knowing that propelling efficiency is given by:

$$\eta_P = W'_D / W'_{TOT} \quad (2)$$

(e.g. Alexander, 1977; Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005), where W'_D is the power needed to overcome drag ($W'_D = F_D\ v = k\ v^3$).

At a given, constant, speed the power to overcome drag (W'_D) should equal the power that a swimmer can utilize in water to propel himself forward (W'_T, which is indeed only a fraction of W'_{TOT}) since, in these conditions, resistive forces should equal propulsive forces (e.g. Gatta, Cortesi, & Zamparo, 2016). Therefore, Equation 2 can also be written as:

$$\eta_P = W'_T / W'_{TOT} \quad (3)$$

As pointed out by Zamparo and coworkers (2014) maximal swimming velocity is indeed the result of the interplay between k (the lower the better), η_p and W'_{TOT} (the higher the better). Assessing these parameters separately may not allow prediction of swimming velocity (e.g. performance) with sufficient accuracy: it is necessary to take account of all three factors when attempting to evaluate the effects of a training program on swimming performance. This presents a difficulty for many swimming coaches and scientists, especially because gathering data of k, η_p and W'_{TOT} can involve quite complex measurements.

Based on Equation 1, a strong correlation between performance (maximal velocity) and total mechanical power output (W'_{TOT}) should be expected in a group of swimmers with similar values of speed-specific drag (k) and propelling efficiency (η_p), e.g. when k and η_p can be considered as "constants" in this equation. This was probably the case in studies where a strong relationship was observed between arm power (an index of W'_{TOT}) and swimming performance (Sharp, Troup, & Costill, 1982; Hawley, Williams, Vickovic, & Handcock, 1992; Bradshaw, & Hoyle, 1993; Johnson, Sharp, & Hendrick, 1993). However, in swimmers with different technical skills (with different values of η_p), it is necessary to also take account of η_p. In this case, a larger correlation would be expected between performance (maximal velocity) and the product η_p W'_{TOT}, instead. Thus, the goodness of the correlation between power measurements (on land) and swimming speed depends, to a large extent, upon the homogeneity of the swimming proficiency of the swimmers that are assessed.

Total mechanical power (W'_{TOT}) generated though the action of the upper and lower limbs can be measured by use of laboratory-based ergometers. The most utilized land ergometers are swim benches where the swimmer imitates the movements of front crawl swimming in a prone position. The validity of these ergometers has been widely discussed in the literature, because the mechanical action required to produce propulsion in the water cannot be exactly reproduced on land (Hall, Bisson, & O'Hare, 1990; Dalamitros, Manou, & Pelarigo, 2014). Furthermore, with a swim bench only arm power output can be measured and this leads to an incomplete assessment of

W'_{TOT}. This issue was solved initially by investigating the leg-kicking movements in a separate series of measurements (Bachman, 1986). However, the independent simulation of leg and arm movements is not equivalent to the combined co-ordinated whole swimming action as performed during front crawl swimming itself. More-recently, Swaine and co-workers (Swaine, Hunter, Carlton, Wiles, & Coleman, 2010) proposed a novel whole-body swimming ergometer to assess the upper and lower limbs power output during a whole-body swimming simulation and with this device it has become possible to derive a measure of W'_{TOT}, as the sum of the leg and arm power output (Swaine et al., 2010; Zamparo, & Swaine, 2012).

As indicated by Equation 2, propelling efficiency is given by the ratio of the power to overcome drag (W'_D) and total mechanical power output (W'_{TOT}) but, as indicated above, both are difficult to measure. One of the methods proposed in the literature to estimate propelling efficiency is based on the ratio of average swimming velocity to hand velocity, which was first proposed for the study of animal locomotion in water (Alexander, 1977) and which avoids a direct measure of W'_D and W'_{TOT}. Hand velocity can be assessed by means of 3D kinematic analysis (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011) or estimated by using a "paddle-wheel model", as proposed by Zamparo et al. (2005). In this latter case propelling (or more correctly, Froude) efficiency is calculated based (among the others) on the ratio between swimming speed and stroke frequency (i.e. on the distance covered per stroke: d/S); propelling efficiency and d/S were indeed found to be highly related (Zamparo et al., 2014) so that the former can be estimated based on simple measures of d/S. According to the paddle wheel model propelling efficiency is of about 30-40% (i.e. more than 50% of W'_{TOT} is wasted to give water kinetic energy not useful for propulsion (e.g. Zamparo et al., 2005; Figuereido et al., 2011).

As indicated by Equation 3, propelling efficiency can also be calculated from the ratio of thrust power (W'_T) and total mechanical power output (W'_{TOT}) since, at constant velocity, the power required to overcome drag and the power required to propel the swimmer forward should be equal. Indeed, if the propulsive and resistive forces are not balanced, the swimmer would accelerate or decelerate (e.g. Gatta et al., 2016). Measuring propulsive/thrust power is easier than measuring the power required to overcome drag; thrust power can indeed be measured by using widely-available systems which involve a load cell being tethered to the pool wall and by wire or rope attached to a belt around the swimmer. In these experiments (full tethered swimming) the swimmer's action occurs without forward displacement of the body. The force measured by the fully tethered method (F_T) should thus correspond to the useful force exerted by the swimmer to overcome water resistance at maximum velocity (Vorontsov, 2011; Gatta et al., 2016). A strong relationship between average force during an all-out tethered swimming effort and free-swimming velocity has indeed been reported in the literature (Morouço, Keskinen, Vilas-Boas, & Fernandes, 2011; Morouço, Marinho, Keskinen, Badillo, & Marques, 2014; Gatta et al., 2016; Dominguez-Castells, Izquierdo, & Arellano, 2013) By this method, maximal tethered swimming power output (i.e. thrust power, W'_T) can be calculated, as the product of mean tethered swimming force and maximal swimming velocity ($F_T \cdot V_{max}$).

According to Equation 3, W'_T corresponds to the product $W'_{TOT}\ \eta_p$ (e.g. to W'_D at that velocity) (Gatta et al. 2016) so that Equation 1 can be rewritten as:

$$v^3 = 1/k \cdot W'_T \qquad (4)$$

According to this equation, speed specific drag (k) in active conditions can be estimated based on measures of W'_T and swimming speed ($k = W'_T / v^3$). Whereas there is still a debate, in the literature, about the best method to determine hydrodynamic resistance during swimming, active drag should be larger than passive drag (e.g. Gatta et al. 2014; Gatta et al., 2016). As indicated by Havriluk (2007) data of speed specific drag (k) in passive conditions reported in the literature are remarkably consistent and of about 20-25 $N \cdot m^{-2} \cdot s^2$, depending on gender, skill and anthropometric characteristics of swimmers; according to Gatta and coworkers (2014, 2016) in active conditions (during swimming) k should be about 1.5 times larger (i.e. about 30-37.5 $N \cdot m^{-2} \cdot s^2$).

The aim of this study was, therefore, to further test the relationship between mechanical power output, propelling efficiency and velocity in a group of elite short distance swimmers on whom we calculated the mechanical power output with a whole body swimming ergometer (Zamparo, & Swaine, 2012). Furthermore, propelling efficiency was estimated based on data of distance per stroke at V_{max}, maximal speed was measured during a front crawl (whole body) maximal sprint (V_{max}) and full tethered power output (W'_T) was measured as the product of full tethered swimming force (F_T) and maximal swimming velocity: $W'_T = F_T \cdot V_{max}$.

These experiments are intended to test the following hypothesis:

1- W'_{TOT} is larger than W'_T and the ratio W'_T/W'_{TOT} is of about 30-40%.

2- W'_T corresponds to the product η_p W'_{TOT} (where η_p is calculated by means of an independent method based on the paddle wheel model)

3- Maximal swimming speed is better related to W'_T (useful power output in water) than to W'_{TOT} (total power output measured in the laboratory)

4- The values of k, calculated according to Equation 4 would be of about 30-37.5 $N \cdot m^{-2} \cdot s^2$ (e.g. larger than in passive conditions).

Were these hypothesis confirmed, these experiments would support: i) the capability of the paddle wheel model to correctly estimate η_p (as well as the possibility to estimate η_p based on simple measures of distance per stroke); ii) recent findings that indicate that active drag is 1.5 larger than passive drag; iii) the use of the full tethered test as a method to evaluate the capability of swimmers to exert useful power in water (as well as the possibility to estimate swimming performance, V_{max}, based on measures of tethered power); iv) the capability of the whole-body ergometer to estimate correctly $W'_{TOT.}$

Materials and Methods

Participants

Twelve elite male swimmers participated to this study (22.8 ± 3.5 years of age; 79.9 ± 8.3 kg of body mass; 1.88 ± 0.06 m of stature); they were part of the National Italian Team and were competing in short distance sprint events. The long-course 50-m and 100-m freestyle personal best times are 22.5 ± 0.6 s and 49.5 ± 1.3 s, respectively (representing 93 ± 2 and 95 ± 3 % of the World Record). The experiments were performed during the spring of 2016 when the swimmers were in their competition period. All participants were non-smokers; they were requested to avoid strenuous exercise in the 48 h prior to testing and to follow a regular diet in the testing day.

All swimmers received written and oral instructions before the study and gave their written informed consent to the experimental procedure. The experimental protocol was approved by the local Institutional Review Board.

Experimental protocol

The swimmers were requested to perform 3 different tests in the same day; test #1 and #2 were performed in the morning with a 40 min rest in-between whereas test #3 was performed in the afternoon (at least after 2 hours from a light meal). During the day the swimmers did not perform any other physical activity. The restricted availability of the athletes prevented us to perform the 3 tests at the same time of the day, in consecutive days, and this could be a limit of this study.

1 - Full tethered swimming test. The participants were asked to perform a 15 s all out test (full tethered swimming, without forward displacement) to their maximum intensity. This test replicates an equal duration of the time trial in short-distance swimming performance (Morouço et al., 2014) and had the same duration of test #2. Full tethered force was measured by means of a load-cell, previously calibrated with 1 - 5 - 10 - 20 kg standard masses, which were connected by a cable to a Globus Ergometer data acquisition system (Globus™, Codognè, Italy) recording with a sampling rate of 1000 Hz. The load-cell was fixed on the swimming pool by a steel cable and the participants were connected to the load cell by means of a belt. Data were recorded and processed with the Globus Ergometer software and then exported to a PC for further analysis. During this test the following parameters were measured: average force (during the entire test of 15 s duration: F_T) and average stroke frequency (SF_T, Hz).

Maximal tethered power output (thrust power) was calculated as the product of mean tethered force and maximal swimming velocity ($W'_T = F_T \cdot V_{max}$); in turn, V_{max} was calculated by means of test #3, see below. As indicated in the Introduction, W'_T should correspond to the product $W'_{TOT} \cdot \eta_P$ (this product is further referred as W'_{EP}) since, as indicated by Equation 3, $\eta_P = W'_T / W'_{TOT}$.

2 - Whole body ergometer test. Participants performed an all-out test of 15 s duration (i.e. the same as test #1) on a whole-body swimming ergometer (Zamparo, & Swaine, 2012). Resistance to the movement of each limb was created by four air-dynes (Lawler Engineering, UK) mounted on spindles which rotated upon pay-out of pull-ropes, attached to hand-paddles or foot-plates. The design of the leg-kick ergometer allowed force to be exerted in the upward and downward kicking action but only during the pulling action of the arms, not during the recovery phase. The revolution rate of each air-dyne was detected by photoelectric sensor. Participants adopted a prone position and were instructed to simulate the front crawl swimming action as closely as possible (including arm recovery), attempting to achieve maximum pull and kick movements in each arm-stroke or leg-kick. Mean power output for leg-kick and arm-stroke was averaged over each arm-pull or leg-kick. The static and dynamic calibration of the air dynes was performed as described in detail by Zamparo and Swaine (2012). During these experiments the power output of legs (W'_L, W, sum of right and left leg's power output) and arms (W'_A, W, sum of right and left arm's power output) was computed, as well as total power output ($W'_{TOT} = W'_L + W'_A$).

3 - Maximal swim test. The swimmers were asked to swim the front crawl (in a 25 m pool) at different, incremental, velocities up to maximal swimming velocity (V_{max}, m · s^{-1}), starting without diving, from the starting block. Eight even-paced steps, with restart after 2 min, graded from easy to maximal, were completed. The actual velocity was calculated by means of two synchronized cameras, with a sampling rate of 25 Hz (TS-6021PSC, Sony Hyper Head, Tokyo, Japan), that were placed on the side of the swimming pool, perpendicular to the swimmer's direction, on the 10^{th} and 20^{th} meter from the start. Swimming velocity was calculated from the time needed to cover this distance (the position of the swimmer's head was considered in this calculation), with the swimmer already at maximum velocity after the first 10 m. During these experiments stroke frequency (SF, Hz, cycles · s^{-1}) was measured and distance per stroke (d/S, m · $cycle^{-1}$) was calculated from the ratio: V / SF. The stroke frequency was computed from the time taken to complete three stroke cycles between the 10^{th} and 20^{th} meter from the start. In this paper only data referring to the highest velocity (V_{max}) and corresponding values for stroke frequency (SF_{max}) and distance per stroke (d/S_{max}) at maximum velocity are reported. The maximal swim test lasted about 10 s, a duration comparable to that of tests # 1 and 2.

Propelling efficiency was not directly measured but calculated based on the measured values of distance per stroke (d/S_{max}), utilizing an equation reported in the literature (Zamparo et al., 2014). Indeed, as shown by these authors, about 80% of the variability of η_p could be explained by the variability of d/S: $\eta_p = 0.045 + 0.151 \cdot d/S$, $R = 0.899$, $p < 0.001$. According to the paddle wheel model (e.g. Zamparo et al., 2005) η_p is calculated from the ratio of forward speed (V) to tangential hand speed and the latter is estimated by assuming that the arm is a rigid segment rotating at constant angular speed ($2\pi SF$) around the shoulder: hence η_p is proportional to the V/SF ratio which is indeed the distance covered per stroke (see above).

Statistics

Data are reported as mean ± 1SD. Paired t-tests were utilized to assess eventual differences in the variables measured by means of different methods. A Shapiro-Wilk test was performed for the evaluation of normality for statistical distribution. Correlation between variables in linear regression analysis was evaluated as indicated by Geigy Scientific Tables, the correlation coefficient (R) was used to indicate the goodness of fit. The α level was set at $p < 0.05$. Statistical analysis was performed using SPSS for Windows (SPSS Statistic 17.0).

Test-retest variability was assessed by means of the coefficient of variation. CV% of data assessed by means of the swim bench (W'_L, W'_A and W'_{TOT}) was calculated on 7 (out of 12) swimmers who repeated this test 3-5 times (in a preliminary series of experiments). CV% of V_{max} and F_T data was calculated over 3 trials on 10 elite sprinters participating to a previous study (Gatta et al., 2016) where the same protocol to assess V_{max} and F_T adopted in this study was applied (most of the swimmers participated to both studies).

Results

The coefficient of variation for the parameters measured in this study ranged from 2 to 6%. The CV% values for data assessed by means of the swim bench were 6.1 ± 3.9% (W'_L), 6.4 ± 2.4% (W'_A) and 3.9 ± 1.2% (W'_{TOT}). CV% for V_{max} and F_T was 1.74 ± 0.86% and 6.2 ± 1.7%, respectively.

The mean force exerted during the full tethered swimming test (F_T) was 172 ± 24 N and the stroke frequency during this test (SF_T) was 0.92 ± 0.07 Hz. This was a value close to that attained during the maximal swimming test (SF_{max}: 0.95 ± 0.07 Hz). During the maximal swimming test maximal distance per stroke (d/S_{max}) was 2.32 ± 0.14 m, maximal velocity (V_{max}) was 2.17 ± 0.07

$m \cdot s^{-1}$ and propelling efficiency (η_P) was 0.39 ± 0.02. Maximal tethered power output ($W_T = F_T \cdot V_{max}$) was 374 ± 62 W.

The power output generated by the upper limbs (W'_A), assessed by means of the whole body swimming ergometer, was 306 ± 45 W; that generated by the lower limbs (W'_L) was 548 ± 172 W and total power output (W'_{TOT}) was 940 ± 92 W (11.8 ± 0.9 $W \cdot kg^{-1}$). The ratio W'_L/W'_A was 1.8 ± 0.7.

---------Figure 1 near here--------

In Figure 1 the relationships between maximal swimming velocity (V_{max}) and power output measured in the pool (W'_T) and in the laboratory (W'_{TOT}) are reported; both relationships are highly significant ($R = 0.943$, $P < 0.001$ and $R = 0.744$, $P < 0.01$, respectively). A stronger relationship was observed between maximal swimming velocity (V_{max}) and arm's power output (W'_A, $R = 0.740$, $P < 0.01$) than with leg's power output (W'_L, $R = 0.400$, NS). The relationship between V_{max} and W'_{EP} ($R = 0.711$, $P < 0.01$) was significant whereas no relationship was observed between V_{max} and η_P ($R = 0.090$, NS).

---------Figure 2 near here--------

In Figure 2 maximal power output is reported as calculated by means of three different methods: W'_{TOT}, as determined with the whole body swimming ergometer; W'_T as determined by the product of maximal swimming velocity and tethered force and W'_{EP}, as determined by the product of W'_{TOT} η_P (371 ± 39 W). No significant differences ($P = 0.89$ t-test for paired data) were observed between W'_T and W'_{EP}.

Finally, speed specific drag, calculated from the ratio W'_T / v^3 (see Equation 4) was found to be 36.2 ± 3.3 $N \cdot m^{-2} \cdot s^2$ (range: 30.2-41.1).

Discussion

Data reported in this study indicate that maximal speed in sprint swimming (V_{max}) depends on the interplay between power output in dry conditions (W'_{TOT}) and propelling efficiency (η_P), as it can be hypothesized on theoretical grounds (Equation 1). The best relationship between V_{max} and power data was observed with W'_T: the power actually available in water, which corresponds to the product $W'_{TOT}\ \eta_P$ (see Equation 3). Our data furthermore indicate (by means of two independent methods) that, in these experimental conditions, propelling efficiency is of about 40% and that speed specific drag is about 1.5 times larger than the values generally reported during passive drag measurements. Thus, all hypotheses were confirmed and this was possible because we were able to calculate W'_{TOT} by means of the whole body swimming ergometer; this indeed constitutes the novelty of this study.

Power output calculated from the tethered test and propelling efficiency.

The “useful power “in swimming can be measured using either a laboratory-based ergometer (and by taking into account propelling efficiency) or by means of tethered experiments; data reported in this study indicate that this parameter is better estimated by means of a tethered test (W'_T) since imprecision arises when measuring W'_{TOT} (especially in the determination of the leg’s power output, W'_L, see below). Indeed, data of W'_T have a lower standard deviation than data of W'_{TOT} and are more strongly related to swimming performance (lower scatter and larger coefficient of correlation). There is, indeed, general agreement in the literature that tethered swimming is a valid measure of power output in water even if the kinematics of this action is not completely comparable with free swimming at maximal velocity, (Morouço et al., 2011; Morouço et al., 2014; Gatta et al., 2016).

W'_T was approximately 40% of total mechanical power output produced by upper and lower limbs in “dry conditions” (i.e. W'_{TOT}). Additionally, the mechanical power output produced by the upper and lower limbs in water, calculated by the product $W'_{TOT} \cdot \eta_P$ (e.g. W'_{EP}), was the same as that determined during full tethered swimming (e.g. W'_T). This, not only indicates that these two methods produce similar values of thrust power at maximal velocity but also suggests that propelling efficiency is approximately 40% in these experimental conditions. This was confirmed by the finding that the values of propelling efficiency (calculated based on data of d/S_{max}) were, indeed, of about 40%. These figures are comparable to those reported in the literature for elite male swimmers by Zamparo et al. (2005), Figuereido et al. (2011) and Zamparo and Swaine (2012).

Even if, in this study, propelling efficiency was only roughly estimated based on data of d/S, this finding is relevant because it rules out the possibility that propelling efficiency is larger than that. As an example, Toussaint et al. (2006) in a 100 m front crawl race, report values of η_P of about 75%: was this the case the values of W'_{TOT} should be much lower that those assessed in this study by means of the whole body swimming ergometer.

Compared to a previous study (Zamparo et al., 2014) conducted on these lines of reasoning, the values of propelling efficiency reported here are larger (male elite vs. male master swimmers) and have a much lower variability (0.39 ± 0.02 vs. 0.30 ± 0.05, respectively). As suggested in the introduction, the lack of correlation between V_{max} and η_P observed in this study can thus be attributed to the homogeneity in swimming proficiency of our swimmers.

The lower correlations with swimming speed (in comparison with W'_T) observed when data of W_{TOT}, W'_A and W'_L are considered can thus only partly attributed to the fact that these parameters do not take into account propelling efficiency; this is likely due to sources of variability in the dry land mechanical measurements that will be discussed in the following paragraphs.

Power output calculated with the whole-body swimming ergometer.

Even if the strongest power-performance relationship was observed when mechanical power output was measured during tethered swimming in the pool, in relation to the laboratory-based ergometry, this is the first time that the relationship between mechanical power output from whole-body simulated swimming and swimming velocity has been explored; indeed, previously-reported data referred to arm power only (Sharp et al. 1982; Hawley et al., 1992; Bradshaw et al., 1993; Johnson et al., 1993) and only few studies investigated the contribution of the legs to total mechanical power output (e.g. Hollander, De Groot, Van Ingen Schenau, Kahman, & Toussaint, 1988; Gatta, Cortesi, & Di Michele, 2012).

Sharp et al. (1992) conducted one of the earliest studies showing that arm power, from a swim bench test, correlated strongly with front crawl swimming performance. This was confirmed by Hawley et al. (1992) who measured arm power using an arm-crank ergometer. However, it is difficult to make a direct comparison of performance levels in these studies compared to ours. That is because the maximum swimming velocities are derived from different measures (e.g. from 50 m swimming, in Hawley et al. (1992)). Also, the swimmers in the study by Hawley et al. (1992) seemed to be less homogeneous and of lower performance level: 1.69 $m.s^{-1}$, maximum swimming velocities for their male swimmers whereas our maximum swimming velocity was 2.17 $m.s^{-1}$.

Subsequent studies by Johnson et al. (1993) and by Bradshaw and Hoyle (1993) also showed significant correlations between swim bench arm power and swimming performance. However, when using the swim bench, only the arm-stroke was utilised and this (in a similar way to that for the arm-cranking used by Hawley et al. (1992)) somewhat compromises its generalizability to whole-body front crawl swimming in water. Nevertheless, the present data adds further evidence for the role of mechanical power output in sprint swimmers who wish to achieve high swimming velocities. Furthermore, the whole-body swimming ergometer addresses some of the factors that compromised validity in the previous studies (Sharp et al., 1982; Hawley et al., 1992; Bradshaw et al., 1993). It also provides an alternative means by which this important characteristic of mechanical power output can be measured for the purposes of monitoring the likely performance-enhancement effects of training. Much of the previous work that has sought to monitor the effects of training in swimmers has almost exclusively utilised upper-body ergometry. Many efforts have been made previously to monitor the training enhancements in the mechanical power of swimmers but with limited success, probably because of the arms-only ergometers that have been used.

It is interesting to note that, in two participants the W'_L/W'_A ratio was lower than 1 (it is of about 2 in the other swimmers). This suggests that either these swimmers were not able to properly reproduce the leg-kicking action when using the laboratory-ergometer (perhaps a longer habituation should be considered for these participants) or that their legs power output was indeed lower than average. In the latter case, the leg-kick power measurement might allow identification of the swimmers who have greater need for specific leg-kick training.

To further develop a land ergometer that is better able to reproduce the swimming movements, the mechanical load of the water and the thrust direction of the swimmer's limbs must be taken into account. However, these characteristics are typically difficult to replicate on land, currently. Nevertheless, data reported in this study indicate that the values of W'_{TOT} assessed with the laboratory-based ergometer are compatible with the values from tethered-swimming, once propelling efficiency is taken into account. Thus, data reported in this study support the validity of this ergometer to assess the power output of the upper and lower limbs in dry conditions.

Speed specific drag

Even if calculating speed specific drag was not a major aim of this study the values of k we estimated suggest that hydrodynamic resistance, in active conditions, is larger than in passive conditions. This was recently demonstrated by Gatta et al. (2016) who did indeed show that, in a similar group of swimmers (most of our swimmers participated also to that study) thrust power

(W'_T) is indeed equal to the power to overcome drag (W'_D) when the latter is calculated by taking into account that frontal area during swimming is 1.5 times larger than when the swimmer is passively towed (Gatta et al., 2014). In that study (Gatta et al., 2016) k in passive conditions was 24.8 ± 1.8 $N \cdot m^{-2} \cdot s^2$ and in active condition was 37.2 ± 2.7 $N \cdot m^{-2} \cdot s^2$, a value similar to that observed in this study (36.2 ± 3.3 $N \cdot m^{-2} \cdot s^2$). This findings rules out the possibility that, during swimming, active drag is equal (or lower) then passive drag as it was reported, an example, by Toussaint, Roos and Kolmogorov (2004).

Conclusions

Data reported in this study allow gathering further insight on the relationships between performance (V_{max}), propelling efficiency (η_P), total power output (in dry conditions: W'_{TOT}) and tethered power output (in water: W'_T) in elite short distance swimmers. W'_T was expected to correspond to the product $W'_{TOT} \cdot \eta_P$, as experimentally found. Our findings thus support the capability of a whole-body ergometer to estimate W'_{TOT} as well as the finding that propelling efficiency (η_P) should be of about 40% in these experimental conditions.

From a practical point of view our data indicate that swimming performance is better related to W'_T than to W'_{TOT} and this is both because the former takes into account the differences in η_P among swimmers and because of a larger imprecision when measuring W'_{TOT} (especially in the determination of the leg's power output, W'_L). Thus these findings support the use of the full tethered test (along with measures of sprinting speed) as a valid test to assess power propulsion in sprinters. Moreover, these findings support the use of the paddle wheel method to assess propelling efficiency in swimming and, in its simpler form, to derive these values from data of distance per stroke.

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Figure captions

Figure 1. The relationship between maximal swimming speed (V_{max}) and maximal tethered power (W'_T, open dots) or mechanical power output at the whole body ergometer (W'_{TOT}, full dots). These relationships are well described by the following equations: $V_{max} = - 1691 + 950 \cdot W'_T$, $R^2 = 0.890$; $V_{max} = - 1460 + 1105 \cdot W'_{TOT}$, $R^2 = 0.554$.

Figure 2. Mechanical power output as measured/calculated with different methods. W'_{TOT}: by means of the whole body swimming ergometer (on land); W'_T: as the product of maximal speed and full tethered force (in water); W'_{EP}: calculated as $\eta_P \cdot W'_{TOT}$, see text for details. Values are means, bars represent 1 SD.