An Updated Protocol to Assess Arm Swimming Power in Front Crawl

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Abstract

Muscle power output is a critical issue in sport performance [10, 13]. As swim power is a reliable predictor of swim speed in the front crawl [3, 9, 23–26, 36], it is considered an important practical issue in swimming [7, 28, 37]. However, the calculation of the optimal load that maximises power output has not been fully achieved. The maximal swimming power output has been positively related to the maximal swimming speed despite fatigue [31] or varying skill levels [23]. In other studies [5, 7, 20], however, the correlation between dry-land power and maximum swim speed was only moderate (r = 0.54–0.74), possibly because the authors did not use a specific protocol to assess power [16].

Active drag has been used to calculate swim power by means of 2 different methods: the MAD (Measuring Active Drag) system [11, 32, 34, 35] and VPM (Velocity Perturbation Method) [17]. However, constant body velocity was assumed in the former and constant power output in 2 conditions was assumed in the latter. Neither method measured the power used to give water kinetic energy. The same ‘equal power’ assumption was made in a newer method for estimating active drag [39], and the values obtained were similar to those in the previous study [17]. In this case, instantaneous drag was measured instead of mean drag.

Other studies have measured the power delivered to an external load during semi-tethered swimming [12, 14, 30, 38]. Each study used a pulley system, which made it possible to set one or more loads. To our knowledge, however, only a few studies have represented a swim power curve (power vs. load) [15, 27], which calculated the load that optimised the maximal power performance. Klauck and Ungerechts [15] used a semi-tethered swimming device (STSD) to calculate the mechanical power developed to external loads. Instantaneous speed was measured by registering the revolutions produced by the swimmer motion on a wheel. However, an important limitation of most previous studies measuring power output was that only the mean values were reported, and the intra-cycle fluctuations were ignored [6].
Therefore, the purpose of our study was: 1) to obtain a complete power vs. load curve, which will enable the determination of the maximum swim power along with the corresponding load and swim speed. This will allow quick feedback for swimmers and coaches; 2) to examine the intra-cycle power output during pull and push phases of the front crawl arm-stroke by measuring the intra-cycle force and speed synchronised with video recording; and 3) to determine the relationship between the maximum swim power and the 25 m swim speed.

Methods

Experimental design
A quasi-experimental, cross-sectional design was used with a specific swim power test. Our intention was to obtain front crawl arm-stroke swim power values (developed to an external load) by measuring the intra-cycle velocity and force, combined with a video recording.

Subjects
A group of 18 male swimmers (age 22.10 ± 4.31 years; stature 1.79 ± 0.07 m; arm span 1.85 ± 0.08 m; and body mass 76.74 ± 9.00 kg) volunteered to participate in this study. All participants had trained in swimming for at least 5 years and had competed at a regional or national level. The protocol was fully explained to the participants before they provided written consent to participate in the study, which was approved by the university ethics committee and was in accordance with the ethical standards of the IJSM [8].

Swim power assessment – power delivered to an external load
The test consisted of 12.5 m all-out front crawl swims across the pool while pulling a different load during each trial. After a standardised 800 m warm-up, the test started with a 4.5 kg load, although the real load pulled by each swimmer was 1.59 kg. The load increased by 2.5 kg for each trial. The swimmers rested for 5 min between 2 consecutive repetitions. The protocol ended when the swimmer was not able to complete a trial. After the first 5–6 m, which corresponded to the impulse from the wall and were not considered, 3 complete strokes were required to consider a trial for analysis. The test was recorded with 1 frontal and 2 lateral underwater cameras (Sony, frequency 50 Hz, shutter speed 1/250 s) that were fixed to the pool wall (Fig. 1).

The swim power (SP) output was calculated by multiplying the speed and force data produced against an external load. A linear velocity transducer was used to measure the intra-cycle speed (Sportmetrics S.L., Spain, frequency: 200 Hz, accuracy: 0.1 mm), and a force transducer was used to record the instantaneous force (Sportmetrics S.L., Spain, frequency: 200 Hz, accuracy: 0.01 N) while the swimmer displaced a load that was added by a block and tackle pulley system. One pulley was fixed 4 m high, and another was hung above the load. The swimmer was connected to the load by a rope (flexible but not elastic and taut due to the load) and a belt. The belt was attached to the speedometer wire (rigid) and to the load cell by a simple pulley, which changed the rope direction from the pulley system towards the water displacement path. The feet of each swimmer were tied together and a pull buoy was placed between their legs, which isolated the upper limb action. The leg action was excluded to avoid interaction with the arms and to prevent the feet from touching the wire and interfering with the measurements.

The pulley-system was calibrated with 6 loads (4.5, 9.5, 14.5, 19.5, 29.5 and 39.5 kg) placed in the same position as was used to measure the swim power. The following regression equation (x: the force value given by the load cell; y: the real force value obtained by multiplying the mass by the gravity acceleration; R²=0.9998) was used to correct the effect of the pulley system on our force data such as the mechanical advantage and the weight of the pulleys and the weight and friction of the rope:

\[ y = 0.5518x + 0.4752. \]

An example of the intra-cycle speed, force, and power curves obtained for each trial and subject is presented in Fig. 2. With the individual curves, we obtained the intra-cycle power that was delivered to an external load during the pull and push stroke phases [1] of the right arm, overlapped with the phases of the left limb (Fig. 3). The mean power for pull and push phases and peak stroke power was calculated for the trial where maximum power was delivered.
As the swim speed was assessed in each trial, we calculated the mean speed achieved in the MSP trial. Lastly, we assessed the relationship between the 25 m swim speed and the maximum swim power delivered to an external load.

Statistical analyses

Descriptive statistical methods were used to calculate means and standard deviations. The swim power variables (MSP and MSPR) did not follow the normal distribution (Shapiro-Wilk normality test). Therefore, Spearman’s correlation coefficient was calculated to describe the relationship between the maximum swim power delivered to an external weight (MSP and MSPR) and the 25 m swim speed. Statistical significance was set at p < 0.05. The statistical analysis was conducted with a statistical software package (SPSS 16.0).

Results

The maximum front crawl arm-stroke swim power in absolute values (MSP) and relative to body mass (MSPR) was 66.49 ± 19.09 W and 0.86 ± 0.21 W/kg, respectively. The load associated with the MSP was 3.95 ± 0.79 kg or 47.07 ± 9.45 % of the individual maximum load. The mean swimming speed achieved in the MSP trial was 0.75 ± 0.18 m/s (43.75 ± 8.94 % of the 25 m all-out sprint speed). The average swim power curve for the group is represented in Fig. 5.

During the MSP trial, the mean swimming power delivered during the push phase (71.21 ± 21.06 W) was greater than that recorded during the pull phase (60.32 ± 18.87 W). The peak stroke power was 114.37 ± 33.16 W. All these values correspond to the right arm phases, overlapped with the phases of the left limb (Fig. 3).

A significant positive relationship was observed between the maximum swim power and the 25 m swim speed (r = 0.76 and r = 0.73, p < 0.01, for absolute –MSP- and relative to body mass –MSPR- data, respectively) (Fig. 6).

Discussion

A unique finding of the present study is that the intra-cycle power output from different propulsive phases of the front crawl...
Arm-stroke was obtained by measuring intra-cycle force and speed synchronised with video recording at different loading intensities. A complete power vs. load curve was described, and the maximum swimming power (66.49±19.09W) was determined together with the corresponding load and swimming speed. A relatively easy-to-implement method for measuring swim power was presented; this method will potentially allow fast feedback for swimmers and coaches.

Despite the similarities between the arm actions in a bio-kinetic strength test and sprint swimming, only the power measure-ments made in the water are specific to the propulsive forces of front crawl swimming [2]. A limited number of scientific studies have analysed the front crawl swim power with contradictory results (© Table 1). In addition, the load corresponding to the maximal swim power has received little attention in the scientific literature. In the present study, we found that the absolute load that maximised the power output during swimming was 3.95 kg or 47.07% of the maximal load (as it is usually expressed for dry-land power [22]).

In agreement with our results, semi-resisted swim tests showed power values that ranged from 25 to 90 W. Some of the tests [12,14,29,38] used a weight rack; other studies [2,21,27,28] used an ergometer, which was placed on the pool edge and measured mean force and velocity. In doing so, it was possible to calculate the mean swim power for each trial. Among the first group, Johnson et al. [14] determined a MSP of 85 W with 1.5 kg. This value was higher than in the present study, possibly because in our study only the arm action was studied. The same load range was used in both studies, but only 2 loads were set in the former. Higher power levels might have been obtained with an intermediate load. Swaine and Doyle [30] obtained a mean power of 45.1 W; they considered only the arm action and had a test duration that was similar to this study. Given that this result was a mean value, the MSP would have been higher presumably and also similar to our MSP. Shionoya et al. [27] used an ergometer with several loads (1, 4, 7, 10 kg). The MSP was 51.20 W, developed to 9.53 kg, while in our study the MSP was achieved with 3.95 kg on average. A similar test [28] was made only with one 7 kg load (33 s long). Due to the longer test duration, the MSP was lower, but it was 44.5 when it was measured between seconds 5 and 10 of the test. For a similar load (7.21 kg), a mean power of 33.40 W was obtained in our study; the trials lasted approximately 12 s. Costill et al. [2] calculated an MSP of 55 W. Despite reaching higher speeds (0.3–1.6 m/s), the power was a bit lower than in the present study. Thus, it was deduced that the force values were possibly lower because the participants were younger.

Swim power can also be estimated by comparing the swim velocity with and without an added resistance under the assumption of equal power output in both cases (Velocity Perturbation Method – VPM, [17]). Using this method, Toussaint et al. [33] determined a mean swim power value during 25 m of free swimming (with no load) of 110.5 W. Consistently, the maximal swim power should have been higher than this value and may have been delivered to some load. Kolmogorov et al. [18] used the VPM to estimate a swim power of 225 W when swim-

![Image](https://example.com/image.png)

**Fig. 6** The correlation between maximum swimming speed and maximum swim power delivered to an external load. MSP: maximum swimming power; MSPR: maximum swimming power relative to body mass.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Test time/distance</th>
<th>Load</th>
<th>MSP (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costill et al. (1986)</td>
<td>STS</td>
<td>12 s (13 m)</td>
<td>5 speeds (from 0.3 to 1.6 m/s)</td>
<td>55</td>
</tr>
<tr>
<td>Dominguez-Castells &amp; Arellano</td>
<td>STS</td>
<td>10–12 s (12.5 m)</td>
<td>1.59–7.84 kg</td>
<td>66.49W; 0.86 W/kg (with 3.95 kg)</td>
</tr>
<tr>
<td>Hopper et al. (1983)</td>
<td>STS</td>
<td>5–10 s</td>
<td>from 13.5 kg, increases of 4.5 kg</td>
<td>0.54 per stroke*</td>
</tr>
<tr>
<td>Johnson et al. (1993)</td>
<td>STS</td>
<td>1.5, 7.8 kg</td>
<td></td>
<td>85 (with 1.5 kg)</td>
</tr>
<tr>
<td>Kolmogorov et al. (1997)</td>
<td>VPM</td>
<td>15–20 s (30 m)</td>
<td>additional hydrodynamic body</td>
<td>225</td>
</tr>
<tr>
<td>Saitoh et al. (2008)</td>
<td>STS</td>
<td>10 s</td>
<td></td>
<td>25–90*</td>
</tr>
<tr>
<td>Shionoya et al. (1999)</td>
<td>STS</td>
<td>7 s</td>
<td>1, 4, 7, 10 kg</td>
<td>51.20 (with 9.53 kg)</td>
</tr>
<tr>
<td>Shionoya et al. (2001)</td>
<td>STS</td>
<td>33 s</td>
<td>7 kg</td>
<td>26.9</td>
</tr>
<tr>
<td>Swaine &amp; Doyle (2000)</td>
<td>STS</td>
<td>10 s</td>
<td></td>
<td>45.1*</td>
</tr>
<tr>
<td>Toussaint et al. (2004)</td>
<td>VPM</td>
<td>25 m</td>
<td>0 kg</td>
<td>110.5*</td>
</tr>
<tr>
<td>Toussaint et al. (2006a)</td>
<td>MAD</td>
<td>14.79 s (25 m)</td>
<td>0 kg</td>
<td>200</td>
</tr>
<tr>
<td>Toussaint et al. (2006b)</td>
<td>MAD</td>
<td>24.27 s (50 m)</td>
<td>0 kg</td>
<td>220</td>
</tr>
</tbody>
</table>


*Mean instead of maximal swimming power
ming while pulling an additional hydrodynamic body. These swim power values are higher than in the present study, possibly because the power lost to give water kinetic energy was included in their measurements, and it was not in this study. However, ‘equal power assumption’ has been proved to be problematic [33] and may have led to some calculation errors.

Another classical method to estimate swim power is the MAD-system test [11], where the swimmers push off from fixed pads at each stroke. As they are connected to a force transducer, the push-off forces can be measured. 2 studies [31, 35] estimated the swim power values of 200 W and 220 W, respectively. As in the present study, the swimmers used their arms only, which should make both methods more comparable. However, in the MAD-system, no power was lost in transferring energy to the water (the push-off pads were fixed), and the force was only measured during the propulsive phases. Therefore, higher power values were obtained. No load was used and the fixed push-off points may have partially modified individual swimming techniques. The determination of speed on the MSP trial has seldom been addressed. Similar to the present results (0.75 m/s), the maximum swim power was achieved at a tether velocity of 0.93 m/s [2]. The values obtained by Toussaint et al. [31] and Toussaint and Truijens [35] (1.8 m/s and 2.06 m/s, respectively) are considerably higher, probably due to the high level of the swimmers or because the MAD-system (without load) was used. Knowing how fast their swimmers need to swim to develop their highest power may be useful information for coaches.

Swim power vs. different loads [15,27] or speeds [2,29] while semi-tethered has been represented. The former option was chosen in the present study to simplify the protocol. Swim power vs. load presented an inverted ‘U’ shape, similar to the dry-land power curves [22]. As the loads grew, the force needed to overcome them increased, while the speed decreased. The maximum swim power was developed from the best combination of force and speed. As the level of force grew more sharply with the loads than the speed decreased, the power would be expected to grow along with the test. However, this did not happen, possibly due to the loss of efficiency when a load becomes too heavy. The external work increases more than the work delivered to overcome drag, which makes the Froude efficiency decrease:

\[ \eta_f = \frac{W_f}{W_{net}} = \frac{W_f}{W_f + W_d} \]

Compared to previous studies, one improvement was that the intra-cycle force, speed and power data were considered in the present study, and an underwater video synchronised with the aforementioned recordings was included. This video enabled us to relate power to the overlapped stroke phases. The group mean swim power for the overlapped propulsive stroke phases of the right arm during the MSP trial was as follows: pull: 60.32 ± 18.87 W; push: 71.21 ± 21.06 W. Note that ‘push’ is the most powerful phase. The power for the entry and recovery phases was not reported, as these values would be highly affected by overlapping with the pull and push phases. The effect of the loads on the stroke and coordination parameters (including the Index of Coordination – IdC) was analysed in a recent study [4]. Future investigations should examine the relationship between swim power and the IdC in semi-tethered swimming.

As hypothesised, a high positive correlation between the maximum front crawl arm-stroke swim power and the 25 m swim speed was found, which confirmed the findings of Costill et al. [2] (r = 0.84), Johnson et al. [14] (r = 0.87), Shionoya et al. [28] (r = 0.88) and Shimomaga et al. [26] (r = 0.92). The correlation in our study was r = 0.76 for the MSP (absolute data) and r = 0.73 for the MSPr (relative to body mass) (p < 0.01). These results are in agreement with Morouço et al. [19], who affirmed that 50 m performances are more strongly associated with the absolute force values than with relative ones (normalised to body mass). Although the force production capacity might be expected to relate to muscle and body mass, it was suggested that in swimming this particular relationship might be affected by the specific ability of a swimmer to apply force in water. However, the Morouço et al. [19] study used tethered swimming, where the alteration of swimming technique may be more important than in semi-tethered swimming. This would explain the smaller difference found in the present study between the absolute and relative values. However, a positive association between the MSP and the 25 m swim speed does not necessarily mean causality. Therefore, further investigation (including intervention) is required to find out whether higher swim power measured with this protocol might lead to larger maximum swim speeds.

It is assumed as a limitation of the present study that some power components (e.g., energy given to water, added mass) were not measured; therefore, the total power developed by a swimmer was underestimated. However, a simplified test was developed to determine the power delivered to an external load. Coaches could take advantage of this updated methodology to periodically assess athlete power during training, observe the evolution of a swimmer and personalise in-water power development programs. Further studies are necessary to confirm the reliability of the method.

In conclusion, the maximal swimming power delivered to an external load was 66.49 ± 19.09 W, achieved with a load of 3.95 ± 0.79 kg and a swimming speed of 0.75 ± 0.18 m/s. The intra-cycle power output during the front crawl arm-stroke was examined by measuring the intra-cycle force and speed synchronised with video recording. The mean power during the push phase was higher than during the pull phase. A high positive correlation was found between the maximum swim power and the 25 m swim speed. An easily implemented method for measuring swim power was presented, and it will potentially allow for fast feedback for swimmers and coaches.

Acknowledgements

The authors would like to thank the group “Physical Activity and Sport in the Aquatic Environment” (CTS 527) and the Physical Education Department for providing all the necessary equipment and the Faculty of Physical Activity and Sport Sciences of University of Granada for allowing the use of the swimming pool and the fitness room. This study was possible thanks to a FPU fellowship (AP2008-03243) and a Project funded by VI National Plan for Research, Development and Technological Innovation (1+D+i) 2005-2008, Ref: DEP2009-08411, Ministry of Science and Innovation of Spain.

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Dominguez-Castells R et al. An Updated Protocol to... Int J Sports Med