International Doctoral Thesis / Tesis Doctoral Internacional

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Programa de Doctorado "Nuevas perspectivas en la investigación de las ciencias de la actividad física y el deporte"

Universidad de Granada

Rocío Domínguez Castells

2013

Editor: Editorial de la Universidad de Granada
Autor: Rocío Domínguez Castells
D.L.: GR 343-2014
ISBN: 978-84-9028-748-4

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Departamento de Educación Física y Deportiva

Facultad de Ciencias del Deporte

Universidad de Granada

Rocío Domínguez Castells

2013

Prof. Dr. Raúl Arellano Colomina
Catedrático de Universidad

Dpto. Educación Física y Deportiva
Facultad de Ciencias del Deporte
Universidad de Granada

RAÚL ARELLANO COLOMINA, CATEDRÁTICO DE LA UNIVERSIDAD DE GRANADA

CERTIFICA:

Que la Tesis Doctoral titulada "Estudio de la potencia aplicada en natación: su relación con la potencia muscular, la técnica y su modificación con el entrenamiento" que presenta, como agrupación de publicaciones, Dña. ROCÍO DOMÍNGUEZ CASTELLS al superior juicio del Tribunal que designe la Universidad de Granada, ha sido realizada bajo mi dirección durante los años 2009-2013, siendo expresión de la capacidad técnica e interpretativa de su autora en condiciones tan aventajadas que le hacen merecedor del Título de Doctor, siempre y cuando así lo considere el citado Tribunal.

Asimismo, expresa su aceptación de presentar los artículos de que es coautor dentro de esta tesis y su renuncia a presentarlos dentro de otra tesis.

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Prof. Dr. Mikel Izquierdo Redín
Catedrático de Universidad

Dpto. Ciencias de la Salud
Escuela Universitaria de Estudios Sanitarios
Universidad Pública de Navarra

MIKEL IZQUIERDO REDÍN, CATEDRÁTICO DE LA UNIVERSIDAD PÚBLICA DE NAVARRA

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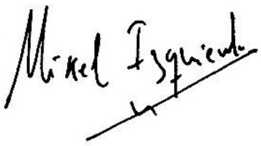

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CONTENTS

GRANTS

- Grant for technical assistance to innovation and teaching improvement within the project "*Podcasting and videopodcasting applied to teaching in the Master of Science Physical Activity and Sport*". Vice-chancellorship for Teaching and Innovation, University of Granada (July-December 2008).

- This thesis was possible thanks to a predoctoral fellowship (AP2008-03243) from the National Program for University Professors Education, awarded by the Spanish Ministry of Science and Innovation (2009-2013).

PUBLICATIONS

The following parts of this thesis have been published or submitted:

1. Domínguez-Castells, R., Arellano, R. (2012). Effect of different loads on stroke and coordination parameters during freestyle semi-tethered swimming. Journal of Human Kinetics, 32, 33-41. doi: 10.2478/v10078-012-0021-9. (Impact Factor: 0.33, Journal ranking: 4th Quartil; Sports Sciences).

2. Domínguez-Castells, R., Izquierdo, M., Arellano, R. (2013). An updated protocol to assess arm swimming power in front crawl. International Journal of Sports Medicine, 34 (4), 324-329. doi: 10.1055/s-0032-1323721. (Impact Factor: 2.43, Journal ranking: 1st Quartil; Sports Sciences).

3. Domínguez-Castells, R., Izquierdo, M., Arellano, R. How is dry-land power training transferred to swimming performance? Submitted to Human Movement Science in February 2013. (Impact Factor: 1.78, Journal ranking: 2nd Quartil; Sports Sciences).

Other publications related with this thesis:

1. Domínguez-Castells, R., Arellano, R. (2011). Muscular and arm crawl stroke power: evaluating their relationship. Portuguese Journal of Sport Sciences, 11 (Suppl. 2), 203-206.

2. Domínguez-Castells, R., Arellano, R., Morales, E., Perez-Infantes, E. (2010). Potencia aplicada en natación y su relación con la potencia muscular en “press” de banca. Presented at the XXXIII Congreso de la Sociedad Ibérica de Biomecánica y Biomateriales. Valencia, Spain.

3. Domínguez-Castells, R., Morales, E., Arellano, R. (2012). Arm coordination in semi-tethered swimming**.** Presented at the 17th Annual Congress of the European College of Sport Science. Brugge, Belgium.

4. Domínguez-Castells, R., Schreven, S., van der Vliet, R., Toussaint, H. M., Arellano, R. (2012). Dry-land exercises to assess arm power on swimmers. Presented at the 7th International Congress of the Spanish Association of Sport Sciences. Granada, Spain.

Abstract

Muscle power output is a critical issue in sport performance. Thus, since swim power is a reliable predictor of swim speed in front crawl, it is considered an important practical issue in swimming. Therefore, the main purposes of this thesis were to further investigate upper-limb swimming power output, to determine the relationships among swimming power, dry-land muscular power output and swimming velocity, and to assess the effect of power training on dry-land power and swimming performance.

Despite the importance of swim power, a complete power curve (power vs. load) for swimming has not been described, and intra-cycle power has not been quantitatively assessed. In **Chapter 2**, intra-cycle power output during propulsive phases was examined. The maximum swimming power, the corresponding load and swimming speed were also determined. Eighteen male swimmers performed a swim power test for this purpose. It consisted of 12.5-m all-out swims using only the arms, with a load attached to the swimmer. A linear encoder and a load cell recorded intra-cycle speed and force, respectively, in each trial. The test was recorded with two underwater cameras. Intra-cycle power was obtained for propulsive stroke phases (pull: 60.32±18.87 W; push: 71.21±21.06 W). Mean maximum swim power was 66.49 W (0.86 W/kg), which was achieved at a swimming velocity of 0.75m/s with a 47.07 % of the individual maximal load. Significant positive correlation ($r = 0.76$, $p < 0.01$) between maximum swim power and maximum swim speed was observed. These results suggested that the proposed test may be a useful training tool that is relatively simple to implement and would provide swimmers and coaches with quick feedback.

The former protocol may be used in resisted swimming training to develop specific swim power. The continued use of resisted swimming in training may have, however, an effect on several swimming parameters. In **Chapter 3**, it was analysed to what extent the use of load during semi-tethered swimming modifies the freestyle stroke and coordination parameters, and it was examined whether those changes are positive or negative to swimming performance. First, behaviour of swim speed (v), stroke rate (SR) and stroke length (SL) with increasing load was examined. Secondly, mean and peak speed of propulsive phases ($propv_{mean}$ and $propv_{peak}$) were analysed, as well as the relative difference between them (%v). Finally, index of coordination (IdC) was assessed. The same sample and protocol as in Chapter 2 were used. Variables v and SL decreased significantly when load increased ($p < 0.05$), while SR remained constant. $Propv_{mean}$ and $propv_{peak}$ decreased significantly with increasing load ($p < 0.05$). In contrast, %v grew when load rose ($r = 0.922$, $p < 0.01$), being significantly different from free swimming over 4.71 kg. For loads heavier than 4.71 kg, swimmers did not manage to keep a constant velocity during a complete trial. IdC was found to increase with load, significantly over 2.84 kg ($p < 0.05$). It was concluded that semi-tethered swimming is a useful training method to enhance swimmers' performance, although load needs to be individually determined and carefully controlled.

It is accepted that power measured during swimming is a better predictor of swim velocity than power measured on dry-land exercises. In **Chapter 4**, dry-land power and swim power values were obtained by means of different methods. The relationships among dry-land power, swim power and swim velocity in each case were determined, and these relationships were compared between methods. The bench press power was higher than arm stroke power and swim power. Complete power vs. load curves were represented for bench press and semi-tethered swimming. High correlations were found between power on dry-land exercises and swim power, being higher for the arm stroke exercise. There was a high and significant correlation between swim velocity and swim power; it was high but not significant between swim velocity and arm stroke power, and moderate and almost significant between swim velocity and bench press power. This confirmed that swimming is the most specific way to measure swim power, although the arm stroke exercise may be a suitable dry-land alternative.

However, despite muscular power being positively related to optimal performance, this does not necessarily indicate that training power will enhance swimming performance. The effects of an easy-to-implement dry-land power training program on arm muscular power were assessed in **Chapter 5**, and whether this resulted in faster sprint swimming was determined. Eight male swimmers performed dry-land power tests (bench press and bench pull) and swimming velocity tests (free, 2.5 kg, 5 kg, 7.5 kg) before and after a 7-week training period. The maximum propulsive power increased significantly on bench press (7.27±7.77 %, ES=0.60) and bench pull (7.52±6.99 %, ES=0.52) after seven weeks of training. Free swimming velocity increased significantly (15.59±6.61 %, ES=1.61), as well as when swimming pulling three different loads. Stroke rate decreased in free swimming, while stroke length was enhanced in every condition. These findings suggest that dry-land power training may be an effective method to complement and optimise swimming training.

The results of this thesis evidence the important role of power in swimming, as it happens in many other sports.

Resumen

La potencia muscular es un elemento de crucial importancia en el rendimiento deportivo. Así, dado que la potencia de nado es una buena variable predictiva de la velocidad de nado en el estilo crol, se considera un elemento importante en la práctica de la natación. Por tanto, los principales objetivos de esta tesis fueron investigar con mayor profundidad la potencia de nado en el tren superior, determinar las relaciones entre la potencia de nado, la potencia muscular en seco y la velocidad de nado, y evaluar el efecto de un entrenamiento de potencia sobre la potencia muscular en seco y el rendimiento en natación.

A pesar de la importancia de la potencia de nado, no se ha descrito previamente una curva completa de potencia (potencia vs. carga) en natación, y la potencia intraciclo no se ha evaluado cuantitativamente. En el **Capítulo 2** se analizó la potencia intraciclo durante las fases propulsivas del ciclo. También se determinaron la máxima potencia de nado y la carga y velocidad de nado correspondientes. Dieciocho nadadores realizaron un test de potencia de nado, que consistió en desplazar una carga a lo largo de 12.5 m, nadando a estilo crol a máxima velocidad, utilizando sólo los brazos. En cada repetición se registraron la velocidad y la fuerza intraciclo mediante un encóder lineal y una célula de carga, respectivamente. El test se grabó con dos cámaras subacuáticas. Se obtuvo la potencia intraciclo para las fases propulsivas (tracción: 60.32±18.87 W; empuje: 71.21±21.06 W). La máxima potencia de nado promedio fue de 66.49W (0.86W/kg). Fue alcanzada a una velocidad de nado de 0.75 m/s, con un 47.07 % de la máxima carga individual. Se observó una correlación significativa y positiva ($r = 0.76$, $p < 0.01$) entre la máxima potencia de nado y la máxima velocidad de nado. Estos resultados indicaron que el test propuesto podría constituir una herramienta útil de entrenamiento, relativamente simple de utilizar y que podría proporcionar feedback de forma rápida a nadadores y entrenadores.

El protocolo anterior podría utilizarse en el entrenamiento de natación resistida para desarrollar la potencia específica de nado. Sin embargo, el uso continuado de la natación resistida en el entrenamiento podría tener cierto efecto sobre diferentes parámetros. En el **Capítulo 3** se analizó en qué medida el uso de cargas en la natación semi-resistida modifica diversas variables técnicas y de coordinación en el estilo crol. En primer lugar, se examinó el comportamiento de la velocidad de nado (v), la frecuencia de ciclo (SR) y la longitud de ciclo (SL) ante el aumento de la carga. Se analizaron las velocidades media y pico de las fases propulsivas ($propv_{mean}$ y $propv_{peak}$), así como la diferencia relativa entre ellas (%v). Por último, se evaluó el índice de coordinación (IdC). Para ello se utilizaron la misma muestra y el mismo protocolo que en el Capítulo 2. Las variables v y SL disminuyeron significativamente con el aumento de la carga ($p < 0.05$), mientras que SR permaneció constante. $Propv_{mean}$ y $propv_{peak}$ se redujeron de forma significativa a medida que la carga aumentó ($p < 0.05$). Por el contrario, %v creció cuando la carga se incrementó ($r = 0.922$, $p < 0.01$), siendo significativamente diferente del nado sin carga a partir de 4.71 kg. Para cargas superiores a este valor, los

nadadores no fueron capaces de mantener una velocidad constante durante una repetición completa. IdC aumentó con la carga, de forma significativa a partir de 2.84 kg ($p < 0.05$). Se concluyó que la natación semi-resistida es un método útil para mejorar el rendimiento de los nadadores, aunque la carga ha de ser controlada y determinada de forma individual.

Es conocido que la potencia medida durante la natación real permite una mejor predicción de la velocidad de nado que la potencia medida en ejercicios en seco. En el **Capítulo 4** se obtuvieron valores de potencia en seco y potencia de nado a través de diferentes métodos. En cada caso, se determinaron las relaciones entre la potencia en seco, la potencia de nado y la velocidad de nado, y se compararon estas relaciones entre sí. La potencia en press de banca fue superior a la potencia en el ejercicio de tracción de brazos, y ambas mayores que la potencia de nado. Se representaron curvas completas de potencia vs. carga para press de banca y natación semi-resistida. Se encontraron altas correlaciones entre la potencia en los ejercicios en seco y la potencia de nado, siendo mayor para el ejercicio de tracción de brazos. La correlación fue alta y significativa entre la velocidad de nado y la potencia de nado, alta pero no significativa entre la velocidad de nado y la potencia en el ejercicio de tracción de brazos, y moderada y casi significativa entre la velocidad de nado y la potencia en press de banca. Estos resultados confirmaron que la natación real es el método más específico para medir potencia de nado, aunque el ejercicio de tracción de brazos podría ser una alternativa adecuada fuera del agua.

Sin embargo, a pesar de que la potencia muscular se relaciona positivamente con el máximo rendimiento, esto no significa que el entrenamiento de la potencia mejore el rendimiento en natación. En el **Capítulo 5** se evaluaron los efectos de un programa de entrenamiento en seco dirigido a mejorar la potencia sobre la potencia muscular, y se determinó si este efecto provocó un aumento de la velocidad de nado. Ocho nadadores realizaron tests de potencia en seco (press de banca y remo tumbado) y tests de velocidad de nado (sin carga, con 2.5 kg, 5 kg y 7.5 kg), antes y después de un periodo de entrenamiento de siete semanas de duración. La máxima potencia propulsiva aumentó significativamente tras las siete semanas, tanto en press de banca (7.27±7.77 %, ES=0.60) como en remo tumbado (7.52±6.99 %, ES=0.52). La velocidad de nado sin carga aumentó de forma significativa (15.59±6.61 %, ES=1.61). También lo hicieron las tres velocidades de nado con carga. La frecuencia de ciclo disminuyó en el nado sin carga, mientras que la longitud de ciclo aumentó en todas las condiciones. Estos resultados sugieren que el entrenamiento de potencia en seco podría ser un método efectivo para complementar y optimizar el entrenamiento en el agua en natación.

Los resultados de esta tesis ponen de manifiesto el importante papel de la potencia en la natación, tal como ocurre en muchos otros deportes.

Chapter 1

Introduction

In physics, power is the rate at which work is performed. The same amount of work can be done at different velocities, being a higher power developed when this work is done faster. The unit of power in the International System is the watt (W). Equation (1) must be used to calculate the average power over a period of time. Similarly, instantaneous power may be calculated as shown in equation (2). Power in mechanical systems is the combination of forces and movement. In particular, linear power is the product of a force on an object and the object's velocity (equation (3)).

$$P_{avg} = \frac{\Delta W}{\Delta t} \ (1) \ ; \qquad P_{inst} = \frac{dW}{dt} \ (2) \ ; \qquad P(t) = F(t) \cdot v(t) \ (3)$$

Muscle power output is a critical issue in sport performance. In many sports the training program includes a section focused on developing muscular and/or applied power. Unfortunately, sport-specific assessment methods for muscle power output of the arms and legs for swimming are poorly developed compared with other sports (Swaine, 2000). Due to this fact, we became interested in measuring and studying this variable in swimming. We focused on the upper limb, since the swim power output developed by the arms was found to be higher than that developed by the legs (Swaine & Doyle, 2000). Within the assessment of power in swimmers, tests can be divided into three categories: a) dry-land tests for measuring muscular power output on non-specific exercises; b) dry-land tests for measuring power output using swimming movements; and c) in-water tests for measuring power during actual swimming.

1.1. Dry-land tests for measuring muscular power output on non-specific exercises.

The most commonly used methods for measuring muscular power output in the upper limb are described in Table 1. They may be used for any kind of athletes, including swimmers.

Bench press is one of the main exercises used in upper body strength training. When the power tests reviewed involved the bench press exercise, the participants lay supine on a flat bench, placing the legs on the floor, the bench or in the air, depending on the authors. Each participant was instructed to lower the bar to the chest, in a slow and controlled manner and wait there, until hearing a command from an evaluator. After this short pause, a concentric contraction with maximal velocity was executed, finishing with extended elbows. Athletes were not allowed to bounce the bar off their chests or raise the shoulders or trunk off the bench.

Table 1. Brief description of dry-land tests used for measuring muscular power output on non-specific exercises.

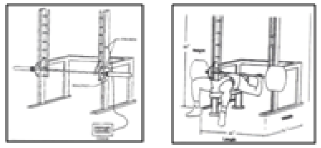
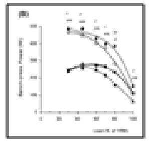
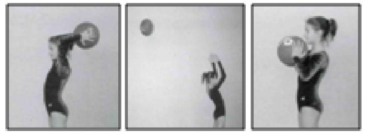
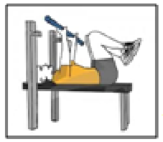
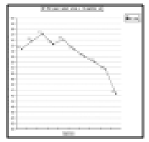
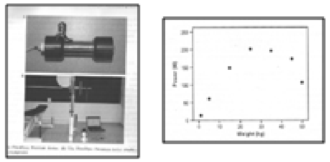
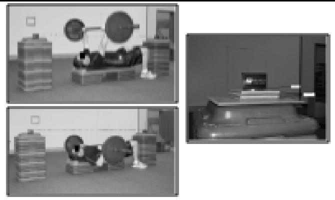
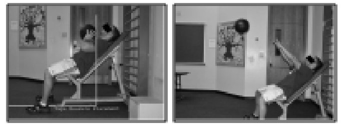
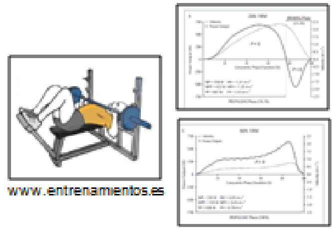
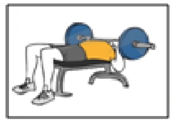
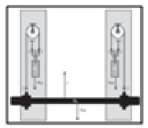
AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE
Murphy & Wilson (1996) Cochrane & Hawke (2007)	Medicine ball throw.	Throwing distance	Sitting on a bench, 15° from vertical, and tied to it, the athletes performed two and four chest throws, respectively. 15 s rest. Take-off angle should be close to 37° from horizontal. 4 and 3-kg ball, respectively. No contribution of legs or trunk.	
Shim, Bailey & Westings (2001)	Incremental test on bench press with relative loads, using a digital timing device with magnetic sensors.	Displacement Time Force Mean power per load Maximum mean power	On bench press, the athletes performed three explosive repetitions with each load (30, 40, 50, 60, 70 and 80% 1RM). 2 min rest between repetitions.	
Izquierdo, Hakkinen, Gonzalez-Badillo, Ibáñez & Gorostiaga (2002)	Incremental test on bench press with relative loads. Rotary encoder attached to the bar.	Displacement Velocity Mean power per load Maximum power	On bench press, the athletes performed two repetitions at maximal velocity with 30, 45, 60, 70, 80 and 100% 1RM. 1.5 min rest.	
Salonia, Chu, Cheifetz & Freidhoff (2004)	Medicine ball throw.	Throwing distance	From a standing position, the athletes performed two repetitions of one of three types of throw: overhead forward throw, overhead backward throw or chest pass throw. 2 min rest. 6-lb (2.72-kg) ball.	
Requena, Zabala, Ribas, Ereline, Paasuke & González-Badillo (2005)	Incremental test on bench press with absolute loads. Rotary encoder attached to the bar.	Mean power per load Maximum power	On bench press, the athletes performed two repetitions with each load, throwing the bar at maximal velocity. 10-kg increments, starting with 10 kg until 1RM. 3 min rest.	 www.entrenamientos.es
Baker & Newton (2007)	Power output test across a high-repetition set on bench press. Rotary encoder attached to the bar.	Mean power per repetition	On bench press, the athletes performed ten repetitions with 60 kg (≈ 45% 1RM), throwing the bar at maximal velocity.	
Jandacka & Vaverka (2008)	Incremental test on bench press with relative loads. Rotary encoder attached to the bar.	Velocity Mean power per load Maximum power	On bench press, the athletes performed two repetitions at maximal velocity with 0, 10, 30, 50, 70, 90 y 100% 1RM. 3 min rest.	

Table 1. Brief description of dry-land tests used for measuring muscular power output on non-specific exercises.

AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE
Clemons, Campbell, & Jeansonne (2010)	Bench press power test using infra-red light.	Time Mean power (P = m·g·s/t)	On bench press, the athletes performed three repetitions at maximal velocity with 61.4 kg (males) or 25 kg (females). 2 min rest between reps. Timing was initiated manually at the moment of upward bar movement and stopped automatically when the bar broke an infrared beam 0.3 m above the chest.	
Clemons, Campbell, & Jeansonne (2010)	Medicine ball put.	Throwing distance	Sitting on a bench, 45° from vertical, the athletes performed two chest throws. 2 min rest. Take-off angle should be close to 45° from horizontal. 6 and 9-kg ball for women and men, respectively. No contribution of legs or trunk.	
Garrido, Marinho, Barbosa, Costa, Silva, Pérez-Turpin & Marques (2010)	Medicine ball throw using a radar gun.	Maximal ball velocity Throwing distance	Sitting on the floor with their back against the wall, the swimmers performed three throws at maximal velocity with 1 and 3-kg medicine balls. 1 min rest.	
Sanchez-Medina, Perez & Gonzalez-Badillo (2010)	Incremental test on bench press with absolute loads. Linear encoder attached to the bar.	Displacement Velocity Acceleration Force Mean propulsive power Maximum mean propulsive power	On bench press, the athletes performed 3, 2 or 1 repetition at maximal velocity with light, medium and heavy loads, respectively. Initial load was 20 kg. 10-kg increments until the mean propulsive velocity (MPV) was lower than 0.5 m · s $^{-1}$. Thereafter, 5-kg increments were used until 1RM. 2-3 min rest for light and medium loads, 5-6 for the heavy ones. Only the propulsive phase of the movement (a ≥ − 9.81 m • s $^{-2}$) was considered for analysis. The braking phase (a < -g) was excluded.	
Silva, Fields, Heymsfield & Sardinha (2010)	Incremental test on bench press with absolute loads. Linear encoder attached to the bar.	Displacement Velocity Mean power per load	On bench press, the athletes performed three repetitions at maximal velocity with each load. 5-kg increments. 3 min rest.	
Kobayashi, Narazaki, Akagi, Nakagaki, Kawamori, Ohta (2013)	Incremental test on bench press with absolute loads. Linear encoder attached to the bar.	Displacement Velocity Acceleration Force Power (see Figure)	On bench press, the athletes performed two repetitions with each load, throwing the bar at maximal velocity. From 15 kg to 40 kg, with 5-kg increments.	$F_2 = (M_b - M_c)g + (M_b + \frac{M_c}{2})\ddot{y}$  $P_2 = F_2\dot{y}$

In this thesis, the former protocol was used to determine muscular power output, letting the participants choose the leg position, which they felt most comfortable with. The bar throw was not used because it was not possible to do the same on bench pull, which was also included in the second study of this thesis. Instead, in order to avoid underestimation of power, only the propulsive phase ($a \geq -g$) of the movement was considered for analysis (Sánchez-Medina, Perez, & Gonzalez-Badillo, 2010). The braking phase ($a < -g$) was excluded. Absolute loads were utilised for the tests and the obtained power data were expressed in both absolute values and relative to body mass.

In a more specific approach, the bench pull was the second exercise used in the present thesis for evaluation of upper-body muscle power. In doing so, the swimmer was able to develop power in a supine position, closer to the front crawl swimming position. The athletes started with the elbows extended to the ground and were asked to raise the bar to the chest as fast as possible. This movement was also more similar to the arm propulsive actions performed during swimming. This exercise will be further explained in Chapter 5.

Finally, a pilot testing with the front-crawl arm stroke exercise is included in Chapter 3. Leaning against an inclined bench, the swimmers were asked to perform a shoulder flexion, simulating the pull-push swimming action. The swimmers were instructed to keep the elbows extended during the complete exercise, to exclude the effect of the different pulling techniques.

1.2. Dry-land tests for measuring power output using swimming movements.

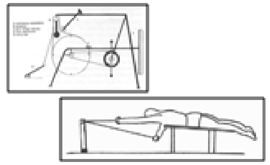
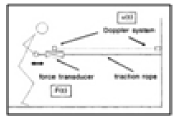
Still in the dry-land environment, specific methods may be used to measure power during simulated swimming. The principal methods for measuring power output using swimming movements are briefly described in Table 2. These methods allow to control the load and the muscles involved.

Two kinds of equipment were mostly used in this category: the cycle ergometer and the swim bench. The former one was modified to be used as an arm ergometer, while the latter one allowed the swimmer to better reproduce the arm swimming movements. Several protocols were applied with these methods, being the Wingate test the most usual one.

Front crawl movements were used in most of the tests, although butterfly and, in one case, breaststroke, were also employed (Cavanaigh & Musch, 1989; Barzdukas, Spry, Cappaert & Troup, 1992; Klauck & Daniel, 1992; Takahashi, Bone, Cappaert, Barzdukas, D'Aquisto, Hollander & Troup, 1992; Trappe, Costill & Thomas, 2001; Shimonagata, Taguchi & Miura, 2002).

Dry-land methods for measuring power during simulated swimming were not used in the present thesis.

Table 2. Brief description of dry-land tests used for measuring power output during simulated swimming.

AUTHORS	EQUIPMENT	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE
Cavanaigh & Musch (1989)	Biokinetic swim bench	Mean arm power	In a prone position, the swimmers simulated all-out butterfly swimming arm movements during 90 s. Speed setting: 4, 50 strokes/min.	
Rohrs, Mayhew, Arabas & Shelton (1990)	Arm ergometer Biokinetic swim bench	Peak arm power Mean arm power Single-arm pulling force	a) Wingate test on a cycle arm ergometer: sitting on a chair, the swimmers stroked for 30 s at maximal velocity. b) Three maximal arm pulls with each arm on a swim bench. c) 30-s maximal anaerobic power test, simulating front crawl on a swim bench.	
Hawley & Williams (1991)	Upper-body ergometer	Mean arm power (every 5 s and total, relative to body mass) Peak arm power (relative to body mass) Fatigue index (power drop-off): (PP-MP last 5s)·100/PP	Wingate anaerobic arm test: sitting on the floor, the swimmers had to crank at maximal velocity for 30 s. Forces chosen were 48 g/kg body mass for females and 62 g/kg body mass for males.	
Reilly & Marshall (1991)	Biokinetic swim bench	Mean arm power Maximum arm power	30-s test, all-out stroking on the swim bench, speed setting: 4.	
Roberts, Termin, Reilly & Pendergast (1991)	Swim bench Brake ergometer	Stroking velocity Mean arm power	a) Three trials at speed settings of 0, 3, 6, 9 (1.44, 2.05, 2.66, 3.28 m/s) on the swim bench. b) 45 s stroking at speed setting 0 (lightest resistance) on the swim bench. c) Wingate test: 30 s cranking with both arms on a mechanical brake ergometer placed on a table at shoulder height.	
Barzdukas, Spry, Cappaert & Troup (1992)	Biokinetic swim ergometer	Mean arm power Maximum arm power	In prone position, the swimmers did four sets of three bilateral arm pulls at speed settings 0, 3, 6, 9. The highest power of each set was considered.	
Hawley, Williams, Vickovic & Handcock (1992)	Arm ergometer	Mean arm power Maximum arm power Peak sustained workload	a) Upper body Wingate anaerobic test: 30 s stroking at maximal velocity with a resistance of 0.037kg · kg^{-1} body mass for males and 0.029 kg · kg^{-1} body mass for females. b) Maximal sustained power output test: arm cranking at 80 r.p.m. against an increasing workload (+16 W every 2 min) until a cadence of 70 rpm could not be maintained. Initial work rate: 24 W/min for males and 16 W/min for females.	
Klauck & Daniel (1992)	Traction elastic ropes	Instantaneous arm force Instantaneous hand velocity Instantaneous power: P(t) = F(t)·v(t)	In standing position, the swimmers simulated swimming movements (butterfly and breaststroke) while pulling a rope. A strain gauge load cell and an ultra-sound Doppler velocimeter were placed on the rope to measure force and velocity, respectively.	

MP: mean power; PP: peak power.

Table 2. Brief description of dry-land tests used for measuring power output during simulated swimming.

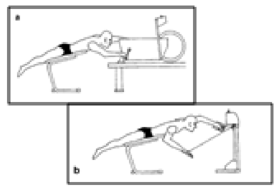
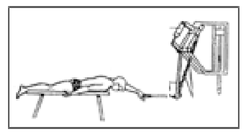
AUTHORS	EQUIPMENT	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE
Takahashi, Bone, Cappaert, Barzdukas, D'Aquisto, Hollander & Troup (1992)	Isokinetic swim bench	Peak power Mean arm force and power in the last 5 s Total work Fatigue ratio (% of power decrease)	a) One double-arm pull. b) 45 s of double-arm pull at maximal velocity.	
Bradshaw & Hoyle (1993)	Biokinetic swim bench	Mean arm power	Stroking for the same time duration (and same number of strokes) as in their individual best 25-m arms-only sprint (15.47±1.45 s).	
Johnson, Sharp & Hedrick (1993)	Biokinetic swim bench	Stroking velocity Peak arm power Maximum power per speed	Three arm strokes at speed settings of 0, 3, 6, 9.	
Swaine (1996)	Isokinetic swim bench	Force Distance Work (W) Time (t) Mean power Critical power: slope 'b' in the equation W = a+bt	Critical power test: in prone position, the swimmers did four all-out sets to exhaustion on a swim bench. 1 h rest. Resistances: 100, 125, 150, 175 W.	
Swaine & Winter (1999)	Modified cycle ergometer Isokinetic swim bench	Peak exercise intensity Peak VO_2	a) Arm cranking on a modified cycle ergometer, with increments of 10 W/min. b) Simulated front-crawl arm-pull on an isokinetic arm bench, with increments of 1 W every 6 s. Initial load for a) and b): 35 W. 50 strokes/min. Tests ended voluntarily at exhaustion or when power could not be maintained by the swimmer.	
Fomitchenko (2000)	Huttel-Mertence device	Total power (P = load·nr strokes·arm length)	Maximal 30-s test simulating swimming movements on the Huttel-Mertence device.	 Platonov & Fessenko(1984)
Swaine (2000)	Isokinetic swim bench	Distance Force Mean arm power Peak arm power	30-s all-out front-crawl stroking on a swim bench with isokinetic resistance pulley-ropes.	
Trappe, Costill & Thomas (2001)	Biokinetic swim bench	Highest arm power output for each setting	Four maximal double arm pulls at each of each speed setting: 0, 3, 6, 9.	

Table 2. Brief description of dry-land tests used for measuring power output during simulated swimming.

AUTHORS	EQUIPMENT	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE
Potts, Charlton & Smith (2002)	Biokinetic swim bench	Instantaneous right- and left-arm power (100 Hz) Mean right- and left-arm power every 30 s Relative contribution of right and left arm to total power output	Four incremental tests to exhaustion on swim bench. 1-week intervals. Initial load: individual. Increments: 1 W every 6 s.	
Shimonagata, Taguchi & Miura (2002)	Biokinetic swim bench	Maximum stroke power Arm stroke power endurance	Five maximum two-arm strokes at 2.49 m/s. 60 strokes in 1 min (freq: 1 Hz).	
Petriaev & Kleshnev (2006)	Swim bench with visual immediate feedback	Power Force Velocity Stroke rate Stroke length Stroke dynamical structure Mean arm power Maximum arm power	a) T10: 10 butterfly strokes with maximal intensity. b) T1: 1 min at competitive intensity. c) ST10: 10x1 min, increasing power.	
Trinity, Pahnke, Reese & Coyle (2006)	Arm ergometer with inertial loading	Stroking velocity Maximum arm power	Lying on a bench in prone position, swimmers completed four trials of 3-5 s of maximal effort. Inertial load used was 3.65 kg/m^2. 1 min rest.	
Swaine (2010)	Whole-body swimming training machine	Mean power output for each arm stroke	Two reps of an incremental test to volitional exhaustion. Initial work rate: 100 W; increments: 25 W/min. Four-limb swimming action should be simulated as close as possible.	
Nikolaidis (2012)	Arm-cranking ergometer	Mean arm power in each sprint Maximum arm power	Five sprints at maximal velocity, each lasting 7 s. Initial braking force was 20 N. Increments of 10 N. 5 min rest.	

1.3. Aquatic tests for measuring power during actual swimming.

Even though both kinds of exercise use the muscles of the upper body, muscle groups involved during simulated swimming on the swim bench are different and/or smaller, and maximal stress on the cardio-respiratory system is lower when compared to actual swimming (Ogita & Taniguchi, 1995). Despite the similarities between the arm actions in the biokinetic strength test and sprint swimming, only measurements of power made in the water are specific to the propulsive forces of front crawl swimming (Costill, Rayfield, Kirwan, & Thomas, 1986). Most of the studies found in the literature found a positive correlation between swim power and sprint swim velocity. It was shown that strength and power measured in swimming (tethered or semi-tethered swimming) are more reliable predictors of swim velocity than strength and power measured in dry-land tests (Vorontsov, 2011).

Measuring power in an aquatic environment entails methodological difficulties that do not exist in a dry-land environment. Therefore, varied methods for measuring the power a swimmer is able to develop while displacing through the water have been proposed in the literature. Some of these methods are summarized in Table 3, together with some of the obtained values. A wide range of power values was found due to the lack of standardization of the power measurements and/or protocols, and/or due to subject characteristics. MAD (Measurement of Active Drag) system, VPM (Velocity Perturbation Method) and ATM (Assisted Towing Method) yielded higher values than the different versions of STS (Semi-Tethered Swimming).

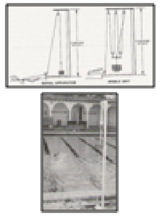
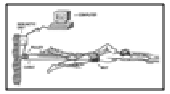
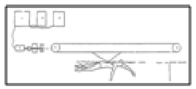
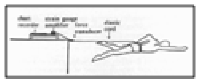
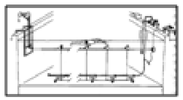
STS methods have been widely used in different versions. Most of them used an ergometer, which was placed on the pool deck and connected to the swimmer by a rope or a cable, to measure mean swimming force and velocity. This method is relatively easy to implement and the power calculation is simple ($P = F \cdot v$). In contrast to the mean data approach, intra-cycle force, velocity and power data were used, synchronised with video recording, to allow for technical analysis and qualitative feedback during backstroke swimming (Alves, Santos, Veloso, Correia, & Gomes-Pereira, 1994). In swimming, power is used to give the water kinetic energy and to overcome drag. Only the last component is measured by STS methods. The semi-tethered condition presents other limitations, such as longer duration of the aquatic phase of the stroke (especially the last part), compared to free swimming (Maglischo, Maglischo, Sharp, Zier, & Katz, 1984). Furthermore, the testing distance is in most cases limited by the experimental set-up. This was overcome by the Velocity Perturbation Method (VPM; Kolmogorov & Duplischeva, 1992), which allowed for calculation of active drag by attaching a known additional drag to the swimmers. The main limitation of this method is the equal power assumption in free swimming and carrying a hydrodynamic body, which is still a controversial issue. On the MAD (Measurement of Active Drag) system the swimmer swam at constant velocity pushing on pads fixed on a rod mounted 0.8 m below the water surface along the length of the pool. Force was measured by a force transducer placed at the end of the rod. Since the pads are fixed, no energy is transferred to the water in this method. Therefore, the power produced by the swimmer is fully used to overcome drag. This method has been criticised due to the changes in swimming technique in respect to actual swimming, where propulsion is created in different planes.

Measurement of pulling force during tethered swimming may be used in the swimming flume over a range of velocities to determine swim power. A common recommendation is to use elastic cords in order to eliminate interference from dynamic impacts at the beginning of every swimming stroke.

In the present thesis, a STS method was employed. Intra-cycle velocity and force were measured, from which intra-cycle power was calculated. Video footage was synchronised with the previous signals, allowing for analysis of power along the stroke cycle in front crawl. Several loads were progressively attached to the swimmer, obtaining a swim power curve, similar to those typical from dry-land exercises.

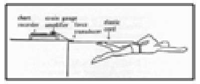
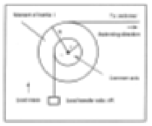
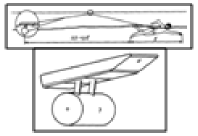
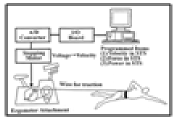
In this introduction, a review of the main methods to measure power in dry-land and aquatic conditions has been conducted. This methodological comparison is the starting point for the rest of the thesis. For more specific comments about the related topics, see the introduction of each chapter.

Table 3. Description of aquatic tests used for measuring power during actual swimming. 'Max swim power' means peak swim power in the tests where there is only one load or velocity. It means maximum mean swim power when the test consists of several trials with different loads or velocities. When male and female data are given separately, only male data are included in this table. When different swimming strokes are studied, only values for front crawl are selected.

AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE	MEAN SWIM POWER (W)	MAX SWIM POWER (W)	P-V RELATIONSHIP
Hopper, Hadley, Piva & Bambauer (1983)	STS with a pulley system	Distance swum Time Weight (force) Number of strokes Power/stroke delivered to an external weight Maximum power/stroke	Three to ten maximal-effort swims against a resistance on a five-pulley system (mechanical advantage 5:1). 1 min rest. Initial load: 13.5 kg, 4.5-kg increments. Swim time since the load starts to move until it reaches the top pulley was measured.			P/stroke: 0.54±0.15 kg·m/s/stroke	P/stroke - 50-m freestyle time: r = -0.80
Costill, Rayfield, Kirwan & Thomas (1986)	STS with a biokinetic system	Velocity Force Work Power (absolute and relative to body mass)	Five all-out swimming trials for 13 m at several velocities between 0.3 and 1.6 m/s. A cable was attached to a biokietic system on one side and to the swimmer on the other. The force generated was measured by a force transducer placed in the biokinetic system.		43.6±3.3 W (0.656 W/kg) (average of all trials)	55 W	swim P - 22.86-m v (25 yd): r = 0.84
Ria, Falgairette, & Robert (1990)	STS with force and optical sensor	Instantaneous propulsive force Instantaneous swim velocity Mean external mechanical power (absolute and relative to body mass): EMP = F·v	Two 6-s maximal effort front-crawl swimming. The swimmer was connected to a pole and a force sensor (which measured the propulsive force) and to a pulley through a stiff cable. The velocity was measured by an optical sensor.	force:  velocity: 	71.2±17.3 W 1.80±0.44 W/kg		EMP - 50-m v: r = 0.70 EMP - 100-m v: r = 0.72 relative EMP - 50-m v: r = 0.70 relative EMP - 100-m v: r = 0.80
Rohrs, Mayhew, Arabas & Shelton (1990)	STS with a force transducer	Peak force Mean force	Semi-tethered anaerobic swim test: swimmers had to swim for 30 s against the resistance of an elastic cord, which was connected to a force transducer.		F = 0.138 ±0.034 N/kg	F = 0.173 ±0.038 N/kg	not significant (heterogeneous level sample)
Toussaint & Vervoorn (1990)	MAD system	Mean swim velocity Mean swim force Mean swim power (P = F·v)	The swimmers swam 25 m at maximal velocity (arms only) pushing off 16 fix pads, which were mounted on a rod at 0.8 m below the surface. One end of the rod was connected to a force transducer, which measured propulsive force. Velocity was calculated from time to cover 18.9 m.			142.5±39. W to 171.6±51.3 W, depending on the group and training condition	P - 50-m time: r = -0.83 P - 100-m time: r = -0.74 P - 200-m time: r = -0.59

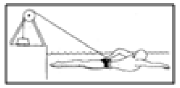
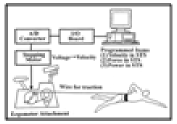
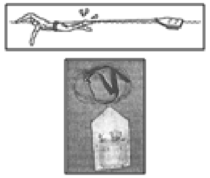
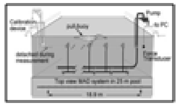
STS: semi-tethered swimming; EESP: equipment for estimating swimming power; MAD: measurement of active drag; VPM: velocity perturbation method; ATM: assisted towing method; EMP: external mechanical power (W); v: velocity (m/s); F: force (N); P: power (W); m: mass of load (kg); M: mass of the swimmer + added hydrodynamical mass; I: moment of inertia of the wheel system; v_s: swimmer's speed; r, R: radii of the wheel system; h: height of the load mass (m).

Table 3. Description of aquatic tests used for measuring power during actual swimming.

AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE	MEAN SWIM POWER (W)	MAX SWIM POWER (W)	P-V RELATIONSHIP
Rohrs & Stager (1991)	STS with a force transducer	Peak force Mean force	Semi-tethered anaerobic swim test: swimmers had to swim for 30 s against the resistance of an elastic cord, which was connected to a force transducer.		F = 10.8±1.3 N	F = 12.5±1.7 N	max swim F - v 22.86m: r = 0.53 max swim F - 45.72-m v: r = 0.63 max swim F - 91.44-m v: r = 0.55 mean swim F - 22.86-m v: r=0.47 mean swim F - 45.72-m v: r=0.45 mean swim F - 91.44-m v: r=0.37
Johnson, Sharp & Hedrick (1993)	STS using a power rack with an electronic timing system	Mean power for each resistance (absolute and relative to body mass) Maximum swim power Power/stroke at each resistance	The swimmers swam once at each resistance of 0.5, 1.5, 3.1, 4.7, 6.2, 7.8 and 9.3 kg.			85±23 W	max P – v max (22.86 m): r =0.87 P 1.5kg – v max: r = 0.88 P 7.8kg – v max: r = 0.84
Klauck & Ungerechts (1997)	STS with an electro-optical system	Swim velocity Mechanical power delivered to an external weight	Swimming against resistances of 20, 40, 60, 80, 100 kg. Power is calculated according to the equation: $P=mg\frac{r}{R}\frac{(h(T)-h(0))}{T}+\frac{1}{2T}(v_s^2(T)-v_s^2(0))(m\frac{r^2}{R^2}+M+\frac{I}{R^2})*$			75 W, if speed is considered constant; 550 W, if acceleration is included	
Kolmogorov, Rumyantseva, Gordon & Cappaert (1997)	VPM	Mechanical power output (P = active drag·max swim v)	2x30 m all-out swimming: 1 free swimming + 1 carrying a hydrodynamic body.			225 W (group with highest velocity)	
D'Acquisto & Costill (1998)	STS using an isokinetic dynamometer	Velocity Force Mean power	The swimmers had to swim for 22.86 m at 0.9 m/s (mean velocity), while connected to an isokinetic dynamometer through a wire. Force was measured by a force transducer.		64.45±17.63 W		P - 22.86-m v: not significant P - 91.4-m v: r = 0.91 P – 365.8-m v: r = 0.86
Shionoya, Shibukura, Koizumi, Shimizu, Tachikawa, Hasegawa & Miyake (1999)	STS with an ergometer attachment	Mean force, velocity and power for each load Maximum power Load for max power Force-power curve	Each swimmer was instructed to swim at full strength for 7 s with 1, 4, 7 and 10 kgf traction, without pushing off the wall.		1 kg: 17.10±1.45 W; 4 kg: 41.20±1.50 W; 7 kg: 49.10±2.65 W; 10 kg: 50.70±3.89 W	51.20±3.91 W	P with 7 kg - front crawl performance: r = 0.87
Fomitchenko (2000)	VPM	Total external mechanical power	2x50 m all-out swimming: 1 free swimming + 1 with an additional hydrodynamic body.				Total P - 25-m v: r = 0.64 and r = 0.94 for 13.8 and 17.4 year-old swimmers, respectively

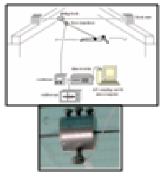
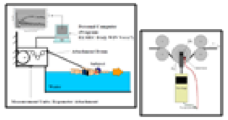
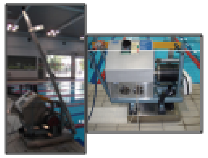
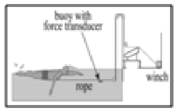
STS: semi-tethered swimming; EESP: equipment for estimating swimming power; MAD: measurement of active drag; VPM: velocity perturbation method; ATM: assisted towing method; EMP: external mechanical power (W); v: velocity (m/s); F: force (N); P: power (W); m: mass of load (kg); M: mass of the swimmer + added hydrodynamical mass; I: moment of inertia of the wheel system; v_s: swimmer's speed; r, R: radii of the wheel system; h: height of the load mass (m).

Table 3. Description of aquatic tests used for measuring power during actual swimming.

AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE	MEAN SWIM POWER (W)	MAX SWIM POWER (W)	P-V RELATIONSHIP
Swaine & Doyle (2000)	STS with a weight rack	Time Distance Weight Mean arm power output for each load Maximum mean power output	All-out bouts of arm stroking until the load reached the top (10 s approx.). The load range used was 20-50 N. Time was measured by two opto-switches placed on the weight rack.		only arms: 45.1±3.4 W		
Trappe, Costill & Thomas (2000)	Tethered isokinetic device	Force and power every 3 s Mean power at 1 m/s	The athletes swam at maximal velocity pulling an isokinetic device, which was set at 1 m/s.		114±8 W		
Shionoya, Shibukura, Shimizu, Ohba, Tachikawa & Miyake (2001)	STS with an ergometer attachment	Mean power in 3 phases of the test and average of the 33 s Power decreasing rate between phases	STS33 test: 33-s all-out swimming against 7-kg traction.		26.9±7.5 W	From seconds 5-10: 44.5±7.7 W	mean P – 50-m v: r = 0.88 mean P – 100-m v: r = 0.94
Shimonagata, Taguchi & Miura (2002)	STS with EESP	Swim velocity every 10 m EESP drag force Mean swim power for each trial Maximum swim power Swim power reduction coefficient	a) 5x25 m all-out: 1 free swimming + 4 STS with EESP (floating body + resistant part). b) 1x50 m all-out with EESP.			100.71±11.50 W	max swim P – 25-m v: r = 0.92 swim velocity reduction coefficient on 100 m freestyle - swim power reduction coefficient on 50 m: r = 0.65
White & Stager (2004)	STS with a pulley system	Mean swim power ($P = F \cdot v$) Maximum swim power	10-m sets of all-out swimming against a resistance coming from a pulley system. Resistance increased progressively until power peaked.				max P - max v (13.72 m): $R^2 = 0.85$ (non linear relationship: $P_{max} = 11.4 \cdot v_{max}^{3.37}$)
Toussaint, Carol, Kranenborg & Truijens (2006)	MAD system, modified to measure force in both directions	Mean velocity Mean force Mean power ($P = F \cdot v$) Work per stroke	100-m front crawl swimming on the MAD (arms only), measuring power every 25 m (25-m pool). Swimmers started from the water (push-off starts) and turned using touch turns (not tumble turns).			200 W	$P = K \cdot v^3$
Toussaint & Truijens (2006)	MAD system	Mean velocity Mean force Mean power ($P = F \cdot v$)	25 m all-out front crawl swimming (only arms) on the MAD system.			arms only: 220 W; arms and legs: 281 W	$P = K \cdot v^n$ ($P = 27.37 \cdot v^{2.821}$)

STS: semi-tethered swimming; EESP: equipment for estimating swimming power; MAD: measurement of active drag; VPM: velocity perturbation method; ATM: assisted towing method; EMP: external mechanical power (W); v: velocity (m/s); F: force (N); P: power (W); m: mass of load (kg); M: mass of the swimmer + added hydrodynamical mass; I: moment of inertia of the wheel system; v_s: swimmer's speed; r, R: radii of the wheel system; h: height of the load mass (m).

Table 3. Description of aquatic tests used for measuring power during actual swimming.

AUTHORS	METHOD	OBTAINED VARIABLES	PROTOCOL DESCRIPTION	FIGURE	MEAN SWIM POWER (W)	MAX SWIM POWER (W)	P-V RELATIONSHIP
Vorontsov, Popov, Binevsky & Dyrko (2006)	Tethered swimming in a flume	Flow velocity Mean pulling force	The swimmer was instructed to exert maximal effort for 5-6 s while tethered in a flume. Eight flow velocities were used: 0.6, 0.8, 1, 1.2, 1.4, 1.5, 1.6, 1.7 m/s. 1.5 min rest.			calculated from paper: 118.2 W	
Xin-Feng, Lian-Ze, Wei-Xing, De-Jian & Xiong (2007)	VPM using a gliding block	Maximum free velocity Maximum velocity with additional drag Additional drag Active drag	1x25 m all-out swimming + 10 min rest + 1x25 m with an additional drag, provided by a gliding block. The swimmers were connected to the gliding block and a force transducer measured the force.		calculated from paper: 130.20±56.54 W		
Saijoh, Ohba & Shionoya (2008)	STS with ergometer attachment	Mean swim force Mean swim velocity Mean swim power (P = F·v)	Force was measured by a force gauge and velocity by an optical sensor.		40-90 W		
Mason, Formosa & Rollason (2009)	ATM, using a towing device mounted on a force platform	Maximum free swim velocity Towing swim velocity Mean propulsive force (active drag) Mean propulsive power at maximum velocity	3x10-m free swimming trials at maximum velocity + 5x20-m assisted swimming trials (5% faster than max v). Four strokes were considered for analysis.		421.48±107.52 W		
Tomikawa & Nomura (2009)	VPM	Maximal mechanical power output	2x25 m all-out swimming: 1 free swimming + 1 carrying a hydrodynamic body. 5 min rest. The swimmers did the test twice: wearing their swim suit and wearing a wetsuit.			With swim suit: 131.2±46.2 W; with wetsuit: 135.6±36.9 W	swim suit: P max - 25-m v: r = 0.75 wetsuit: P max - 25-m v: r = 0.86
Seifert, Toussaint, Alberty, Schnitzler & Chollet (2010)	MAD system	Mean power to overcome drag for every speed (P_d = Drag·v)	Intermittent graded speed test in randomized order, using front crawl with arms only on the MAD-system (10x25 m), from ~60% to 100% of maximal speed (increment: 0.05 m/s - 5%).			national level: 214.2 W; regional level: 181.0 W	P - 25-m v: r = 0.79
Formosa, Toussaint, Mason & Burkett (2012)	ATM, using a towing device and a strain gauge	Maximum free swim velocity Towing swim velocity Towing force Active drag	3x10-m free swimming trials at maximum velocity + 3x20-m assisted swimming trials (10% faster than max v).		calculated from paper: 249.14 W		

STS: semi-tethered swimming; EESP: equipment for estimating swimming power; MAD: measurement of active drag; VPM: velocity perturbation method; ATM: assisted towing method; EMP: external mechanical power (W); v: velocity (m/s); F: force (N); P: power (W); m: mass of load (kg); M: mass of the swimmer + added hydrodynamical mass; I: moment of inertia of the wheel system; v_s: swimmer's speed; r, R: radii of the wheel system; h: height of the load mass (m).

Outline of this Thesis

The present thesis attempts to understand the importance of upper-body power in front crawl swimming. The behavior of this variable and the relationships with dry-land muscular power output, as well as with swimming velocity, will be determined. The effects of a dry-land power-oriented training on swimming performance will be assessed. Three studies will be conducted to achieve these purposes. Firstly, in Study 1, a protocol to measure swim power is proposed and swim power is assessed. Moreover, maximal swim velocity, dry-land power and dry-land maximal strength are determined. A dry-land training program is administered in Study 2 and its effects are evaluated. Lastly, in Study 3, swim power, maximal swim velocity and dry-land power are measured by means of different methods from Study 1 and compared.

The content of this thesis is divided into six chapters. In **Chapter 2**, a complete swim power vs. load curve is obtained by means of an updated protocol, together with the maximum swim power and the corresponding load and swim speed. The intra-cycle power is analysed and compared to video footage. Finally, the relationship between the maximum swim power and the 25 m swim velocity is determined. *(Study 1)*

In **Chapter 3**, the effect of the use of loads on front crawl stroking and coordination parameters is analysed. It is examined whether those changes are positive or negative regarding swimming performance. *(Study 1)*

Relationships among dry-land muscular power output (measured on different exercises), swim power (measured by means of two different protocols, including the one presented in Chapter 2) and swim velocity are established and discussed in **Chapter 4**. *(Studies 1 and 3)*

The effects of a power-oriented dry-land training program for the upper limb on dry-land power and swimming performance are evaluated in **Chapter 5**. *(Study 2)*

In **Chapter 6**, the main conclusions of the previous research projects are summarized. Practical recommendations regarding power testing and training in swimmers are presented along with future research areas.

Aims

A review on methods to measure power on swimmers, both dry-land and in water, was completed. Given the importance this variable has in swimming and in many other sports, the main purposes of this thesis were: to further investigate swimming power output, to determine the relationships among swimming power, dry-land muscular power output and swimming velocity, and to assess the effect of power training on dry-land power and swimming performance. The specific objectives of the present thesis are listed below:

- 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. *(Study 1, Chapter 2)*

- To obtain a complete swim power vs. load curve, which will enable the determination of the maximum swim power along with the corresponding load and swim velocity. *(Study 1, Chapter 2)*

- To analyse the effects that the use of loads in semi-tethered swimming may have on stroke and coordination parameters. *(Study 1, Chapter 3)*

- To assess and compare the relationships among dry-land muscular power output, swim power and swim velocity, measured by means of different methods. *(Studies 1 and 3, Chapter 4)*

- To determine the effects of a dry-land power training program during seven weeks on upper body muscular power and whether this resulted in faster front crawl sprint swimming. *(Study 2, Chapter 5)*

Objetivos

Se realizó una revisión acerca de los métodos disponibles para medir la potencia en nadadores, tanto en seco como dentro del agua. Dada la importancia que esta variable tiene en natación y en otros muchos deportes, los principales objetivos de esta tesis fueron: analizar la potencia de nado en mayor profundidad, determinar las relaciones entre la potencia de nado, la potencia muscular en seco y la velocidad de nado, y evaluar el efecto del entrenamiento de potencia sobre la potencia en seco y el rendimiento en natación. Los objetivos específicos de la presente tesis se enumeran a continuación:

- Examinar la potencia intraciclo durante las fases de tracción y empuje del estilo crol, midiendo la fuerza y velocidad intraciclo sincronizadas con la grabación en vídeo. *(Estudio 1, Capítulo 2)*

- Obtener un curva de potencia de nado vs. carga, que permitirá determinar la máxima potencia en natación, junto con las correspondientes carga y velocidad de nado. *(Estudio 1, Capítulo 2)*

- Analizar los efectos que la aplicación de cargas en la natación semi-resistida puede tener sobre variables relativas al ciclo natatorio y su coordinación. *(Estudio 1, Capítulo 3)*

- Evaluar y comparar las relaciones entre la potencia muscular en seco, la potencia en natación y la velocidad de nado, medidas a través de diferentes métodos. *(Estudios 1 y 3, Capítulo 4)*

- Determinar los efectos de un programa de entrenamiento de potencia en seco durante siete semanas sobre la potencia muscular del tren superior, y observar si estos efectos se tradujeron en un aumento de la velocidad de nado en el estilo crol. *(Estudio 2, Capítulo 5)*

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Chapter 2

An updated protocol to assess arm swimming power in front crawl

Domínguez-Castells, R., Izquierdo, M., Arellano, R.

Published in International Journal of Sports Medicine.

Abstract

Mechanical power output is a reliable predictor of swim speed in front crawl. However, a complete power curve (power vs. load) has not been described for swimming, and intra-cycle power has not been assessed. The purpose of this study was to examine intra-cycle power output at propulsive phases and to determine maximum swimming power, the corresponding load and swimming speed. Eighteen swimmers (age 22.10±4.31 years, height 1.79±0.07 m, arm span 1.85±0.08 m and body mass 76.74±9.00 kg) performed a swim power test. It consisted of 12.5 m all-out swims with only the arms, with a load attached to the swimmer. A linear encoder and a load cell recorded intra-cycle speed and force in each trial. The test was recorded with two underwater cameras. Intra-cycle power was obtained for propulsive stroke phases (pull: 60.32±18.87 W; push: 71.21±21.06 W). Peak power was 114.37±33.16 W. Mean maximum swim power was 66.49 W (0.86 W/kg), which was reached at a swimming velocity of 0.75 m/s with a 47.07 % of the individual maximal load. Significant positive correlation ($r = 0.76$, $p < 0.01$) between maximum swim power and maximum swim speed was observed. These results suggest that the proposed test may be a training tool that is relatively simple to implement and would provide swimmers and coaches with quick feedback.

Keywords: semi-tethered swimming, intra-cycle speed, stroke phases.

Introduction

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, 24, 25, 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 [7], 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 two different methods: the MAD (Measuring Active Drag) system [11, 32, 35] and VPM (Velocity Perturbation Method) [16]. However, constant body velocity was assumed in the former and constant power output in two 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. 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 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 [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 each trial. The swimmers rested for 5 minutes between two 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, three complete strokes were required to consider a trial for analysis. The test was recorded with one frontal and two lateral underwater cameras (Sony, frequency 50 Hz, shutter speed 1/250 s) that were fixed to the pool wall (Figure 1).

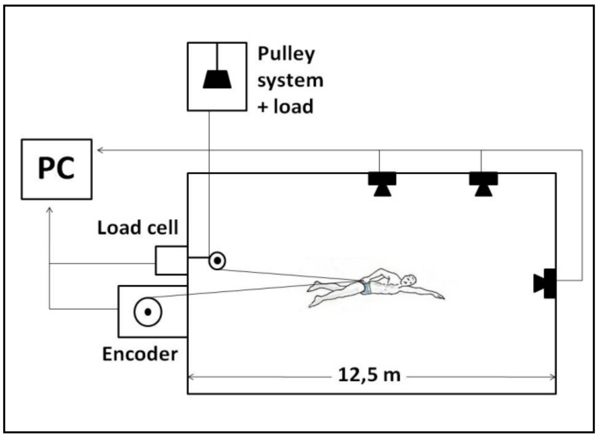

Figure 1. Layout of the swimming power test.

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: 0.01N) 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 his 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 six 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; $R^2 = 0.9998$) was used to correct the effect of the pulley system on our force data such as the mechanical advantage and 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 Figure 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 (Figure 3). The mean power for pull and push phases and peak stroke power was calculated for the trial where maximum power was delivered.

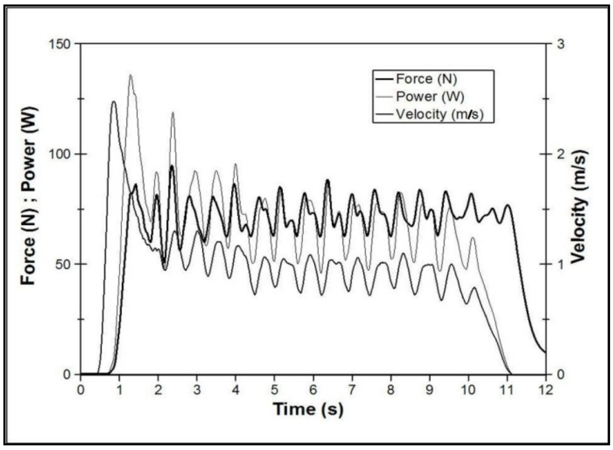

Figure 2. An example of the intra-cycle speed, force and power curves. The first pronounced increase is due to the impulse from the wall. The decrease at the end corresponds to the moment when the swimmer stops.

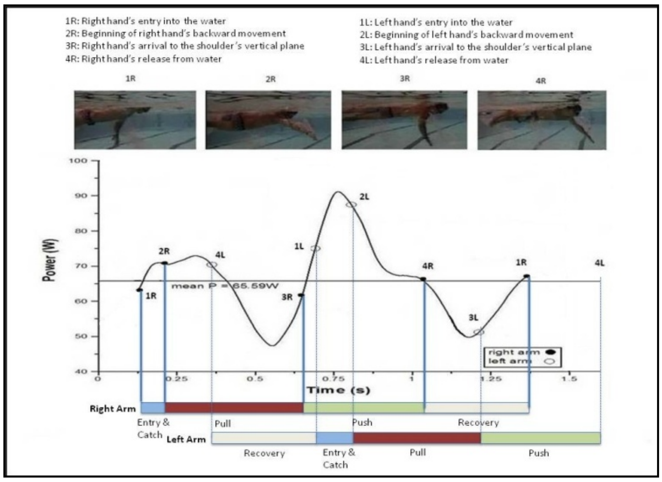

Figure 3. An example of individual intra-cycle swim power related to the different stroke phases. The overlapping of phases from both arms is represented. The points indicate the beginning of each phase for both arms (1R-4L). The video frames are shown for 1R-4R. The mean power for right arm propulsive phases was 61.97 W (pull) and 75.69 W (push).

For each trial, we selected three middle strokes to avoid the effect of the impulse from the wall and the speed decrease at the end. From these three strokes, we obtained a mean swimming power (SP) value for each subject and trial, and then we provided the individual power curves (power vs. load) for the complete test. An example is shown in Figure 4. For each swimmer, we selected the maximum SP value of the whole test, which was called the maximum swimming power (MSP). For each load, we calculated the mean power for all of the subjects and obtained an average power curve. We also calculated the mean MSP for the whole group, the maximum swimming power relative to body mass (MSPR), and the percentage of the individual maximum load that was associated with the MSP. Additionally, the group average power was calculated for each stroke phase in the MSP trial. 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.

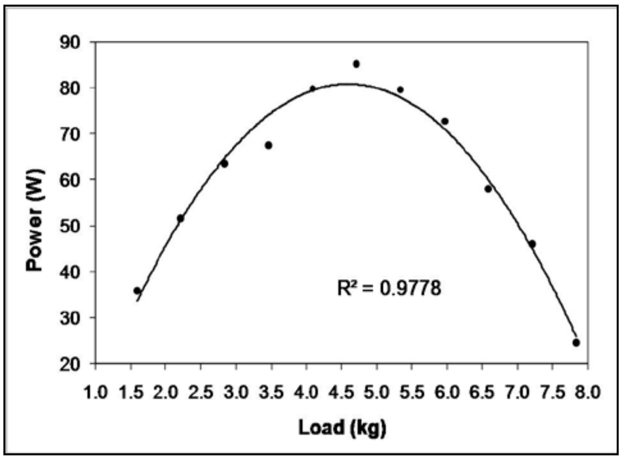

Figure 4. The swim power curve. An example of individual swim power values along the test. The actual loads after the pulley system effects are 1.59, 2.21, 2.84, 3.46, 4.09, 4.71, 5.34, 5.96, 6.59, 7.21 and 7.84 kg.

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 Figure 5.

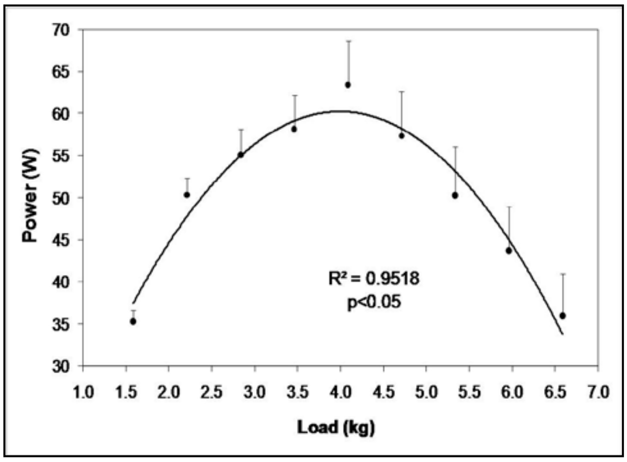

Figure 5. Group swim power curve. Average swim power for each load and all participants during the swim power test. The actual loads after the pulley system effects are: 1.59, 2.21, 2.84, 3.46, 4.09, 4.71, 5.34, 5.96, 6.59, 7.21 and 7.84 kg.

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 (Figure 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) (Figure 6).

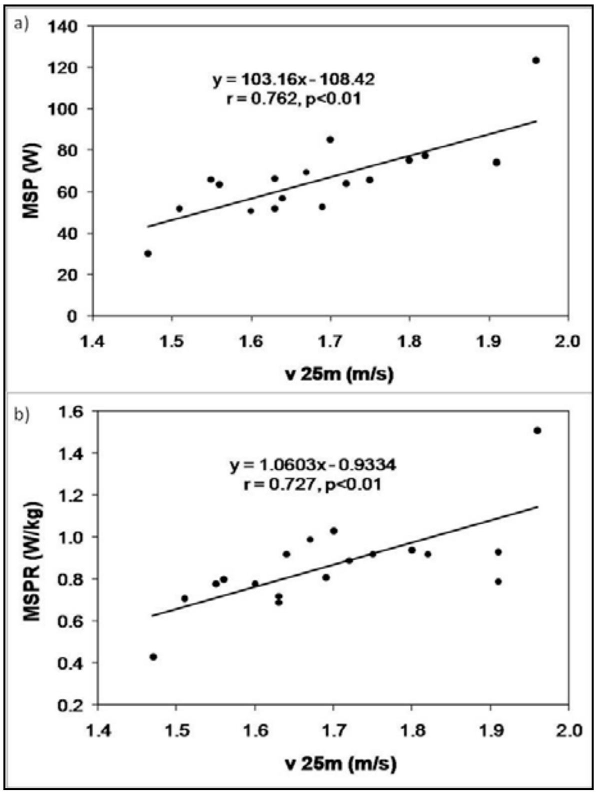

Figure 6. The correlation between maximum swimming speed and maximum swim power delivered to an external load. MSP: maximum swimming power; MSPR: maximum swimming power relative to body mass.

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±19.09 W) 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 measurements 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]).

Table 1. Maximal swimming power (front crawl) calculated in other studies.

Authors	Method	Test time/distance	Load	MSP (W)
Costill et al. (1986)	STS	12 s (13 m)	5 speeds (from 0.3 to 1.6 m/s)	55
Dominguez-Castells & Arellano (2012)	STS	10-12 s (12.5 m)	1.59-7.84 kg	66.49 W; 0.86 W/kg (with 3.95 kg)
Hopper et al. (1983)	STS	5-10 s	from 13.5 kg, increases of 4.5 kg	0.54 per stroke*
Johnson et al. (1993)	STS		1.5, 7.8 kg	85 (with 1.5 kg)
Kolmogorov et al. (1997)	VPM	15-20 s (30 m)	additional hydrodynamic body	225
Saijoh et al. (2008)	STS	10 s		25-90*
Shionoya et al. (1999)	STS	7 s	1, 4, 7, 10 kg	51.20 (with 9.53 kg)
Shionoya et al. (2001)	STS	33 s	7 kg	26.9
Swaine & Doyle (2000)	STS	10 s		45.1*
Toussaint et al. (2004)	VPM	25 m	0 kg	110.5*
Toussaint et al. (2006a)	MAD	14.79 s (25 m)	0 kg	200
Toussaint et al. (2006b)	MAD	24.27 s (50 m)	0 kg	220

MSP: maximum swim power. STS: semi-tethered swimming. VPM: Velocity Perturbation Method. MAD: Measurement of Active Drag. *Mean instead of maximal swimming power.

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 two 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 9.53kg, 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 time 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 swimming 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. Two 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:

$$\eta_F = \frac{W_d}{W_{ext}} = \frac{W_d}{W_k + W_d}.$$

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 Shimonagata 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. 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 gymnasium. This study was possible thanks to a FPU fellowship (AP2008-03243), funded by the Ministry of Science and Innovation of Spain.

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Chapter 3

Effect of different loads on stroke and coordination parameters during freestyle semi-tethered swimming

Domínguez-Castells, R., Arellano, R.

Published in Journal of Human Kinetics.

Abstract

The aim of this study was to analyse to what extent the use of different loads modifies freestyle stroke and coordination parameters during semi-tethered swimming, and to examine whether those changes are positive or negative to swimming performance. First, behaviour of swimming speed (v), stroke rate (SR) and stroke length (SL) with increasing loads was examined. Secondly, mean and peak speed of propulsive phases ($propv_{mean}$ and $propv_{peak}$) were analysed, as well as the relative difference between them (%v). Finally, index of coordination (IdC) was assessed. Eighteen male swimmers (22.10±4.31 years, 1.79±0.07 m, 76.74±9.00 kg) performed 12.5-m sprints, pulling a different load each trial (0, 1.59, 2.21, 2.84, 3.46, 4.09, 4.71, 5.34, 5.96, 6.59, 7.21 and 7.84 kg). Rest between repetitions was five minutes. Their feet were tied together, keeping a pull-buoy between legs and isolating the upper limb action. A speedometer was used to measure intra-cycle speed and the test was recorded by a frontal and a lateral underwater cameras. Variables v and SL decreased significantly when load increased, while SR remained constant ($p < 0.05$). $Propv_{mean}$ and $propv_{peak}$ decreased significantly with increasing loads ($p < 0.05$). In contrast, %v grew when load rose ($r = 0.922$, $p < 0.01$), being significantly different from free swimming above 4.71 kg. For higher loads, swimmers did not manage to keep a constant velocity during a complete trial. IdC was found to increase with loads, significantly from 2.84 kg ($p < 0.05$). It was concluded that semi-tethered swimming is one training method useful to enhance swimmers' performance, but load needs to be individually determined and carefully controlled.

Keywords: intra-cycle speed, propulsive phases, index of coordination, resisted training.

Introduction

In swimming, race time can be divided into four components: start time, swimming time, turn time and finish time (Arellano et al., 1994). Regarding actual swimming, the time needed to complete one lap can be considered as a function of stroke rate and stroke length. As in other cyclical activities, swimmers need to find the optimal compromise between stroke rate and stroke length to attain and keep the maximal velocity during a race (Alberty et al., 2005).

Numerous studies have been carried out to observe and understand the evolution of this “SL × SR” model during competitive events (Arellano et al., 1994; Chollet et al., 1997; Craig et al., 1985). Throughout the race, as fatigue develops, speed and stroke length decrease whereas stroke rate remains constant or slightly increases at the end of the race (Alberty et al., 2009; Chollet et al., 1997; Craig et al., 1985; Hay, 2002; Keskinen and Komi, 1993). Swimmers can choose different strategies to develop their maximal speed as a function of the race distance and they attempt to maintain this chosen speed in spite of fatigue throughout the race.

Stroke rate and stroke length combinations (and, therefore, speed values) are determined by several factors such as anthropomorphic variables, muscle strength, physical conditioning and swimming economy (Pelayo et al., 2007). Another factor with big influence on swimming speed is load (Shionoya et al., 1999). In the latter study, they assessed speeds from 1.34m/s with 1kg load to 0.45m/s with 10kg load, but stroking parameters were not studied. To our knowledge, only one recent study has analysed speed, stroke rate and stroke length while semi-tethered swimming with increasing resistances (Gourgoulis et al., 2010).

In contrast, swimming speed during propulsive stroke phases has not been previously studied under resisted conditions. Considering the stroke phases proposed by Chollet et al., (2000), we can distinguish two propulsive phases (pull and push) and two non-propulsive ones (entry-catch and recovery). Regardless of every individual combination of stroke rate and stroke length, swimming speed is expected to be higher during propulsive phases in both free and semi-tethered swimming. Intra-cycle velocity variations were studied at different swimming paces (Schnitzler et al., 2010) and while swimming with parachute (Schnitzler et al., 2011), but not with different loads. To the authors’ knowledge, only one study (Telles et al., 2011) has examined changes in index of coordination (IdC) in three different resisted swimming conditions.

Therefore, the aim of the present study was to analyze to what extent the use of different loads modifies freestyle stroke and coordination parameters during semi-tethered swimming, and to examine whether those changes are positive or negative to swimming performance. With this analysis it was intended to bring light to the value of semi-tethered swimming for training purposes.

Materials and Methods

Participants

A group of 18 male college swimmers volunteered to participate in our study (mean 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). All of them had trained in swimming for at least 5 years and had competed at regional or national level (25-m time =14.84±1.21 s). The protocol was fully explained to them before they provided written consent to participate in the study, which was approved by the university ethics committee.

Procedures

The test was conducted in one swimming pool session, at the end of the competitive season. It consisted in 12.5 m swimming across the pool, at maximal speed, pulling a different load each trial, which was added by means of a pulley system. The swimmers rested five minutes between two consecutive repetitions. After a standardized 800-m warm-up, first load was 4.5 kg and it increased 2.5 kg each trial. Considering the pulley system effects (mechanical advantage, friction and components weight), real loads pulled by the swimmers were 0, 1.59, 2.21, 2.84, 3.46, 4.09, 4.71, 5.34, 5.96, 6.59, 7.21 and 7.84 kg. This was checked prior to the test, in the same conditions. Swimmers were connected to the load by means of a rope and a belt. Their feet were tied together, keeping a pull-buoy between legs and isolating the upper limb action. They were asked not to breathe during each trial to keep head position constant.

Measurements

A speedometer attached to the swimmer's belt was used to measure intra-cycle swimming speed (Sportmetrics S.L., Spain, frequency: 200 Hz, accuracy: 0.1 mm). The test was recorded by a frontal and a lateral underwater cameras (Sony, frequency: 50 Hz, shutter speed: 1/250 s), fixed to the pool wall.

Analysis

Intra-cycle speed was recorded for every participant and trial. It was sampled at a frequency of 200 Hz and subsequently smoothed with a fourth-order low-pass Butterworth filter with a cut-off frequency of 5 Hz. For each trial, three middle strokes were selected to avoid both the effect of the impulse from the wall and the speed decrease at the end. One stroke started when one hand first touched the water while entering it and finished the next time the same event happened for the same hand. Mean speed (v) was calculated for these 3 strokes. Stroke rate (SR) was calculated from the 3 strokes time:

SR (Hz) = number of strokes / strokes time (s)

Then, stroke length (SL) was obtained with the following equation:

$$SL(m/cic) = \frac{v(m/s)}{SR(Hz)}$$

Average of every variable for the whole group and every single load was calculated and represented. Intra-cycle speed curves were compared among swimmers and loads, to try to find any repeated patterns.

Within the stroke phases defined by Chollet et al. (2000), 'pull' and 'push' were considered the propulsive ones. 'Pull' phase starts after the hand´s entry into the water, when it reaches the most forward point and begins to move backwards. It ends when the hand is under the shoulder, on an imaginary vertical line. Here begins the 'push' phase, which ends at the moment the hand is completely out of water. With intra-cycle speed and video images mean and peak speed for the propulsive phases (pull and push) in three strokes ($propv_{mean}$ and $propv_{peak}$, respectively) were obtained for each trial and swimmer. In addition, percentage of increase from $propv_{mean}$ to $propv_{peak}$ (%v) was calculated. This variable was used as an indicator of propulsive intra-cycle velocity fluctuations magnitude. Video analysis allowed us to calculate index of coordination (IdC) for every trial. As for the stroke parameters, average IdC, $propv_{mean}$, $propv_{peak}$ and %v for the group and every load were calculated and represented.

Statistical analysis

Descriptive statistics was used to calculate means and standard deviations. All variables (v, SR, SL, $propv_{mean}$, $propv_{peak}$, %v and IdC) were tested for normality (Shapiro-Wilk test). After performing Levene's test for variance homogeneity, one-way repeated measures ANOVA was used to assess differences among loads for every variable. A two-way ANOVA was used to compare $propv_{mean}$ and $propv_{peak}$ along the test. Finally, Pearson's correlation coefficients were calculated between load and the rest of variables. The statistical analysis was carried out using a statistical software package (SPSS 15.0). Statistical significance was set at $p < 0.05$.

Results

Behavior of v, SR and SL during semi-tethered swimming with increasing loads is represented in Figure 1. Stroke rate did not change significantly when load did (0.97±0.02 Hz).

In contrast, v and SL decreased with increasing loads (r = -0.985, -0.989, respectively, $p < 0.01$) (Table 1). Range of values was: v: 1.41-0.16 m/s; SL: 1.52-0.17 m/cic.

	v (m/s)	SR (Hz)	SL (m/cic)	$propv_{mean}$ (m/s)	$propv_{peak}$ (m/s)	%v	IdC (%)
Load	-0.985*	-0.211^{ns}	-0.989*	-0.984*	-0.971*	0.922*	0.910*

Table 1. Pearson´s correlation coefficients between load and the rest of variables. *: $p < 0.01$; ^{ns}: not significant. $propv_{mean}$: mean speed of propulsive stroke phases (pull+push); $propv_{peak}$: peak speed of propulsive stroke phases; %v: percentage of increase from $propv_{mean}$ to $propv_{peak}$.

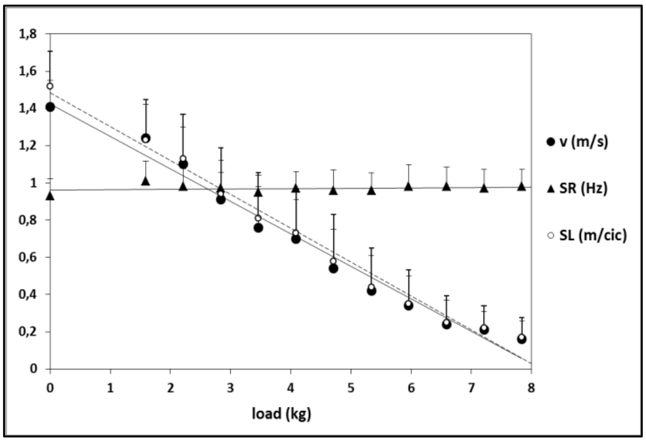

Figure 1. Behavior of some stroking parameters during semi-tethered swimming. Error bars are standard deviation (SD).

When comparing intra-cycle speed curves among participants and loads three main patterns were observed (Figure 2). Regardless of the impulse from the wall, speed followed a horizontal trend for the first six loads (until 4.71 kg) (Fig. 2a). For the next two loads (5.34-5.96 kg) speed decreased progressively in the first part of the trial and then remained constant in the second part (Fig. 2b). Finally, for the highest loads (6.59 kg and higher) speed described a concave upward curve, dropping quickly at the beginning and more gradually at the end, until reaching 0m/s (Fig. 2c).

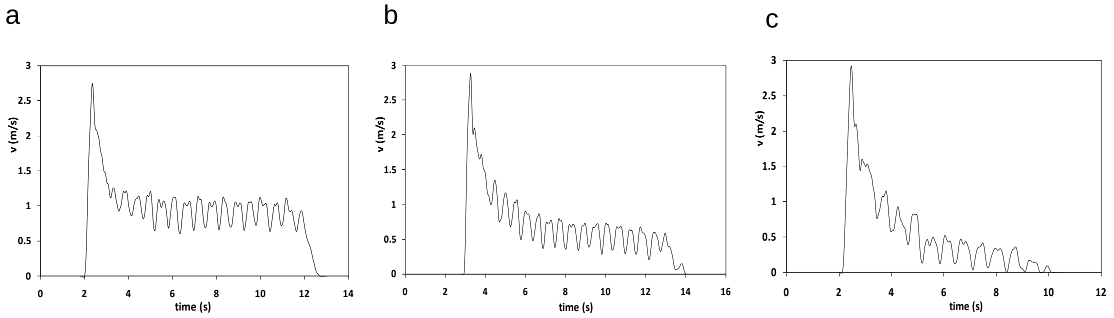

Figure 2. Behavior patterns of intra-cycle speed while semi-tethered swimming. a) 4.09kg load; b) 5.96kg load; c) 7.84kg load. The analysis started from the dotted line.

Variable $propv_{peak}$ was significantly higher than $propv_{mean}$ ($p < 0.05$) and they were positively correlated ($r = 0.995$, $p < 0.01$). Mean speed in propulsive stroke phases ($propv_{mean}$) decreased significantly with increasing loads in semi-tethered swimming ($r = -0.984$, $p < 0.01$) (Table 1), from 1.39±0.17 m/s with 0 kg to 0.25±0.10 m/s with 7.84 kg load (Figure 3). Peak speed ($propv_{peak}$) dropped significantly from 1.79±0.17 m/s with 0 kg to 0.73±0.22 m/s with 5.96 kg load (first nine loads) and did not change significantly for the highest loads ($r = -0.971$, $p < 0.01$). Percentage of increase from mean to peak speed in the propulsive phases (%v) did not undergo any significant changes neither from 0kg to 4.09 kg load (first six trials; %v = 36.94±9.57 %) nor from 6.59 kg to 7.21 kg load (%v = 149.23±13.21 %) (Figure 4). In contrast, it increased significantly and in a quadratic way when load raised between 4.09 kg and 6.59 kg and from 7.21 kg to 7.84 kg, when it almost reached 200 % ($r = 0.922$, $p < 0.01$). Consistently, $propv_{mean}$ and $propv_{peak}$ were negatively correlated with %v ($r = -0.871$, -0.824, respectively, $p < 0.01$).

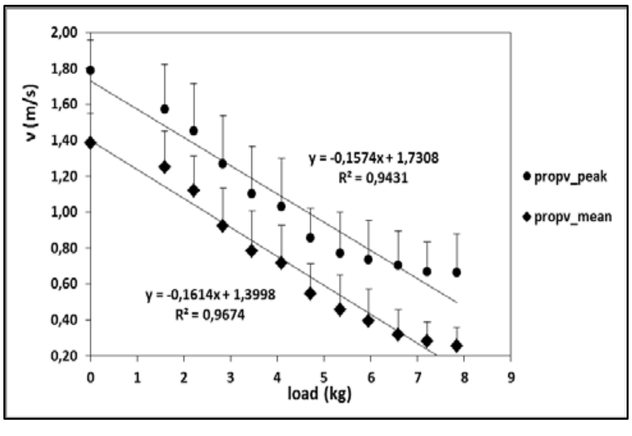

Figure 3. Mean and peak speed of propulsive phases (pull+push) while semi-tethered swimming. Error bars are standard deviation (SD).

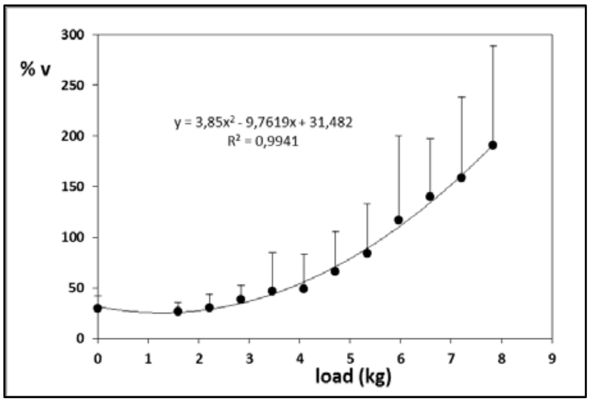

Figure 4. Percentage of increase from mean to peak propulsive speed during semi-tethered swimming. Error bars are standard deviation (SD).

Coordination mode used in free and semi-tethered swimming was superposition (IdC>0%). IdC was 6.6±4.6 % when swimming free and it increased significantly with loads ($p < 0.05$), from 7.1±5.3 % with 1.59 kg to 14.8±3.7 % with 7.84 kg (Figure 5). High positive significant correlation was found between load and IdC ($r = 0.910$, $p < 0.01$).

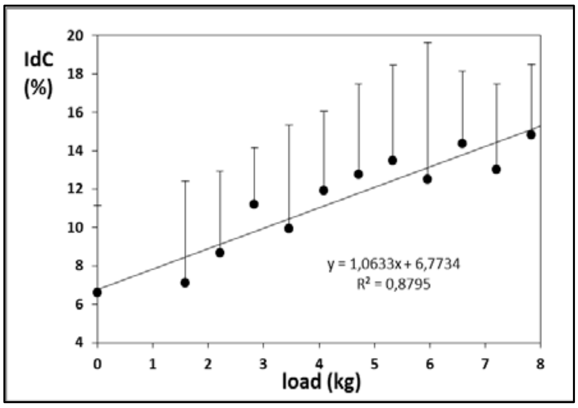

Figure 5. Index of coordination during semi-tethered swimming. Error bars are standard deviation (SD).

Discussion

The aim of the present study was to analyze the effect of different loads on freestyle stroke and coordination parameters during semi-tethered swimming and to examine whether those changes are positive or negative to swimming performance. The main findings of our study showed that percentage of increase from mean to peak speed in the propulsive phases grew following a quadratic trend with increasing loads. Besides, IdC rose significantly with load. Three different intra-cycle velocity patterns were noticed throughout loads.

Swaine and Reilly (1983) stated that freely chosen stroke rate led to maximum swimming speed. Strictly, combination of stroke rate and stroke length determines swimming speed ($v = SR \cdot SL$). For that reason, most swimmers try to increase SR when SL starts to decrease due to fatigue (Alberty et al., 2009; Craig et al., 1985; Keskinen and Komi, 1993; Pelayo et al., 2007). If they do not achieve it, their swimming speed decreases (Alberty et al., 2005). In the present study, rest between consecutive trials was five minutes, so fatigue did not appear. As expected, v and SL dropped when load increased, due to the increased drag. Significant drop compared to free swimming was observed in these variables from the first load. On the other hand, SR did not change significantly when speed (and load) did. This was consistent with the studies conducted by Alberty et al. (2005) and Pelayo et al., (1996). Gourgoulis et al. (2010) reported that SR dropped when swimming with loads compared to free swimming, but no difference was found in SR between loads. However, in some other studies (Alberty et al., 2009; Craig et al., 1985; Keskinen and Komi, 1993; Pelayo et al., 2007) swimmers managed to increase SR when speed started to decrease. This difference is presumably owing to the fact that the limiting factor in our case was not fatigue, but load. There was not a point where v, SL or SR trends clearly changed (Fig. 1), but it is interesting to observe that they all intersected close to 1m/s, around 2.84 kg load.

To the best of our knowledge, there are no studies which have compared intra-cycle speed while semi-tethered swimming, pulling different loads. We observed three main patterns (Fig. 2). Only for the first loads, up to 4.71 kg, swimmers were able to keep a constant and relatively high average speed (0.9 m/s) after a sharp decrease due to the impulse from the wall. In the rest of trials, excessive load made average 3 strokes speed drop to 0.5-0 m/s. Speed reduction was linear and longer in time until swimmers reached a stable speed for next two loads. In the last trials, load was too high for the swimmers to keep any constant speed, so it decreased gradually during the whole trial until 0 m/s.

To the authors' knowledge, no previous investigation has analyzed speed during propulsive phases while semi-tethered swimming. Shionoya et al. (1999) assessed average speed during semi-tethered swimming with several loads: 1, 4, 7 and 10 kg. The values obtained were: 1.34, 1.07, 0.79 and 0.45 m/s, which are similar to our $propv_{peak}$ data, considering that loads were slightly different. In the present study, peak speed was significantly higher than mean speed during propulsive phases in semi-tethered swimming ($p < 0.05$). Like in stroke parameters, significant decrease compared to zero load was observed in $propv_{mean}$ and $propv_{peak}$ from the first resisted condition. In contrast, no significant change in peak propulsive speed was observed over 5.96 kg, but this was not enough to enable swimmers to reach a stable speed during a trial. This stagnation of $propv_{peak}$ may be owing to the fact that, despite having their legs tied, most swimmers tried to move them for stabilization when swimming with the highest loads, what turned into a bigger propulsion and higher speed. Despite this, there was a high correlation between load and peak speed ($r = -0.971$, $p < 0.01$). On the other hand, significant change in %v compared to no load condition was first noticed with 4.71 kg. This was also the last load with which swimmers could keep a constant speed during the whole trial. As a whole, the higher the load, the lower the mean and peak speed of propulsive phases and the bigger the relative difference between them (%v). This means that intra-cycle speed variations became larger with higher loads. This may have happened because the swimmers may have tried to jerk to move forward pulling too heavy loads.

Skilled swimmers increased IdC when speed increased while swimming free (Schnitzler, et al., 2010; Schnitzler, et al., 2008) or when speed decreased while swimming with added resistance (parachute, paddles or both) (Schnitzler et al., 2011; Telles et al., 2011). In agreement with this, in the present study IdC increased with growing load and decreasing velocity. Significant change compared to free swimming first happened with 2.84 kg. This change in coordination is probably the consequence of the swimmers' adaptations to higher drag minimizing energy costs. They enhanced relative duration of propulsive phases (pull+push) (Gourgoulis et al., 2010) and overlapped propulsive forces of both arms to overcome increased drag (Maglischo et al., 1984). Semi-resisted training may be, therefore, useful to change coordination mode to superposition or to consolidate it, which has been proved to be the more widely used by expert swimmers (Seifert et al., 2004).

Resisted training in swimming enhanced swimming speed (Girold et al., 2006; Mavridis et al., 2006) and strength (Girold et al., 2006; Girold et al., 2007). Conversely, after comparing tethered and non-tethered stroke mechanics, it was concluded that repeated tethered training would entail detrimental adjustments in swimming technique and, therefore, swimmers' performance would probably deteriorate (Maglischo et al., 1984). Nevertheless, no negative changes would be expected if tethered swimming was only a part of the training program (Maglischo et al., 1985). According to Shionoya et al. (1999), the most suitable load for training is the load which produces the maximum power in the force-power curve. Further research is required to determine whether a relationship between swim power production and stroke and coordination parameters exists.

Summing up, the most interesting findings of this study were that, over 4.71 kg load, a constant swimming speed could not be maintained during a short period of time, and differences between mean and peak propulsive speed were significantly higher than in free swimming. Besides, IdC was found to increase with loads, significantly over 2.84 kg. In light of the results, it is suggested that optimal load for resisted training in swimming should be individually determined between 2.84 and 4.71 kg (swimming speed between 0.91 and 0.54 m/s, respectively).

As a concluding remark, it can be stated that semi-tethered swimming is one training method to enhance swimmers' performance, although load needs to be carefully controlled. Our results showed that stroke and coordination parameters were not modified to a great extent under certain load. Moreover, resisted training would be beneficial to coordination mode. Training load should be, however, individually determined.

Acknowledgements

The authors would like to thank the swimmers for their kind cooperation. This study was possible thanks to an FPU fellowship AP2008-03243.

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Chapter 4

Relationships among upper-body dry-land muscular power output, swimming power and swimming velocity

Domínguez-Castells, R., Arellano, R.

Submission process started

Abstract

It is accepted that power measured during swimming is a better predictor of swimming velocity than power measured in dry-land exercises. Several authors have assessed maximum power in swimmers during swimming and on dry-land, calculating thereafter the correlations between them. The aims of the present study were to obtain dry-land and swim power values by means of different methods, to determine the relationships among dry-land power, swim power and swim velocity in each case, and to compare these relationships between methods. The bench press power was higher than arm stroke power and swim power. Complete power vs. load curves were represented for bench press and semi-tethered swimming. High correlations were found between power on dry-land exercises and swim power, being higher for the arm stroke exercise. There was a high and significant correlation between swim velocity and swim power; it was high but not significant between swim velocity and arm stroke power, and moderate and almost significant between swim velocity and bench press power. This confirmed that swimming is the most specific way to measure swim power, although the arm stroke exercise may be a suitable dry-land alternative.

Keywords: dry-land, bench press, stroke, power, swimming.

Introduction

Power plays an essential role in many sports, including swimming. It is accepted that strength and power measured during swimming are more reliable predictors of swimming velocity and competitive performance than strength characteristics measured in dry-land exercises (Vorontsov, 2011). Swimming power has been previously measured by means of different methods: Measurement of Active Drag (MAD) system, Velocity Perturbation Method (VPM), Assisted Towing Method (ATM), semi-resisted swimming with ergometers or pulley-systems, etc. However, it is not always possible or operational to measure swimming power in the water. Therefore, other alternatives have to be used in a dry-land environment. Bench press is the most extended exercise for muscular power assessment in different sports, but it has been scarcely used in swimming. The arm ergometer or the swim bench are the most common methods to assess power on more specific dry-land exercises in swimmers. The power measured with these methods has been previously reported to correlate well with swim power or swim performance.

To the authors' knowledge, only a few studies have reported a high positive relationship between dry-land power (measured on a swim bench) and swim power (Shimonagata, Taguchi, & Miura, 2002; Swaine & Doyle, 2000). In agreement with this, several authors have shown relationships between dry-land power and swim velocity (Bradshaw & Hoyle, 1993; Hawley & Williams, 1991; Rohrs, Mayhew, Arabas, & Shelton, 1990; Sharp, Troup & Costill, 1982). The majority evaluated dry-land power on a swim bench. Nevertheless, Morouço, Keskinen, Vilas-Boas, & Fernandes (2011) used conventional strength training exercises, finding a moderate significant correlation between swim performance and muscular power on lat pull down back, but not significant on bench press. Lastly, the positive relationship between swim power and swim performance has been widely reported (Fomitchenko, 2000; Hawley & Williams, 1991; Hopper, Hadley, Piva, & Bambauer, 1983; Seifert, Toussaint, Alberty, Schnitzler, & Chollet, 2010; Shimonagata, et al., 2002; Shionoya, et al., 2001; Tanaka, Costill, Thomas, Fink, & Widrick, 1993; Toussaint & Vervoorn, 1990). Different methods, such as the MAD system or semi-tethered swimming with a power rack were used for this purpose.

Very few authors (Johnson, Sharp, & Hedrick, 1993) have analysed the correlations among dry-land power, swim power and swim performance in one single study. In the present paper two studies were conducted (one was a pilot study) to investigate these relationships. An updated semi-tethered swimming protocol (Dominguez-Castells, Izquierdo & Arellano, 2013) and the MAD system were employed to measure swim power. On dry-land, the bench press exercise was included in both studies, while a second exercise was introduced in the pilot study: the arm stroke exercise. The aims of this study were, therefore, to obtain dry-land and swim power values by means of different methods, to determine the relationships among dry-land power, swim power and swim performance in each case, and to compare these relationships between methods.

Methods

Two different studies were conducted, one of them being a pilot study. The tests used in each of them are described below.

STUDY 1

Subjects

Eighteen 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 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.

Dry-land force and power

Bench press one-repetition maximum (1RM)

After warm up, the swimmers were asked to lift a higher load each trial on a bench press Smith machine until they were not able to do a complete repetition. The last load they could lift completely was their 1RM on bench press (1RM BP). The increments in load were 10 kg at the beginning of the test and 5 kg later. They rested 5 min before each repetition.

Bench press power

An incremental test was conducted on bench press. Participants did one repetition on a Smith machine with each load. They started with the barbell (17.5 kg) and load increased in 10 kg at the beginning of the test and 5 kg later until approximately 1RM. The athletes were instructed to do the concentric contraction at maximal velocity. Upwards barbell velocity was measured by means a linear encoder. Muscular power was calculated with the formula $P = m\cdot(a+g)\cdot v$, using the accelerating part of the curve, where $a>-g$ (i.e. $(a+g)>0$) (Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010). Maximum bench press power, absolute and relative to body mass, was determined ($MBPP_1$, $MBPPR_1$). The group bench press power curves (absolute and relative values) were calculated.

Swim power

The swim power test consisted of 12.5-m all-out front-crawl swims across the pool while pulling a different load in each trial. After a standardised 800-m warm-up, the test started with

1.59 kg load. The load increased by approximately 0.5 kg each trial. The swimmers rested for 5 minutes between two consecutive repetitions. After the first 5-6 m, which corresponded to the impulse from the wall and were not considered, three complete strokes were required to consider a trial for analysis. The protocol ended when the swimmer was not able to complete a trial. The test was recorded with one frontal and two lateral underwater cameras (Sony, frequency: 50 Hz, shutter speed: 1/250 s) that were fixed to the pool wall. A linear velocity transducer was used to measure the intra-cycle velocity (frequency: 200 Hz, accuracy: 0.1 mm), and a force transducer was used to record the instantaneous force (frequency: 200 Hz, accuracy: 0.01N) while the swimmer displaced the load that was added by a pulley system. The swim power output was calculated by multiplying the velocity and force data produced against the external load. The feet of each swimmer were tied together and a pull buoy was placed between his legs, which isolated the upper limb action. Mean swimming power was obtained from three strokes for each subject and trial. The maximum swimming power of the complete test was selected for each swimmer and averaged for the group (MSP_1). The maximum swimming power relative to body mass ($MSPR_1$), and the percentage of the individual maximum load that was associated with the MSP were also calculated. The group swim power curves (absolute and relative values) were represented. See Chapter 2 for further test description.

Swim velocity

The test consisted of 2 x 25 m all-out front crawl swimming, with a water start and 5 min rest between them. The swimmers were asked to use full stroke in the first trial and only arms in the second trial. Their legs were then tied together and they carried a pull-buoy between them. The test was filmed by two underwater cameras (frontal and lateral views) and mean sprint velocity (v25) was obtained by means of a touchpad. Stroke length, stroke rate and stroke index were calculated (SL, SR, SI).

Statistical analyses

The swim power variables (MSP and MSPR) did not follow the normal distribution (Shapiro-Wilk normality test). Therefore, Spearman correlation coefficients were calculated to describe the relationships among dry-land and in-water variables. Statistical significance was set at $p < 0.05$. The statistical analysis was conducted with a statistical software package (SPSS 16.0).

STUDY 2

Subjects

Four male national-level swimmers (age 19.4±3.6 years, height 1.90±0.02 m, and body mass 83.65±3.11 kg) volunteered to participate in this pilot study. 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.

Dry-land power

Bench press power

An incremental power test was performed on bench press. Five or six loads were used in total for each swimmer, with 5-kg increments first and 2.5 kg-increments at the end of the test. They performed two repetitions with each load, with 2 min rest between them. The swimmers started lying supine on a bench, holding the barbell with elbows straight. They were asked to lower the bar in a controlled way to the chest, to stop there for 0.5 s and to extend the elbows to push the bar at maximum speed. A linear encoder was used to measure propulsive velocity, force and power in every repetition. The maximum power repetition was selected from every set and maximum power output was determined in absolute and relative to body mass values ($MBPP_2$, $MBPPR_2$). The corresponding load, force and velocity were assessed.

Arm stroke power

A more specific power test was performed to evaluate the arm stroke power (Figure 1). The incremental test consisted on completing two repetitions with each load, with 2 min rest between loads. The swimmers started sitting on an inclined bench (45° from vertical), the chest lying upon it. They extended the arms horizontally to the front, each hand holding one handle. The machine exerted some tension, so the arms were relaxed. The swimmers were instructed to do a shoulder extension, similar to the front-crawl underwater phase, but keeping the elbows straight. One repetition finished when the arms reached the trunk line, i.e. 135° shoulder extension. The participants were asked to do the complete movement at maximal velocity, return to the starting position in a controlled way, stop there for 0.5 s and do the second repetition. A linear encoder was used to measure propulsive velocity, force and power in every repetition. The maximum power repetition was selected from every set and maximum power output was determined in absolute and relative values (MSTP, MSTPR). The corresponding load, force and velocity were assessed.

Figure 1. Arm stroke power test on dry-land.

Swim power

The MAD system was used to measure swim power in this study. The swimmers completed 6 x 25 m all-out front crawl swimming (only arms) on the MAD system (Hollander et al., 1986) in a 50-m pool. In a random order, they did two free trials, two with one hydrodynamical body attached to their waist and two with two hydrodynamical bodies. The participants were instructed to start at 30 m from the wall and achieve maximum velocity before reaching the MAD system. Thereafter, they continued swimming pushing off 13 fixed pads, mounted on a rod 0.8 m below the surface. Mean propulsive force and mean velocity from the second to the last pad (14.85 m) were measured by means of a force transducer, connected to the rod's end. Mean swim power was calculated for each of the three conditions and maximum absolute and relative swim power (MSP_2, $MSPR_2$) were determined.

Swim velocity

The test consisted of 2 x 25 m all-out front crawl swimming (only arms) in a 50-m pool. The swimmers started 30 m away from the wall and had to reach maximal velocity at 20 m to the wall. Mean swim velocity ($v25_2$) between 15 and 5 m to the wall was determined with video and the two trials were averaged. Stroke rate, stroke length and stroke index were calculated in this 10 m.

Statistical analyses

All the variables followed a normal distribution (Shapiro-Wilk normality test). Therefore, and despite the small sample size, Pearson correlation coefficients were calculated to describe the trend of the relationships among dry-land and in-water variables. Statistical significance was set at $p < 0.05$. The statistical analysis was conducted with a statistical software package (SPSS 20.0).

Results

STUDY 1

Mean 1RM BP was 81.94±21.27 kg. $MBPP_1$ was 418.18±134.53 W or 5.41±1.47 W/kg (Table 1). The bench press power curves (absolute and relative values) are represented in Figure 2. MSP_1 was 66.49±19.09 W or 0.86±0.21 W/kg (Table 1). The swim power curves (absolute and relative values) are represented in Figure 3. Mean 25 m sprint velocity ($v25_1$) was 1.70±0.14 m/s (Table 2). When only arms were used, 25-m velocity (v25) was 1.41±0.14 m/s.

Table 1. Maximum bench press and swim power for the group of swimmers, load and velocities associated.

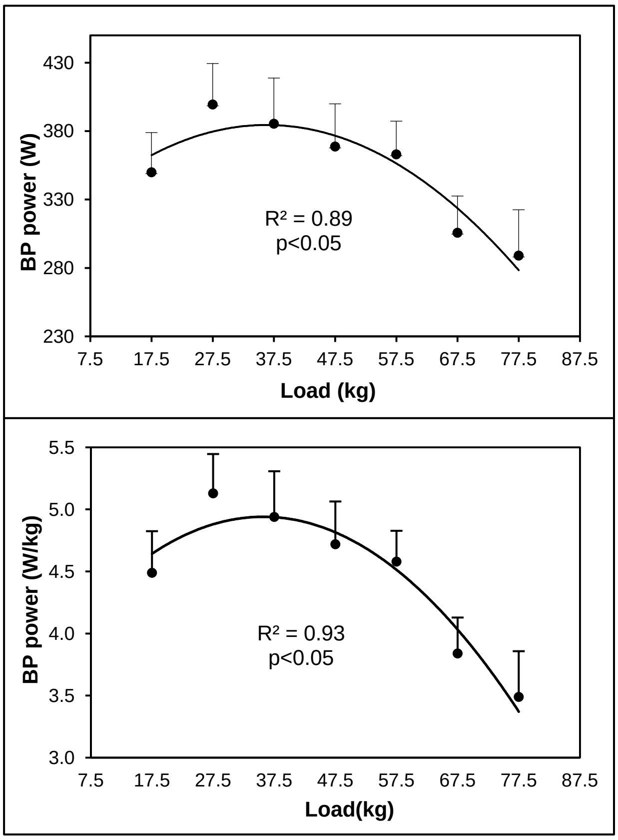
	$MBPP_1$ (W)	$MBPPR_1$ (W/kg)	% RM-$MBPP_1$	v-$MBPP_1$ (m/s)	MSP_1 (W)	$MSPR_1$ (W/kg)	load-MSP_1 (kg)	% max load-MSP_1	v-MSP_1 (m/s)	%v max-MSP_1
MEAN	418.18	5.41	41.32	1.04	66.49	0.86	3.95	47.07	0.75	43.75
SD	134.53	1.47	14.64	0.26	19.09	0.21	0.79	9.45	0.18	8.94

$MBPP_1$: maximum bench press power; $MBPPR_1$: maximum bench press power relative to body mass; % RM-$MBPP_1$: % RM which $MBPP_1$ is developed with; v-$MBPP_1$: barbell velocity used to achieve $MBPP_1$; MSP_1: maximum swim power; $MSPR_1$: maximum swim power relative to body mass; load-MSP_1: load which MSP_1 is developed with; % max load-MSP_1: percentage of each swimmer´s maximal load used to achieve MSP_1; v-MSP_1: swim velocity used to deliver MSP; %v max-MSP_1: percentage of each swimmer´s maximal velocity (v25) used to achieve MSP_1.

Table 2. Variables measured in the 25 m all-out front crawl swimming test.

	Full stroke $v25_1$ (m/s)	SR_1 (Hz)	SL_1 (m/cic)	SI_1	Arms only v25 (m/s)	SR (Hz)	SL (m/cic)	SI
MEAN	1.70	0.95	1.80	3.07	1.41	0.93	1.52	2.17
SD	0.14	0.08	0.20	0.54	0.14	0.09	0.19	0.43

v25: maximal 25-m front crawl all-out velocity; SR: stroke rate; SL: stroke length: SI: stroke index.



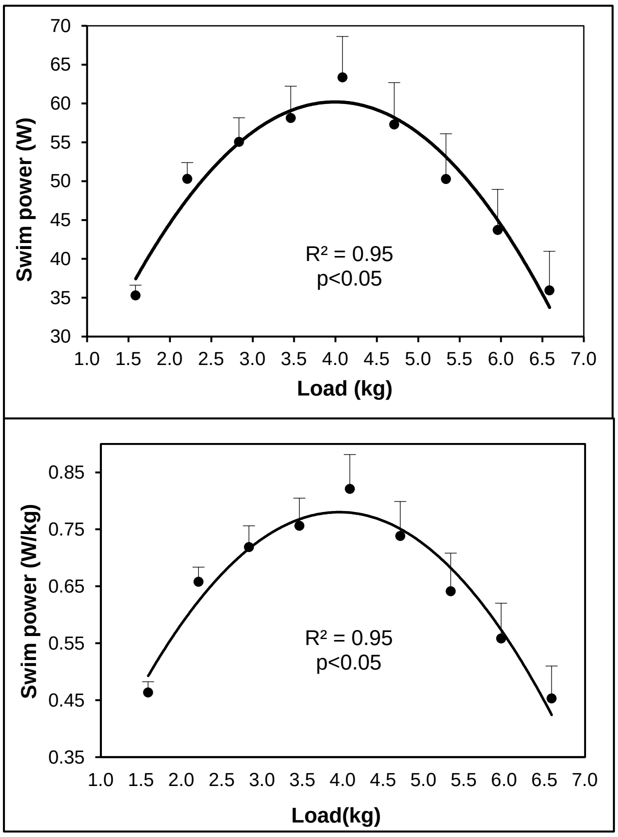


Figure 2. Bench press power curves, with absolute and relative values.

Figure 3. Swim power curves, with absolute and relative values.

Values are expressed as means, and error bars are standard error of the mean.

Correlations

A high positive linear correlation between 1RM BP and $MBPP_1$ ($r = 0.84$, $p < 0.01$) and a lower one between 1RM BP and MSP_1 ($r = 0.48$, $p < 0.05$) were found. $MBPP_1$ was positively correlated with MSP_1 ($r = 0.54$, $p < 0.05$) (Figure 4), but only when absolute values were used. The variables obtained from the 25 m front-crawl swimming using arms only showed lower correlations than when the full stroke was employed. Therefore, the full stroke trial was used for correlations. The relationship between $MBPP_1$ and $v25_1$ was almost significant ($r = 0.47$, $p = 0.051$). However, there was a positive correlation between $MBPP_1$ and both SL_1 ($r = 0.52$, $p < 0.05$) and SI_1 ($r = 0.62$, $p < 0.01$). Besides, $MSPR_1$ was related to $v25_1$ ($r = 0.73$, $p < 0.01$) but, the correlation was slightly higher when absolute values of power (MSP_1) were used ($r = 0.76$, $p < 0.01$) (Figure 5). Finally, MSP_1 was highly correlated to SL_1 ($r = 0.69$, $p < 0.01$) and SI_1 ($r = 0.81$, $p < 0.01$).

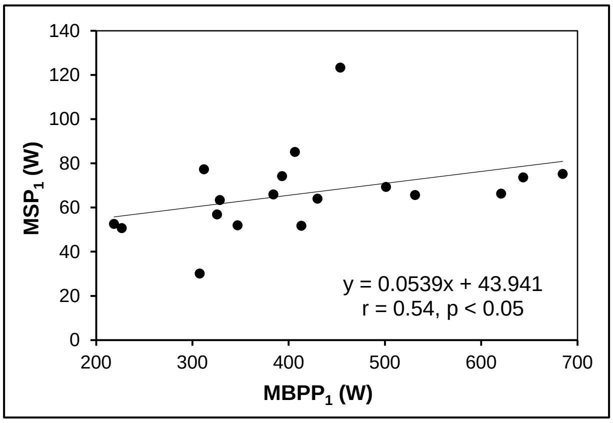


Figure 4. Linear correlation between maximum swim power (MSP_1) and maximum bench press power ($MBPP_1$).

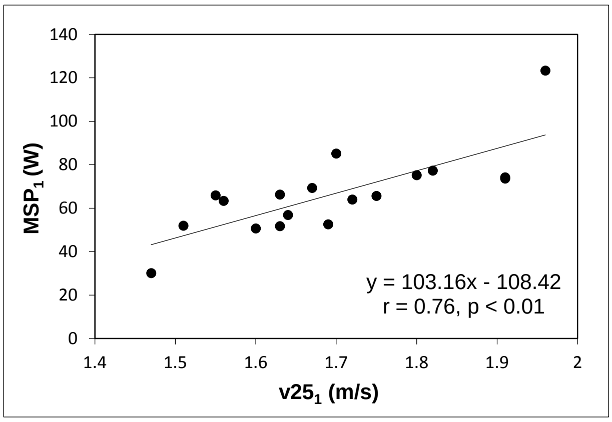


Figure 5. Linear correlation between maximum swim power (MSP_1) and maximum swim velocity ($v25_1$).

STUDY 2

Maximum power on bench press ($MBPP_2$: 345.45±114.51 W) (Table 3) was higher than maximum arm stroke power (MSTP: 203.75±72.28 W) and maximum swim power (MSP_2: 178.96±42.00 W) (Table 4). Expressed as power relative to body mass, $MBPPR_2$ was 4.17±1.48 W/kg, MSTPR was 2.46±0.94 W/kg and $MSPR_2$ was 2.15±0.57 W/kg. The drag added by the first buoy when it was attached to the swimmer was 26.61±4.44 N, dependent on each swimmer's swim velocity ($D = k \cdot v^2$). The drag added by the two buoys was 40.53±5.66 N, dependent on individual velocities. Both loads lie within the recommended range for resisted swimming training (Dominguez-Castells & Arellano, 2012). Mean 25-m maximal velocity ($v25_2$) with arms only was 1.59±0.07 m/s (Table 4).

Table 3. Maximum bench press and arm stroke power, load and velocities associated.

	$MBPP_2$ (W)	$MBPPR_2$ (W/kg)	load-$MBPP_2$ (kg)	v-$MBPP_2$ (m/s)	MSTP (W)	MSTPR (W/kg)	load-MSTP (kg)	v-MSTP (m/s)
MEAN	345.45	4.17	41.88	0.80	203.75	2.46	21.50	0.96
SD	114.51	1.48	14.05	0.21	72.28	0.94	6.65	0.15

$MBPP_2$: maximum bench press power; $MBPPR_2$: maximum bench press power relative to body mass; load-$MBPP_2$: load which $MBPP_2$ is developed with; v-$MBPP_2$: barbell velocity used to achieve $MBPP_2$; MSTP: maximum arm stroke power; MSTPR: maximum arm stroke power relative to body mass; load-MSTP: load which MSTP is developed with; v-MSTP: barbell velocity used to achieve MSTP.

Table 4. Maximum swim power, load and velocities associated, and variables measured in the 25 m all-out front crawl (only arms) swimming test.

	MSP_2 (W)	$MSPR_2$ (W/kg)	v-MSP_2 (m/s)	%v max-MSP_2	$v25_2$ (m/s)	SR_2 (Hz)	SL_2 (m/cic)	SI_2
MEAN	178.96	2.15	1.73	109.03	1.59	0.88	1.82	2.88
SD	42.00	0.57	0.13	6.89	0.07	0.05	0.07	0.16

MSP_2: maximum swim power; $MSPR_2$: maximum swim power relative to body mass; v-MSP_2: swim velocity used to achieve MSP_2; %v max-MSP_2: percentage of each swimmer´s maximal velocity ($v25_2$) used to achieve MSP_2; $v25_2$: maximal 25-m front crawl (only arms) all-out velocity; SR_2: stroke rate; SL_2: stroke length: SI_2: stroke index.

Correlations

It was difficult to find significant correlations in study 2 due to the small sample size. However, some interesting correlations and trends were observed. High positive tendency was found between $MBPP_2$ and the other two power variables (MSTP: $r = 0.94$, MSP_2: $r = 0.86$, $p \geq 0.05$) (Figure 6). Moreover, the correlations became significant when $MBPP_2$ was related to the force developed to achieve MSTP or MSP_2 ($r = 0.98$, $r = 0.97$, respectively, $p < 0.05$). A high and close to significant correlation was observed between MSTP and MSP_2 ($r = 0.91$, $p = 0.091$) (Figure 6), as well as between the forces delivered to achieve MSTP and MSP_2 ($r = 0.91$, $p = 0.089$). The correlations between swim power and the dry-land power variables when expressed as relative to body mass values were similar to when they were expressed in absolute values ($MBPPR_2$ - $MSPR_2$: $r = 0.88$, MSTPR - $MSPR_2$: $r = 0.93$, $p \geq 0.05$). There were moderate and high correlations between $v25_2$ and the power variables ($MBPP_2$: $r = 0.62$, MSTP: $r = 0.85$, MSP_2: $r = 0.72$, $p \geq 0.05$) (Figure 7). Similar correlations were observed when the power was expressed in relative values ($MBPPR_2$: $r = 0.65$, MSTPR: $r = 0.86$, $MSPR_2$: $r = 0.74$, $p \geq 0.05$).

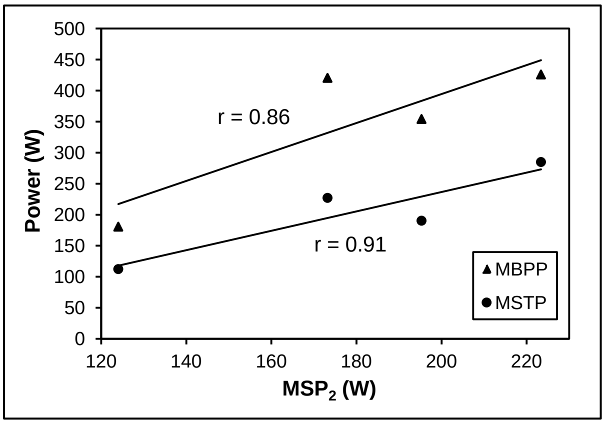


Figure 6. Linear correlation between maximum dry-land power ($MBPP_2$, MSTP) and maximum swim power (MSP_2). $p > 0.05$.

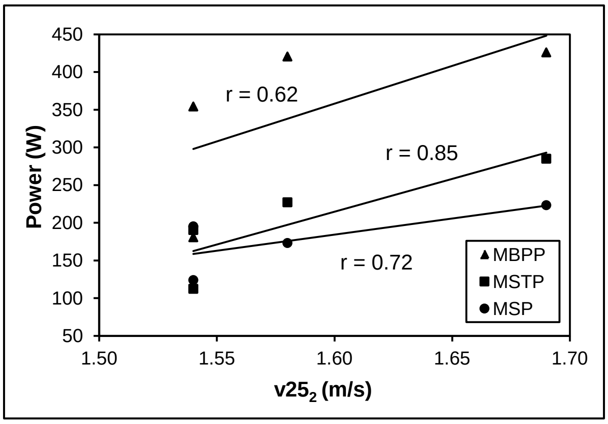


Figure 7. Linear correlation between maximum power ($MBPP_2$, MSTP, MSP_2) and maximum swim velocity ($v25_2$). $p > 0.05$.

Discussion and conclusion

The aims of this study were to obtain dry-land and swim power values by means of different methods, to determine the relationships among dry-land power, swim power and swim performance in each case, and to compare these relationships between methods. The results showed that bench press power was higher than arm stroke power and swim power. Complete power load vs. curves were represented for bench press and semi-tethered swimming. Moderate significant correlation was found between bench press power and swim power, while it was high (although not significant) between arms stroke power and swim power. There were high and moderate relationships between maximal swim velocity and the power variables, both dry-land and swimming, being higher for the arm stroke exercise than for bench press.

Power was assessed both dry-land and swimming in the present study. On dry-land, two exercises were used: bench press and arm stroke. Maximum power on bench press was higher in the first study than in the second one, although it did not lead to a higher swim velocity. In the second study, the arm stroke exercise was introduced, which allowed to measure maximum upper body power on a simple but more specific exercise for front-crawl swimmers, and to relate this power to swim power and swim velocity. MSTP was lower than MBPP, since fewer muscles were involved in the arm stroke action.

In order to represent a complete power vs. load curve (from the barbell alone to 1RM), the load increments were bigger in the first study. For the second one, smaller increments and a maximum of six loads were used, close to 40% of their perceived 1RM. Thus, the test was shorter, more precise and useful for training, despite not knowing the 1RM. The maximum power on the arm stroke exercise and maximum swim power were relatively close to each other, compared to the power on bench press. This was probably because the muscular action required on the arm stroke exercise is more similar to swimming than bench press.

Regarding swim power, a complete power vs. load curve was represented in the first study, while only free swimming and two loads were included in the pilot study. The drag added by one and two hydrodynamical buoys were 26.61 and 40.53 N, respectively, which are within the recommended range for resisted swimming training by Dominguez-Castells & Arellano (2012). It must be kept in mind that MSP_2 obtained on the MAD system was not absolute maximum swim power, but maximum power among three different conditions. However, since the added drag values were close to the load used on the pulley system to achieve MSP in the first study (3.95 kg), we considered MSP_2 as a good estimation of actual MSP. MSP was considerably lower in the first study, due to the method used to measure it. In this case, there was an amount of power lost in giving kinetic energy to the water, while all the energy was used to push off the fix pads while swimming on the MAD system. Due to this methodological difference, the swim velocity during the MSP trial was slower than v25 in the first study, but faster than v25 in the second one. Maximal swim velocity using arms only was faster in the second study, due to the higher level of the swimmers. They used a lower SR but higher SL.

Several correlations were found among the variables analysed in the present study (Figure 8). Despite the absence of significance in most of the relationships found in the pilot study due to the small sample size, very interesting trends were observed. The relationship between swim power and sprint swim performance has been previously assessed (Costill, Rayfield, Kirwan, & Thomas, 1986; Fomitchenko, 2000; Hawley & Williams, 1991; Hopper, et al., 1983; Seifert, et al., 2010; Sharp, 1986; Sharp, et al., 1982; Shimonagata, et al., 2002; Shionoya, et al., 2001; Tanaka, et al., 1993; Toussaint & Vervoorn, 1990), correlations between r = 0.82 and r = 0.92 being reported. Different methods, such as the MAD system or semi-tethered swimming with a power rack or an ergometer were used for this purpose. In the two studies of this paper, using full stroke and arms only for v25, and semi-tethered swimming and the MAD system for MSP, the correlations between MSP and v25 lay between r = 0.72 and r = 0.76, using absolute or relative power values. Moreover, the first study yielded significant moderate and high correlation between MSP and SL, SI, respectively.

Shimonagata, et al. (2002) and Swaine & Doyle (2000) have reported a high positive relationship between dry-land power (measured on a swim bench) and swim power. In the present study, strength training exercises were employed to assess dry-land power. In regard to the bench press exercise, there was a moderate significant correlation between $MBPP_1$ and MSP_1. Although not significant, the tendency was higher when MSP was measured with the MAD system (r = 0.86 vs. r = 0.54), maybe because there was no energy loss with this method. A larger and close to significant correlation was observed between MSTP and MSP_2 (r = 0.91), confirming the higher specificity of the arm stroke exercise for front-crawl swimmers.

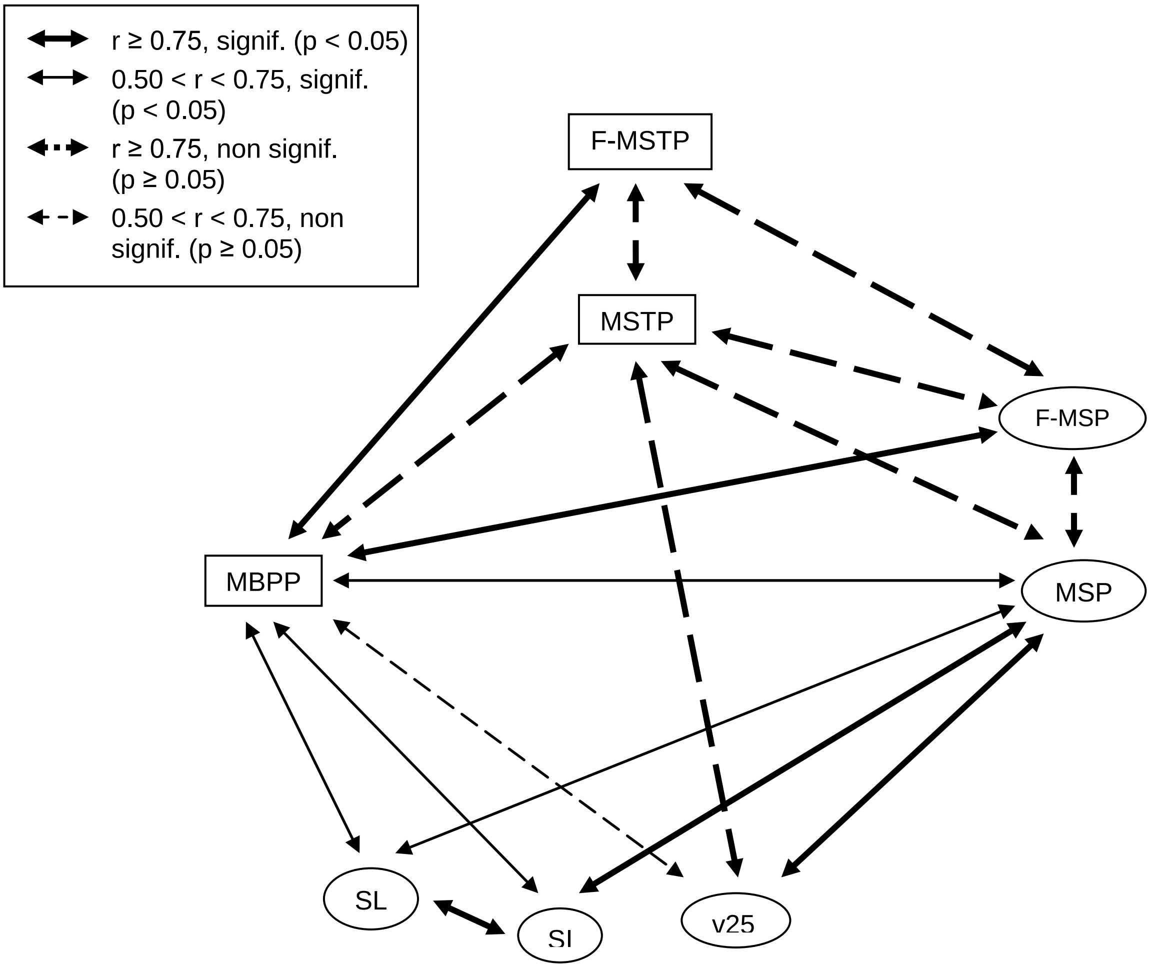


Figure 8. Relationships found among the main variables analysed in the study (dry-land variables in rectangles, aquatic variables in ellipses). 1 RM BP: one repetition maximum on bench press; MBPP: maximum bench press power; MSTP: maximum arm stroke power; F-MSTP: force delivered to elicit MSTP; MSP: maximum swim power; F-MSP: force delivered to elicit MSP; v25: maximal 25-m front crawl all-out velocity; SL: stroke length used to achieve v25; SI: stroke index used to achieve v25.

Previous studies have shown positive relationships between dry-land power assessed on a swim bench and swim velocity (Bradshaw & Hoyle, 1993; Hawley & Williams, 1991; Rohrs, et al., 1990; Rohrs & Stager, 1991; Sharp, et al., 1982). In our study, MBPP was positively and significantly correlated with SL_1 and SI_1, and almost significantly with $v25_1$ and $v25_2$. Morouço et al. (2011) reported a moderate significant correlation between swim performance and muscular power on lat pull down back. In line with this result, there was a positive trend between MSTP and $v25_2$ ($r = 0.85$), higher than between $MBPP_1$ and $v25_1$ ($r = 0.47$) and between $MBPP_2$ and $v25_2$ ($r = 0.62$). This suggests that the arm stroke exercise may be suitable to be used as a more specific means to determine maximum dry-land power on the upper body for swimmers.

Summing up, dry-land power and swim power were measured by means of different methods in the present study. Bench press power was higher than arm stroke power and swim power. The results showed that bench press power was significantly but moderately related to maximum swim power. A higher but not significant correlation was found between arm stroke power and maximum swim power. There was a high and significant correlation between swim velocity and swim power, high but not significant between swim velocity and arm stroke power, and moderate and almost significant between swim velocity and bench press power. These results confirmed that swimming is the most specific way to measure power in swimmers, although the arm stroke exercise may be a suitable dry-land alternative. Further studies with a larger sample are necessary to find significant relationships among arm stroke power, swim power in semi-tethered swimming and maximal swim velocity.

Acknowledgements

The authors would like to thank the group "Physical Activity and Sport in the Aquatic Environment" (CTS-527), the Faculty of Sport Sciences of the University of Granada and InnoSportLab De Tongelreep in Eindhoven for their cooperation. The authors wish to thank the swimmers for their kind participation. This study was possible thanks to a FPU fellowship (AP2008-03243) awarded by the Spanish Ministry of Science and Innovation.

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Chapter 5

How is dry-land power training transferred to swimming performance?

Domínguez-Castells, R., Izquierdo, M., Arellano, R.

Submitted to Human Movement Science in February 2013.

Abstract

Mechanical power output is an attribute of paramount importance in many sporting activities, including swimming. Despite muscular power being positively related to optimal performance, this does not necessarily indicate that training power will enhance swimming performance. The main aim of the study was thus to assess the effects of an easy-to-implement dry-land power training program on arm muscular power and whether this resulted in faster sprint swimming. Eight male swimmers performed dry-land power tests (bench press and bench pull) and swimming velocity tests (free, 2.5 kg, 5 kg, 7.5 kg) before and after a 7-week training period. The maximum propulsive power increased significantly on bench press (7.27±7.77%, ES=0.60) and bench pull (7.52±6.99%, ES=0.52) after 7 weeks of training. Free swimming velocity increased significantly (15.59±6.61%, ES=1.61), as well as swimming pulling three different loads. Stroke rate decreased in free swimming, while stroke length was enhanced in every condition. These findings suggest that dry-land power training may be an effective method to complement and optimise swimming training.

Keywords: bench press, bench pull, velocity, stroke length, stroke rate.

Introduction

Mechanical power output is the cornerstone of successful performance of many sporting activities (Cronin & Sleivert, 2005; Izquierdo, Häkkinen, Gonzalez-Badillo, Ibáñez & Gorostiaga, 2002), and swimming is no exception to this (Hawley, Williams, Vickovic & Handcock, 1992). Many coaches, therefore, firmly believe that a power-specific training program should include strength-specific exercises, where the athlete uses the sport movement with an added resistance as the training exercise. In doing so, positive power-specific stimulus creates optimal conditions for subsequent sprinting exercises enabling them to be undertaken with a greater effort than could be achieved without the prior heavy resistance exercise (Jones & Lees, 2003).

Several methods have been used for specific power training in the water (Girold, Calmels, Maurin, Milhau & Chatard, 2006; Girold, Maurin, Dugué, Chatard & Millet, 2007; Toussaint & Vervoorn, 1990) and on dry-land (Garrido et al., 2010; Girold, Jalab, Bernard, Carette, Kemoun & Dugué, 2012; Girold et al., 2007; Pichon, Chatard, Martin & Cometti, 1995; Strass, 1988; Trappe & Pearson, 1994). In regards to water-based methods, training on the MAD (Measurement of Active Drag) system (Hollander et al., 1986), which enabled an enhancement of force, velocity and power, demosntrated an improvement in performance across 50 m, 100 m and 200m freestyle events(Toussaint & Vervoorn, 1990). In a different study (Girold et al., 2006), it was found that resisted-sprint training was more efficient than assisted-sprint training to increase performance in 100-m front crawl swimming, whereas dry-land strength training and assisted + resisted swimming induced similar gains in 50 m performance (Girold et al., 2007). The authors concluded that resisted sprint training could be used to increase strength and power, whereas assisted sprint training could be used to increase stroke rate and strength at a high velocity. In addition, several studies have been focused on the relationship between upper body power and swim performance over short distances (Bradshaw & Hoyle, 1993; Garrido et al., 2010; Hawley & Williams, 1991; Hawley et al., 1992; Rohrs, Mayhew, Arabas & Shelton, 1990; Sharp, Troup & Costill, 1982; Trinity, Pahnke, Reese & Coyle, 2006). Indeed, different dry-land tests (swim bench, medicine ball throw, arm ergometer) have shown relationships with 25 or 50m times ($r = 0.53$-0.83).

To achieve the greatest exercise specificity, one of the main objectives of strength training in swimming is to create a specific time-space structure of strength application in swimming technique. Because of the high specificity of swimming, reproduction of complex swimming movements is difficult on land. It is also likely that swimming pools or suitable equipment are not always available for athletes to complete training in water. Therefore, dry-land training methods are widely used by coaches to complement their training programs. Scientific literature has produced contradictory results regarding dry-land training, alone or in combination with swimming, and its concomitant effects on swimming performance. Girold et al. (2007) determined that the combination of swimming and dry-land resistance training was more effective than swim training alone for improving swim performance. Other studies which included dry-land training protocols, reported gains in front-crawl sprint swimming performance between 2 and 4.5% (Costill, Sharp & Troup, 1980; Garrido et al., 2010; Girold et al., 2012; Pichon et al., 1995; Sharp et al., 1982; Strass, 1988; Trappe & Pearson, 1994). In contrast, a different combination of dry-land resistance training and swimming did not improve swim performance, despite increasing power measured on both the biokinetic swim bench and during a tethered swimming test (Tanaka, Costill, Thomas, Fink & Widrick, 1993). The biokinetic resistance training did not add any improvement to the benefits obtained from high velocity swim training alone (Roberts et al., 1991). Dry-land power training on a hydroisokinetic ergometer enhanced tethered swimming force in youth swimmers, but the improvement in swim performance was not significant (Sadowski, Mastalerz, Gromisz & Niźnikowski, 2012). Tanaka et al. (1993) suggested that the lack of a positive transfer between dry-land strength gains and swimming propulsive force may be due to training specificity. Despite muscular strength or power and its potential positive relationship to optimal performance, it does not necessarily indicate that training those particular attributes will enhance performance (Cronin & Sleivert, 2005).

Further research is, needed to determine whether this is true for swimming. Therefore, considering that power is a component of paramount importance in swimming performance and that athletes might have limited access to swimming pools, it seems important to analyze the effectiveness of supplementary dry-land training methods. To the best of the authors´ knowledge, there is no previous research which has studied the influence of a power-oriented dry-land weight training method for the upper limb on swimming performance. The main aim of the study was to assess the effects of an easy-to-implement dry-land power training program on upper body muscular power and whether this resulted in faster front crawl sprint swimming. It was hypothesized that the upper body power would be enhanced due to specific power training and that this would result in improvement of front crawl swim performance.

Methods

Participants

Eight male swimmers (age 24.14 ± 2.49 years; stature 1.79 ± 0.06 m; arm span 1.81 ± 0.07 m; and body mass 79.40 ± 11.40 kg) volunteered to participate in this study. A verbal and written explanation of the procedure was administered before they provided written consent to participate in the study, which was approved by the university ethics committee. All participants had a minimum 5 years experience in swimming training and 2 years in strength training. They had competed at regional or national level. Throughout the duration of the study, they were swimming 2 or 3 times a week, and taking part in regional or national master competitions every 2-3 months. Because of ethical considerations, it was not possible to include a control group, so all swimmers completed the same dry-land power training program.

Procedure

The swimmers followed a dry-land power training program for a total of seven weeks, with two sessions per week (14 sessions) (Figure 1). Both dry-land (bench press and bench pull) and swimming tests were conducted before (pretest) and after (posttest) the training program. Details of the dry-land power tests and dry-land power training will be given in more detail below. All swimmers had previous experience with completing the bench press exercise; however, not all of the swimmers had experience in the bench pull exercise. Therefore, for the pretest, the dry-land tests were performed twice, with a week interval, to prevent any learning effects. The trial with highest power was considered for analysis. Research suggests that maximum power is transient and must be, therefore, constantly monitored (Cronin & Sleivert, 2005). To achieve this, an extra set of dry-land tests was conducted after 4 weeks of training to adjust training load and volume related to maximum power.

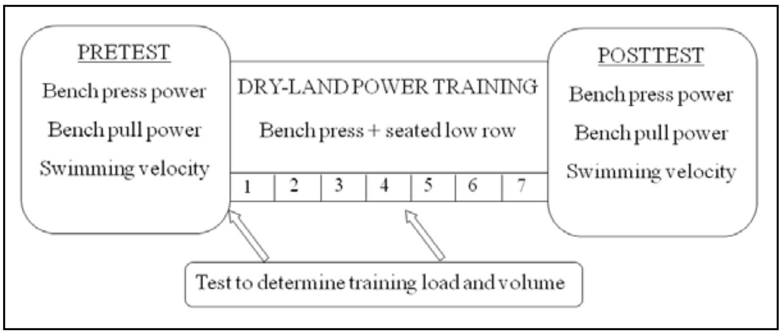

Figure 1. Dry-land power and swim velocity were tested before and after 7 weeks of dry-land training. An additional test was performed after 4 weeks, to adjust training load and volume.

Dry-land power tests

Incremental dry-land power tests were performed using bench press and bench pull exercises and following the same protocol. The bench pull set up was built ad-hoc for the tests (Figure 2). After a standardised warm-up, the test started with 30-40% of the perceived 1RM and continued in 5kg increments. Rest between sets lasted 3 min. This was considered to be sufficient to minimize any load order effects, such as fatigue or potentiation on later lifts in the sequence (Pearson, Cronin, Hume & Slyfield, 2009). The swimmers were instructed to complete the concentric phase as fast as possible. The number of repetitions for a particular load was determined according to the velocity of the first repetition. Three repetitions were performed when the swimmer displaced the bar with an average velocity ≥ 1m/s. In contrast, only two repetitions were executed when the average velocity was < 1m/s (López-Segovia, Marques, van den Tillaar & González-Badillo, 2011). The test ended when the mean propulsive power decreased in two consecutive loads after a previous increase. Five different loads were used for most of the swimmers to determine maximum power. Mean power, force and velocity of the propulsive phase of every repetition were measured by means of a linear encoder (T-Force

System v. 2.35, Ergotech S.L., Murcia, Spain. Freq: 1000Hz). According to Sánchez-Medina, Perez and González-Badillo (2010), the propulsive phase is defined as that portion of the concentric phase during which the measured acceleration is greater than acceleration due to gravity (i.e. a>-9.81 m/s^2). In every set, the repetition with the highest mean propulsive power was selected for analysis. Overall maximum propulsive power (MPP), and the corresponding load (MPL), propulsive force (MPF) and propulsive velocity (MPV) were assessed for both exercises. A short test to determine the training load and volume for each swimmer was performed before the training program and after 4 weeks. It consisted in one set with the MPL previously determined, where propulsive velocity was assessed in every repetition with the linear encoder. The number of repetitions selected for training was the number of repetitions that a swimmer was able to perform before MPV decreased 15% (Padulo, Mignogna, Mignardi, Tonni & D'Ottavio, 2012). After 4 training weeks, a short power test (3 loads) was performed together with this test to adjust the training load and volume. During all the tests, the swimmers were verbally encouraged to give their maximal effort.

Figure 2. Ad-hoc set up for the bench pull test.

Swimming velocity test

The swimming velocity test consisted of 4x25m all-out front crawl swimming in a 50m pool. The swimmers performed one free swimming trial and three pulling against a specific load (2.5, 5, 7.5 kg). Rest between trials was 10 min. The swimmers were instructed to do push-off starts and not to kick (using a pull-buoy between their legs), in order to make the results more comparable to arm dry-land power data. The load was attached to the swimmer's waist by means of a rope and a belt. It was displaced over the pool bottom, in the opposite direction to the swimmer. The rope changed direction by means of a pulley placed at the starting wall. The test was recorded from a lateral view by three underwater cameras (Sony, frequency: 50 Hz, shutter speed: 1/250s), which were fixed to the pool wall at 10, 15 and 20m from the starting wall. Mean velocity (v), stroke rate (SR) and stroke length (SL) between 10 and 20m were determined for every condition. By only collecting over the 10 m interval, the effects of start and finish were excluded from the experiment.

Description of the power training sessions

The training program lasted for 7 weeks, with two sessions per week on non consecutive days (14 sessions). All the swimmers included in the study completed at least 11 sessions (>75%). The main muscular groups involved were pectoralis major (bench press) and latissimus dorsi (seated low row). The bench pull set up was built ad-hoc for the tests; however, it could not be used for training due to the availability of facilities. For this reason the bench pull exercise was only used for testing, whilst the seated low row was utilised in the training program. The swimmers performed 5 sets of each exercise. The number of repetitions per set (between 3 and 8 in all cases) was determined for each swimmer by means of a short test prior to the training program (described in section 2.2.1). As it was established to increase explosive power output (Wilson, Newton, Murphy & Humphries, 1993), athletes trained with the resistance that maximised mechanical power output. Consequently, the load was different for each swimmer. The exercise rate was approximately 1 movement every 5 seconds (2 sec eccentric + 2 sec pause + 1 sec concentric) (Alcaraz, Romero-Arenas, Vila & Ferragut, 2011). The swimmers were asked to do the concentric contraction at maximal velocity (Newton & Kraemer, 1994). To allow each participant to perform at maximal efforts, a 5 minute rest interval was implemented between sets and exercises. After 4 training weeks, dry-land power tests were performed again to adjust training load and volume, which were different for each swimmer.

Statistical Analyses

Descriptive statistical methods were used to calculate mean, standard deviation and confidence limits (C.I., 95%) for all the variables. Percentages of increase and effect sizes from pre- to posttest for every variable were also calculated. Effect sizes were calculated according to the following formula (Coe, 2002):

Effect size = $(mean_{post} - mean_{pre})/SD_{pooled}$, where SD_{pooled} is:

$$SD_{pooled} = \sqrt{\frac{(n_{post}-1)SD_{post}^{\ 2} + (n_{pre}-1)SD_{pre}^{\ 2}}{n_{post}+n_{pre}-2}} ,$$

SD is standard deviation, n is sample size.

Due to the small sample size, a non parametric test (Wilcoxon matched-pairs signed-ranks test) was used to determine significant differences between pre- and posttest. Dry-land variables were normalised by body mass before calculating Spearman correlation coefficients with swimming variables. Statistical significance was set at $p \leq 0.05$. The statistical analysis was conducted using SPSS (Version 20).

Results

Effects of training on dry-land variables

Short-term dry-land training significantly increased bench-press maximum propulsive power (MPP) ($p \leq 0.05$) (from 442.41±57.88W to 471.09±34.31W) (Figure 3), and bench pull MPP (from 578.28±78.12W to 621.15±85.15W) (Table 1). The load (MPL), mean propulsive force (MPF) and mean propulsive velocity (MPV) did not change significantly after the training program in either exercise.

Table 1. Results of the dry-land power tests. MPP: maximum mean power of the propulsive phase; MPL: load displaced during the MPP repetition; MPF: mean propulsive force developed during the MPP repetition; MPV: mean propulsive velocity measured during the MPP repetition.

BENCH PRESS							
	pretest		posttest		% increase		Effect size
	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	
MPP (W)	442.41 57.88	23.09 38.41	471.09$^{p=0.05}$ 34.31	32.01 38.24	7.27 7.77	-22.12 68.39	0.60
MPL (kg)	30.75 9.16	394.02 490.80	35.13 3.72	442.41 499.77	24.87 45.57	0.25 15.42	0.63
MPF (N)	423.65 78.74	357.81 489.48	468.05 34.75	439.00 497.10	13.84 23.42	-10.25 36.31	0.73
MPV (m/s)	1.14 0.21	0.96 1.32	1.07 0.07	1.02 1.13	-2.88 20.13	-20.52 18.37	-0.45

BENCH PULL							
	pretest		posttest		% increase		Effect size
	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	
MPP (W)	578.28 78.12	31.05 50.09	621.15* 85.15	32.09 48.16	7.52 6.99	-16.53 8.82	0.52
MPL (kg)	40.57 10.29	512.96 643.59	40.13 9.61	549.96 692.34	-3.86 13.71	0.43 11.67	-0.04
MPF (N)	556.80 92.28	479.65 633.95	574.26 94.94	494.89 653.63	3.41 8.01	-4.89 8.74	0.19
MPV (m/s)	1.16 0.09	1.09 1.24	1.19 0.13	1.09 1.30	2.71 9.27	-6.77 11.70	0.27

*significantly higher than pretest, $p<0.05$.

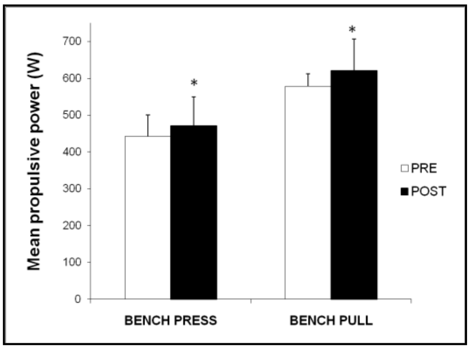

Figure 3. Mean propulsive power (MPP) before and after 7-week training period (mean±SD); *p ≤ 0.05.

Effects of training on swimming velocity and stroking parameters

The effect of short-term land training on maximal swim velocity (push-off start and no leg kick) is presented in Figure 4. Mean free swim velocity was significantly enhanced after the training program (from 1.28±0.06m/s to 1.48±0.09m/s, p≤0.05) (Table 2). The dry-land training program significantly increased maximal swimming velocity (12-16%) pulling different loads. After training, the stroke rate (SR) in free swimming decreased significantly from 1.08±0.11Hz to 1.03±0.12Hz, while the SR in loaded swimming trials did not change significantly. In contrast, the stroke length (SL) in every condition increased (11-27%) after the dry-land program.

Before training no significant correlation was observed between dry-land variables and maximal swimming velocity. No significant correlation was found between dry-land MPP and swimming velocity in any condition after 7 weeks of training. After the dry-land program, significant relationships were observed (r = 0.71, p < 0.05) between bench pull MPF and swimming velocity with 2.5 kg. In addition, significant negative relationships were observed between the individual values of bench press MPL and swimming velocity with 5 and 7.5 kg (r = -0.71 and -0.76, respectively; p < 0.05) after the prescribed training. The correlation between the change (%) in bench pull MPP and the change (%) in swimming velocity with 2.5kg load after the training was found to be close to significant (r = 0.69, p = 0.058).

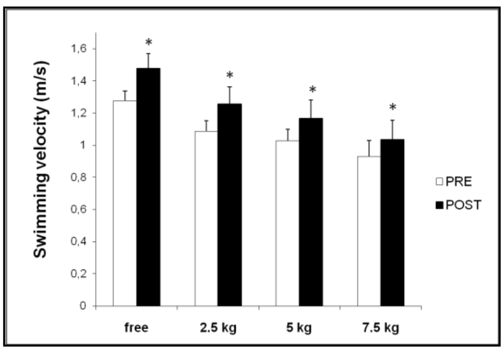

Figure 4. Maximal swim velocity ($v_{free,}$ $v_{2.5}$, v_5, $v_{7.5}$) before and after 7-week training period (mean±SD); *p ≤ 0.05.

Table 2. 25m freestyle swimming velocities (in-water start and no leg kick). v_{free}: with no load; $v_{2.5}$: with 2.5 kg; v_5: with 5 kg; $v_{7.5}$: with 7.5 kg.

SWIMMING TEST							
	pretest		posttest		% increase		Effect size
	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	MEAN SD	C.I. (95%)	
v_{free}	1.28	1.23	1.48*	1.40	15.59	8.82	1.61*
(m/s)	0.06	1.33	0.09	1.56	6.61	21.97	
$v_{2.5}$	1.09	1.03	1.26*	1.17	15.79	8.33	1.97*
(m/s)	0.07	1.14	0.10	1.35	7.04	21.46	
v_5	1.03	0.97	1.17*	1.07	13.42	4.03	1.43*
(m/s)	0.07	1.09	0.12	1.26	8.95	19.90	
$v_{7.5}$	0.93	0.84	$1.04^{p=0.05}$	0.94	12.36	-2.30	1.00
(m/s)	0.10	1.01	0.12	1.14	14.81	27.29	
SR_{free}	1.08	0.99	1.03*	0.92	-11.02	-9.90	-0.43
(Hz)	0.11	1.17	0.12	1.13	2.73	0.19	
$SR_{2.5}$	1.01	0.90	1.00	0.90	-2.00	-5.54	-0.08
(Hz)	0.12	1.11	0.12	1.11	6.93	5.32	
SR_5	1.04	0.95	0.98	0.88	-15.49	-12.71	-0.50
(Hz)	0.12	1.14	0.12	1.08	9.32	0.83	
$SR_{7.5}$	1.04	0.93	0.97	0.88	-12.27	-16.06	-0.58
(Hz)	0.13	1.15	0.11	1.05	22.59	3.94	
SL_{free}	1.20	1.08	1.45*	1.33	26.85	14.49	1.72*
(m/cic)	0.14	1.32	0.15	1.58	8.81	29.12	
$SL_{2.5}$	1.09	1.02	1.26*	1.16	11.08	10.63	1.67*
(m/cic)	0.08	1.16	0.12	1.36	0.90	21.57	
SL_5	0.99	0.93	1.20*	1.11	23.29	12.10	1.43*
(m/cic)	0.07	1.05	0.10	1.28	20.70	30.04	
$SL_{7.5}$	0.90	0.82	1.08*	0.97	22.62	3.75	1.70*
(m/cic)	0.09	0.98	0.12	1.18	33.72	38.55	

*significantly higher than pretest, $p < 0.05$.

Discussion

One common limitation attributed to strength training is the limited transfer of strength developed in land training into specific pulling force (Vorontsov, 2010). In the present study, a unique approach was the design to distinguish between the effects of dry-land training on dry-land or swimming variables. Thus, the main aim of the study was to determine the effects of a dry-land power training program on upper body muscular power output and sprint swimming enhancement. The results of the present study showed that the maximum propulsive power increased significantly on bench press (7.27±7.77%) and bench pull (7.52±6.99%) after 7 weeks of training. An interesting result was a concomitantly significant increase in free swim velocity (15.59±6.61%), as well as in swimming pulling three different loads. Stroke rate decreased in free swimming, while stroke length was enhanced in every condition. These findings suggest that dry-land power training may be an effective method to complement and optimise swimming training.

Several training methods have been tested to develop power in order to improve sprint swimming performance. Thus, depending on the desired objectives, the following have been used: (a) work against the athlete's own weight (e.g., plyometric exercises); (b) resisted training, where the swimming movement is performed with an added resistance (e.g., towing, parachutes, etc.); (c) traditional strength training with external loads; and (d) strength training using the optimum load to maximise power. In the present study, because the aim was to enhance power output, the swimmers were asked to train with the velocity and load that maximised this variable (Cronin & Sleivert, 2005; Jandacka & Vaverka, 2009; Wilson et al., 1993). This agrees with Newton and Kraemer (1994), who stated that increases in power are specific to the training resistance and velocity used. Thus, the use of high speed is recommended if the purpose of the training is to increase power (Newton & Kraemer, 1994; Porter, 2006; Sayers et al., 2003). Conversely, Moss, Refsnes, Abildgaard, Nicolaysen and Jensen (1997) and McBride, Triplett-McBride, Davie and Newton (2002) suggested that there was very little difference in the effects of heavy- and light-load training in terms of power and performance.

The bench press is the preferred exercise for upper limb strength or power tests (Izquierdo et al., 2002; Sanchez-Medina et al., 2010). In the present study, bench press was used as a standard exercise and bench pull was included because latissimus dorsi is the predominant muscle involved in this exercise. The contraction of this muscle produces internal rotation, extension and adduction of the shoulder joint, which is a close description of front crawltechnique. Therefore, by including the bench pull power exercise in the training program the swimmers are able to increase their pulling power.. An increase in pulling power would not only allow a swimmer to increase theirpropulsion during each stroke cycle, but also assist in maintaining proper body position and alignment in the water, which would lead to a higher velocity (Santana, 2010). On the other hand, the load that elicits the maximal power in the upper extremities is reported to be approximately 40% RM (Izquierdo et al., 2002). However, when training power, it is important to bear in mind that the specific load must be individually deteined (Cronin & Sleivert, 2005). In agreement with this, the training program carried out in the present study was very similar to the one in Wilson et al. (1993), which consisted of 3-6 sets, 6-10 reps, 3 min rest between sets, of jump squat with the load that maximised mechanical power output. Only in this group the improvement in 30 m running sprint was almost significant, in contrast to the weight and plyometric groups. Garrido et al. (2010) used a very similar training method for swimmers, which included2-3 sets, 6-8 reps at 50-75% 6RM over four exercises (two for upper and two for lower limb). An improvement in dry-land strength and power was found, but the results did not clearly show that swimming performance was enhanced by strength training, although slight improvements were noticed. A greater effect was expected in our study with 10 training sets (5 per exercise) for the upper limb per session during 7 weeks, one less than in the latter study. In the present study, maximum propulsive power increased from 442.41±57.88W to 471.09±34.31 W on bench press and from 578.28±78.12 W to 621.15±85.15 W on bench pull after the training program. These values are in keeping with Izquierdo et al. (2002), who obtained mean power values of 250-500 W on bench press, depending on the sport modality. For participants whose 1RM was 80 kg (predicted bench press 1RM in our study was 77.0±11.0 kg), Sanchez-Medina et al. (2010) found MPP to be close to 450 W. After 12 weeks of strength training (3-4 sets, 3-8 reps, 50-80% RM), volleyball players showed a strength improvement by 15% in the bench press and an 11.8% increase in ball throwing distance. In the present study, the increase in bench press maximum propulsive power (MPP) was due to an increase in force but a reduction in velocity, while the growth of bench pull MPP happened because both force and velocity increased, but to a lesser extent. Despite the fact that the test and training exercises were the same for bench press and different for bench pull, the relative improvement was very similar for both (7.27±7.77% and 7.52±6.99%, respectively). MPF or MPV changes were not significant on either exercise.

A limited amount of power values or its increase after training was found in the scientific literature for swimmers. Morouço et al. (2011) reported a lower value for bench press MPP (221.77±58.57W), possibly because the measured swimmers were adolescents. In another study, the swimmers who completed a strength training program (3-2 sets, 6-8 reps, 50-75% 6RM) besides swimming obtained significantly larger improvements in bench press 6RM (43%) and ball-throwing distance (6-8%) than those who only did aerobic swimming training (15% and 2.5-6%, respectively) (Garrido et al., 2010). Girold et al. (2012) found that a group of swimmers who combined swimming and dry-land strength training (3 sets, 6 reps, 80-90% RM, concentric phase as fast as possible) during 4 weeks had their arm extension peak torque further improved than the group who did only swimming training. As it is a less popular exercise for evaluating strength and power, power values for bench pull were not found. It must be noted that the validity of generalising findings from novice subjects to athletes with experience in weight training needs to be done with caution as the findings may be compromised by the trainability of the novice subjects (Cronin & Sleivert, 2005). Although the swimmers included in the current study were not novice in weight training, they were not experts either. Thus, increases in MPP might be lower in highly weight-trained competitive swimmers.

The transference of power developed in land to actual pulling power during swimming is a controversial issue. Therefore, one of the main aims of the current study was to determine the effects of a dry-land training program on swimming performance. The results of the current study showed that front crawl free swim velocity, as well as pulling three different loads, was significantly enhanced (12-16%) after the dry-land training program. Considering that the participants were experienced swimmers who should not change their technique while swimming with loads from pre- to posttest, the results suggest that swimming power increased within every load between both tests, since velocity increased. A higher velocity would imply a greater drag which was overcome by greater propulsion per stroke, as the stroke frequencies were not higher. Swim performance enhancement in the present study was larger than reported in other dry-land training studies. Costill et al. (1980) reported 28% and 3.6% improvements in power output and sprinting performance, respectively, following resistance training on a biokinetic swim bench. Eight weeks of isokinetic training on a swim bench produced 18.66% improvement in arm power and 3.76% on 25 yd swimming (Sharp et al., 1982). Two groups who underwent swimming training plus either weight-assisted or free-weight strength training demonstrated similar improvements (close to 4%) in 365.8m time (Trappe & Pearson, 1994). The combination of aerobic swimming, running and strength training for the upper limb during 4 and 12 weeks yielded 2 and 2.8% improvement in 50 m front crawlperformance, respectively (Girold et al., 2012; Girold et al., 2007). A dry-land power training (bench press and ball throwing, 2-3 sets, 6-8 reps, 50-75% 6RM) combined with swimming induced 4.45% and 1.94% enhancement in 25 m and 50 m performance, respectively, in young swimmers (Garrido et al., 2010). The group who only swam showed no improvement in 25m and 1.88% in 50m. A similar improvement in 50 m time (2.1%) was obtained after a 6-week dry-land training period (bench press, 90-100% RM, explosive contraction) prescribed by Strass (1988). The swimmers also improved rate of force development (RFD, 24.8%) and 25 m speed (4.4%). In general, the training tended to induce greater improvements in dry-land power output and RFD than in the front crawl swim performance. This difference might be a result of similar arm movements during strength training and strength test exercises. Conversely, in the present study, the improvements were larger in swimming velocity than in muscular power. The dry-land training focused on power development, which may have had a larger effect on actual swimming, and it included the bench pull, which is considered to be more similar to the swimming movement. The inclusion of this exercise might have been the cause of the greater improvement in 25 m swim performance (15.59%) found in the current study.

On the contrary, several studies did not find improvements in swimming performance after a combined dry-land and swimming training period, compared to only swimming training. Muscular strength and power were improved by 8 weeks resistance training (5 exercises, 3 sets, 8-12 reps), however this improvement did not transfer to a swim performance enhancement (Tanaka et al., 1993). The authors suggested that the lack of positive transfer between dry-land strength gains and swimming propulsive force may be due to the specificity of training. However, maximal swim velocity decreased for both groups, suggesting that the swimming program may not have been focused on improving performance. Jensen (1963) reported that different combinations of swim training and weight training improved 100 yd swim performance. Nevertheless, swim training or weight training alone also caused significant improvements in swimming performance, and no significant differences were observed among groups. High-velocity swim training alone and combined with biokinetic resistance training on the swim bench (3ses/week, 4x[4x(10”pull/10”rest)]) were compared by Roberts, Termin, Reilly and Pendergast (1991). Strength, power or endurance did not increase significantly in either group, although there was a significant reduction in the 100 yd freestyle time in both of them. The biokinetic resistance training did not add to the improvement obtained from high-velocity swim training. In light of the results of these studies, dry-land training may not appear to add large benefits to swimming training effects. However, the results of the current study suggest that, when in-water training only may not be possible due to swimming pool restrictions, or the coaches may not have the necessary equipment at their disposal, a dry-land power training program may be an effective tool to achieve significant improvements in swimming performance.

In addition to the enhancement in swimming velocity after dry-land power training, positive training-related changes were also observed in stroke parameters. Thus, stroke rate (SR) decreased in every condition after the dry-land training proposed in the present study, but the change was only significant in the free swimming condition (11%). On the contrary, the stroke length (SL) in every condition increased significantly (11-27%) after the dry-land program. This concurs with Strass (1988), who reported 7% and 7.3% improvements in 25m and 50m SL. In contrast, Girold et al. (2007) found a stroke depth decrease but no change in SR or SL. Using the same, but shorter, dry-land training program, Girold et al. (2012) found SL increases, while SR remained unchanged.

The primary limitation of this investigation was the small sample size. This was due to the limited number of former elite swimmers who were still training regularly throughout the week, but who are only competitive at a sub-elite level. The sample agreed to trial a new training method, with the possibility of it leading to improvements in performance. However, for ethical reasons, it was decided that the entire sample should follow the same program, which unfortunately lead to the lack of a control group. Therefore, it was not possible to compare the effects of combined dry-land and swimming training to only dry-land training. Although all the dry-land power and swim velocity variables were enhanced with the program proposed in this study, it might be necessary to increase training frequency or duration to obtain significant results in all the dry-land variables.

Conclusion

In summary, the purpose of the present study was to determine the effect of a dry-land power training program on upper body muscular power output and whether this resulted in faster sprint swimming. The results showed that the maximum propulsive power increased significantly on bench press and bench pull after 7 weeks of training. Furthermore, front crawl free swim velocity, as well as in three loaded conditions, improved significantly. The same happened with stroke length. These findings suggest that dry-land power weight training may be an effective method to complement swimming training, when a swimming pool or equipment for specific in-water power training are not available. Nevertheless, it must be kept in mind that dry-land exercises should only be a complement to swimming training, as this is the most specific way of training.

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 for the use of the swimming pool and the fitness room. In addition, the authors wish to thank the swimmers for their kind cooperation. This study was possible thanks to a FPU fellowship (AP2008-03243), funded by the Ministry of Science and Innovation of Spain.

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Chapter 6

Conclusions

In this thesis several studies were carried out in order to better understand the importance and behaviour of power in swimmers, both on dry-land and in the water. First of all, a review on methods used to measure dry-land and swim power was conducted in Chapter 1. Among the methods available to assess swim power, semi-tethered swimming was selected for our first study. An updated protocol, which included intra-cycle swim power synchronized with video recording, was presented in Chapter 2. It allowed for deep analysis of the behaviour of power along front crawl propulsive stroke phases. Reference values for maximum swim power, as well as for the load and velocities associated, were obtained.

The previous method would be suitable for resisted swimming training, which would help the swimmer build specific swimming power. A study was conducted in Chapter 3 to evaluate the effect of swimming with load on stroke and coordination parameters. Swim velocity could not be kept constant for longer than 5-6 s when load was heavier than 4.71 kg. From this load, the differences between mean and peak velocity were significantly higher than in free swimming. Index of coordination underwent a significant increase over 2.84 kg. It was suggested that the optimal load for resisted swimming training should lie between 2.84 and 4.71 kg. In doing so, the swimmer would be able to increase their swimming power and change to or consolidate superposition as the coordination mode, without experiencing important changes in stroke parameters.

Swim power is considered to be a good predictor of sprint swimming performance. However, when measuring this variable in the water is not possible, several alternatives can be found to determine power in swimmers on dry-land. In the present thesis, bench press and arm stroke exercises were chosen for this task. Several relationships and trends were found in Chapter 4 among dry-land power (on both exercises), swim power and swim velocity, suggesting that the arm stroke power could also be a good predictor of sprint swimming velocity.

Dry-land training is usually included in a swimmer’s training program, to help increase physical capacities that will be applied during actual swimming. The effects of a dry-land power-oriented training program during seven weeks were determined in Chapter 5. Maximum power on bench press and bench pull increased after seven weeks of training. This improvement was transferred to swimming, where maximal velocity increased significantly after the training program.

The studies presented in this thesis led to the following specific conclusions:

- The intra-cycle power output during the front crawl arm-stroke was examined. The mean power during the push phase was found to be higher than during the pull phase.

- The maximum swim power delivered to an external load was 66.49±19.09 W. It was achieved with a load of 3.95±0.79 kg and a swim velocity of 0.75±0.18 m/s.

- Stroke parameters in front crawl semi-tethered swimming were not greatly modified by the addition of load, when the weight was limited to a maximum. Stroke rate did not change and stroke length decreased with load. Index of coordination increased with load.

- The optimal load range for semi-resisted swimming training was suggested to be between 2.84 and 4.71 kg.

- Bench press power was higher than arm stroke power and swim power. Swim power measured on the MAD system was higher than measured by means of an updated semi-tethered swimming protocol, due to methodological differences.

- Bench press power was moderately related to maximum swim power. A higher but not significant correlation was found between arm stroke power and maximum swim power. There was a high and significant correlation between swim velocity and swim power, high but not significant between swim velocity and arm stroke power, and moderate and almost significant between swim velocity and bench press power. These results confirmed that swimming is the most specific way to measure swim power, although the arm stroke exercise may be a suitable dry-land alternative.

- Maximum propulsive power on bench press and bench pull significantly enhanced after a 7-week dry-land power training program on bench press and seated low row.

- Maximal front crawl swim velocity increased after a 7-week dry-land power training program. Stroke rate decreased while stroke length increased.

Practical recommendations

As it was showed in Chapter 1, there are many different types of equipment and protocols that can be used to measure and train power in swimmers. From our experience, we would recommend that the testing or training exercise be as similar to competitive swimming as possible. Semi-tethered swimming with a force transducer and a speedometer seems appropriate for this purpose. Other characteristics we would aim at are simplicity, portability and repeatability, concerning the measuring equipment as well as the system to administer the load.

Regarding the protocol which was proposed in Chapter 2, the intra-cycle power synchronized with the video footage would allow to obtain useful feedback for swimmers and coaches in a short period of time. This would make them able to detect the phases of the stroke where higher power needs to be developed and they could work to correct it. Coaches could take advantage of this updated methodology to periodically assess the athletes' swim power during training, observe their evolution and personalise in-water power training programs.

In regard to power training, dry-land or in water, it is of paramount importance to determine the load which elicits the maximum power in every swimmer individually, and to adjust it periodically. It must be also checked by the coach that technique is maintained correct. On dry-land the concentric contraction must be performed at maximal velocity and during semi-resisted training swimming technique, stroke rate and stroke length should not be greatly modified.

Positive correlation or tendency was found in Chapter 4 between dry-land power (bench press and arm stroke exercise) and both swim power and swim velocity. Moreover, it is generally easier to set up and conduct dry-land tests than in-water tests. In this case, it is suggested that the swimmers' strength and power are periodically monitorised by means of dry-land tests, while aquatic tests are conducted with longer time intervals.

Future research areas

In the present thesis we tried to better understand the behaviour of dry-land and swim power in swimmers, as well as to determine the relationship between them and with swim velocity. However, further studies with a larger sample are needed to find significant relationships among arm stroke power, swim power in semi-tethered swimming and maximal swim velocity. In order to make this feasible, it is recommended to substitute the pulley system used in semi-tethered swimming for a portable device which can deliver a known and replicable resistance.

A complete swim power curve on semi-tethered swimming was represented. A similar curve on the MAD system could be described, and the data compared to the one obtained for semi-tethered swimming.

A dry-land power-oriented training program had an increasing effect on maximum dry-land power and maximum swim velocity. It may be interesting to compare these effects to the ones obtained with a swimming power-oriented training, or with a combination of both.

Finally, more versions of dry-land exercises to determine upper-limb power in swimmers might be introduced. Furthermore, it would be also interesting to determine the lower-limb power on dry-land and during swimming, as well as to compare it to the upper-limb power.

Conclusiones

En la presente tesis doctoral se llevaron a cabo diversos estudios con el propósito de comprender mejor la importancia y el comportamiento de la potencia en nadadores, tanto en seco como dentro del agua. En primer lugar, en el Capítulo 1 se realizó una revisión acerca de los métodos empleados para evaluar la potencia en seco y en el agua. Entre los métodos que existen para medir la potencia de nado, la natación semi-resistida fue la elegida para nuestro estudio. En el Capítulo 2 se presentó un protocolo actualizado, que incluyó el registro intraciclo de la potencia de nado y la grabación en vídeo. Este protocolo permitió analizar el comportamiento de la potencia a lo largo de las fases propulsivas del ciclo en el estilo crol. Se obtuvieron valores de referencia de potencia máxima de nado, así como de la carga y velocidad asociadas.

El método anterior parece apropiado para el entrenamiento con natación resistida, que ayudaría al nadador a aumentar su potencia de nado específica. En el Capítulo 3 se desarrolló un estudio para evaluar el efecto de la natación con cargas sobre los parámetros técnicos y de coordinación. La velocidad de nado no pudo mantenerse constante durante más de 5-6 s cuando la carga fue superior a 4.71 kg. A partir de esta carga, las diferencias entre las velocidades media y pico fueron significativamente mayores que en la natación sin carga. El índice de coordinación sufrió un aumento significativo a partir de los 2.84 kg. Una carga de entre 2.84 y 4.71 kg fue propuesta como la carga óptima para el entrenamiento de natación resistida. Con ella el nadador sería capaz de aumentar su potencia de nado y modificar su patrón de coordinación hacia superposición o consolidarlo, sin sufrir cambios importantes en su técnica de nado.

La potencia de nado es considerada una buena variable predictiva del rendimiento en natación. Sin embargo, en caso de que no sea posible medir esta variable en el agua, existen diversas alternativas para determinar la potencia de los nadadores en seco. En la presente tesis se eligieron para este fin los ejercicios de press de banca y tracción de crol. En el Capítulo 4 se encontraron numerosas relaciones y tendencias entre la potencia en seco (en ambos ejercicios), la potencia de nado y la velocidad de nado, sugiriendo que la potencia en el ejercicio de tracción de crol podría ser también una buena variable predictiva de la velocidad en natación.

El entrenamiento de un nadador incluye generalmente una parte de entrenamiento en seco, para ayudarle a mejorar ciertas capacidades físicas que más tarde se aplicarán durante la natación. En el Capítulo 5 se determinaron los efectos de un programa de entrenamiento en seco y orientado a la potencia, de siete semanas de duración. Tras este periodo, la máxima potencia en press de banca y remo tumbado aumentó. Esta mejora se transfirió al nado real, donde la velocidad aumentó también significativamente tras el entrenamiento.

Las siguientes conclusiones específicas fueron extraídas de los estudios presentados en esta tesis:

- La potencia intraciclo fue examinada a lo largo del ciclo natatorio en el estilo crol. La potencia promedio durante la fase de empuje fue mayor que durante la fase de tracción.

- La máxima potencia de nado desarrollada sobre una carga externa fue de 66.49±19.09 W. Fue alcanzada con una carga de 3.95±0.79 kg y una velocidad de nado de 0.75±0.18 m/s.

- Las variables relativas al ciclo natatorio no sufrieron grandes modificaciones con la aplicación de cargas durante la natación semi-resistida, siempre que la carga no sobrepasara cierto límite máximo. La frecuencia de ciclo permaneció constante y la longitud de ciclo disminuyó a medida que la carga aumentó. El índice de coordinación aumentó con el aumento de la carga.

- Se propuso un rango óptimo de cargas para el entrenamiento de natación semi-resistida, situado entre 2.84 y 4.71 kg.

- La potencia en press de banca fue superior a la potencia en el ejercicio de tracción de crol y ambas, mayores que la potencia de nado. La potencia de nado medida en el sistema MAD fue mayor que la medida a través de un protocolo actualizado de natación semi-resistida, debido a diferencias metodológicas.

- La potencia en press de banca se relacionó de forma moderada con la potencia de nado. Se encontró una mayor correlación, aunque no significativa, entre la potencia en el ejercicio de tracción de crol y la potencia de nado. La correlación entre la velocidad de nado y la potencia de nado fue alta y significativa, entre la velocidad de nado y la potencia en la tracción de crol fue alta pero no significativa, y entre la velocidad de nado y la potencia en press de banca fue moderada y casi significativa. Estos resultados confirmaron que la forma más específica de medir la potencia de nado es durante la natación, aunque el ejercicio de tracción de crol podría ser una alternativa adecuada en seco.

- La potencia máxima propulsiva en press de banca y remo tumbado aumentó significativamente tras un entrenamiento de potencia en seco de siete semanas de duración en press de banca y remo sentado.

- La velocidad máxima de nado estilo crol aumentó tras un programa de entrenamiento de potencia en seco de siete semanas de duración. La frecuencia de ciclo se redujo, mientras que la longitud de ciclo aumentó.

Recomendaciones prácticas

Tal como se mostró en el Capítulo 1, existen numerosos instrumentos y protocolos que pueden utilizarse para medir y entrenar la potencia en nadadores. A partir de nuestra experiencia, recomendamos que el ejercicio que se utilice para entrenar o realizar un test sea lo más parecido posible a la situación de competición. Para este propósito parece apropiada la natación semi-resistida, utilizando un transductor de fuerza y un velocímetro como instrumentos de medida. Otras características que parecen importantes son la simplicidad, la portabilidad y la repetibilidad, tanto del instrumento de medida como del sistema que se utilice para aplicar la carga.

En relación al protocolo propuesto en el Capítulo 2, el registro de potencia intraciclo sincronizado con el vídeo permitiría obtener feedback útil y rápido a nadadores y entrenadores. Esto haría posible detectar las fases del ciclo en que se podría aumentar la potencia y trabajar para corregirlo. Los entrenadores podrían utilizar esta metodología para evaluar la potencia de nado durante el entrenamiento de forma periódica, observar su evolución y desarrollar programas de entrenamiento de potencia en el agua de forma personalizada.

En el entrenamiento de potencia, tanto en seco como en el agua, es muy importante determinar individualmente la carga con la que cada nadador desarrolla la máxima potencia, así como ajustarla periódicamente. Además, el entrenador debe comprobar que la técnica es correcta en todo momento. En seco, la contracción concéntrica debe realizarse a máxima velocidad, y durante el entrenamiento de natación resistida, la técnica, la frecuencia y la longitud de ciclo no deben modificarse en gran medida.

En el Capítulo 4 se encontraron correlaciones o tendencias positivas entre la potencia en seco (press de banca y ejercicio de tracción de brazos) y la potencia y la velocidad de nado. Además, en general, el montaje y desarrollo de los tests en seco son más sencillos que para los tests dentro del agua. En ese caso, se recomienda monitorizar la fuerza y potencia de los nadadores de forma periódica mediante tests en seco, mientras que los tests acuáticos se realizan con mayores intervalos de tiempo entre ellos.

Futuras áreas de investigación

En la presente tesis hemos tratado de comprender mejor el comportamiento de la potencia en nadadores, en seco y dentro del agua, así como determinar la relación existente entre ellas y con la velocidad de nado. Sin embargo, es necesario realizar otros estudios con una muestra mayor para encontrar relaciones significativas entre la potencia en el ejercicio de tracción de brazos, la potencia de nado en natación semi-resistida y la máxima velocidad de nado. Para que esto sea posible, se recomienda sustituir el sistema de poleas que fue usado en la natación semi-resistida por un dispositivo portátil que pueda ejercer una resistencia conocida y repetible.

Se representó una curva completa de potencia en natación semi-resistida. Se podría describir una curva similar utilizando el sistema MAD, y comparar los datos con los obtenidos con natación semi-resistida.

Un programa de entrenamiento en seco orientado a desarrollar la potencia incrementó la máxima potencia en seco y la máxima velocidad de nado. Podría ser interesante comparar estos efectos con los que se obtendrían con un entrenamiento de natación orientado a desarrollar la potencia, o con una combinación de entrenamiento en agua y en seco.

Por último, podrían introducirse nuevas versiones de ejercicios en seco para determinar la potencia del tren superior en nadadores. Además, sería igualmente interesante determinar la potencia del tren inferior, tanto en seco como durante la natación, así como comparar estos resultados con la potencia del tren superior.

Appendix

An Updated Protocol to Assess Arm Swimming Power in Front Crawl

Authors R. Dominguez-Castells[1], M. Izquierdo[2], R. Arellano[1]

Affiliations [1] Department of Physical Education and Sports, Faculty of Sports Sciences, University of Granada, Granada, Spain
[2] Department of Health Sciences, Public University of Navarre, Tudela, Spain

Key words
- semi-tethered swimming
- intra-cycle speed
- stroke phases

Abstract

Mechanical power output is a reliable predictor of swim speed in front crawl. However, a complete power curve (power vs. load) has not been described for swimming, and intra-cycle power has not been assessed. The purpose of this study was to examine intra-cycle power output at propulsive phases and to determine maximum swimming power, the corresponding load and swimming speed. 18 swimmers (age 22.10 ± 4.31years, height 1.79 ± 0.07 m, arm span 1.85 ± 0.08 m and body mass 76.74 ± 9.00 kg) performed a swim power test. It consisted of 12.5 m all-out swims with only the arms, with a load attached to the swimmer. A linear encoder and a load cell recorded intra-cycle speed and force in each trial. The test was recorded with 2 underwater cameras. Intra-cycle power was obtained for propulsive stroke phases (pull: 60.32 ± 18.87 W; push: 71.21 ± 21.06 W). Peak power was 114.37 ± 33.16 W. Mean maximum swim power was 66.49 W (0.86 W/kg), which was reached at a swimming velocity of 0.75 m/s with a 47.07 % of the individual maximal load. Significant positive correlation ($r = 0.76$, $p < 0.01$) between maximum swim power and maximum swim speed was observed. These results suggest that the proposed test may be a training tool that is relatively simple to implement and would provide swimmers and coaches with quick feedback.

Introduction

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].

accepted after revision
July 23, 2012

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DOI http://dx.doi.org/10.1055/s-0032-1323721
Published online: October 12, 2012
Int J Sports Med 2013; 34: 324–329 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

Correspondence
Rocio Dominguez-Castells
Department of Physical Education and Sports
University of Granada
Ctra. Alfacar
18011 Granada
Spain
Tel.: + 34/645/191 078
Fax: + 34/958/244 369
rdc@ugr.es

Journal of Human Kinetics volume 32/2012, 33-41 DOI: 10.2478/v10078-012-0021-9
Section - Swimming

Effect of Different Loads on Stroke and Coordination Parameters During Freestyle Semi-Tethered Swimming

by
Rocio Dominguez-Castells[1], Raul Arellano[1]

The aim of this study was to analyse to what extent the use of different loads modifies freestyle stroke and coordination parameters during semi-tethered swimming, and to examine whether those changes are positive or negative to swimming performance. First, behaviour of swimming speed (v), stroke rate (SR) and stroke length (SL) with increasing loads was examined. Secondly, mean and peak speed of propulsive phases ($propv_{mean}$ and $propv_{peak}$) were analysed, as well as the relative difference between them (%v). Finally, index of coordination (IdC) was assessed. Eighteen male swimmers (22.10±4.31years, 1.79±0.07m, 76.74±9.00kg) performed 12.5m maximal sprints, pulling a different load each trial (0, 1.59, 2.21, 2.84, 3.46, 4.09, 4.71, 5.34, 5.96, 6.59, 7.21 and 7.84kg). Rest between repetitions was five minutes. Their feet were tied together, keeping a pull-buoy between legs and isolating the upper limb action. A speedometer was used to measure intra-cycle speed and the test was recorded by a frontal and a lateral underwater cameras. Variables v and SL decreased significantly when load increased, while SR remained constant ($p<0.05$). $Propv_{mean}$ and $propv_{peak}$ decreased significantly with increasing loads ($p<0.05$). In contrast, %v grew when load rose ($r = 0.922$, $p<0.01$), being significantly different from free swimming above 4.71kg. For higher loads, swimmers did not manage to keep a constant velocity during a complete trial. IdC was found to increase with loads, significantly from 2.84kg ($p<0.05$). It was concluded that semi-tethered swimming is one training method useful to enhance swimmers' performance, but load needs to be individually determined and carefully controlled.

Key words: *intra-cycle speed, propulsive phases, index of coordination, resisted training.*

Introduction

In swimming, race time can be divided into four components: start time, swimming time, turn time and finish time (Arellano et al., 1994). Regarding actual swimming, the time needed to complete one lap can be considered as a function of stroke rate and stroke length. As in other cyclical activities, swimmers need to find the optimal compromise between stroke rate and stroke length to attain and keep the maximal velocity during a race (Alberty et al., 2005).

Numerous studies have been carried out to observe and understand the evolution of this "SL × SR" model during competitive events (Arellano et al., 1994; Chollet et al., 1997; Craig et al., 1985). Throughout the race, as fatigue develops, speed and stroke length decrease whereas stroke rate remains constant or slightly increases at the end of the race (Alberty et al., 2009; Chollet et al., 1997; Craig et al., 1985; Hay, 2002; Keskinen and Komi, 1993). Swimmers can choose different strategies to develop their maximal speed as a function of the race distance and they attempt to maintain this chosen speed in spite of fatigue throughout the race.

Stroke rate and stroke length combinations (and, therefore, speed values) are determined by several factors such as anthropomorphic variables, muscle strength, physical conditioning

[1]- *Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Spain.*

Authors submitted their contribution of the article to the editorial board.
Accepted for printing in Journal of Human Kinetics vol. 32/2012 on May 2012.

Acknowledgements

This thesis was possible thanks to a fellowship (AP2008-03243) from the National Program for University Professors Education, awarded by the Spanish Ministry of Science and Innovation (2009-2013).

Me gustaría dar las gracias de forma especial a:

La Facultad de Ciencias del Deporte de Granada, por permitir el uso de la antigua piscina y la sala de musculación en el desarrollo experimental.

El Departamento de Educación Física y Deportiva, que se ha adaptado en cada momento a mis necesidades.

El grupo de investigación Actividad Física y Deportiva en el Medio Acuático (CTS-527), que me ha proporcionado los medios necesarios para el desarrollo de mi investigación.

Todos los nadadores que participaron desinteresadamente y con una sonrisa, tanto aquéllos que fueron incluidos finalmente en los diferentes estudios, como los que no.

Todos los que colaboraron en alguna parte del proceso.

Raúl. Por iniciarme y guiarme en el mundo de la investigación. Por darme siempre los recursos que estuvieron a su alcance. Por permitirme cumplir un sueño en el tercer año de la tesis, aunque no fuera lo más conveniente y fácil para él. Por confiar en mí.

Mikel Izquierdo. Por recibirme en Pamplona y guiarme en el proceso de publicación, permitiendo que avanzara en mi trabajo mucho más rápido de lo que lo hubiera hecho sin su ayuda.

Luis Sánchez Medina, al que molesté infinidad de veces con dudas sobre el uso del t-force. Por tener siempre para mí una respuesta amable y rápida.

Huub Toussaint and Roald van der Vliet. For sharing with me their way of working and letting me be part of it, both in Amsterdam and Eindhoven. For helping me become more active, creative and critical in research.

Bruce Mason. For making me feel at home in the antipodes. For doing his best to make my stay and research at the AIS fruitful and successful.

Elena. Por ser mi compañera de viaje en la primera etapa de la tesis (DEA) y compartir conmigo buenos y malos momentos en ese primer año y mucho después.

Julia. Por haber compartido conmigo tantos momentos y sentimientos comunes durante nuestras respectivas tesis. Por haberme apoyado cuando lo necesitaba y valorarme tanto siempre, más que yo misma.

Los locos del laboratorio. Por hacerme cada día más ameno y sacarme una sonrisa en los momentos de estrés o frustración. Por “sacarme” de vez en cuando del agua para enseñarme un poquito sobre otras áreas de investigación.

Carol y Esther. Por ser mi referencia en el mundo de la investigación, en cada una de sus etapas, por servirme de ejemplo y darme siempre buenos consejos.

Xabi y Elsa. Por ser amigos especiales que compartieron conmigo las dificultades de la investigación y el virus del waterpolo.

Equipo de waterpolo CDU Granada. Por servirme de vía de escape día tras día durante siete años y darme la energía necesaria para continuar con el trabajo al día siguiente.

Equipo de waterpolo WP UPNA 98-02. Por darme la oportunidad de cumplir un sueño y permitirme que lo compaginara con la realización de esta tesis.

Sander. For answering that first call and being always there since then, giving me extra happiness and support in the final part of this work.

A mi hermana, que fue la primera Dra. Domínguez Castells. Por enseñarme que nada era el fin del mundo y abrirme camino en tantas cosas, a pesar de ser la hermana pequeña.

A mis padres. Por darme todos los medios y la mejor formación posible. Por compartir conmigo los buenos momentos y, sobre todo, aguantarme y apoyarme en los malos. Por escucharme siempre, aconsejarme y confiar en mí cuando no tomé las decisiones esperadas.

Gracias a todos.