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Tethered swimming and dry land force parameters.
Useful tools to characterize front crawl performance in both genders.

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KEY WORDS: SWIMMING, FRONT CRAWL, TETHERED SWIMMING, DRY-LAND, STRENGTH, TRAINING & TESTING.

"Choose a job you love, and you will never
have to work a day in your life."
Confucius.

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List of Publications

This Doctoral Thesis was based on the following papers, which are referred in the text by their Arabic and Roman numerals, respectively:

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1. Morouço PG, Marinho DA, Fernandes RJ, Marques MC. Biophysical evaluation of swimmers using tethered swimming: a qualitative review. Submitted for publication to *Journal of Strength and Conditioning Research*.

2. Morouço PG, Marinho DA, Amaro NM, Turpin JP, Marques MC. Effects of dry-land strength training on swimming performance: a brief review. *Journal of Human Sport & Exercise* in press.

3. Morouço PG, Marinho DA, Keskinen KL, Marques MC. Stroking force and front crawl swimming velocity in male swimmers. Submitted for publication to *Scandinavian Journal of Medicine & Science in Sports*.

4. Morouço PG, Fernandes RJ, Marques MC, Marinho DA. Front crawl arm asymmetries assessment using tethered swimming. Submitted for publication to *Human Movement Science*.

5. Morouço PG, Marinho DA, Izquierdo M, Neiva HP, Marques MC. Relative contribution of arms and legs in front crawl tethered swimming, according to gender. Submitted for publication to *Journal of Science and Medicine in Sport*.

6. Morouço, PG, Neiva HP, González-Badillo J, Garrido N, Marinho DA, Marques MC. Associations between dry-land strength and power measurements with swimming performance in elite athletes: a pilot study. *Journal of Human Kinetics* 2011; SI: 105-112.

7. Morouço PG, Neiva HP, Marques MC. Squat, lat pull down and bench press: which is the most related to female swimmers performance? *Motricidade* 2012; 8(S1): 35-40.

Throughout the experiments carried, this work took a lot of steps, conducting to some preliminary studies. These experiments allowed a sharing of knowledge in scientific congresses and, more important, the exchange of ideas with different people:

I. Morouço PG, Marinho DA, Marques MC. Force production in tethered swimming: differences between hands in front crawl. *Medicine & Science in Sports & Exercise* 2010; 42(5): S489.

II. Morouço PG, Marinho DA, Fernandes RJ, Marques MC. Tethered swimming as an useful tool to measure unbalance between arms and force production decrease. In JP Vilas-Boas, L Machado, K Wangdo & AP Veloso (Eds.), *Biomechanics in Sports 29, Portuguese Journal of Sport Sciences*, 2011; 11(S2): 339-342.

III. Morouço, PG, Neiva HP, Marinho DA, Marques MC. Tethered swimming as an estimator of anaerobic capacity. *Congress of the European College of Sport Sciences*, 2012; accepted.

IV. Morouço, PG, Neiva HP, Marinho DA, Marques MC. Relationships between power in dry land exercises and swimming performance. *Congress of the European Society of Biomechanics, Journal of Biomechanics,* 2012; accepted.

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Abstract

The major purpose of this work was to examine possible relationships between tethered forces and dry-land exercises with swimming performance, for both males and female swimmers. Additionally, it was intended to verify if tethered swimming could be an easy, operative and accurate methodology for the biophysical evaluation of swimmers. For the accomplishment of these purposes the following sequence was used: (i) reviewing available literature; (ii) comparison of tethered swimming with free swimming; (iii) analyzing variables and relationships obtained in tethered swimming and dry-land strength tests with swimming performance; (iv) assessing front crawl arm (a)symmetries through tethered swimming; (v) and indentifying the relative contribution of arms and legs for whole-body tethered forces. Results suggest that: (i) tethered swimming does not alter stroke rate, blood lactate concentrations, heart rate and perceived exertion when compared to free swimming of equal duration; (ii) the relationship between maximum force and swimming velocity is non-linear, whereas with impulse is linear; (iii) power assessed in dry-land strength exercises seems to be a more accurate parameter than maximum load; (iv) for boys lat pull down, and for girls squat, are the most related dry-land exercises with swimming performance; (v) tethered swimming can be a simple, low cost and time saving methodology in terms of whole-body coordination and arm stroke (a)symmetries evaluation; (vi) the leg-kicking represents a higher role for all body propulsion than assumed; (vii) swimmers present asymmetries within arms force production that tend to decrease along a maximal effort.

Key words: Swimming, Front Crawl, Tethered Swimming, Dry-Land, Strength, Training & Testing

Resumo

O principal objetivo deste trabalho foi analisar as possíveis relações entre parâmetros de força em nado amarrado e exercícios de força em seco com a performance em nado livre, em nadadores do sexo masculino e do sexo feminino. Adicionalmente, pretendeu-se verificar se o nado amarrado pode ser uma metodologia de fácil operacionalização e elevada precisão para avaliação biofísica de nadadores. Para se alcançar estes objetivos foram adotados os seguintes passos: (i) revisão da literatura existente; (ii) comparação do nado amarrado com o nado livre; (iii) análise de variáveis e relações obtidas em nado amarrado e em exercícios de força em seco, com a performance de nado; (iv) identificação de (as)simetrias bilaterais dos membros superiores em nado crol, através de nado amarrado; (v) e medição da contribuição relativa dos membros superiores e inferiores para a produção de forças propulsivas. Os resultados sugerem que: (i) o nado amarrado não altera a frequência de braçada, concentração de lactato sanguíneo, frequência cardíaca e perceção de esforço, em comparação com o nado livre com igual duração; (ii) a relação da velocidade em nado livre com a força máxima em nado amarrado é não-linear, enquanto que a relação com o impulso é linear; (iii) a potência em exercícios de força parece ser um parâmetro mais preciso do que a carga máxima; (iv) para rapazes, o latíssimos, e para raparigas, o agachamento, são os exercícios que mais se relacionam com a performance em nado; (v) o nado amarrado pode ser uma metodologia simples, de baixo custo e com avaliações num curto espaço de tempo, para avaliação de índices de coordenação e (as)simetrias de braçada; (vi) a ação dos membros inferiores é determinante para a propulsão dos nadadores, presumivelmente maior do que a assumida; (vii) nadadores apresentam assimetrias de braçada que tendem a atenuar-se ao longo de um esforço máximo.

Palavras-chave: Natação, Crol, Nado Amarrado, Treino em seco, Força, Treino e Avaliação.

Resumen

El principal objetivo del presente trabajo fue examinar las posibles relaciones entre las diferentes medidas de fuerzas propulsivas a velocidad cero y distinticos ejercicios en seco con la performance del nado, en nadadores masculinos y femeninos. Además, si intentó verificar se él nado a velocidad cero puede ser una fácil, operativa y precisa metodología para evaluar desde el punto de vista biofísico los nadadores. Para ello, se han propuesto una secuencia de objetivos: (i) revisión de la literatura disponible; (ii) comparación del nado a velocidad cero con nado libre; (iii) analice de las variables y relaciones obtenidas en el nado a velocidad cero y teste de fuerza en seco con la performance de nado; (iv) evaluación de las (a)simetrías en la brazada de crol a través del nado a velocidad cero; (v) y identificar la contribución relativa de los miembros superiores y inferiores para las fuerzas medidas con la totalidad del cuerpo. Los resultados sugieren que: (i) el nado a velocidad cero no cambia la frecuencia de brazada, las concentraciones de lactato sanguíneo, la frecuencia cardiaca y la percepción de esfuerzo cuando comparado con el nado libre con igual duración; (ii) las relaciones entre el pico máximo de fuerza y la velocidad de nado nos es linear, mientras que la fuerza de impulsión sí; (iii) evaluaciones de la potencia en ejercicios de fuerza en seco parece ser un parámetro más preciso que la carga máxima; (iv) para los hombres el *lat pull down*, y para las mujeres el *squat*, son los ejercicios en seco que mejor relación tienen con la performance de nado; (v) el nado a velocidad cero puede ser una simples, económica y rápida metodología para valorar la coordinación y (a)simetrías de la brazada; (iv) la pernada representa ser más importancia en la propulsión de todo el cuerpo, que tomado; (vii) los nadadores a presentan asimetrías entre la producción de fuerza de brazos que tiene tendencia a disminuir al largo del máximo esfuerzo.

Palabras clave: Natación, Crol, Nado a velocidad cero, Ejercicios en seco, Fuerza, Entrenamiento e evaluación

List of Abbreviations

1RM – one maximal repetition

Ar – arms

avgF – average force

avgI – average impulse

BLa – blood lactate concentrations

bp – bench press

CMJ – countermovement jump

compl – complete

d – dominant

HG – handgrip strength

HR – heart rate

Lg – legs

lpd – lat pull down

maxF – maximum force

maxI – maximum impulse

MP – maximum power

MPP – mean propulsive power

MPV – mean propulsive velocity

nd – non-dominant

PE – perceived exertion

SI – symmetry index

sq – squat

SR – stroke rate

TS – tethered swimming

v100 – mean swimming velocity in 100 m

v50 – mean swimming velocity in 50 m

Wb – whole-body

Chapter 1. General Introduction

Competitive swimming can be an enriching and exciting process (Wilke & Madsen, 1990); continuous training efforts, the feeling of accomplishment, ultimately, improving. It is not surprising that there is a huge amount of studies developed in this field, as swimming becomes a high interest sporting event, with records being broken frequently. Investigations can be carried out in different areas (e.g. biomechanical, physiological and psychological), although biomechanics and physiology/energetics have been pointed as the more susceptible areas to enhance swimming performance (Barbosa et al., 2010), being nominated as "Biophysics of swimming". Indeed, Vilas-Boas (2010) stated that 5.6% of the works presented in Biomechanics and Medicine in Swimming Symposia (a major important congress to swimming community that takes place every four years) used the biophysical approach. The role of strength and force for competitive swimming has long been a matter of discussion. Furthermore, the benefits of dry-land strength training with the scope of enhancing swimming velocities are inconsistent (Garrido et al., 2010). Thus, studies aiming to clarify these topics of research may give new insights to the swimming community, regarding the improvement of performance in competitive swimming.

Actually there is no measurement system that can quantify the exact magnitude of the propelling forces of a swimmer, due to the characteristics of the aquatic environment. Estimation of propulsive forces can be performed through video analysis (Schleihauf et al., 1983; 1988), pressure differences (Takagi & Wilson, 1999), measurement of active drag system (Toussaint et al., 1988), semi-tethered system (Costill et al., 1986) and tethered system (Kjendlie & Thorsvald, 2006); with advantages and disadvantages concerning the purpose of the evaluation. The tethered swimming approach allows the swimmers to replicate the movements of free-swimming, enhancing the possibility of measuring the maximum force that (theoretically) corresponds to the propelling force that a swimmer must produce, to overcome the water resistance at maximum free-swimming velocity (Yeater et al., 1981; Dopsaj et al., 2000; 2003). Moreover, tethered swimming has proven to be a highly reliable methodology (Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), and with similar muscular activity (Bollens et al., 1988) and oxygen consumption (Lavoie & Montpetit, 1986) to free-swimming. In addition, it is an easy, operative and inexpensive methodology (Morouço et al., 2012) inducing that to swim with higher velocities the swimmer must produce more propulsive force (Keskinen, 1997). This association enables the comparison of the swimmer's capacity for muscular force production and the technical ability, as shown in Figure 1. However, the nature (linear or non-linear) and strength (small, moderate, large or very large) of this correlation is not elucidated.

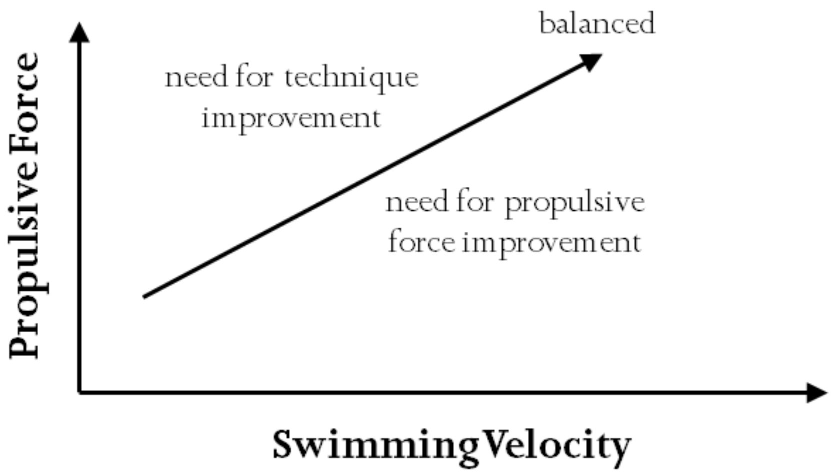

Figure 1. Representation of the relationship between maximum force in tethered swimming and swimming velocity (adapted with permission of the author and journal; Keskinen, 1997).

Dry-land strength training is a common practice in swimming training, as it may have beneficial effects on work economy through different mechanisms (e.g. improved reflex potentiation, alterations of the synergists; Aspenes et al., 2009). In addition, strength training possibly increases maximal power output (Tanaka et al., 1993) leading to a swimming performance enhancement, namely in short competitive distances (Hawley et al., 1992). However, the results from the available experiments remain inconclusive (Tanaka et al., 1993; Trappe & Pearson, 1994; Girold et al., 2007; Garrido et al., 2010).

The reviewing papers aiming to summarize existent knowledge, in order to identify the gaps and limitations, are presented in Chapters 2 and 3 of this Thesis. The experiments carried out to overcome some of those gaps and limitations are presented in Chapters 4 to 8. In addition, a general discussion in Chapter 9 was elaborated upon the results obtained from the performed studies and with the experiments available in literature. The main conclusions and suggestions for future studies are presented in Chapters 10 and 11, respectively.

This research was carried in front crawl swimming technique; the most used technique in swimming training and the one that attain higher average velocities. In addition, it is common to combine dry-land strength training with swimming training, in order to increase specific swimmers strength conditioning. However, some investigations have pointed that the ability to exert force in water is more related with swimming performance, than maximum strength. Thus, studying the relationship between force produced in water and in dry-land may provide new insights over the requirements to enhance performance, mainly in the short competitive events.

Tethered swimming has been considered a reliable methodology to assess forces exerted in water, and several studies have pointed that these forces are highly correlated with swimming performance. Nonetheless, some incongruous statements can be observed in literature. Thus, **Chapter 2** presents a qualitative review over tethered swimming as a methodology to evaluate swimmers, regarding to biomechanical and bioenergetical (i.e. biophysical) aspects. This review intends to summarize the existent knowledge, and to identify gaps and limitations. In **Chapter 3** a brief review over the effects and relationships considering dry-land strength parameters and swimming performance is presented. Several studies have shown that swimming performance is highly dependent on muscular strength and power, thus the improvement of strength and power may lead to a swimming performance enhancement. However, the swimming stroke is characterized by a complex series of sculls and diagonal movement that cannot be replicated in dry-land testing techniques, and these two chapters indicate some inconsistent areas that should be further studied.

Relationships between tethered swimming forces and front crawl free-swimming velocity have been reported by several studies (e.g. Yeater et al., 1981; Sidney et al., 1996). This methodology provides an individual Force-time curve that can be analyzed regarding different mechanical variables (maximum, average, impulse, etc...). In addition, most investigations assumed that this relationship is linear, diverging from the non-linear relationship established by Keskinen et al. (1989). So, it is important to carry out experiments gathering the different perspectives, establishing higher accuracy for the purpose of the research. The nature of this relationship using different variables and comparing kinematical and physiological parameters between tethered swimming and free-swimming was conducted (**Chapter 4**).

A recent review highlighted the diagnosis of asymmetries in swimming (Sanders et al., 2011). Taking into consideration that main propulsive segments in front crawl are the upper-limbs, balance in propulsive forces of right and left arms may influence swimming accelerations, and positively affect mean velocities. To the best of our knowledge, the comparison of tethered forces within arms along a maximal effort has not been previously studied and is presented in **Chapter 5**. Since handgrip strength has been included in swimming talent identification models (Silva et al., 2007; Garrido et al., 2012), it was aimed also to analyze if this test could provide valid information about hand (a)symmetries.

The relative contribution of arms and legs to overall front crawl swimming performance has been a matter of major interest for swimming research. Although leg kicking has often been neglected of secondary importance for propulsion, this became a controversial assumption (Swaine et al., 2010). Regarding that stroke efficiency is also determined by propulsive forces, tethered swimming could provide new insights over this matter. Additionally, there is a lack of studies comparing stroking force between genders, being conventionally accepted that male swimmers rely more in strength than female counterparts. Thus, an experiment assessing forces exerted with whole-body, arms-only and legs-only with both genders competitive swimmers was performed (**Chapter 6**).

Dry-land strength training should be prescript aiming to increase maximal power outputs through an overload of the muscles used in swimming (Tanaka et al., 1993). Indeed, it is a regular component for swimmers training and it may enhance swimming technique (Maglischo, 2003). Nevertheless, few studies have analyzed the relationships between dry-land strength exercises and swimming performance and the scientific evidence is still scarce (Aspenes et al., 2009; Garrido et al., 2010). Most available studies used (bio)isokinetic or isometric evaluations and results are incongruous. Further, maximum effort repetitions were performed, which seems to be more related with maximum force than power (González-Badillo & Sánchez-Medina, 2010). Strength and power assessment may be useful to understand the role of strength in swimming performance, and moreover to improve dry-land training programs. To address this issue, a velocity linear wire encoder was used to measure power in dry-land exercises. When performing studies aiming to identify associations between dry-land strength and swimming performance, gender differences should be taken into consideration. Therefore, experiments were conducted with male (**Chapter 7**) and female (**Chapter 8**) competitive swimmers.

The identification of which parameters more accurately determine the relationship between tethered forces and dry-land exercises with swimming performance, could provide new ideas regarding the issue of stroking force significance. Moreover, assessing the relative contributions of arms and legs to overall swimming performance and the bilateral (a)symmetries within arms may provide a useful tool for training diagnosis. Thus, **Chapters 9** and **10** present the General Discussion and main Conclusions of this work, respectively.

Chapter 2.

Biophysical evaluation of swimmers using tethered swimming: a qualitative review

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Journal of Strength and Conditioning Research (submitted)

Abstract

It is presented a qualitative review of the specialized literature on tethered swimming, with the scopes of summarizing and highlighting published knowledge, identifying its gaps and limitations, and motivate future research. The major research conclusions can be summarized as follows: (i) tethered swimming is a reliable test to evaluate force exerted in water by swimmers; (ii) higher maximum values of force are obtained in breaststroke and butterfly, while average values are higher in front crawl; (iii) tethered forces present moderate to strong relationships with swimming velocity, and associations between forces diminish as swimming distance increases; (iv) 30 s maximal tethered swimming may be used as an adaptation of Wingate test for swimming; (v) differences in stroke mechanics can occur in tethered swimming but there is no evidence to suggest that they affect swimming performance. Based on and stimulated by current knowledge, further research should focus on the following topics: (i) bilateral asymmetries in exerted forces, and corresponding influence of breathing; (ii) relative contribution of arms and legs for whole-body propelling forces; (iii) differences in force parameters induced by gender or level; and (iv) defining accurate variables for estimation of anaerobic power and/or capacity using tethered swimming.

Key words: biomechanics, bioenergetics, training, testing, performance.

Introduction

The improvement of swimming performance requires the control of multiple variables (e.g. biomechanical, physiological and psychological), which positive or negative influences the four phases of a swimming competition: start, swimming, turn(s), and finish. In these phases, the measuring of individual performance-related parameters may present a profile for each swimmer that can be used in the perspective of increasing performance (Toussaint, 2007). However, which, when, how often and how performance parameters should be evaluated? The responses to those questions are complex, but may lead to an increase in the efficiency of the training process (Maglischo, 2003) and performance prediction (Wright & Smith, 1994). Recently, Barbosa et al. (2010) indicated the synergy between the bioenergetics and biomechanical fields of study as a "biophysical intervention" which could bring new conclusions to the training process. Following a biophysical approach, tethered swimming is a methodology that allows to assess the propelling forces that a swimmer can exert in water and to evaluate aerobic and anaerobic capacity or power.

It is well known that swimming velocity is the result of: (i) a circumstantial prevalence of total propulsive forces (P) or the drag force (D), or; (ii) a consequence of an increased (or decreased) added mass effect during a given swim cycle (Vilas-Boas et al., 2010). Therefore, the estimation of propulsive forces is important to identify determinant factors for swimming performance enhancement (Marinho et al., 2011); however, assessing its magnitude is extremely complex due to the characteristics of the aquatic environment. Tethered swimming has shown to be a methodology that enhances the possibility of measuring the maximum force that (theoretically) corresponds to the propelling force that a swimmer must produce to overcome the water resistance at maximum free swim velocity (Magel, 1970; Dopsaj et al., 2000). Magel (1970) was one of the first authors to emphasize the potential of tethered swimming as an evaluation tool for swimmers, suggesting that measuring the propelling forces at zero velocity could provide a good estimation of the force that can be developed during free swimming. Complementarily tethered swimming is considered a highly reliable methodology (Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), maximum force assessed by tethered swimming is highly related to maximum velocity, namely in front crawl (Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999), and tethered swimming may evaluate aerobic (Pessôa-Filho & Denadai, 2008) and anaerobic (Ogonowska et al., 2009; Morouço et al., 2012) energetic profiles.

More than four decades after Magel (1970) suggestions, tethered swimming is being used through different methodologies, particularly fully-tethered (with elastic or non-elastic cable) and semi-tethered procedures, with an effort duration from 5 s to 12 min, which should be taking in consideration when comparing results. In the current manuscript it is presented a qualitative review of the specialized literature on tethered swimming, aiming to summarize and highlight published knowledge, identify the gaps and limitations, and motivate future research. Concerning the differences in the used methodologies and, essentially, in the scope of the studies, this review is divided in four sections: the apparatus and procedures used to measure tethered forces, an analysis over available experiments conducted under a biomechanical perspective, studies that used tethered swimming with a bioenergetical perspective, and the main research findings.

Experiments available in the literature were gathered by searching databases (SportDiscus, PubMed, and Scopus). The search was carried with "swimming" as the main keyword, combined with the following words: "tethered", "force", "power", and "thrust". With the purpose of limiting the number of studies to be analysed, referred words were occasionally coupled. In addition, references from relevant proceedings were taken into consideration and added to review.

Apparatus and procedures

Tethered swimming allows the measurement of the exerted forces, being possible to represent an individual Force-time curve chart during the exercise. Consequently, its use improves the possibility of analysis and comparison of swimming technique profiles, allowing to more accurately knowing the sequence of propulsive forces during swimming (Keskinen, 1997). Hence, tethered swimming has been considered a high specific ergometer for swimmers, as it implies the use of all body structure in a similar way to the form used in competitive swimming (Costill et al., 1986; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), although some kinematical changes have been reported (Maglischo et al., 1984).

In the most common apparatus, fully-tethered and with non-elastic cable are employed (Magel, 1970; Yeater et al., 1981; Christensen & Smith, 1987; Ria et al., 1990; Sidney et al., 1996; Fomitchenko, 1999; Taylor et al., 2003), being the swimmer fixed to the edge of the pool through a hardened cable or rope, and the force measurement provided from an acting weight (e.g. Magel, 1970; Hopper et al., 1983) or a force transducer (e.g. Dopsaj et al., 2000; Morouço et al., 2011). The force transducer can be fixed on the pool wall with the advantage of minimizing any interference with swimmers normal technique as the rope is aligned with the direction of swimming (Psycharakis et al., 2011), but presenting the disadvantage of the feet touching the cable producing alterations to assessed values. It could be also fixed in the starting block (the most usual procedure) that may overcome this latter inconvenience by creating an angle between the cable and the water surface (that should be rectified as it is intended to evaluate the horizontal components of the force exerted) (Taylor et al., 2001; 2003). These calculations were not referred in the pioneer studies (e.g Magel, 1970; Goldfuss & Nelson, 1970) as forces were measured through an electrical output that was converted to voltage being recorded in paper. The advance in technology allowed that the signal of the measurement system could be amplified and acquired through an analogue-to-digital converter, being directly recorded on a computer (Dopsaj et al., 2000; 2003; Morouço et al., 2011), reducing considerably time consumption.

Tethered swimming could cause changes to stroke pattern (Maglischo et al., 1984; Psycharakis et al., 2011), being suggested that evaluations should be performed with swimmers experienced in tethered swimming drills (Psycharakis et al., 2011). Complementarily, there is a general agreement that preceding the measurement swimmers must first adopt a horizontal position with the cable completely extended and perform some strokes at a low intensity (Keskinen et al., 1989). The data acquisition should initiate after the first stroke in order to evade the inertial effect provoked by the maximal extension of the cable (Trappe & Pearson, 1994; Morouço et al., 2011).

Pioneer studies aimed to characterize the force patterns by testing swimmers in 2 to 3 min exercise durations (Goldfuss & Nelson, 1970; Magel, 1970). Subsequent studies intended to understand the relation between tethered forces and swimming velocities (or performance), reducing the duration of the tests to 2, 5, 7, 10, 20, 30, 45 or 60 s, choosing the test duration based on the swimming distance to be compared. Keskinen et al. (1989) measured the tethered forces for 5-10 s and compared it with 10 m free swimming performance, and, more recently, Cortesi et al. (2010) implemented tethered tests at maximum intensity for 15, 30, 45 and 60 s, reporting higher correlations between the best-time performance on the distances of 50 m and 100 m and the values of force measured using tests with duration of 30 s. This data was in accordance with the statements by Dopsaj et al. (2000) that accurate establishment of relationships between tethered swimming forces and swimming velocity requires that both testing have equal time. In addition, some researchers suggest the use of the 30 s at maximum intensity as an adaptation of the Wingate test for swimmers evaluation (Papoti et al., 2007; Ogonowska et al., 2009; Soares et al., 2010; Morouço et al., 2012).

From the individual Force-time curves several parameters can be calculated, but are sparsely used: peak maximum force (e.g. Christensen & Smith, 1987; Keskinen et al., 1989), average of maximum force (e.g. Yeater et al., 1981; Fomitchenko, 1999), average force (e.g. Ria et al., 1990; Morouço et al., 2011), minimum force (e.g. Dopsaj et al. 2003), impulse (Dopsaj et al., 2000) and fatigue index (e.g. Diogo et al., 2010; Morouço et al., 2012) are the most common in literature. It does not appear to be a clear evidence of which parameter is more reliable, as Taylor et al. (2001) found that only average force was a reliable parameter to estimate swimming performance, diverging from the experiments of Dopsaj et al. (2000) that stated that impulse is the most accurate parameter. In addition, investigations have commonly used absolute values (e.g. Christensen & Smith, 1987; Kjendlie & Thorsvald, 2006; Pessôa-Filho & Denadai, 2008) and not relative values (normalized to body mass). Since the testing is performed in water reduces the weight of the body to a few kilograms (Taylor et al., 2001; 2003), which does not enhance accuracy in relationships between variables (Yeater et al., 1981; Morouço et al., 2011).

Biomechanical perspective

Swimming biomechanics aims to define the fundamental parameters that characterize and describe the movement of the swimmer using mechanical principles and approaches (Barbosa et al., 2010). Its purpose is to obtain results of the causes and consequences processed in swimmers' body and the resultant movement on specific environment: through kinematics for the visible result and kinetics for the non-visible. Thus, a fundamental goal is to quantify the propulsive and drag forces, and their relationship to a swimmer respective technique and performance (Akis & Orcan, 2004; Sanders & Psycharakis, 2009; Marinho et al., 2011). The method of tethering a swimmer to the edge of the pool and measuring the force in the tether line is the most commonly used in the literature (Akis & Orcan, 2004).

Regarding the characterization of force-time curves Magel (1970) evaluated 26 highly trained college swimmers during 3 min, in each of the four competitive swimming techniques, being possible to collect individual force-time curves sensitive to the variations of propelling force within a stroke: an upward trace indicates a positive acceleration or propulsive moment, and a downward trace indicates a negative acceleration or recovery moment. In those experiments, swimmers had to adjust their stroke rate to remain on a fixed spot, since force was delivered by the swimmer to an external weight. Average forces during the 3 min were similar for all techniques, except for breaststroke swimmers that recorded significant higher values. Regarding the role of arms and legs, it was stated that for front crawl and backstroke the arms were responsible for majority of propulsive force, for butterfly propelling forces delivered by arms and legs were similar, and for breaststroke the legs made a much larger contribution to the total propulsive force.

Afterwards some studies supported the data obtained by Magel (1970), whereas others were in opposition. Yeater et al. (1981) stated that breaststroke does not lead to higher average values but to highest peak forces, once the high peak values induced by the powerful leg kick characteristic of this technique does not ensure a high average tethered force (this was also reported by Morouço et al., 2011). It is worth noting that in breaststroke, it is common to have a reduction of hip velocity near 0 $m.s^{-1}$ due to legs recovery (Barbosa et al., 2006; Vilas-Boas et al., 2010). Contextualizing to tethered swimming, this negative acceleration may cause a decrease in the cable tension, which by resuming maximum tension, may lead to an overestimation of the force values. In a recent study, Morouço et al. (2011) tested 32 swimmers of international level during a 30 s maximum tethered swimming, observing different profiles for each swimming technique: breaststroke and butterfly obtained both higher and lower values of force production than front crawl and backstroke, resultant of the simultaneous actions of both arms and legs, and consequently leading to a higher intracycle velocity variation (Craig & Pendergast, 1979; Barbosa et al., 2006; Craig et al., 2006).

The relative contribution of the legs in swimming propulsion remains uncertain for the conventional swimming techniques, namely for front crawl and backstroke, as for these swimming techniques the role of the legs has been neglected as a secondary factor (Bucher, 1974; Hollander et al., 1988; Toussaint & Beek, 1992; Deschodt et al., 1999). However, these results may be uncertain due to the calculation of the legs contribution by subtracting the arms contribution to the value of the whole body while swimming. For example, Yeater et al. (1981) analyzed the arms and legs components separately and reported high values of mean tethered force with legs-only in front crawl, questioning the contribution of leg kicking for body propulsion. In addition, these authors reported that for all swimmers the sum of arms-only and legs-only tethered forces were higher than in whole-body testing. Interestingly, Ogita et al. (1996) also noted this fact in terms of energy consumption in front crawl swimming. Considering that explanations to this factor are not clear, researchers should attempt to confirm these findings using variables that may explain the role of arms and legs for whole-body tethered swimming, especially in front crawl and backstroke.

Knowing that in the front crawl and backstroke swimming techniques, the symmetry between right and left arms may positively affect the average speed of a swimmer and contribute to a more appropriate posture minimizing the resistive drag (Sanders et al., 2011), tethered swimming could also be used to identify asymmetries. In a pioneer experiment with 2 male swimmers, asymmetries between the tethered forces of left and right strokes were noticed (Goldfuss & Nelson, 1970). Likewise, kinematical (Seifert et al., 2005; Tourny-Chollet et al., 2009) and kinetical asymmetries (Toubekis et al. 2010; Formosa et al., 2011) have been reported, inducing that an arm is mostly used for propulsion and the other primarily responsible for support and control (Psycharakis & Sanders, 2008). However, studies that examine this asymmetry over a time spectrum are scarce. Since tethered swimming performs a constant measuring of the forces exerted, it may enable new inferences on this issue and may assist the training process with specific technical corrections that aim to achieve bilateral balance.

Relationships between tethered forces and swimming performance

Tethered Swimming allows the evaluation of forces production created by swimmers, independently of the technique performed, being useful to the evaluation of swimmers and respective training control. As it is accepted that more important than increasing the strength of a swimmer is to measure his ability to effectively use muscular force production in water (Keskinen et al., 1989), relationships between tethered forces and swimming performance may provide the appropriate tool for specific evaluation.

Most studies that aimed to correlate tethered swimming forces with swimming velocity or performance were conducted performing the front crawl swimming technique (e.g. Costill et al., 1986; Christensen & Smith, 1987; Fomitchenko, 1999), leaving a lack of analysis regarding to other swimming techniques. Several investigations found significant (moderate to very large) relationships between swimming velocity and front crawl tethered forces (e.g. Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999). For example, Christensen and Smith (1987) tested 39 competitive swimmers (26 male and 15 female) for a 3 s maximal tethered swimming bout, reporting significant relationships ($r = 0.69$ for males and $r = 0.58$ for females) between swimming velocity and tethered forces, suggesting that sprint velocity is related to the stroking force a swimmer can generate. This assumption was supported by subsequent studies (e.g. Fomitchenko, 1999; Dopsaj et al., 2000; Morouço et al., 2011) proposing that to improve maximum velocity the swimmer must improve maximum stroking force.

The above referred studies followed the assumption that the relationship between tethered forces and swimming velocities is linear; however, if this relationship is not linear, the variability in swimming velocity may not be indicative of variability in stroking force. Keskinen et al. (1989) scattered the correlation between maximum force and maximum velocity and fit the best second order polynomial ($r = 0.86$), which were explained on the force-velocity relationship of the skeletal muscle (Komi, 1973), inducing that at a very high velocities it is not easy to produce very high force values (Keskinen et al., 1989). While it is perceptible that an association does exist, the nature and strength of this relationship remain inconclusive.

As previously referred, studies with the purpose of analyzing the relationships between tethered forces and swimming velocity apart from front crawl are scarce. Yeater et al. (1981) were the first authors to analyze relationships between tethered forces and swimming velocities in backstroke and breaststroke, reporting no significant correlations between tethered forces and swimming velocities. In a similar approach, Hopper et al. (1983) measured the power delivered to an external weight in the four swimming techniques, and, when the data of men and women, and elite and developmental swimmers were combined, negative correlations between swimming power and swimming performance were observed (breaststroke $r = -0.90$, butterfly $r = -0.89$, backstroke $r = -0.84$, and front crawl $r = -0.80$). This data was recently supported for a more homogeneous sample cohort by Morouço et al. (2011) that observed that for all swimming techniques stroking force measured through a tethered system may estimate free swimming velocities.

Wilke and Madsen (1990) enunciated that as the swimming distance diminishes the role of maximum force increases, and as the swimming distance increases the endurance force takes a major role; however, this phenomenon has not been extensively studied. Rohrs and Stager (1991) assessed the relationships between maximum tethered force and free swimming velocities for 22.86, 45.72 and 91.44 m and observed that tethered forces related significantly with all swimming distances. Subsequently, D'Acquisto and Costill (1998) tested 17 breaststroke swimmers and obtained significant correlations for both 91.4 and 365.8 m. Recently, a clear evidence of higher relationships between short competitive distances and tethered swimming forces was found (Morouço et al., 2011). Further investigations, with diverging free swimming distances, may provide new insights over this issue.

Bioenergetical perspective

The physiology/energetics is a very important field of training evaluation and control, with a fundamental topic on the energetic systems and its relationship with performance (Fernandes et al., 2009; Barbosa et al., 2010). Competitive swimming events can go from less than 21 s to more than 15 min, making remarkable differences in the relative contributions of aerobic and anaerobic processes (Maglischo, 2003). Thus, bioenergetical evaluations must take into consideration the time spectrum of the effort.

Maximal lactate steady-state is considered the gold standard protocol for aerobic capacity determination (Benecke, 2003). However, the time consumption and cost of the protocol led Wakayoshi et al. (1992) to propose a new concept: critical velocity. This procedure was proven to be an accurate estimator of aerobic performance in swimmers, and researchers attempted to transfer this concept to tethered swimming: critical force (Ikuta et al., 1996). Evaluating 13 male competitive swimmers, those authors reported high correlations between critical force and swimming velocity in 400 m freestyle ($r = 0.70$), critical velocity ($r = 0.69$) and swimming velocity corresponding to 4 $mmol.l^{-1}$ ($r = 0.68$), suggesting that critical force determined in tethered swimming may correspond to the swimming intensity at maximal lactate steady-state. Although these results were supported by following studies (Papoti et al., 2009), its reliability as an index of performance must be explored in further research (Pessôa-Filho & Denadai, 2008).

Most competitive swimming events takes two min or less (~80% dividing the relays time by the number of swimmers involved) at maximal intensity. However, the evaluation of the anaerobic capacity of swimmers stays inconclusive (Papoti et al., 2007), being controversial and the results far from consensus (Smith et al., 2002; Stager & Coyle, 2005; Soares et al., 2006). The most common methodology used and studied for highly anaerobic efforts is the Wingate anaerobic test, but the muscular responses from that test differ a lot from the ones used in swimming (Soares et al., 2010). Aiming to achieve a more specific methodological approach, experiments have been carried using: (i) the accumulated oxygen deficit (e.g. Reis et al., 2010), (ii) the Wingate arm cranking test (e.g. Driss et al., 2002), (iii) the force-velocity test (e.g. Driss et al., 2002); and (iv) tethered swimming test (e.g. Papoti et al., 2007; Ogonowska et al., 2009; Morouço et al., 2012). Among these various approaches, it seems that tethered swimming stands out as being operational, with easy application and a low cost procedure.

Using tethered swimming, the maximum peak force output (that seem to occur in the first 10 s) was pointed as an indicator of the maximum rate of phosphagens catabolism, and the average force value of 30 s representative of the athlete's anaerobic capacity, associated with the glycolytic metabolism (Soares et al., 2010). In addition, Stager and Coyle (2005) suggested that the analysis of the decline in the force exerted by a swimmer may indicate a greater predisposition of the swimmers for endurance or sprint competitive events; this decline reflects the occurring of fatigue that incurs a lower capacity to produce mechanical force.

The possibility of the capacity and/or anaerobic power evaluation of swimmers through tethered swimming depends from the time and intensity of the effort required. In one of the few studies applying tethered swimming to evaluate the anaerobic capacity of swimmers, Ogonowska et al. (2009) showed that tethered forces highly correlated with power obtained in Wingate arm cranking test. Moreover, the relationship between the decrease in force output and performance in sprint events seems to be highly correlated (Morouço et al., 2012), inducing that tethered swimming energetic demands are similar to free swimming events of equal duration. This assumption was corroborated by Thanopoulos et al. (2010) that reported similar values of net blood lactate concentrations between 100 m free swimming and tethered swimming with equal duration, at maximal intensity. Being aware that the evaluation of a swimmer anaerobic capacity and/or power are doubtful and questionable, emerging methodologies that are easy to operate and with direct results are one of the main purposes of swimming science (Stager & Coyle, 2005) and should be more investigated in the future.

Summary and future directions

Swimming coaches and researchers have the perception that the evaluation of their swimmers should be specific and correspond to the nature of the sport. In this sense it is essential to choose an adequate methodology to be applied. In this perspective, tethered swimming can be a useful and valid, as well as easy, simple and fast procedure for a biophysical evaluation of swimmers. This is based on the principles that swimmers who can most effectively exert forces that are directly related to propulsion will perform best in sprint swimming. However, researchers should be conscious that the qualities to determine success in competitive swimming are based on more than strength. Thus, the main research findings can be summarized as follows:

- Tethered swimming is a reliable test to evaluate force exerted in water by swimmers;
- Higher maximum values of force are obtained in breaststroke and butterfly, while average values are higher in front crawl and backstroke;
- Tethered forces present moderate to strong relationships with swimming velocity, and associations between forces diminish as swimming distance increases;
- 30 s maximal tethered swimming may be used as an adaptation of Wingate anaerobic test;
- Differences in stroke mechanics can occur in tethered swimming but there is no evidence to suggest that they affect swimming performance.

Regarding to the state of the art, researchers should aim future investigations in order to explore issues that are not completely clear in the available literature. Some of those main topics can be:

- Bilateral asymmetries in exerted forces, and correspondent influence of breathing;
- Relative contribution of upper-limbs and lower-limbs for whole-body propelling forces;

- Differences in force parameters induced by gender or level;
- Defining accurate variables for estimation of anaerobic power and/or capacity using tethered swimming.

Chapter 3.

Effects of dry-land strength training on swimming performance: a brief review

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Abstract

This article provides a brief review over the state of art concerning dry-land training for swimmers. It is important to understand the role of muscular strength for swimming performance and how it might be improved. Firstly, this article analyzes the relationships between strength or power assessment in dry-land and swimming performance. Secondly, the results of studies aiming to evaluate the influence of dry-land strength training to swimming performance improvement are presented. These results allow coaches to realize the benefits that may be obtained by an appropriate strength training program, according to gender and level.

Key words: strength, power, force, testing.

Introduction

Swimming performance is highly dependent on muscular strength and power (Sharp et al., 1982; Costill et al., 1986; Tanaka et al., 1993; Tanaka & Swensen, 1998; Girold et al., 2007). Using a variety of testing equipment, upper-body muscular strength and swimming power have demonstrated to be well correlated with swimming velocity (Sharp et al., 1982; Costill et al., 1986; Toussaint & Vervoorn, 1990; Hawley & Williams, 1991; Tanaka & Swensen, 1998; Aspenes et al., 2009). Therefore, improvements in arm strength may result in higher maximum force per stroke, subsequently in higher swimming velocities, specifically in sprint distances (Strzala & Tyka, 2009; Morouço et al., 2011a).

Dry-land strength training aims to increase maximal power outputs through an overload of the muscles used in swimming (Tanaka et al., 1993) and it may enhance swimming technique (Maglischo, 2003). If these two points of view are correct, then the increase of muscular strength would improve swimming performance. However, results from the available experiments remain inconclusive (Tanaka et al., 1993; Trappe & Pearson, 1994; Girold et al., 2007; Garrido et al., 2010). In this article it is presented a critical review of the swimming literature concerning the effects of dry-land strength training on the swimming performance, not taking into account the effects for starts and turns. It is aimed to summarize existent knowledge, in order to stimulate further researches.

Experiments available in the literature were gathered by searching databases (SportDiscus, PubMed, and Scopus). The search was carried with "swimming" as the main keyword, combined with the following words: "dry-land", "power", "strength", and "force". With the purpose of limiting the number of studies to be analysed, referred words were occasionally coupled. Additionally, references from relevant proceedings and abstracts were taken into consideration and added to review.

Relationship between dry-land assessments of strength/power with swimming performance

The ultimate goal of a competitive swimmer is to expend the minimum time covering a known distance. Accordingly, as the distance to be swam diminishes so does the number of strokes executed. Therefore, for shorter competitive distances strength has been pointed as one of the main multi-factorial factor that may enhance swimming velocity (Toussaint, 2007). Moreover, relating strength and technique, it is assumed that, as the distance diminishes strength role increases, when comparing with technical parameters (Wilke & Madsen, 1990; Stager & Coyle, 2005; Morouço et al., 2011a).

From out the last three decades strength and power measurements in dry-land were performed using isokinetic and isometric strengths (Garrido et al., 2010; Morouço et al., 2011b). This assessment was pointed to be useful to understand how much does swimming performance relies on these parameters, and moreover to improve training programs. In one of the pioneer studies, Sharp et al. (1982) evaluated 22 female and 18 male swimmers, and stated that arm muscle power determined on a biokinetic swim bench is highly related with 25 yard swimming velocity in front crawl ($r = 0.90$). Latter, these findings were corroborated by experiments in a cycle-ergometer using arms-only. Hawley and Williams (1991) assessed the upper body anaerobic power of 30 age-group swimmers (14 males and 16 females), presenting moderate-high correlations of peak power, mean power and fatigue index with 50 m swimming velocity ($r = 0.82$; $r = 0.83$; $r = 0.41$, respectively). Additionally, the same research group (Hawley et al., 1992) stated that power indices for the legs did not increase the estimation for 50 m swimming performance, and that arm power is also important in longer swim events (400 m). Other studies supported these relationships (Rohrs et al., 1990; Johnson et al., 1993; Strzala & Tyka, 2009; Garrido et al., 2010). Nevertheless, the validity of the correlations seems to be misleading in above referred studies through the use of heterogeneous samples in age, gender and possibly maturation. Doubtful conclusions from heterogeneous groups in swimming have long been recognized (Costill et al., 1983; Rohrs et al., 1990). Moreover, the use of biokinetic swim bench or a cycle ergometer using arms-only neglect the role of lower limbs and body roll, and their importance for body coordination.

Beneficial effects on work economy through different mechanisms (e.g. improved reflex potentiation, alterations of the synergists) may be caused by dry-land strength training (Aspenes et al., 2009). Moreover, dry-land strength training is a common practice in swimming training, though the scientific evidence is still scarce (Aspenes et al., 2009; Garrido et al., 2010). Actually, few studies have assessed associations between force parameters in strength training (e.g. bench press) and swimming performance. Johnson et al. (1993) assessed one repetition of maximum bench press (results not presented in paper) of 29 male swimmers, with ages ranging between 14 and 22 years, and 25 yard swimming velocity (ranging from 1.72 to 2.31 $m.s^{-1}$). These authors suggested that this measure of dry-land strength did not contribute significantly to the prediction of sprint velocity. It must be noticed that the spectrum of ages should be taken into consideration, especially when within this range significant changes in somatotype occur. By means of a more homogenous group, Garrido et al. (2010) presented a moderate but significant correlation between 6 maximum repetitions of bench press and swimming performance (both 25 and 50 m performance times; $\rho \sim -0.58$; $p < 0.01$) with young competitive swimmers. To the best of our knowledge, the only authors that assessed strength parameters using more exercises were Crowe et al. (1999). Their study evaluated one maximum repetition in bench press, lat pull down and triceps press, for male and female swimmers. Although significant relationships were obtained between the 3 exercises and tethered swimming forces, significant correlations with swimming performance were only verified in lat pull down for the female swimmers group ($r = 0.64$, $p < 0.05$).

The above referred studies only evaluated maximum load that swimmers could achieve during maximum repetitions, which is more related to maximum force than with explosive force (González-Badillo & Sánchez-Medina, 2010). In order to overcome these limitations, Dominguez-Castells and Arellano (2011) using a velocity linear wire encoder measured the power developed in bench press maximum velocity repetitions. The authors stated a moderate relationship between maximum bench press power and swimming power ($r = 0.63$) but did not present the r value with swimming velocity. This is a first approach to new insights related to strength training suggesting that more studies are necessary.

In summary, the incongruous results of experiments developed so far, point out that the associations of dry-land strength and swimming performance remains uncertain. More studies are necessary and they should: (i) evaluate homogeneous groups of subjects; (ii) assess strength/power parameters in more strength exercises with muscular solicitations similar to the swimming movements; and (iii) study which parameters (e.g. one maximum repetition or velocity displacement) are more appropriate to explain the variation in swimming velocity. Further approaches may lead to an elucidation of the role of muscular strength and/or power to swimming performance.

Effects of strength training over swimming performance

An optimal level of strength and power is necessary for successful performance in swimming (Newton et al., 2002) as it is dependent on the maximization of the ability to generate propelling forces and minimizing the resistance offered by the liquid environment (Vilas-Boas et al., 2010). Therefore, strength training programs are a common practice for swimmers (Aspenes et al., 2009; Garrido et al., 2010) even if beneficial effects are controversial in specialized literature (Tanaka et al., 1993; Trappe & Pearson, 1994; Girold et al., 2007). Moreover, the benefits of strength training are questioned as many coaches think that it may cause an increase on the muscular mass (hypertrophy) or a decrease on flexibility levels, which would negatively affect swimming ability and increase drag forces (Newton et al., 2002). Accordingly, two assumptions emerge: (i) there are many components of a dry-land strength training program and the improvement of power is certainly one of the most important one (Toussaint, 2007); (ii) the selected exercises should be consistent with the types of movement that are involved in swimming (Maglischo, 2003).

To the best of our knowledge, concerning the effects of strength training programs for swimming performance enhancement, few experiments were performed. In one of the initiate conducted experiments, Strass (1988) in adult swimmers (n = 10), detected improvements of 20 to 40% on muscle strength after a strength program using free weights. These improvements corresponded to a significant 4.4 to 2.1% increase in performance over 25 and 50 m freestyle, respectively. However, few years later, Tanaka et al. (1993) questioned if the strength gained on land could be positively transferred to propulsive force used in water, as the specificity of training seems to differ. These authors applied a strength training program 3 days per week over 8 weeks, using weight lifting machines and free weights. It was reported an increase of 25 to 35 % in muscular strength but this did not correspond to an improvement on swimming performance, as corroborated by Trappe and Pearson (1994). These inconsistent results pointed that more studies were necessary in order to evaluate the amount of muscular strength improvement required to enhance swimming performance.

More recently, three studies investigated the effects of dry-land strength training on swimming (Girold et al., 2007; Aspenes et al., 2009; Garrido et al., 2010). Girold et al. (2007) applied the dry-land strength program twice a week (45 min each session) during 12 weeks with an intensity between 80 to 90% of maximum load; Aspenes et al. (2009) between 1 to 3 sessions per week during 11 weeks were carried out with the heaviest load possible at each session; and Garrido et al. (2010) implemented a strength training regimen twice a week during 8 weeks and lasting approximately 20 min each session. Secondly, the intervention group varied between n = 7 (Girold et al., 2007) coupling indifferently male and female swimmers (16.5 ± 2.5 years-old), n = 11 (Aspenes et al., 2009) with 6 boys and 5 girls (17.5 ± 2.9 years-old), to n = 12 (Garrido et al., 2010) with 8 boys and 4 girls (12.0 ± 0.78 years-old). If strength gains during preadolescence exhibit quite similar rates among boys and girls (Faigenbaum et al., 2002), after puberty, boys tend to present higher muscle strength levels than girls (Bencke et al., 2002), which may mislead the conclusions of Girold et al. (2007) and Aspenes et al. (2009). Finally, swimming performance assessment was made after a warm-up not described or of 2000 m (Girold et al., 2007), with in-water starts (Garrido et al., 2010), or with diving start (Girold et al., 2007; Aspenes et al., 2009) in a 25 m pool. The effects of warm-up are controversial but may influence swimming performance, especially in short distances with maximum intensity (Neiva et al., 2012; Balilionis et al., 2012). Moreover, the diving, glide and turns, are responsible for of the overall performance and this may be taken into consideration when assessing swimming performance. Overcoming the refereed limitations, these studies point that combining swimming and dry-land strength training is more efficient than the swimming program alone to increase 50 m (Girold et al., 2007) and 400 m (Aspenes et al., 2009) freestyle performance. Although this could not be proven to prepubescent swimmers, there seems to be a tendency to enhance swimming performance in 25 and 50 m freestyle due to strength training (Garrido et al., 2010).

In conclusion, strength training using dry-land regimens may enhance the ability to produce propulsive forces in-water, especially in short distance events. More studies are essential to identify appropriate volume and intensities of training programs, according to gender and level. Additionally, movement velocity should be taken in consideration as it may improve the specificity of the exercises performed (González-Badillo & Sánchez-Medina, 2010).

Conclusions

The present article highlighted the available experiments in the literature conducted with the aim of establishing associations between dry-land strength or power measurements and swimming performance, and the experiments aiming to analyze the effects of dry-land strength training programs in swimming performance. Some new insights are suggested for future investigations.

Chapter 4.

Stroking force and front crawl swimming velocity in male swimmers

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Abstract

The purpose of this study was to compare kinematical and physiological variables between 30 s tethered swimming and free swimming (50 and 100 m) in front crawl at maximal effort, and to examine relationship between the characteristics of the stroking force and swimming velocities (v50 and v100). The mechanical characteristics of pulling forces were assessed for 34 male competitive swimmers. Additionally, stroke rate (SR), blood lactate concentration (BLa), heart rate (HR) and perceived exertion (PE) were measured. No differences were obtained between SR, BLa, HR and PE between tethered swimming and 50 m test, but higher values were obtained in the 100 m test (except for lower values of SR). Average force was found to correlate significantly to v50 ($r = 0.81$), v100 ($r = 0.84$), SR ($r = 0.49$) and BLa ($r = 0.66$) in the 50 m test. Maximum impulse per stroke correlated with v50 ($r = 0.91$), v100 ($r = 0.74$), and SR ($r = 0.36$) and BLa in the 50 m test ($r = 0.66$). The relationship of swimming velocities with maximum force tended to be non-linear, whereas with maximum impulse linear relationships were obtained. The results indicate that for 50 m front crawl swimming, maximum impulse was found to be a determinant factor of swimming velocity performance.

Key words: tethered swimming, impulse, training, testing, performance.

Introduction

Swimming competitive performance is dependent of multi-factorial parameters that include muscular strength (Keskinen et al., 1989), swimming technique (Chollet et al., 2000; Vilas-Boas et al., 2010) and aerobic and anaerobic energetics (Maglischo et al., 2003). The influence of force production on swimming velocity has been discussed since Yeater et al. (1981) who stated that average maximum force in tethered swimming correlated positively to swimming velocity. Moreover, it has been demonstrated that the force exerted in water is a major factor for success in swimming performance (Costill et al., 1986; Keskinen et al., 1989; Keskinen, 1997), being its importance increased as the competitive distance diminishes (Morouço et al., 2011).

The swimming velocity is dependent both on the drag force that the swimmer has to overcome while moving through the water, and the propelling force exerted on the water by the swimmer (Vilas-Boas et al., 2010). The increase in velocity increases drag, having the swimmer to emphasize further on the propulsive force (Keskinen et al., 1989). The measurement of these forces has been a major topic of interest for many years. However, due to the aquatic circumstances the assessment of the magnitude of these forces is complex and difficult (Akis & Orcan, 2004). Accordingly, tethered swimming has been pointed as a methodology that enhances the possibility of measuring the maximum force that (theoretically) corresponds to the propelling force that a swimmer must produce to overcome the water resistance at maximum free swimming velocity (Keskinen, 1997; Morouço et al., 2011).

Different experiments using tethered swimming yield multiple force metrics (e.g. maximum force, average of maximum force, average force, and impulse). For example, a sprint velocity have been significantly correlated with maximum force (e.g. Keskinen et al., 1989) or average of maximum force (e.g. Yeater et al., 1981), although Taylor et al. (2001) found that only average force was a reliable parameter to estimate swimming performance in age group swimmers. Recently, Morouço et al. (2011) reported higher correlations between 50 m front crawl swimming velocity and average force, than maximum force (r = 0.77 and r = 0.47, respectively). These incongruous data point that more studies are required in order to achieve a better understanding on this topic. Furthermore, Dopsaj et al. (2000) indicated that when tethered swimming is used in top swimmers, the values of impulse should also be analyzed. Indeed, maximum force comprises information about a single point per stroke: when maximum force is reached. However, propulsion can occur along all the propulsive phase of the stroke (Marinho et al., 2011) and lower force applied in a longer stroke can produce similar (or even higher) momentum change than a higher force applied in a shorter stroke, according to the integral of a force with respect to time:

$$I = \int_{t_1}^{t_2} F \cdot dt \tag{1}$$

where I is the impulse and F is the applied force from time t_1 to t_2. Consequently, the calculation of the impulse, as proposed by Dopsaj et al. (2000), may be more accurate for the purpose of evaluating tethered forces.

In terms of the nature of the relationship between tethered forces and swimming velocities, most studies followed the assumption that this relationship is linear. Yet, Keskinen et al. (1989) demonstrated positive nonlinear interrelationships ($y = -90 + 97.256x - 21.301x^2$; $r = 0.86$, $p < 0.001$) between maximum force and maximum velocity, reporting that at a very high velocity it is difficult to produce very high force values. If so, the variability in swimming velocity may not be indicative of the variability in stroking force. While it is perceptible that an association does exist, the nature and strength of this relationship remain inconclusive.

A maximal effort with 30 s duration engages energetical demands provided mainly by intramuscular ATP and phosphocreatine, and by anaerobic glucose metabolism (Gastin, 1994). Moreover, the accurate establishment of relationships between tethered swimming forces and swimming velocity requires that the test takes at least approximately as long as the distance covered (Dopsaj et al., 2000). In this manner, it is possible to take into consideration the load exertion on the same energy system (Cortesi et al., 2010). Peyrebrune et al. (2001) estimated an anaerobic energy contribution of 66.1 ± 7.3% in a 30 s maximum tethered swimming test. Nevertheless, the evaluation of the anaerobic capacity of swimmers stays inconclusive (Papoti et al., 2007) requiring additional studies. Experiments comparing physiological variables and stroke mechanics between tethered swimming and free swimming are scarce, but may give new insights under this issue.

Therefore, the aims of the present study were to verify if kinematical (stroke rate) and physiological (blood lactate concentration, net heart rate and perceived exertion scale) parameters were similar between tethered swimming and free swimming; and to examine possible relationships between tethered forces (maximum, average, and impulse) and swimming velocities (50 and 100 m front crawl). It was hypothesised that tethered swimming reproduce the swimmer effort of free swimming with equal duration; and that tethered forces are related to swimming velocities during short distance bouts, especially when considering the impulse.

Material and methods

The study involved 34 male competitive swimmers (17.2 ± 2.72 years old; 175.9 ± 8.68 cm of height, 67.4 ± 9.94 kg of body mass) representing different competitive performances in 100 m long course free style swimming (58.39 ± 2.19 s; [52.1 – 63.0] s). All subjects and their parents gave their consent, and the study was approved by the Ethics Committee of the hosting University. All procedures were in accordance to the Declaration of Helsinki in respect to Human research. The subjects had at least 5 years of experience in competitive swimming, participating on regular basis in national and international level competitions. None swimmer suffered from illness or from restrictions that hindered their performances during the tests.

Experimental design

Tests were performed during the competitive period of the spring training cycle to ensure that the subjects were in a prime training period, in a 50 m indoor swimming pool (27 - 28 °C of water temperature).

In day one, after a 1000 m moderate intensity warm-up, each subject executed a 30 s maximal front crawl tethered swimming test. A load-cell system connected to the swimmer was used as a measuring device, recording at 100 Hz with a measurement capacity of 500 kgf, as recently described (cf. Morouço et al., 2011). The participants were told to follow the breathing pattern they would normally apply during a 50 m free style event, and were verbally encouraged throughout the tests, enhancing them to maintain maximal effort over the duration of the trial; the end of the test was set through an acoustic signal. On day two, after a 1000 m moderate intensity warm-up, each subject performed two maximal front crawl swims with an underwater start (selected to diminish the effect of start): the first over 100 m; and the second over 50 m distance. An active recovery for 30 min between trials was controlled.

Data analysis

Tethered swimming data was exported to a signal processing software (AcqKnowledge v.3.7, Biopac Systems, Santa Barbara, USA) and filtered with a 4.5Hz cut-off low-pass. The selection of the cut-off value was done according to residual analysis (residual error versus cut-off frequency). As the force vector in the tethered system presented a small angle to the horizontal, data was corrected computing the horizontal component of force (cf. Taylor et al., 2001). The following parameters were estimated for each participant: maximum force (maxF) as the higher value obtained in individual Force-time curve, average force (avgF) as the mean of F values registered along the 30 s, maximum impulse (maxI) as the higher value of impulse (cf. equation 1) in a single-stroke, and average impulse (avgI) as the quotient of the sum of single-stroke impulse and the number of strokes performed in the 30 s. The swimming velocities were calculated for 50 m (v50) and 100 m (v100) from the chronometric time spent in the tests.

Stroke rate (Hz) was determined with the use of a portable SR counter: for tethered swimming (SRts) at the middle of the test (~15 s), for the 50 m (SR_{50}) free swimming in the midsection of the pool (~25 m), and for the 100 m (SR_{100}) free swimming as the average of the 2 values in the midsection of the pool (~25 and ~75 m). Capillary blood samples for blood lactate analysis (Lactate Pro, Arkay, Inc., Kyoto, Japan) were collected from the earlobe in the final of the warm-up and after each test. These data allowed the assessment of the increase of blood lactate concentration (BLa), i.e., the difference between the maximal values measured after the test and those obtained after the warm-up. Net heart rate was assessed using a heart rate monitor with a recording rate of 1 s

(RS800CX, Polar, Finland) and perceived exertion was scaled after each test (Borg, 1985).

Statistical analysis

Standard statistical methods were used for the calculation of means and standard deviations (*sd*) for all variables. Normality assumption was checked by Kolmogorov-Smirnov tests, thus parametric statistical analyses were applied. The magnitude of differences in SR, BLa, HR and PE between tethered and free swimming tests was evaluated with a repeated measures analysis of variance (ANOVA; post hoc Bonferroni). Pearson's correlation coefficient (r) was determined to assess the relationships among selected variables; linear and non-linear regression analyses to evaluate the potential associations were also applied. Limits of agreement between parameters measured in tethered swimming and 50 m front crawl bout were derived following the recommendations by Bland and Altman. All statistical procedures were performed using SPSS 20.0 for Windows® (Chicago, IL, USA). The level of statistical significance was set at $p < 0.05$.

Results

The stroking force parameters and swimming velocities are presented in Table 1. The variation coefficients ranged between 4.4 % for the 100 m swimming velocity, and 14.7 % for the average impulse. There were no differences in stroke rate, blood lactate concentration, heart rate or perceived exertion within the 30 s tethered swimming test and the 50 m front crawl bout (time = 28.3 ± 1.6 s), but the 100 m front crawl bout (time = 62.2 ± 2.7 s) obtained higher values of blood lactate, heart rate and perceived exertion and lower values of stroke rate (Table 2).

Table 1. The results of force measurements and swimming velocities.

	Mean ± *sd*	Range	Coef. of variation
Maximum force (N)	331.8 ± 40.6	401.5 – 251.3	12.2 %
Average force (N)	112.7 ± 15.6	139.1 – 86.9	13.9 %
Maximum impulse (N.s)	108.7 ± 13.9	133.3 – 84.5	12.8 %
Average impulse (N.s)	78.3 ± 11.5	103.0 – 57.6	14.7 %
Velocity 50 ($m.s^{-1}$)	1.77 ± 0.10	1.98 – 1.62	5.8 %
Velocity 100 ($m.s^{-1}$)	1.61 ± 0.07	1.78 – 1.50	4.4 %

As strong correlations were obtained in stroke rate and blood lactate concentration between tethered swimming and 50 m front crawl, the Bland and Altman plots of the difference are reported in Fig. 1 (panel A and B, respectively). The average differences were rather low with limits of agreement (average ± 1.96 *sd*) ranging from -0.079 to 0.112 for stroke rate and from -1.108 to 1.414 for blood lactate concentration.

Table 2. The results of common variables in tethered and free swimming testing.

	Tethered swimming	50 m front crawl	100 m front crawl
Stroke rate (Hz)	0.90 ± 0.08**	0.89 ± 0.09**	0.80 ± 0.09
Blood lactate ($mmol.l^{-1}$)	8.09 ± 1.65**	7.94 ± 1.62**	10.21 ± 2.05
Heart rate (bpm)	175.5 ± 10.8**	170.9 ± 8.5**	188.3 ± 8.4
Perceived exertion	15.4 ± 1.3**	15.3 ± 1.4**	17.6 ± 1.1

** Significant difference from the 100 m front crawl bout ($p < 0.01$).

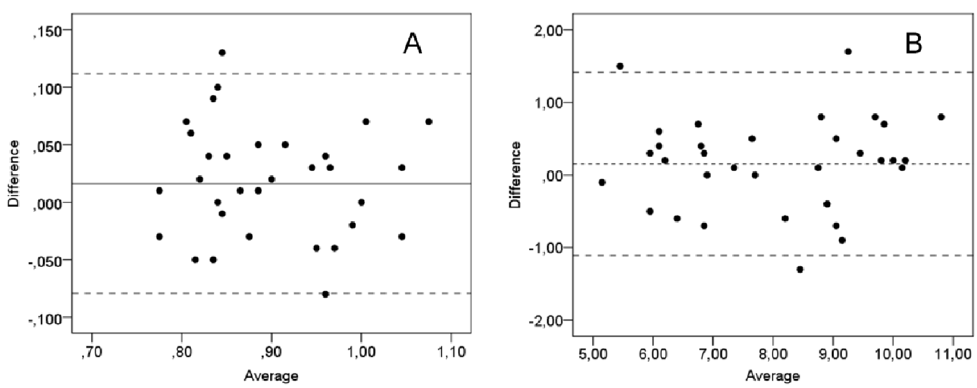

Figure 1. Bland and Altman plots of comparison between the assessments of stroke rate (panel A) and blood lactate concentration (panel B) in tethered swimming and 50 m front crawl. Average difference (solid line) and 95% CI (dashed lines) are indicated.

There were several significant correlations between tethered swimming results and free swimming variables, as shown in Table 3. Free swimming velocities (v50 and v100) were found to positively correlate to both force and impulse measurements. However, the stronger correlation for v50 was found with maxI, and for v100 with avgF. In addition, v50 presented a significant correlation with v100 ($r = 0.843$, $p < 0.000$).

SR assessed in tethered swimming was noted to be positively related with SR in free swimming, with higher values of relationships obtained with the shorter swimming distance (50 m). BLa presented a very strong correlation between the tethered swimming and 50 m free swimming. Moreover, moderate to strong relationships were observed between BLa in tethered swimming and v50, v100 and BLa in 100 m free swimming (cf. Table 3). HR did not present significant correlations with other variables, with the exception of HR in tethered swimming with PE in the 100 m front crawl bout. A strong correlation of PE rated after tethered swimming and after 50 m free swimming bout was noted. Figure 2 shows the individual plots of v50 with maxI (panel A) and maxF (panel B).

Table 3. Correlation coefficients (r) between tethered swimming (TS) parameters and free swimming (50 and 100 m) variables.

		50 m free swimming					*100 m free swimming*				
		v50	SR	BLa	HR	PE	v100	SR	BLa	HR	PE
TS parameters	maxF	.757**	.321	.614**	.088	-.026	.819**	.106	.402*	-.132	-.209
	avgF	.812**	.492**	.658**	.000	.128	.836**	.312	.297	.035	-.017
	maxI	.912**	.357*	.656**	-.125	.125	.740**	.214	.273	.060	-.068
	avgI	.699**	.307	.535**	-.131	.216	.657**	.288	-.002	.037	.017
	SR	.304	.837**	.332	.001	.227	.123	.663**	.176	.238	.218
	BLa	.554**	.391*	.923**	.025	.106	.493**	.359*	.636**	.313	-.110
	HR	.167	.096	.089	.038	-.364	.267	-.007	-.026	.002	-.482*
	PE	.188	.160	.173	.207	.724**	.298	.126	.178	.238	.272

maxF – maximum force, avgF – average force, maxI – maximum impulse, avgI – average impulse, v50 – swimming velocity in 50 m front crawl, v100 – swimming velocity in 100 m front crawl, SR – stroke rate, BLa – blood lactate concentration, HR – heart rate, and PE – perceived exertion. * $p < 0.05$, ** $p < 0.01$

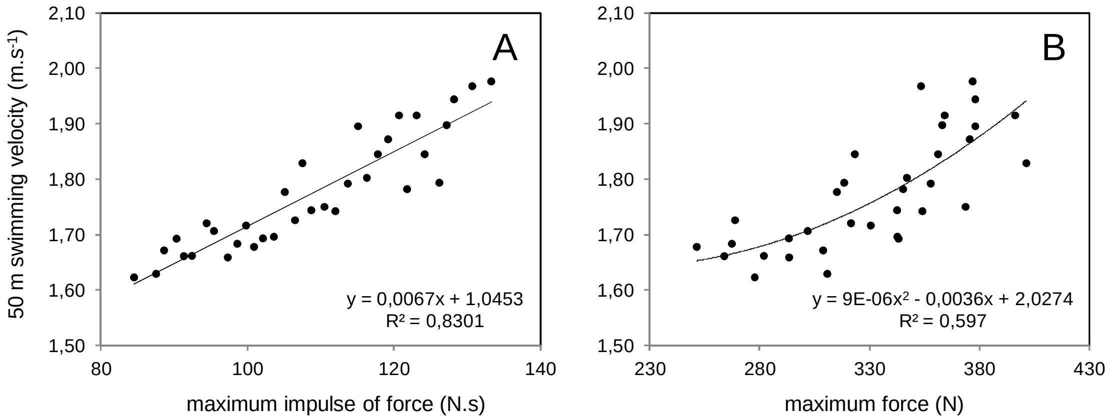

Figure 2. The relationships between 50 m swimming velocity and maximum impulse (panel A), and maximum force (panel B).

Discussion

The purposes of this study were to verify if tethered swimming imposes the same stroke rate, blood lactate concentration, heart rate and perceived exertion than free swimming; and to analyze the relationships between exerted forces and free swimming velocities. The main findings were that high similarity was found between 30 s tethered swimming and 50 m front crawl free swimming at maximal intensity. In addition, maximum impulse per stroke presented higher accuracy to estimate swimming velocity in 50 m maximum front crawl than maximum force. Analyses of tethered swimming variables gave new insights on the role of tethered forces that can be used to achieve higher improvements in swimming performance, in agreement with the previously established hypothesis.

Tethered swimming has proven to be a highly reliable methodology (Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006) measuring the force that provides a feasible estimation of the propelling force necessary to overcome water resistance in free swimming (Magel et al., 1970). Keskinen et al. (1989) reported maximum forces of 144.4 ± 34.5 N; lower than the present study, as expectable as the authors used an elastic cord to attach the swimmer. Using a non-elastic cable, Sidney et al. (1996) presented higher values of maximum force ($\bar{x}$ = 371.9 ± 78.1 N); which may be explained by the higher level of those swimmers as confirmed by their higher swimming velocity ($\bar{x}$ = 1.92 ± 0.08 $m.s^{-1}$). Average force is dependent from the time of testing and most experiments undertook tests with less than 30 s, achieving higher outputs as normal (e.g. Yeater et al., 1981). For the present study 30 s maximal tethered swimming was used in an attempt to simulate time duration of the 50 m maximal front crawl free swimming (a typical distance in training series); no differences ($p < 0.001$) were observed between tests duration. Regarding that propulsion can occur during all the propulsive phase of the stroke (Marinho et al., 2011), the impulse per stroke was calculated and maximum and average values were registered. To the best of our knowledge, there are no previous tethered force studies using this approach. Similarly, Dopsaj et al. (2000) conducted an experiment with 20 s maximal tethered swimming and assessed the average values of impulse realised for 5, 10, 15 and 20 s; which were higher than results of current study since time was enlarged.

Kinematical and physiological parameters were identical between the 30 s tethered swimming and the 50 m free swimming; differences for the 100 m distance were noticed ($p < 0.01$). Stroke rate is informative with respect to performance potential (Psycharakis et al., 2008), but it should be evaluated from an individual perspective, as swimmers tend to employ a freely-chosen stroke rate (Keskinen & Komi, 1993). Accordingly, the present data showed low differences between tethered swimming and 50 m free swimming, inducing that 30 s of tethered test closely replicated the effort of 50 m maximal front crawl for this sample cohort. For the 100 m free swimming a significant decrease in the stroke rate values was noticed which was expectable since high level swimmers increase stroke length and decrease stroke rate with longer swimming distances (Craig & Pendergast, 1979).

Blood lactate concentration reflects the balance between production and removal processes (Psycharakis et al., 2008), and its relationship with swimming velocity is important for the enhancement of swimming performance (Bonifazi et al., 1993). Although not being a direct measure of acidosis or a true representation of the lactate in the working muscle (Gastin, 1994) its assessment is a common practice to measure anaerobic capacity (Maglischo, 2003). No differences were obtained in blood lactate concentration within tests of the same duration, corroborating the results of Thanopoulos et al. (2010). These authors compared the blood lactate concentration attained in 100 m front crawl and in tethered swimming with equal duration, and no differences were noticed.

Perceived exertion has been pointed as an effective measure of exercise intensity (Borg, 1985) and can be used for swimming training prescription (Ueda & Kurokawa, 1995). In the current study both heart rate and perceived exertion illustrated the same pattern: similarity between tests with the same duration, and higher values in 100 m free swimming. It is possible to assume that 30 s maximal tethered swimming is an accurate procedure to reproduce performance in 50 m maximal swimming bouts regarding kinematical and physiological determinants. These findings confirm the link between the 30 s tethered test and the performances with greater use of power and predominance of anaerobic energy (Cortesi et al., 2010).

Since the study of Yeater et al. (1981), several investigations have shown a high relationship between tethered forces and swimming velocity (e.g. Keskinen et al., 1989; Dopsaj et al., 2000; 2003). This relationship differs according to age and maturity

(Taylor et al., 2001), competitive level (Sidney et al., 1996) and swimming distance (Morouço et al., 2011). Nevertheless, most of the above referred studies related the tethered forces with swimming velocity in non-competitive distances (e.g. 10 m). Enhancing the transfer to swimming training, this study has found a very high relationship between tethered forces and performance in 50 and 100 m free swimming; 2 distances commonly used in training bouts (Maglischo, 2003). Firstly, it was observed a very strong relationship between 50 m swimming velocity and maximum impulse, suggesting that the impulse is more adequate to describe sprinters' performance in shorter distances (Dopsaj et al., 2000). Secondly, a strong correlation between average forces and 100 m free swimming velocity was obtained, demonstrating that the ability to maintain high outputs of force production may lead to an increase performance for this distance (Morouço et al., 2011). Thirdly, blood lactate concentration after 50 m front crawl free swimming presented moderate to strong relationships with stroking force parameters, supporting the data of Thanopoulos et al. (2010) for the 100 m distance. These findings point that the energy cost of front crawl swimming appears to be strongly influenced by the effective application of force during the arm stroke (Costill et al., 1985).

In terms of maximum force (most common variable assessed in tethered swimming), a non-linear relationship with 50 m swimming velocity was demonstrated (cf. Figure 2, panel B) suggesting that studies assessing this variable sub estimated the role of stroke force mechanics in swimming performance. A similar non-linear association was reported by Keskinen et al. (1989) stating that a limit for force to increase swimming velocity necessarily occurs. Impulse takes into consideration not only the magnitude of the exerted forces, but also the time spectrum of its application. In tethered swimming it represents the magnitude of the applied pull drive, and as such represents the working potential to be carried-out in free swimming (Dopsaj et al., 2000).

Perspective

The present study provides a novel insight in swimming performance evaluation for male swimmers, especially proficient in short competitive distances. The results point that 30 s maximum tethered swimming replicates 50 m free swimming in terms of kinematical and physiological parameters. Moreover, the impulse should be taken into consideration when assessing stroking forces, and may be used to predict free swimming velocity. Tethered swimming has proven to be an easy, operative and short time consuming methodology to analyze the balance between force and the ability to effectively apply force.

Chapter 5.

Front crawl arm asymmetries assessment using tethered swimming

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Human Movement Science (submitted)

Abstract

The aim of this study was to quantify arm asymmetries in front crawl technique along a 30 s maximum tethered swimming effort, and to analyse its relation with swimming velocity. 12 intermediate and 9 advanced level male swimmers performed a handgrip strength test, a 30 s maximal front crawl tethered swimming test, and a 50 m front crawl swim at maximal intensity. Individual force-time curves were registered to assess average of peak forces, maximum peak force, and slope of peak forces for both dominant and non-dominant arms; symmetry index was also computed. Advanced swimmers presented superior handgrip strength (in both hands), average peak force and maximum peak force in tethered swimming (in both arms), and swimming velocity ($p < 0.01$) than intermediate participants. Asymmetries were observed in handgrip strength (for 5 swimmers) and tethered swimming forces (for 15 swimmers). Force exerted by the dominant arm presents a higher decrease than non-dominant arm. A tendency of higher decrease in advanced swimmers was noticed. Handgrip strength did not correlate with swimming velocity but tethered swimming parameters may predict swimming performance in 50 m.

Key words: symmetry, force, training, performance.

Introduction

Front crawl is the alternated swimming technique in which higher average velocities are obtained. This is due to the fact that: (i) when one arm is recovering the other arm is propelling, diminishing the period of no force application (Toussaint & Beek, 1992); and (ii) diverging from backstroke (the other alternated stroke), higher values of force can be exerted in the prone position (flexion/adduction) than in supine position (extension/abduction) (Craig & Pendergast, 1979). Thus, lower intracycle velocity variations are attained in front crawl, which are well reported and related to higher swimming velocities (Barbosa et al., 2010; Craig & Pendergast, 1979). Intracycle velocity variations are due to the consecutive exertion of force in water:

$$F = m.a \tag{1}$$

where F is the resultant force, m is the body mass and a is the acceleration. The resultant force includes propulsive and drag forces, and the body mass should consider added water mass (Vilas-Boas et al., 2010). From this point of view, equation (1) can be rearranged as:

$$a = \frac{P + D}{m_b + m_a} \tag{2}$$

being a the swimmer's acceleration, P the total propulsive forces, D the hydrodynamic drag force, m_b the swimmer's body mass, and m_a the added water mass. Hence, swimming velocity is the result of a circumstantial prevalence of P or D, or a consequence of an increased (or decreased) added mass effect during a given swim cycle (Vilas-Boas et al., 2010). Concerning short competitive events, the ability to obtain high values of P is considered one of the main factors to enhance performance (Morouço et al., 2011). In fact, it has been reported high associations between forces generated in water and high swimming velocities (Toussaint & Beek, 1992; Keskinen et al., 1989). So, being the arms the main contributors for propulsion in front crawl (Deschodt et al., 1999), symmetry in force exertion within right and left arms may influence swimming accelerations, and positively affect mean velocities. Furthermore, the alternated actions of the arms do not ensure propulsion symmetry (Aujouannet et al., 2006), as it was reported an asymmetric pattern regarding hand speed (Keskinen, 1994), hand path (Aujouannet et al., 2006), and propulsive forces (Yeater et al., 1981). Therefore, being able to apply similar propelling forces from the right and left arm may positively affect swimming velocity, and contribute for a more adequate body position reducing the resistive drag that a swimmer has to overcome (Sanders et al., 2011).

Despite the current efforts aiming to quantify the above referred forces, their assessment in free swimming is vastly complex, if not almost impossible (Sanders & Psycharakis, 2009). Different methodologies haven been used for that purpose, namely: tethered and partial-tethered swimming (Kjendlie & Thorsvald, 2006; Keskinen, 1994), 3D video analysis (Gourgoulis et al., 2008), and hand pressures (Takagi & Wilson, 1999). Although handgrip strength does not apply in the mentioned methodologies, it has been included in talent identification models (Silva et al., 2007), being reported significant associations between these parameters and swimming performance in young (Geladas et al., 2005) and master swimmers (Zampagni et al., 2008).

In swimming evaluation, the appropriate selection of the methodology to be used is essential, as it should closely replicate the movement patterns employed in ecologic training and competition conditions (Swaine et al., 2010). Tethered swimming seems to be a specific and valid methodology to measure the propelling force exerted by a swimmer in water (Costill et al., 1986; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), and it is an easy, operative, time-saving and inexpensive procedure (Toubekis et al., 2010). Using a load cell, it is possible to assess individual force to time curves, improving the possibility of characterization and comparison of stroke patterns, and allowing a more accurate knowledge of the propulsive forces sequence during swimming (Morouço et al., 2011); it allows even to recognize that the movements relative to the water are to some extent different from free swimming conditions (Adams et al., 1983; Maglischo et al., 1984).

As above stated, the similarity between arms can maximize propulsion, but also enhance body postures, minimising hydrodynamic drag (Sanders et al., 2011). Cappaert and colleagues (1995) claimed that the rotation of hips and shoulders are more symmetrical in elite than novice swimmers, but asymmetrical strokes have been reported in arm coordination (Seifert et al., 2005) and force-time profiles (Formosa et al., 2011); nevertheless, these studies neglected the behaviour of (a)symmetry along a maximum effort. Providing the identification of force (a)symmetries may highlight factors that enhance performance, leading to improvements in coaches training prescription. Indeed, a comparison of the forces exerted is necessary to identify differences between advanced and intermediate swimmers.

Force production is related to the total number, area and tension, and to the percentage of fibers activated (Häkkinen, 2000). However, in swimming, this relationship may be affected by specific swimming ability (Morouço et al., 2011). The aims of the current study were to measure the force exerted by each arm in a 30 s maximum front crawl tethered swimming test, to quantify the (a)symmetries between arms, and to analyze the pattern of (a)symmetries along the test. Additionally, eventual associations between handgrip strength, tethered swimming parameters and swimming performance were searched to predict swimming performance. It was hypothesized that peak forces during tethered swimming would decrease during the test, and asymmetries in peak forces would exert a negative influence over velocity. In addition, it was hypothesized that strength parameters measured through handgrip strength and tethered swimming could predict swimming performance.

Materials and methods

Subjects

Twenty-one male swimmers volunteered to participate, and were separated in two homogeneous groups (coefficient of variation < 4.5% in personal best at the 100 m freestyle): intermediate (GR1 $n = 12$; 14.3 ± 1.06 years old, 1.68 ± 0.05 m of height, 59.7 ± 3.65 kg of body mass, 62.4 ± 2.75 s of personal best at the 100 m freestyle) and advanced swimmers (GR2 $n = 9$; 17.9 ± 0.93 years-old, 1.77 ± 0.05 m of height, 77.1 ± 3.95 kg of body mass, 54.8 ± 1.64 s of personal best at the 100 m freestyle). Subjects had at least 5-years of experience in competitive swimming, participating on regular basis in regional and national (GR1), and national and international (GR2) level competitions. Swimmers suffered neither from illness nor from restrictions that hindered their performances during the tests. Parents and coaches gave their consent for the subjects' participation in this study. All procedures were in accordance to the Declaration of Helsinki in respect to Human research. The Ethics Committee of the hosting University approved the study design, which has been performed in accordance with the ethical standards proposed by Harris and Atkinson (2011).

Experimental procedure

After a dry-land warm-up of 10 min, each participant exerted maximal grip isometric strength with a fully extended elbow in a standing position, using an adjustable digital strain-gauge dynamometer (Takei TKK 5401, Takei Scientific Instruments, Tokyo, Japan). Three repetitions for each hand were performed in the following order: right, left, left, right, right and left; pauses of 2 min between trials were controlled. The hand dynamometer was individually adjusted at the most comfortable distance. For analysis, values of the three trials (per hand) were registered (kg_f). The dominant hand was determined as the strongest hand as measured with the dynamometer. Afterwards, mean values were calculated for dominant (HG_d) and non-dominant hand (HG_{nd}). Finally, handgrip strength asymmetries were also quantified with the use of the Symmetry Index (SI) as described by Robinson et al. (1987), according to the following equation:

$$HG_{SI}(\%) = \frac{2(HG_d - HG_{nd})}{HG_d + HG_{nd}} \times 100 \qquad (3)$$

As suggested by the referred authors, a value between -10% and 10% for the SI implies symmetry, and dominant and non-dominant asymmetries are identified when SI < -10% and when SI > 10%, respectively. It should be noted that all the tested swimmers had already experienced previous assessments with this instrument.

Following the handgrip test, each swimmer undertook one 50 m maximal front crawl swim after an 800 m (GR1) or 1000 m (GR2) low intensity warm-up. A 50 m indoor swimming pool (27 ºC of water temperature) and an underwater start were selected to diminish the effect of start and glide. The swimming velocities were estimated according to:

$$v50 = 50.\Delta t^{-1} \qquad (4)$$

being Δt the chronometric time in the test.

24h later, after an 800 m (GR1) or 1000 m (GR2) low intensity warm-up, each subject performed a 30 s all-out front crawl tethered swimming test. The subjects wore a belt attached to a steel cable (sufficiently inflexible that its elasticity could be neglected) with 3.5 m length. A load-cell system connected to the cable was used as a measuring device, recording at 100 Hz, with a measure capacity of 500 kg_f. The load-cell was connected to a Globus Ergometer data acquisition system (Globus™, Cologne, Italy) that exported the data to a PC. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended, and swam three strokes with low intensity; data collection only started after the first maximum stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually observed immediately before or during the first arm action (cf. Morouço et al., 2011). The participants were told to follow the breathing pattern they would normally apply during a 50 m freestyle event, and were verbally encouraged throughout the tests, enhancing them to maintain maximal effort over the duration of the trial; the end of the test was set through an acoustic signal.

Individual force to time - F(t) - curves were assessed and registered to obtain the values of maximum force production, per stroke, for the right and left arms. As the force vector in the tethered system presented a small angle to the horizontal, data was corrected computing the horizontal component of force (cf. Morouço et al., 2011). Video image was captured (Casio Exilim EX-F1, Casio, NJ, USA) allowing the identification of dominant (TS_d) or non-dominant (TS_{nd}) arm, being determined as the first arm to accomplish higher peaks in five consecutive strokes. The following parameters were estimated for each participant: average of the peak forces along the 30 s (AvgTS), and the maximum peak force (MaxTS), for both dominant ($_d$) and non-dominant ($_{nd}$) arms. Finally, force symmetry for tethered swimming (TS_{SI}) was assessed for each stroke, according to equation (3).

Data analysis

Statistical analyses were performed using SPSS 20.0 for Windows® (Chicago, IL). Variables were expressed as means and standard deviations (*sd*). Normality and homoscedasticity assumption were checked by Shapiro-Wilk and Levene tests, respectively. Independent and dependent t-tests were performed between groups and between forces of dominant and non-dominant hand/arm, respectively. Pearson's correlation coefficient (r) was determined to assess the relationships among selected variables. Repeated measures analysis of the dominant and non-dominant tethered swimming forces were performed (within-subjects' ANOVA, with Bonferroni Post-hoc test), according to the swimmers level. Linear regression was computed to estimate the slope of peak forces along the 30 s exercise, for each arm. Multiple regression analyses (forward method) were used to verify the combination of significant variables that could predict performance in 50 m, according to swimmers level. The level of statistical significance was set at $p < 0.05$. Effect size was computed based on Eta-squared (η^2) procedure, and values interpreted as being: without effect if $0 < \eta^2 \leq 0.04$; minimum if $0.04 < \eta^2 \leq 0.25$; moderate if $0.25 < \eta^2 \leq 0.64$; and strong if $\eta^2 > 0.64$.

Results

The mean ± *sd* values for handgrip strength, tethered swimming parameters, and swimming performance are presented in Table 1, for each studied group. Advanced swimmers presented superior handgrip strength (in both hands), average peak force and maximum peak force in tethered swimming (in both arms), and swimming velocity ($p < 0.01$) than intermediate participants, and no differences were assessed in symmetry index (handgrip and tethered swimming tests) and slope of force along the 30 s tethered swimming test. Three intermediate and two advanced swimmers presented a symmetry index for handgrip higher than 10%, and, in tethered swimming, the symmetry index was higher than 10% in 15 of 21 tested swimmers. The video analysis showed that there was a correspondence between tethered swimming and handgrip bilateral dominance, for the total subjects.

Table 1. Mean ± *sd* values of handgrip strength, tethered swimming parameters and swimming velocity, according to swimmers level.

	Intermediate Swimmers (n = 12)	Advanced Swimmers (n = 9)
Handgrip dominant (kg_f)**	38.50 ± 4.44	49.89 ± 4.40
Handgrip non-dominant (kg_f)**	35.83 ± 4.20††	46.33 ± 3.57††
Handgrip Symmetry Index (%)	7.18 ± 3.92	7.32 ± 2.96
Average maximum forces dominant (N)**	189.9 ± 10.52	246.4 ± 17.73
Average maximum forces non-dominant (N)**	157.2 ± 23.06††	199.9 ± 23.30††
Symmetry Index (%)	19.6 ± 17.11	21.1 ± 12.75
Maximum peak dominant (N)**	252.0 ± 12.74	303.0 ± 16.98
Maximum peak non-dominant (N)**	199.0 ± 18.50††	241.0 ± 19.24††
Slope dominant ($N.s^{-1}$)	-3.71 ± 1.78	-4.28 ± 1.00
Slope non-dominant ($N.s^{-1}$)	-2.19 ± 1.03†	-2.59 ± 0.77††
Swimming Velocity ($m.s^{-1}$)**	1.68 ± 0.05	1.87 ± 0.04

**($p < 0.01$) significant difference between intermediate and advanced swimmers.

†($p < 0.05$) and ††($p < 0.01$) significant difference between dominant and non-dominant hand/arm.

With reference to swimming performance (cf. Table 2), handgrip strength did not correlate with swimming velocity for intermediate nor advanced swimmers. Swimming velocity correlated with the slope of maximum peaks in dominant and non-dominant arm, for intermediate swimmers. Thus, swimming performance for this medium proficiency level swimmers may be estimated by 50 m (s) = 29.997 + 0.524 $slope_d$ – 0.235 $slope_{nd}$ ($r^2 = 0.69$, $p < 0.05$). For advanced swimmers, swimming velocity correlated with average peak forces along the test and with maximum force, of dominant arm. Thus, variables obtained in tethered swimming test may predict swimming performance for this high level swimmers in 50 m (s) = 14.918 – 0.443 $AvgTS_d$ + 0.497 $AvgTS_{nd}$ + 1.014 TS_{SI} ($r^2 = 0.78$, $p < 0.05$).

Table 2. Correlation coefficients (r) between swimming velocity and handgrip strength, and tethered swimming variables, according to swimmers level.

	HG_d	HG_{nd}	HG_{SI}	$AvgTS_d$	$AvgTS_{nd}$	TS_{SI}	$MaxTS_d$	$MaxTS_{nd}$	$slope_d$	$slope_{nd}$
intermediate swimmers (n = 12)										
v50	-.031	-.122	.325	.573	.203	-.020	-.175	.390	.588*	-.710**
advanced swimmers (n = 9)										
v50	.347	.308	.222	.766*	-.102	.518	.687*	-.170	-.210	.536

HG – handgrip strength, AvgTS – average of peaks in tethered swimming forces, TS – tethered swimming, MaxTS – maximum peaks in tethered swimming forces, slope – slope of peak forces along the 30 s tethered swimming, $_d$ – dominant, $_{nd}$ – non-dominant, $_{SI}$ – symmetry index, and v50 – swimming velocity in 50 m bout. * $p < 0.05$, ** $p < 0.01$

Figure 1 show the mean ± *sd* of peak force for dominant and non-dominant arms along the 30 s maximum tethered swimming effort for intermediate and advanced level swimmers (A and B panels, respectively). For intermediate swimmers, differences within arms were obtained from the 1st to the 18th stroke, higher values were obtained in 3rd and 4th stroke for dominant and non-dominant arms (respectively), and meaningful variations are observable in the dominant [$F(3.130, 34.430) = 18.328$, $p < 0.001$; $\eta^2 = 0.63$] and non-dominant [$F(4.462, 49.081) = 13.518$, $p < 0.001$; $\eta^2 = 0.55$] tethered swimming forces; were revealed significant differences ($p < 0.05$) between highest values and 17th to last stroke in TS_d and with 14th to last stroke in TS_{nd}. Concerning advanced participants, differences within arms were obtained for all strokes, except in the 24th stroke, highest values were obtained in the 1st and the 2nd stroke for dominant and non-dominant arms (respectively), and meaningful variations are observable in the dominant [$F(2.667, 21.334) = 63.793$, $p < 0.001$; $\eta^2 = 0.89$] and non-dominant [$F(3.544, 28.354) = 26.305$, $p < 0.001$; $\eta^2 = 0.77$] tethered swimming forces; were revealed significant differences ($p < 0.01$) between higher values and 12th to last stroke in TS_d and with 14th to last stroke in TS_{nd}.

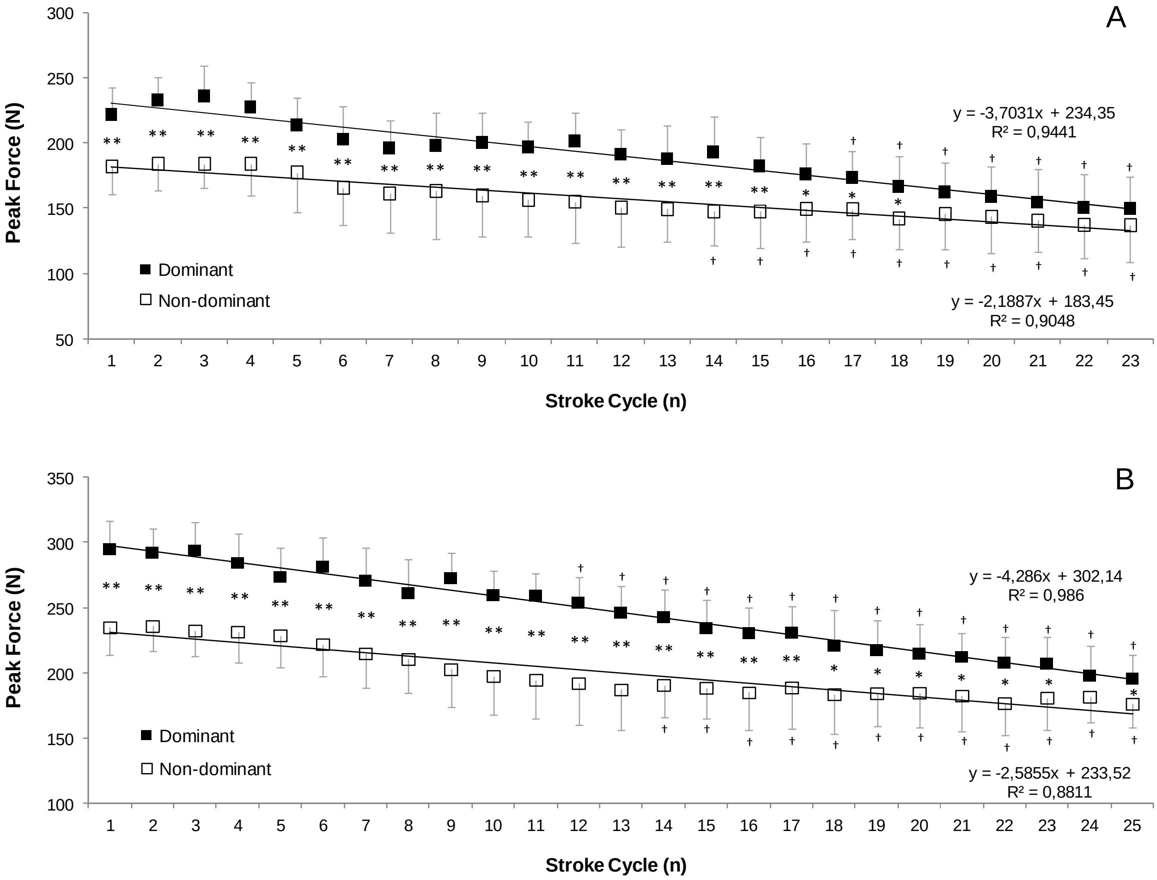

Figure 1. Maximum peaks of force exerted per stroke, for dominant and non-dominant arms, of intermediate level swimmers (panel A) and advanced level swimmers (panel B). Statistically different from dominant arm represented by * ($p < 0.05$) and ** ($p < 0.01$). † ($p < 0.05$) Statistically different between the highest value of the arm and each further stroke.

Discussion

The purposes of this study were to assess the force exerted by each arm along a 30 s maximum front crawl tethered swimming effort, to quantify the asymmetries between arms, and to analyze the pattern of a(symmetries) along the 30 s test. The main findings were that swimmers presented an asymmetrical force pattern between arms that is more evident in the first strokes of a 30 s maximum bout. Analyses of tethered swimming variables gave new insights on the symmetry patterns that can be used to achieve higher improvements in swimming performance, in agreement with the previously established hypothesis.

Firstly, a commonly used land strength assessment test was conducted. The handgrip strength values were similar to the literature, considering swimmers' gender and level. Geladas et al. (2005) found handgrip strength values of 34.0 ± 0.6 and 28.2 ± 0.6 kg_f for younger males and females (respectively), whereas Zampagni et al. (2008) reported values of 43.2 ± 11.8 kg_f for master swimmers. In the present study, higher values were obtained in advanced level swimmers, indicating that handgrip strength is sensitive to the swimmers' proficiency (Geladas et al., 2005; Zampagni et al., 2008). This is not surprising once previous studies reported moderate to high relationships between handgrip strength and swimming performance, leading to an inclusion of handgrip strength in talent identification models (Silva et al., 2007): Geladas et al. (2005) pointed out a correlation of r = -0.73 ($p < 0.01$) with 100 m freestyle performance in boys (but not in girls, r = -0.18, $p > 0.05$), and Zampagni et al. (2008) observed a value of r = -0.76 ($p < 0.01$) for elite master swimmers when considering the 50 m freestyle performance. However, in the present study no associations between handgrip strength and swimming performance were observed, which could be due to the heterogeneity of the samples of previous studies, and to the lack of specificity of the test. As it is well reported that handgrip strength has direct relationship with anthropometric characteristics (e.g. stature, body mass and muscle mass) (Hewitt, 1997), and as it is known that subjects vary largely in terms of anthropometric profiles, high associations between handgrip strength and swimming performance may be questionable; in fact, if the groups of the current study were coupled, a positive and significant association between this two variables would be obtained (r = 0.74, $p < 0.05$). In addition, it is accepted that swimming velocities are dependent of coordination and technique (Seifert et al., 2005; Toussaint & Beek, 1992), which are not involved in handgrip testing. Keeping in mind that strength is only valuable when swimmers are able to apply it correctly in water (Christensen & Smith, 1987; Keskinen, 1997), and as this depends on a combination of multiple factors (e.g. stroke pattern and the position of the propelling segments) (Marinho et al., 2011), in the current study the tethered swimming test was applied in two homogeneous groups (coefficient of variation of swimming velocity in the tests lower than 3.5%).

The observed values of maximum force in tethered swimming are slightly lower than previously published data (Yeater et al., 1981; Christensen & Smith, 1987; Formosa et al., 2011), possibly due to the different level of the swimmers evaluated; Sidney et al. (1996) also evaluated two male groups divided based upon swimming ability (21 and 17 from intermediate and advanced level, respectively), being reported significant differences between the two groups (371.9 ± 78.1 N vs. 207.8 ± 52 N). Average and maximum forces were significantly higher in advanced swimmers than in intermediate level swimmers; as tethered swimming measures the maximum force that, theoretically, corresponds to the propelling produced to overcome the water resistance at maximum free swim velocity (Morouço et al., 2011). Indeed, the depth of arm movements in tethered swimming may be changed compared to free swimming (Maglischo et al., 1984), but it is not known if tethered swimming modifies the force output (Toubekis et al., 2010).

Asymmetrical stroke patterns have been reported in arm coordination (Seifert et al., 2005) and force-time profiles (Formosa et al., 2011) in high level swimmers, but it is probable that it is also verified in intermediate level swimmers (only 4 swimmers presented a symmetry index lower than 10%). The origin of these differences remains unanswered (Sanders et al., 2011). However, providing a methodology that objectively quantifies force exerted in water closely (replicating the free swimming movements) may allow coaches to identify asymmetrical stroke patterns. In addition, Keskinen (1994) stated that coupling data from tethered swimming and maximum swimming velocity may estimate the interaction between strength and technique; repeated evaluations within season may highlight which factor should be enhanced in training prescription.

All swimmers presented a decline on maximum force per stroke along the 30 s exercise, which was expectable since swimming technique deteriorates along an intense exercise due to fatigue (Toussaint et al., 2006; Morouço et al., 2012); however, it is not known how the fatigue contributes to force (a)symmetries between arms. This was the first study to assess asymmetries between arms in front crawl along a 30 s maximal effort, and two novel insights emerged: (i) force exerted by the dominant arm presented a higher decrease than non-dominant arm in intermediate and advanced swimmers; (ii) although without statistical significance, there exists a tendency to higher decreases of peak forces along the 30 s tethered swimming test in higher level swimmers (for both arms). Accepting that the ability to generate force on stationary water is greater than on water moving in the opposite direction of the body, tethered swimming may provide valid data to evaluate (a)symmetries of swimmers.

The slope of maximum force production per stroke was assessed through linear regression of 23 strokes in intermediate level swimmers and 25 strokes in advanced swimmers, and, for both groups, dominant arm presented a significant higher decline than non-dominant arm. As can be observed in Figure 1, these differences lead to a close up in force production at the end of the test. Tourny-Chollet et al. (2009) reported longer relative duration of medial rotator activity in the asymmetrical patterns, suggesting that repeated front crawl movements during years of training might accentuate the force imbalance between the arms. Therefore, it is expected that the arm that produces higher forces present higher decrease along a maximum effort; these data was corroborated by the association between higher forces and higher velocities (Keskinen, 1997; Morouço et al., 2011), and may suggest that the proposed slope provides a good estimation for swimming performance.

Even though differences in slope among the studied groups were not observed, there seems to exists a tendency to higher decrease in advanced swimmers (proficient front crawl swimmers, specialized in 50 and 100 m distances); an expected outline regarding the statements of Stager & Coyle (2005) that referred that proficient swimmers in short distances present higher decreases in force production. Accordingly, Morouço et al. (2011) mentioned that swimmers who reach higher peaks of force were not able to maintain their values for so long, comparing to swimmers unable to obtain such higher values of tethered force. However, Diogo et al. (2010), although only analysing two subjects, reported that the subject who reached a higher peak of force in a 30 s tethered standard sculling test also reached later minimal values of force.

The results of the present study confirm the conclusions of previous investigations on the relationship between the ability to exert force in the water and swimming velocity (Yeater et al., 1981; Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Keskinen, 1994; Morouço et al., 2011). For intermediate swimmers, swimming velocity had a negative relationship with the decline of non-dominant force production, and a positive relationship with the dominant arm slope, suggesting that higher velocities may be attained with a lower decrease of force production of the dominant arm. Eight of the 12 intermediate level swimmers presented an asymmetrical stroke reinforcing the role of force exerted in water as a major important factor for success in swimming performance, even for lower lever swimmers. Considering advanced level swimmers, maximum and average force of the dominant arm and symmetry index, were the best predictors for swimming velocity, describing about 78% of variance. Thus, tethered swimming may be an easy and operative methodology to predict performance in short distance trials, being particularly useful to monitor and evaluate swimming training.

In summary, this study evidenced a strong decline in tethered forces along a 30 s maximum test. Asymmetries between arms in front crawl can be assessed and quantified. Furthermore, there is a tendency to diminish asymmetries during the effort. Handgrip strength did not correlate with swimming performance, but tethered swimming parameters may predict swimming velocity in intermediate and advanced level swimmers.

Chapter 6.

Relative contribution of arms and legs in front crawl tethered swimming, according to gender

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Abstract

Tethered swimming (TS) is a proposed methodology to assess the forces exerted in water by swimmers. During TS, swimmers using the real environment replicate arm and leg movements as forces measured in real time. The purpose of the present study was to investigate the relative contribution of arms and legs to force production in front crawl tethered swimming, according to gender. A further object was to analyze the relationships between forces exerted and free-swimming velocities. Twenty-three national level swimmers took part in the study (12 boys and 11 girls). Subjects performed three 30 s tethered swimming all-out efforts in whole-body, arms-only and legs-only combinations. Front crawl 50 and 100 m trials were used to assess swimming velocities. Significant differences between genders were found between absolute values of force parameters but not in relative ones. For the whole-body tethered swimming, relative values for arms-only were 75.1-83.9% and legs-only 30.8-38.7%. For all swimmers, the sum of both maximum and average forces with arms-only and legs-only combinations was higher than forces using the whole body. Concerning overall subjects, moderate to high relationships were found between tethered forces and swimming performance. For boys, maximum force presented higher correlations with swimming velocities, while for girls mean values produced higher correlations. The collected data suggest that in short distance swimming, both arms and legs contribute significantly to performance. Tethered swimming tests using whole-body, arms-only and legs-only formats seem to be a valid protocol in evaluating lack of ability to exert force in water. Thus, swim coaches can use this protocol to identify low levels of strength and/or coordination.

Key words: biomechanics, strength, leg-kick, swimming velocity.

Introduction

Swimming speed is known to be the most important issue in competitive trials. Therefore, it is well reported that higher speed is mainly accomplished (i) in the lower distance events, independently of the swimming stroke, and (ii) in freestyle events on which front crawl is employed. To reach high translation speed, swimming technique must be enhanced, in the effort to generate higher propulsive force to overcome water resistance and drag. Thus, swimmers must improve the propulsive action of legs and arms (Maglischo et al., 1986; Deschodt et al., 1999). Accordingly, it has been proposed that, as the swimming distance diminishes, the role of maximum force increases, and as the distance increases, the endurance force takes a major role (Wilke & Madsen, 1990; Hohmann et al., 1999; Stager & Coyle, 2005; Morouço et al., 2011a). Nonetheless, it ought also be pointed out that some variations should be taken into consideration regarding gender and morphological parameters (Hohmann et al., 1999).

Recent records in sprint distance trials may put in question the role of strength for swimming performance, especially in mainly anaerobic races. Indeed, several studies have reported significant correlations between force/power parameters and free swimming style (Miyashita & Kanshisa, 1979; Yeater et al., 1981; Sharp et al., 1982; Hawley et al., 1992; Fomitchenko, 1999; Morouço et al., 2011b). Therefore, the relative importance of arms and legs to overall swimming performance has been matter of interest for swimming research. Although leg action has often been neglected as of secondary importance for propulsion (Deschodt et al., 1999; Hollander et al., 1988), this is still a controversial issue. Moreover, to the best of our knowledge few studies have aimed to identify the relative contribution of arms and legs to swimming propulsion in water (Bucher, 1974; Toussaint & Beek, 1992; Deschodt et al., 1999). Most approaches measured this contribution indirectly, i.e., subtracting the role of arms to whole-body performance. However, the use of a novel swimming training machine, based on indirect measurement of force during free swimming, might have brought new insights to this concern (Swaine et al., 2010). Nevertheless, the relative contribution of arms and legs to force exerted in water remains answered.

Nowadays, the direct measurement of force application during sport performance is not technologically possible and the evaluation of athletes, including swimmers, must be specific to the nature of the sport. Thus, it is reasonable to use tethered swimming (TS) as a methodology to evaluate the force a swimmer exerts in water (Magel, 1970; Costill et al., 1986), this being a valid and reliable methodology (Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006; Psycharakis et al., 2011). An early study focused on the characterisation of force-time patterns, according to swimming stroke (Magel, 1970). Later studies evaluating the relationship between force productions in TS and swimming performance were scarcely more developed (Morouço et al., 2011a). A more recent study on these relationships presented higher associations between average forces exerted during 30 s TS with 50 m swimming velocity, than with 100 m and 200 m (Morouço et al., 2011a).

Unfortunately, research has not yet focused on assessing the relative contribution of force production of arms and legs separately to complete a front crawl TS. The aims of the present study were: (i) to assess the relative contribution of arms and legs in front crawl TS; (ii) to compare values according to gender; and (iii) to identify relationships between force parameters with swimming velocity. It was hypothesised that TS may be a useful methodology to evaluate force production in water according to the limbs used. More specifically we expected that: (i) higher values of force production would be obtained using the whole body, followed by arms-only and then by legs-only combinations, and (ii) as in adult swimmers, boys would present higher values of force production in tethered swimming compared to girls.

Methods

Experimental Approach to the Problem

The research question of interest was the quantification of arms and legs input to whole-body TS. Moreover, the association of each force variable with swimming performance was sought. The TS apparatus provided resistance, insuring that the swimmer remained stationary. This technique has been described above (Morouço et al., 2011a). To assess the relative contribution of arms and legs to total force exerted in TS, three combinations were compared. For each combination, maximum effort was imposed. The TS apparatus does not exactly reproduce the real environment, as the swimmer does not need to overcome drag. Thus, free swimming efforts in 50 and 100 m distances were chosen to relate with force parameters.

Subjects

Twenty-three swimmers (twelve boys and eleven girls) participating on a regular basis in national level competitions volunteered as subjects. Parents and coaches gave their consent for the swimmers' participation in this study. All procedures followed the Declaration of Helsinki concerning Human research. The Ethics Committee of the hosting Research Centre approved the study design. Mean ± *sd* values for the main physical and performance characteristics of the subjects are described in Table 1, according to gender. Body mass and percentage of body mass were assessed by means of the bioelectric impedance analysis method (Tanita BC 420S MA, Japan).

Table 1. Main physical and performance characteristics of the subjects (overall and according to gender; mean ± *sd*).

	Boys (*n* = 12)	Girls (*n* = 11)	Overall (*n* = 23)
Age (years)	15.17 ± 0.94	15.73 ± 1.42	15.44 ± 1.20
Height (m)	1.73 ± 0.07	1.61 ± 0.06*	1.67 ± 0.08
Body mass (kg)	61.76 ± 7.08	55.68 ± 5.75**	58.85 ± 7.05
Body fat (%)	11.71 ± 3.13	23.73 ± 3.56**	17.46 ± 6.95
Personal best 100 m Freestyle (s)	59.51 ± 2.04	67.06 ± 5.91**	63.12 ± 5.73

Legend: Significantly different from male swimmers, * for $p < .05$; ** for $p < .01$

Procedures

Tests were performed during the competitive period of the spring training cycle to ensure that the subjects were in a prime training period.

In day one, after a 1000 m low intensity warm-up, each subject executed three 30 s maximum front crawl tethered swimming tests: first without limb restrictions (Figure 1 a); second using arms-only (Figure 1 b); and third using legs-only (Figure 1 c). A 30 min interval of active recovery between trials was controlled. Subjects were wearing a belt attached to a steel cable (sufficiently inflexible that its elasticity could be neglected) with 3.5 m length and with a 5.7° angle to the water surface. A load-cell system connected to the cable was used as a measuring device, recording at 100 Hz with a measurement capacity of 500 kg_f. The load-cell was connected to a Globus Ergometer data acquisition system (Globus™, Italy) which exported the data in ASCII format to a PC. Before the starting signal, swimmers adopted a horizontal position with the cable fully extended; data collection was started only after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually observed immediately before or during the first arm action. In the second combination (arms-only), a research team member hold the legs of the swimmer evaluated, being instructed that legs should not be pulled. In the third condition (legs-only), a fluctuation device was used in one hand, while the other hand was kept alongside the body. For all experiments, the swimmers were told to follow the breathing pattern they would normally apply during a 50 m freestyle event. Tests termination was marked by means of an acoustic signal.

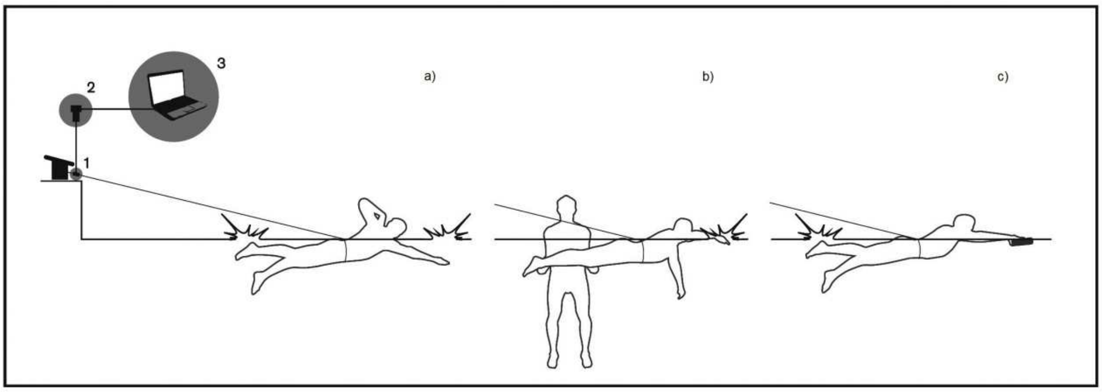

Figure 1. Apparatus of the swimmers situations during the tests in whole-body (a), arms-only (b) and legs-only (c) conditions: 1 – Load cell; 2 – Data Acquisition; 3 – Personal computer

On day two, subjects were tested using a 50 m indoor swimming pool (27 °C of water temperature). After a 1000 m low intensity warm-up, each subject made two maximal front crawl swims with an underwater start: the first over 100 m; and second over 50 m distance. A 30 min period of active recovery between trials was controlled.

Assessment of Variables

As the force vector in the tethered system presented a small angle to the horizontal, in computing the horizontal component of force, data were corrected to compensate. Individual force to time - F(t) - curves were assessed and registered to obtain the following variables: the maximum value of force in the first 10 s using whole-body

(Fmax_compl), using arms-only (Fmax_arms) and using legs-only (Fmax_legs); the average force values during the 30 s using whole-body (Fmean_compl), using arms-only (Fmean_arms) and using legs-only (Fmean_legs). The relative percentage contribution of arms was calculated as follows (Equation 1 and 2):

[1] *%Fmax_arms = Fmax_arms / Fmax_compl* for calculation maximum force and,

[2] *%Fmean_arms = Fmean_arms / Fmean_compl* for calculation of average force values.

Similar procedures were adopted for the legs-only combination.

Statistical Analyses

The assumed normality (Shapiro-Wilk normality test) was verified for all the variables before analysis. Standard statistical methods were used for the calculation of means and standard deviations (*sd*) for all dependent variables by gender. A two-tailed t-test for independent samples to establish differences between genders was applied. Pearson product-moment correlation coefficients (r) were calculated between the performance velocities and the different measured parameters. Additionally, linear regression analysis was used assessing regression coefficient (r^2). The level of statistical significance was set at $p < .05$.

Results

Table 2 presents the measured and estimated variables corresponding to tethered tests and free swimming velocities. Force production values of the relative percentage contribution of arms and legs showed no significant difference between genders, both for maximum and mean values. The variation coefficients ranged between [2.9-28.2%]. These measurements met the requirements to establish the data as reliable and valid in assessing swimming methodology.

Table 2. Mean ± *sd* values of the tethered swimming variables and swimming velocities obtained during data collection (overall and according to gender).

	Boys (n = 12)	Girls (n = 11)	Overall (n = 23)
Fmax_compl (N)	325.40 ± 27.79	222.30 ± 61.79**	276.09 ± 69.96
Fmax_arms (N)	243.70 ± 27.66	168.51 ± 36.24**	207.74 ± 49.54
%Fmax_arms (%)	75.08 ± 7.93	77.95 ± 14.75	76.45 ± 11.51
Fmax_legs (N)	100.10 ± 28.22	71.95 ± 9.41**	86.63 ± 25.40
%Fmax_legs (%)	30.81 ± 8.37	33.81 ± 6.83	32.25 ± 7.65
Fmean_compl (N)	98.84 ± 13.71	73.97 ± 12.37**	86.94 ± 18.02
Fmean_arms (N)	82.49 ± 12.03	56.86 ± 8.70**	70.23 ± 16.68
%Fmean_arms (%)	83.87 ± 9.62	77.68 ± 10.61	80.91 ± 10.36
Fmean_legs (N)	35.09 ± 7.62	28.43 ± 4.61*	31.91 ± 7.09
%Fmean_legs (%)	35.30 ± 4.39	38.73 ± 4.36	36.94 ± 4.62
v50 ($m.s^{-1}$)	1.71 ± 0.05	1.53 ± 0.11**	1.62 ± 0.12
v100 ($m.s^{-1}$)	1.58 ± 0.06	1.43 ± 0.11**	1.51 ± 0.11

Legend: Significantly different from male swimmers, * for $p < .05$; ** for $p < .01$.
Fmax = maximum force; Fmean = average force; v = average velocity

Figure 2 presents the comparison of tethered swimming variables in boys and girls groups. Both maximum and mean force production when deploying the full technique were significantly higher than that using only the arms or using only the legs ($p < 0.001$), separately for boy and girl groups as well as for the whole group of subjects. Additionally, significant relationships were observed between Fmean_compl and the corresponding individuals values of Fmean_arms and Fmean_legs in both boys ($r = 0.69$ and $r = 0.65$, $p < 0.05$, respectively) and girls ($r = 0.85$, $p < 0.01$ and $r = 0.74$, $p < 0.05$, respectively).

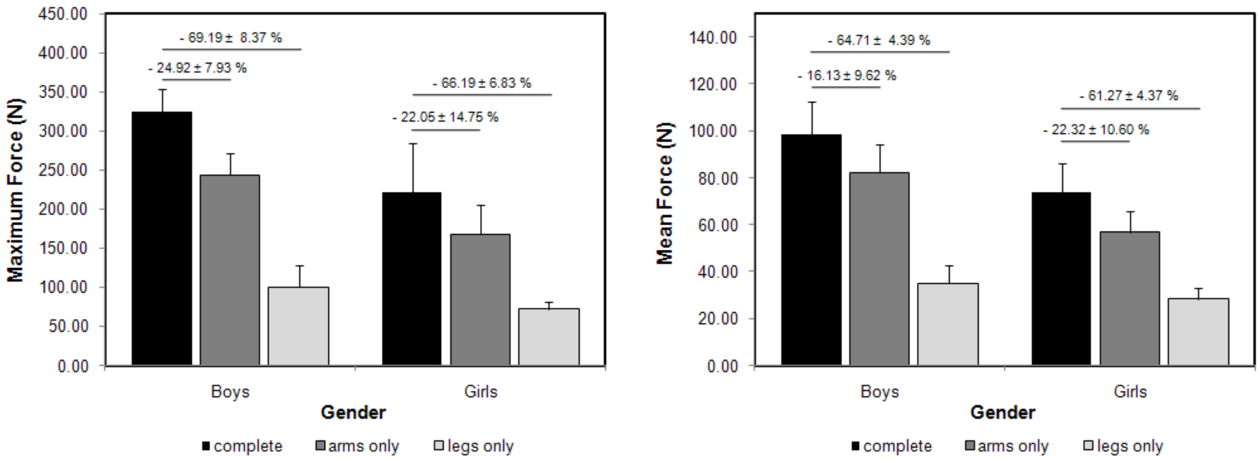

Figure 2. Comparison of the absolute and relative maximum and mean force values assessed, according to limbs restrictions, according to gender. Above bars is pointed the relative contribution of arms and legs, considering the values of whole-body as 100%.

Partial correlations between tethered test variables and swimming velocities, for subjects both overall and according to gender, are shown in table 3. For both genders, significantly higher correlations were observed between maximum and mean forces using whole-body and performance in the shorter swimming distance (ranging from 0.66 to 0.81) than with 100 m. For the whole-body combination, significant relationships were observed between swimming velocities and maximum application of force in boys. In contrast, significant relationships were observed between swimming velocities and mean application of force in girls. Using arms-only, significant relationships were observed between maximum force and swimming velocities in boys, and between mean forces and swimming velocities for boys and girls (cf. Figure 3). Forces assessed with legs-only did not present relationships with free swimming.

Table 3. Partial correlations between tethered force parameters and swimming velocities.

	Boys (n = 12)		Girls (n = 11)		Overall (n = 23)	
	v50	v100	v50	v100	v50	v100
Fmax_compl	0.72 (p = 0.009)	0.67 (p = 0.017)	0.66 (p = 0.028)	0.59 (p = 0.056)	0.85 (p = 0.000)	0.80 (p = 0.000)
Fmax_arms	0.77 (p = 0.004)	0.71 (p = 0.009)	0.49 (p = 0.129)	0.45 (p = 0.163)	0.81 (p = 0.000)	0.77 (p = 0.000)
Fmax_legs	0.29 (p = 0.356)	0.51 (p = 0.089)	0.09 (p = 0.793)	0.07 (p = 0.848)	0.50 (p = 0.015)	0.54 (p = 0.008)
Fmean_compl	0.68 (p = 0.016)	0.57 (p = 0.054)	0.81 (p = 0.002)	0.81 (p = 0.002)	0.86 (p = 0.000)	0.83 (p =0.000)
Fmean_arms	0.66 (p = 0.019)	0.74 (p = 0.006)	0.75 (p = 0.008)	0.73 (p = 0.010)	0.84 (p = 0.000)	0.84 (p = 0.000)
Fmean_legs	0.38 (p = 0.226)	0.36 (p = 0.249)	0.51 (p = 0.107)	0.57 (0.065)	0.58 (p = 0.004)	0.59 (p = 0.003)

Legend: Fmax = maximum force; Fmean = average force; v = average velocity

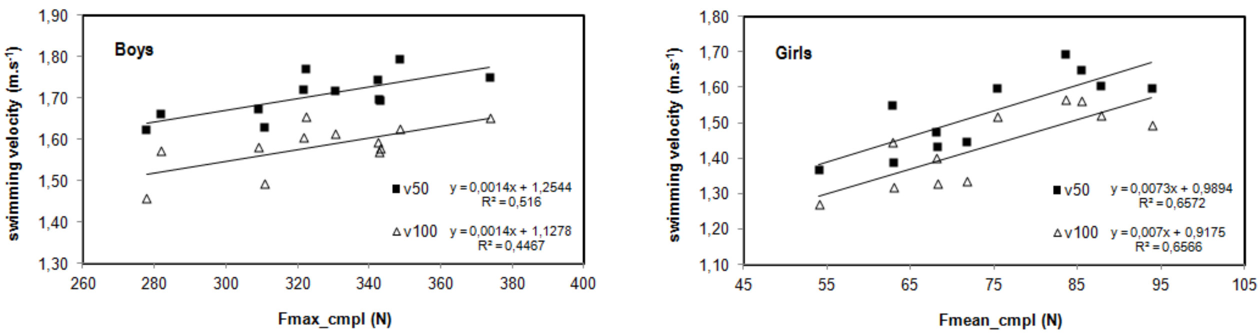

Figure 3. Relationship between tethered force parameters and swimming velocities, according to gender.

Discussion

The purpose of this study was to investigate the relative contribution of arms and legs to force production in front crawl tethered swimming according to gender and to analyse the relationships between forces exerted and free-swimming velocities. Main data of the present study showed 1) a relative independent contribution of arms (~78%) and legs (~35%) to front crawl tethered swimming and 2) a significant relationship between maximum and average force application and swimming performance. An interesting and practical approach of the present study concerned the fact that current data were obtained on well-trained swimmers already familiarised with TS methodology in normal swimming pool conditions (cf. Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006; Psycharakis et al., 2011), allowing real time access to data. The methodology used allowed the gathering of specific, easy to obtain and up to date information regarding the propulsive force that swimmers could exert in each testing combination.

The role played by the leg-kick accords with Swaine et al. (2010) and may reinforce the suggestion that a much greater proportion of the force exerted in water to increase swimming velocity may be attributable to the legs than previously thought. Swaine et al. (2010) reported that the respective contributions to total power output from both legs and both arms were 37.3 ± 4.1% and 62.7 ± 5.1%.

Absolute values of all variables were meaningfully higher for boys than for girls. These gender differentials can be related to the fact that the boys were taller and heavier than the girls, as is common in post-pubescent stages (Kraemer et al., 1989; Schneider & Meyer, 2005). The higher values in TS variables may imply that boys also had higher muscle strength levels than girls. This accords with previous findings that point to a strength differential after puberty (Schneider & Meyer, 2005; Bencke et al., 2002). Furthermore our results, suggesting that those subjects with higher strength levels are also those with higher swimming speed, are related partially to a greater capacity to apply propulsive force to water. This suggestion concurs with the fact that superior swimming velocities were obtained by boys (Morouço et al., 2011b). However, relative values of arms and legs force production did not present significant differences according to gender. This similarity of relative contribution reinforces the idea that TS may be the solution to the common difficulty met with in measuring the force exerted by arms and legs separately.

Previous studies pointed out that the arm stroke generated 90% of the total propulsive force in sprint freestyle (Schleihauf, 1979; Maglisho et al., 1986; Hollander et al., 1988). Accordingly, Deschodt et al. (1999) reported, regarding the 25-m front crawl, that when using the legs 10% higher velocity was achieved. In contrast, Swaine et al. (2010) reported a mean contribution of leg-kicking of 37.3%, which is more similar to our results obtained in water testing. Current higher percentages undoubtedly put in question the statements that swimming propulsion is almost entirely due to arms and trunk (Toussaint & Beek, 1992). For all swimmers tested, maximum and average forces were higher using, respectively, whole-body, followed by arms-only and legs-only combinations. These results were somewhat expected as propulsive capacity decreases in each situation. Moreover, relationships between the average force exerted with whole-body and with limb restrictions encourage the thought that both arms and legs contribute significantly to the results in tethered swimming tests.

To the best of our knowledge, there are no previous tethered force studies where arms-only and legs-only combinations were analysed, thus making it difficult to compare our results. Measuring power output in a new swimming training machine, Swaine et al. (2010) also reported that the sum of the separate values of arms and legs was higher than that produced by the whole-body. In the present study we believe that combining upper and lower limbs in a synchronised manner may generate a small amount of additional force exerted in water. In doing so, a powerful leg-kick may be almost as important as a powerful arm-stroke in swimming, even though the leg-kick contributes much less to propulsion. In addition, we hypothesised that the difference between average force in whole-body TS and the sum of average force with arms-only and legs-only combinations may indicate lack of coordination. This index (equation 3)

$$\text{Index of force coordination} = \frac{Fmean\_wholebody}{Fmean\_arms + Fmean\_legs} \tag{3}$$

follows the suggestions from Deschodt et al. (1999), to the effect that low values may represent situations where strength development of arms and legs might not lead to a gain in performance, as the necessary coordination would be deficient. Interestingly, Ogita et al. (1996) also reported that total energy production during swimming was lower than simply the sum of arm-only and leg kicking-only swimming. It seems that the potentials of both the anaerobic and aerobic energy releasing processes in the muscle groups involved in arm and leg action cannot be fully reached during free swimming (1996).

Relationships between front crawl tethered swimming and swimming performance have been previously studied (Yeater et al., 1981; Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999; Morouço et al., 2011a; Morouço et al., 2011b), mostly with heterogeneous samples indifferently analysing male and female swimmers. In the present study we analyzed the results by gender and as a group with all subjects. In doing so, we are able to state that coupling results of heterogeneous samples can discredit the results. As can be seen in table 3, correlations that were not significant for boys or girls, become significant when using the overall sample. Nevertheless, referred studies showed that the stroke force that a swimmer can generate is moderately to highly related with swimming velocity in sprint distance efforts. One of the purposes of the present study was to verify whether this association would hold also for gender. Indeed, proper scrutiny is to be recommended, since associations of maximum or mean forces differ. Table 3 confirms that maximum force is a better estimator for swimming performance in boys, while mean values are more appropriate for girls. Thus, as is shown in figure 3, it is possible to estimate swimming velocities, according to gender. Differences were also noticeable for arms-only and legs-only combinations. In fact, the musculature of the upper-body seems highly correlated with performance in boys. In girls, however, whole-body plays a major role in estimating swimming performance. As remarked earlier, differences in musculature and strength increase at these ages (Kraemer et al., 1999) and should be considered when prescribing strength training (Morouço et al., 2011b).

Practical applications

Swim coaches are aware that the evaluation of their swimmers should be specific to the nature of the sport. Therefore, it is essential that the chosen apparatus strongly replicate the movement patterns (if possible with the same musculature demands) employed in real training and competition situations. With that in mind we propose TS as a simple, trouble-free and valid methodology to evaluate force exerted in water. Using the whole-body combination, it is possible to evaluate training programs and to identify deficiencies in the exertion of force in water. Indeed, measuring separate arms-only and legs-only combinations allows the establishment of an index [Fmean_compl / (Fmean_arms + Fmean_legs)] that may help coaches identify where best to intervene in improving swimming technique coordination. Moreover, this study also showed that both arm and leg action is important to enhance swimming performance in short distance events and thus ought to be included in daily basis training routines.

Chapter 7.

Associations between dry-land strength and power measurements with swimming performance in elite athletes: a pilot study

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Abstract

The main aim of the present study was to analyze the relationships between dry-land strength and power measurements with swimming performance. Ten male national level swimmers (age: 14.9 ± 0.74 years, body mass: 60.0 ± 6.26 kg, height: 171.9 ± 6.26, 100 m long course front crawl performance: 59.9 ± 1.87 s) volunteered as subjects. Height and work were estimated for CMJ. Mean power in the propulsive phase was assessed for squat, bench press (concentric phase) and lat pull down back. Mean force production was evaluated through 30 s maximal effort tethered swimming in front crawl using whole-body, arms-only and legs-only. Swimming velocity was calculated from a maximal bout of 50 m front crawl. Height of CMJ did not correlate with any of the studied variables. There were positive and moderate-strong associations between the work during CMJ and mean propulsive power in squat with tethered forces during whole-body and legs-only swimming. Mean propulsive power of bench press and lat pull down presented positive and moderate-strong relationships with mean force production in whole-body and arms-only conditions. Swimming performance is related with mean power of lat pull down back. So, lat pull down back is the most related dry-land test with swimming performance; bench press with force production in water arms-only; and work during CMJ with tethered forces legs-only.

Key words: countermovement jump, squat, bench press, lat pull down back, tethered swimming.

Introduction

Strength parameters have been recently proposed as one of the multi-factorial phenomenon that enhances swimming performance (Tanaka et al., 1993; Barbosa et al., 2010). Nevertheless, the assessment of specific muscle power output of both arms and legs seems to be underlying in swimming (Swaine et al., 2010) as the locomotion in the aquatic environment is highly complex, being difficult to assess the magnitude of these forces (Morouço et al., 2011). It has been purposed that as the distance diminishes strength role increases, when comparing with technical parameters (Wilke & Madsen, 1990; Swaine, 2000; Stager & Coyle, 2005; Morouço et al., 2011). Unfortunately, results trying to support this idea remain inconclusive (Girold et al., 2007; Aspenes et al., 2009; Garrido et al., 2010), and more studies are necessary to clarify the specificity of the strength training methods in swimmers.

Tethered swimming was proposed as a methodology to evaluate the force a swimmer can exert in water (Magel, 1970). In fact, several approaches have shown its proximity with swimming performance in short distance events (Yeater et al., 1981; Costill et al., 1986; Christensen & Smith, 1987; Keskinen et al., 1989; Fomitchenko, 1999; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006; Morouço et al., 2011). These findings suggest that tethered swimming might be a useful, not expensive, not invasive, small time consuming methodology to evaluate one major factor (strength) influential of sprint swimming performance; even recognizing that the movements relative to the water are somehow different than in a free swimming situation (Adams et al., 1983; Maglisho et al., 1984).

There have been several studies successfully relating the anaerobic power in dry-land with swimming velocity in front crawl (Sharp et al., 1982; Hopper et al., 1983; Hawley et al., 1992; Johnson et al., 1993). Yet, the relationship between power output in dry-land exercises, apart from isokinetic methods, remains unanswered. Actually, strength and power assessment may be useful to understand the importance of power output for swimming performance, and moreover to improve training programs. This is well stated as the movement velocity with different loads is frequently disregarded in the practice of strength training (González-Badillo & Sánchez-Medina, 2010). Garrido et al. (2010) evaluated 28 young competitive swimmers aiming to identify which dry-land strength and power tests were better associated with sprint swimming performance. These authors presented moderate but significant relationships between strength/power variables with 25 and 50 m sprint tests ($0.542 < \rho < 0.744$; $p < 0.01$). These results are in accordance with previous published of Strzala and Tyka (2009) that evaluated average power produced by arms and legs in a dry-land ergometer. In fact, higher correlations were reported between power and shorter distance swam (25 m vs. 100 m). However, the specificity of leg movements in order to produce propulsion in water seems quite different from the movements used in cycle ergometer (Swaine et al., 2010). Therefore, this higher correlation in shorter distances may be explained by the push of the wall in the start and the turning benefit (Keskinen et al., 2007). Thus, complementary studies relating these parameters with force production in water by the lower limbs are required.

To the best of our knowledge, few studies examined the relationships between dry-land exercises parameters with tethered forces and swimming performance. Here, only Crowe et al. (1999) related different strength and power parameters with swimming performance and tethered forces. However, these authors studied a heterogeneous sample, with subjects of different swimming and strength abilities, analyzing men and women. Therefore, the main aim of the present study was to identify what type of dry-land exercises are better associated with tethered forces and short distance swimming performance. It was hypothesized that variables obtained through countermovement jump, squat, bench press, and lat pull down back, would significantly correlate with tethered swimming force production and short distance swimming performance.

Material and methods

Subjects

Ten male national level swimmers (age: 14.9 ± 0.74 years, body mass: 60.0 ± 6.26 kg, height: 171.9 ± 6.26, 100 m long course front crawl performance: 59.9 ± 1.87 s) participating on regular basis in regional and national level competitions volunteered as subjects. Parents and coaches gave their consent for the swimmers participation in this study. All procedures were in accordance to the Declaration of Helsinki in respect to Human research. The Ethics Committee of the hosting University approved the study design. Body mass was assessed through a bioelectric impedance analysis method (Tanita BC 420S MA, Japan). Performance index was assessed through personal best time in 100 m freestyle long course swimming competitions, within 2 months prior to data collection.

In water tests

All tests were performed in a 50 m indoor swimming pool (27.5°C of water temperature) during the competitive period of the spring training cycle. In day one, after a 1000 m low intensity warm-up, each subject performed three repetitions of 30 s maximum front crawl tethered swimming: first using whole-body; second with arms-only; and third with legs-only. A 30 min of active recovery between bouts was controlled. Subjects were wearing a belt attached to a steel cable (sufficiently stiff that its elasticity could be neglected). A detailed description of the measuring device used in this study has recently been reported elsewhere (Morouço et al., 2011). Preceding the data collection, subjects swam 5 s low intensity, using limbs according to repetition. In the second repetition, a fluctuation device placed between the thighs and another swimmer (instructed that legs shouldn't be pulled), were used to stand up the legs of the swimmer evaluated. For the legs-only test, a fluctuation device was used in one hand, while the other hand was kept alongside the body. The end of the test was set through an acoustic signal. In all repetitions, the swimmers were told to follow the breathing pattern they would normally apply during 50 m freestyle event. The subjects were verbally encouraged throughout the tests, enhancing them to maintain maximal effort over the duration of the experiment. In day two, after a 1000 m low intensity warm-up, each subject performed one 50 m maximal front crawl swim with an underwater start.

Dry-land tests

All tests were performed in a gym starting with 5 min of stationary cycling at a self-selected easy pace, 5 min of static stretches and joint mobilization exercises. In day three, using a dynamic measurement system (T-Force System, Ergotech, Murcia, Spain), each participant executed n repetitions (5 min rest) in concentric only bench press. Initial load was set at 10 kg and was gradually increased in 10 or 5 kg increments until mean propulsive velocity (MPV) got lower than 0.6 $m.s^{-1}$. Following a 30 min rest with active recovery, participants replicated the methodology for Squat, until a MVP lower than 0.9 $m.s^{-1}$ was obtained. A detailed description of the measuring device used in this study has recently been reported elsewhere (Sánchez-Medina & González-Badillo, 2011). A smith-machine was used to ensure a smooth vertical displacement of the bar along a fixed pathway. In day four, same equipment was used. Each subject executed n repetitions (5-min rest) in lat pull down back. Initial load was set at 10 kg and was gradually increased in 10, 5 or 2.5 kg increments until MPV got lower than 0.6 $m.s^{-1}$. After a 30 min rest with active recovery, participants carried out 3 maximal countermovement jumps (Ergojump, Globus, Italy), separated by 1-min rests.

Data analysis

Individual force to time - $F(t)$ - curves of tethered forces were assessed and registered. As the force vector in the tethered system presented a small angle to the horizontal, computing the horizontal component of force, data was corrected. Average force values during the 30 s test for whole-body (avgFWb); for arms-only (avgFAr); and legs-only (avgFLg) were then calculated. The swimming velocities were estimated according to formula $v50 = 50.\Delta t^{-1}$; where Δt is the chronometric time in the test. The height of the center of gravity in the countermovement jump (hCMJ) was obtained using the jump fly time. Subsequently, the work was estimated according to formula $W\text{CMJ} = mg\Delta h$; where m is the body mass (kg), g is the gravitational acceleration ($m.s^{-2}$) and Δh is the elevation of the center of gravity (m). From the dynamic measurement system, data was stored on disk for subsequent analysis. Mean power of the propulsive phase was assessed for each load (cf. figure 1) and maximum value obtained was registered for each test: squat (MPPsq); bench press (MPPbp) and lat pull down back (MPPlpd).

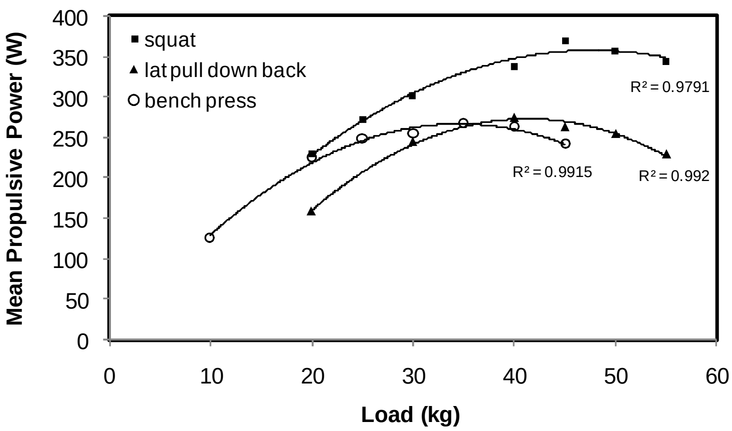

Figure 1. Example of load-power relationships for one representative subject, for each test.

Statistical analysis

Standard statistical methods were used for the calculation of means and standard deviations (*sd*) from all dependent variables. The Shapiro-Wilk test was applied to determine the nature of the data distribution. Since the reduce sample size ($n < 30$) and the rejection of the null hypothesis in the normality assessment, non-parametric procedures were adopted. Spearman correlation coefficients (ρ) were calculated between in water and dry-land parameters assessed. Significance was accepted at the $p < 0.05$ level.

Results

The mean ± *sd* value for the 50 m sprint test was 1.69 ± 0.04 $m.s^{-1}$. The mean ± *sd* values of mean force production in tethered swimming tests were 95.16 ± 11.66 N for whole-body; 80.33 ± 11.58 N for arms-only; and 33.63 ± 7.53 N for legs-only. The height assessed in the CMJ was 0.37 ± 0.05 m, being calculated the correspondent work of 219.30 ± 33.16 J. The maximum mean propulsive power in the squat, bench press and lat pull down back were 381.76 ± 49.70 W; 221.77 ± 58.57; and 271.30 ± 47.60 W, respectively. The table 1 presents the correlation coefficients (ρ) between swimming velocities and average force in tethered tests with dry-land variables assessed. It was found significant associations between in water and dry-land tests. Concerning the CMJ, work during the jump revealed to be more associated with in water variables, than the height. Both tests that involve the lower limbs musculature (CMJ and squat) presented significant relationship with force production in water with the whole-body and legs-only, but not with swimming velocity. In bench press and lat pull down back, significant correlations were observed with force production in water with the whole-body and arms-only, and with swimming velocity for the lat pull down back. Added to that, in the tethered swimming tests, arms-only presented a moderate correlation with swimming performance ($\rho = 0.68$, $p = 0.03$).

Table 1. Correlation coefficients (ρ) between in water and dry-land tests variables.

	*h*CMJ	*W*CMJ	MPPsq	MPPbp	MPPlpd
avgFWb	0.10 ($p = 0.79$)	0.75 ($p = 0.01$)	0.73 ($p = 0.02$)	0.65 ($p = 0.04$)	0.65 ($p = 0.04$)
avgFAr	-0.10 ($p = 0.79$)	0.27 ($p = 0.45$)	0.60 ($p = 0.07$)	0.73 ($p = 0.02$)	0.69 ($p = 0.03$)
avgFLg	0.17 ($p = 0.64$)	0.76 ($p = 0.01$)	0.64 ($p = 0.04$)	0.40 ($p = 0.26$)	0.27 ($p = 0.45$)
v50	0.04 ($p = 0.92$)	0.33 ($p = 0.35$)	0.36 ($p = 0.31$)	0.60 ($p = 0.07$)	0.68 ($p = 0.03$)

avgFWb – 30 s average force with whole-body, avgFAr – 30 s average force with armos-only, avgFLg – average force with legs-only, v50 – swimming velocity in 50 m front crawl, *h*CMJ – height of countermovement jump, *W*CMJ – work in counter movement jump, MPPsq – mean power of propulsive phase in squat, MPPbp – mean power of propulsive phase in bench press, MPPlpd – mean power of propulsive phase in lat pull down.

Discussion

The aim of this study was to analyze the associations between dry-land and in water tests. The mean power of the propulsive phase in the lat pull down back was the only parameter that correlated significantly with swimming performance. Additionally, there were significant associations between dry-land tests and force exerted in water through tethered swimming.

Concerning in water tests, velocity and mean force in tethered swimming seem to present descriptive data similar to other papers in the literature for the same age and gender (Rohrs & Stager, 1991; Taylor et al., 2003b). As the average force production exerted by the swimmers was assessed in water, values were not related to body mass, as the body weight of the body is reduced to a few kilograms when submersed in water (Taylor et al., 2003a). The relative contribution of arms and legs to tethered forces in front crawl swimming remains uncertain. In fact, Yeater et al. (1981) stated that mean forces with arms-only and legs-only are significantly lower than the whole stroke force in the whole-body swimming. In the present study those differences are also noticeable (p = 0.001 and p = 0.000, respectively), nevertheless with the arms-only presenting a higher value than legs-only, contradicting the study previous referred. Even so, special attention should be given to the role of the leg kicking (35.34% of the whole-body mean value). This data may suggest that a greater proportion of whole-body force exerted in water might be done by legs, corroborating the recent findings of Swaine et al. (2010). It is also noticeable that the sum of arms and leg tethered forces (avgFAr + avgFLg) is higher than the whole-body forces (avgFWb), but not about the double as referred by Yeater et al. (1981). The reason for this higher sum remains uncertain and more studies are required.

In short activity patterns (e.g. jumping) muscle strength plays a major role, particularly considering its ability to develop it fast (Bencke et al., 2002). In fact, it is assumed that there is a good correlation between lower limb maximum strength and maximum jump height. However, taking into consideration that maximum force does not represent maximum velocity, power developed should be taken into consideration (González-Badillo & Marques, 2009). The CMJ height and work values are somehow similar to referred in literature, according to age and gender. However, there are no values of mean power in the propulsive phase of dry-land tests, with which to compare our results. There were obtained higher values in squat, followed by lat pull down and bench press.

Studies have stated the relationship between explosive strength of leg extensor muscles and swimming performance (Keskinen et al., 2007; Strzala et al., 2007; Strzala & Tyka, 2009). Yet, these relationships are pointed to be enhanced by the turning benefit (Keskinen et al., 2007). In the present study, the importance of lower limbs strength was consciously reduced with the underwater start of the 50 m free swimming test, and with a long course pool used. Thus, both *h*CMJ and *W*CMJ did not correlate with swimming performance. Still, *W*CMJ and MPPsq presented a high correlation with force production in tethered swimming with the legs-only, and whole-body. These associations were expected as the musculature involved in both tests relies mainly in the lower limbs and core.

Johnson et al. (1993) have reported that swimming power ($0.84 < r < 0.88$), but not dry-land measures of strength ($r = 0.55$) and power ($r = 0.74$), enhance success in freestyle swimming. However, these authors evaluated one maximum repetition (1RM) bench press which is more related to maximum force than with explosive force (González-Badillo & Sánchez-Medina, 2010). Also, in that study the swimmer range of age was 14 - 22 years. This seems to be a heterogeneous sample, especially when in this spectrum of ages significant changes in somatotype occur. On the contrary, Garrido et al. (2010) evaluating young competitive swimmers presented a moderate but significant correlation between 1RM bench press and swimming performance (both 25 and 50 m tests; $\rho \sim -0.58$; $p < 0.01$). This incongruous investigations point out that the role of strength and power to force production in water and, consequently to swimming performance, remain uncertain. Simultaneous dry-land power, swimming power and swim performance have been previously studied. Crowe et al. (1999), evaluated 1RM in bench press, lat pull down and triceps press. Front crawl tethered swimming 30 s maximal effort was measured and swimming performance was based in 50 m and 100 m distances. In both men and women 1RM in the three strength measures were significantly related with tethered forces. Corroborating this data, in the present study mean propulsive power appears to play an important contribution in the tethered swimming performance ($0.65 < \rho < 0.75$). Both bench press and lat pull down back involve mostly the musculature of the upper body. Therefore, it was expected that power evaluated through these tests would relate with the force produced by arms-only in tethered swimming. Indeed, the approach of the present study seems to be more specific as most of the investigations used isokinetic and isometric tests as strength indexes (Marques et al., 2008). Thus, mean propulsive power of the current subjects in bench press and lat pull down back presents a high correlation with tethered forces with arms-only ($0.69 < \rho < 0.73$; $p < 0.05$), and with whole-body.

Regarding the swimming performance, only MPPlpd and avgFAr presented significant correlations with velocity. These records seem to be in accordance with Crowe et al. (1999) and Yeater et al. (1981), respectively. Indeed, Crowe et al. (1999) only reported statistical relationship between swimming performance with 1RM lat pull down, and merely in women ($r = 0.64$, $p < 0.05$).

To the best of our knowledge, this study was the first to assess the mean power of the propulsive phase in three dry-land tests, and to associate this parameter with force production in water and swimming performance. As a conclusion, the present study revealed moderate to high associations between dry-land and in water variables. Work during CMJ is a better estimator of force production in water, than height. Squat mean power is related with legs force production in water, and bench press and lat pull down back with arms-only tethered forces. Lat pull down back is the most associated dry-land test with swimming performance, for the present study.

Chapter 8.

Squat, lat pull down and bench press: which is the most related to female swimmers performance?

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Abstract

Dry-land strength training is a usual procedure is swimming training. However, the association between the performed exercises and swimming performance remains unclear. The aim of the present study was to analyze relationships between strength parameters in three gym exercises (bench press, lat pull down and squat) with a 50 m maximum intensity front crawl swimming. Nine female swimmers, with ages between 14 and 18 years of age, were evaluated. Each subject performed a maximum 50 m test in front crawl and executed n repetitions of the dry-land exercises to estimate the maximum power. It was assessed through a linear transducer (*T-Force*). Maximum power and mean propulsive power were taken to analysis. The exercise that presented higher association with swimming performance was the squat, followed by the lat pull down and the bench press.

Key words: strength training, power, front crawl, female swimmers.

Introduction

Improving athletic performance can only be done with rigorous and highly specific training methods. Relatively, the movements trained both in-water or on land should be as similar to those used in competition as possible. This is called the principle of specificity of training. Sports science has placed a paramount amount of its efforts regarding to this concern, primary seeking to find the relationship between training exercises and athletic performance (Toussaint, 2006).

Strength training has been shown to be a valid complement to the multi-factorial phenomenon that is the improvement of athletic performance in a variety of sports, including swimming (Tanaka et al., 1993; Barbosa et al., 2010). The positive effects of strength training in what concerns to swimming still remains inconclusive, considering that different methodical approaches with different samples have presented inconsistent results.

While there is some documented relation between performance in front crawl and efforts in dry-land strength training (Hawley et al., 1992; Johnson et al., 1993), the relationship between strength dry-land exercises and performance remains unclear. Thus, identifying the transfer from training conducted in a gym by swimmers, to their respective athletic performance seems to us of crucial importance, just like its implementation in the various age groups (Faigenbaum, 2000). In fact, even in adolescents, i.e., before reaching elite training levels, it seems relevant to give a strong framework for the physical demands of the given modality, in order to allow a better athletic condition and progress in the long term. Besides, to the best of our knowledge studies carried-out with younger populations are scarce.

Johnson et al. (1993) showed that only tests executed in water are related to front crawl swimming. These authors used as indicators/measurements (e.g. bench press) 1 RM (one-repetition maximum), which is considered to be more related to maximum strength than potency or explosive strength. It has also been revealed that there is scarce literature focusing on the importance of maximum or/and explosive strength on swimming performance.

Taking into consideration the importance given to strength training, we considered insufficient the literature that supports this theme, and which permits coaches to plan their work. The heterogeneity of samples, followed by the differences in methodology does not allow for a comparison between results and does not make the guidelines for training process very clear. Thus, the present study aims to verify the existence of possible relationships between force production parameters in 3 dry-land strength exercises: bench press, squat and lat pull down back; with the performance in 50 m front crawl swimming.

Materials and methods

Subjects

The experiments were performed by 9 female swimmers that volunteered for the present study. Parental authorization was given for all the swimmers, and the procedures were in accordance with the declaration of Helsinki in what relates to human experimentation. The Ethics Committee of the hosting University approved the study design. The mean values (± *sd*), for the main physical characteristic features of the subjects are presented in Table 1. The body mass and body fat percentage were estimated using a method of bioelectrical impedance analysis (Tanita BC 420S MA, Japan). The participants had a mean value of 6.1 ± 1.7 years of experience, training between 5 to 8 times per week.

Table 1. Mean ± *sd* of main physical characteristics of the subjects.

	Swimmers (*n* = 9)
Age (years)	15.7 ± 1.50
Body mass (kg)	55.4 ± 6.09
Height (cm)	161.6 ± 7.15
Fat mass (%)	23.5 ± 3.93

Experimental procedure

The tests in water were implemented in a 50 m indoor pool, with a water temperature of 27.5°C. The data was collected a week after the most significant competition of the spring training macrocycle of competitive season (National Championships). After an 800 m low intensity warm up, swimmers performed a maximum intensity 50 m front crawl swimming, with an in-water start.

The dry-land strength tests were all carried-out after 5 min of exercise on the stationary bicycle with low intensity and 5 min of stretching. On the first day, using a dynamic measuring system (T-force system, Ergotech, Murcia, Spain), each subject executed n repetitions (with an interval of 5 min between reps) of the bench press concentric phase. The initial resistance was 10kg, which was gradually increased in increments of 10, or 5 kg until the mean propulsive velocity (MPV) was bellow 0.6 $m.s^{-1}$. After a 30 min rest period with active recovery, the swimmers replicated the methodology for the squat, until the MPV dropped below 0.9 $m.s^{-1}$. A Smith machine was used to ensure that the bar retains its horizontality for the duration of all the movements executed. On day 2, a similar methodology was used for the lat pull down back exercise, until MPV dropped below 0.6 $m.s^{-1}$. A detailed description of the apparatus used for the measurements is described elsewhere (Sánchez-Medina & González-Badillo, 2011). The technique of execution was evaluated for all the repetitions by one of the researchers, in order to guarantee that only data from the correct executions was treated.

From the measuring system, data was saved to a computer for subsequent analysis. For each exercise, for each load and for each swimmer, the values of maximum power (MP) and mean power of the propulsive phase (MPP) were assessed. From the data collected the absolute value was selected, independently of the load.

Data analysis

The assumption of the normality of the data was verified with the Shapiro-Wilk test, preceding the descriptive analysis. The mean ± *sd* values were calculated through the standard set methods. The Pearson coefficient of correlation (r) was also obtained to verify relationships between variables. Additionally, linear regression analysis allowed estimating the coefficient of determination (r^2). The level of statistical significance was set to $p < 0.05$.

Results

Table 2 shows the mean values ± *sd* of MP and MPP for each dry-land strength exercise. It also includes the times obtained for completion of 50 m at maximum velocity in the front crawl technique (t50).

Table 2. Mean ± *sd* of assessed variables.

		Swimmers (*n* = 9)
Bench press	MPP (W)	127.2 ± 29.65
	MP (W)	233.5 ± 59.94
Lat pull down	MPP (W)	209.3 ± 35.91
	MP (W)	346.4 ± 66.60
Squat	MPP (W)	260.1 ± 81.77
	MP (W)	632.9 ± 213.64
t50 (s)		33.1 ± 2.50

MP – maximum power; MPP – mean power of the propulsive phase; t50 – performance in front crawl swimming.

Table 3 shows the correlation coefficients (r) between performance in free swimming tests and the power values obtained in the dry-land tests. Significant relationships between variables were obtained, with the most representative presented in Figure 1.

Table 3. Correlation coefficients between swimming performance and dry-land strength exercises.

		t(50)
Bench press	MPP (W)	- 0.64
	MP (W)	- 0.74*
Lat pull down	MPP (W)	- 0.69*
	MP (W)	- 0.71*
Squat	MPP (W)	- 0.85**
	MP (W)	- 0.94**

MP – maximum power; MPP – mean power of the propulsive phase; t50 – performance in front crawl swimming; * - $p < 0.05$; ** - $p < 0.01$.

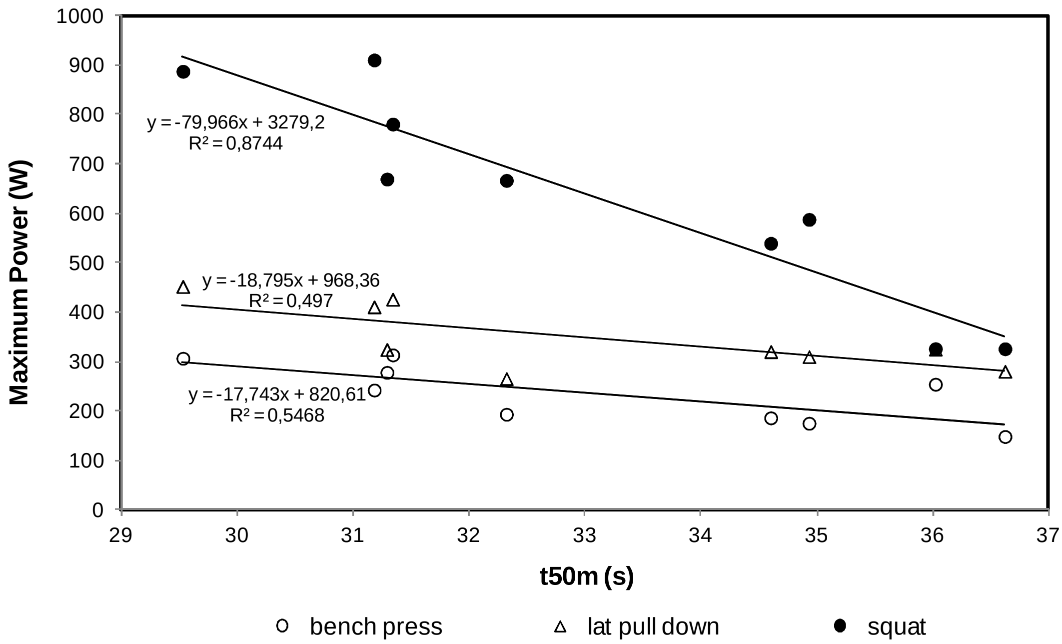

Figure 1. Graphical data of the relationship between maximum power (for each exercise) and swimming performance in front crawl. Linear regression equations with significant statistical value are also presented.

Discussion

With the present study it was intended to analyze possible relations between the power developed in dry-land exercises (bench press, lat pull down back and squat) and the performance in freestyle swimming (maximum in 50m front crawl). The maximum power in the phases of concentric movements analyzed was the parameter that showed higher correlation coefficients; squat showed higher values followed by the lat pull down.

The studies by Jonhson et al. (1993) reported that the values of force measured in dry-land do not influence the performance in swimming in front crawl ($r = 0.55$). Nevertheless, these authors used the 1 RM test for bench press exercise, which seems to have a greater relationship with maximum force than with explosive force (González-Badillo & Sánchez-Medina, 2010). Not to mention that the sample used in this study was very heterogeneous with a large age spectrum. Contradicting this data, Crowe et al. (1999) identified links between swim performance and the lat pull down exercise, for the female subjects tested. Recently, studies carried out by Garrido et al.(2010) with young swimmers showed significant relationships between 1 RM in bench press and short distances swimming (25 and 50 m). The inconsistencies presented in the literature show that the role of force and/or power developed in the gym on the exertion of force in water and consequently in swimming performance is not yet clear. The advances in this area will be able to clarify the importance of muscle power in swimming performance.

The bench press and pull down lat exercises essentially involve the muscles of the upper limbs of the human body. As such, it was expected that the power developed in these tests would present significant correlations with the performance of swimming in front crawl, considering the upper limbs being responsible for the swimmers propulsion in this swimming technique; those correlations were verified for the lat pull down, and bench press test (only concerning maximal power). The data seems to show that the methodology used is more specific for the estimation of parameters of force production, than using isokinetic or isometric approaches (Marques et al., 2008).

Conclusions

To the best of our knowledge, this was the first study that addressed efforts to examine the power values of three gym exercises, commonly used in sports conditioning for swimmers and their relationship with performance in free swimming. Significant relationships were found between the analyzed parameters and performance, in particular with the squat and lat pull down exercises. The advancement of studies under this scope seems to be of high interest, taking into account that the shorter the swim distance, the greater the role-played by muscular strength (Stager & Coyle, 2005; Morouço et al., 2011). In future we believe that the identification of individual power - load curves may be used as planning instruments for devising the appropriate load for the development of resistance strength, power strength and maximum strength.

Chapter 9. General Discussion

The main purpose of this investigation was to analyze relationships between tethered forces and dry-land strength exercises with swimming performance, for both males and female swimmers. Additionally, it was intended to verify if tethered swimming could be an easy, operative and accurate methodology for the biophysical evaluation of swimmers. For the accomplishment of these purposes the following sequence was used: (i) reviewing available literature; (ii) comparing of tethered swimming with free swimming; (iii) analyzing variables and relationships obtained in tethered swimming and dry-land strength tests; (iv) assessing front crawl arm asymmetries through tethered swimming; (v) and indentifying the relative contribution of arms and legs for whole-body tethered forces. Results suggest that: tethered swimming is an underused methodology that can provide significant insights for the enhancement of swimming performance; and swimming performance is significantly related with dry-land strength exercises, when power is considered.

Strength, power and force are common terms in scientific swimming research. According to the aim of each investigation, all these characteristics have shown to be swimming performance determinants, which can be trained in water or on dry-land. Further, more important than the improvement of these characteristics is the ability to produce forces in water, as that is the ultimate goal to increase swimming velocity. So, it was expected that the assessment of propulsive forces in water should be one of the scopes of scientific swimming research. However, the measurement of these forces in free swimming is somewhat questionable, inducing that efforts should be made in order to improve the existing methodologies and consequently to increase the accuracy of the measurements. On this, tethered swimming is one of the methodologies that allow a reliable measurement of forces exerted in water by swimmers, and has been used to ensure freedom of movement, considering the importance of replicating the form applied in free swimming for such a task. For example, another methodology used to evaluate these forces is the (bio)kinetic swim bench. However, this method neglects the role of the lower limbs and body roll for overall propulsion, which are factors that should be taken into consideration when evaluation swimmers, namely in front crawl swimming (**Chapter 6**). Moreover, arm strokes are composed by lateral and diagonal movements, being assumed that only measurements performed in water are valid to appraise specific evaluations.

It has been observed that tethered swimming may induce some kinematical alterations to arm movements when compared to free swimming (Maglischo et al., 1984), but it is not known if the force outputs are modified in the former situation (Toubekis et al., 2010). What is known is that both situations present high similarity in terms of muscular activity (Bollens et al., 1988), maximal oxygen uptake (Bonen et al., 1980), stroke rate, blood lactate concentrations, heart rate and perceived exertion (**Chapter 4**). Therefore, tethered swimming may be a proper tool for the biophysical evaluation of swimmers, besides being a simple and low cost approach that allows the coaches to evaluate a large number of swimmers in a short span of time. In fact, Maglisho et al. (1984) observations suggest that using tethered swimming as a training exercise with high volumes may lead to technique deterioration.

Several studies showed that tethered forces may estimate swimming velocities in free swimming. This association relies on the influence of propulsive forces to swimmers acceleration and, consequently, velocity. However, most existent studies use the maximum force to estimate swimming velocity (e.g. Keskinen et al., 1989; Sidney et al., 1996). The relationships found can be justified by the use of short tethered swimming efforts and swimming velocities assessed in short swimming distances; being the transfer of this knowledge insufficient for training purpose. Nevertheless, these approaches gave new ideas about the role of force for swimming velocity; namely, the experiments of Keskinen et al. (1989). These authors have found a non-linear relationship between maximum force and maximum swimming velocity (cf. Figure 1 (A)), which has been supported by the present work (**Chapter 4**, and Figure 1 (B)). This non-linear nature confirms that at high velocities it is difficult to apply high levels of force. Further studies should examine the association between this non-linear relationship between maximum tethered forces and maximum swimming velocities and the force-velocity relationship of the skeletal muscle (Zatsiorsky, 1995).

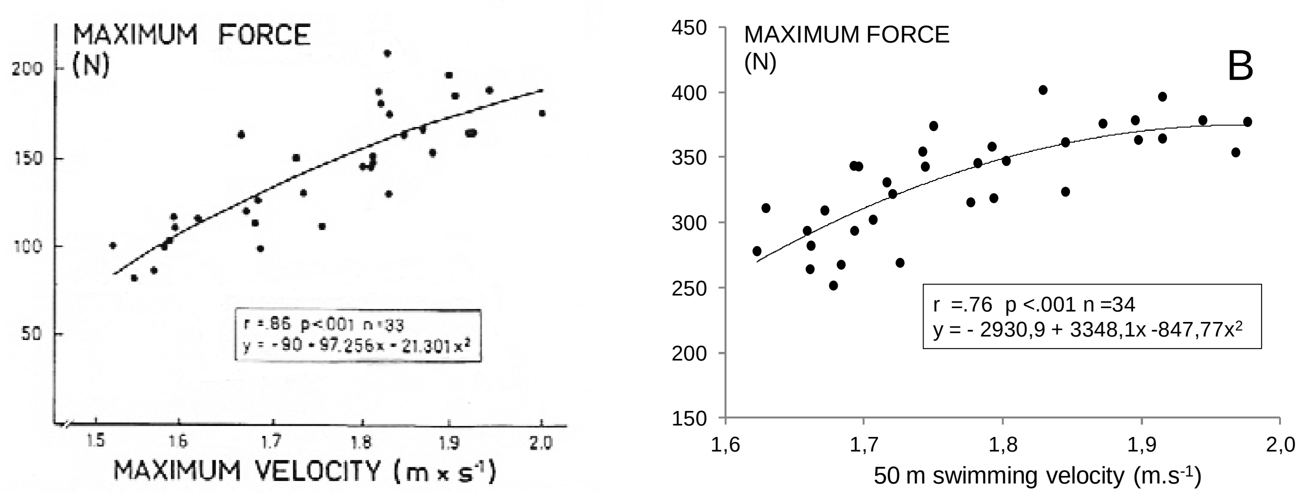

Figure 1. The relationships between maximum force and maximum velocity (panel A – adopted with permission from author, Keskinen et al., 1989), and 50 m average velocity (panel B – Chapter 4).

The assessment of maximum force does not take into consideration that the duration of the exertion is as important as the magnitude of exerted force. Thus, the impulse may be a more accurate variable to analyze stroking force. The use of the average force overcomes some of the referred limitations, yet it is considerably affected by attained standard deviation. Besides, linear relationships with swimming velocities during 50 m front crawl free swimming were observed using the impulse (Dopsaj et al., 2000; **Chapter 4**). These results were to some extent expected, seeing as calculus of the impulse takes into consideration the exerted force during all the sub-aquatic phase of the stroke. This relationship is even more noticeable with shorter swimming distances (i.e. higher swimming velocities), which suggests the importance of having an appropriate balance between force and the ability to effectively apply that force to overcome drag.

In front crawl swimming it is assumed that upper limbs are responsible for 85 to 90% of the overall propulsion of a swimmer. Yet, our results do not corroborate this assumption that assumed that the contribution of legs would be the whole-body propulsion minus the arms-only propulsion (i.e. 10 to 15%). In addition, all swimmers in tethered swimming tests presented a sum of legs-only with arms-only higher than the values attained in whole-body conditions (**Chapter 6**), as observed by Yeater et al. (1981); a similar pattern was reported in energetic cost (Ogita et al., 1996). Whereas the relative contribution of arms for overall propulsion is ~90% or less, the ability to apply similar propulsive forces between right and left arm may enhance swimming front crawl performance. Besides, being an alternated swimming technique, balance between bilateral forces is not ensured. Tethered may be used to evaluate (a)symmetries within arms (Toubekis et al., 2010), and they are common even in elite level swimmers (Formosa et al., 2011). To the best of our knowledge, there were no studies that claimed that asymmetries tend to decrease in a maximal effort due to the incapacity of maintaining such high levels of force with the "stronger" arm (**Chapter 5**), probably due to fatigue.

Resuming the issue of arms and legs contribution for the overall propulsion of swimmers, few studies have assessed direct measurements over its contribution. Swaine et al. (2010) using a novel machine (in dry-land) observed a leg-kicking relative contribution of 37% to total power output; results were corroborated in water testing (**Chapter 6**). The measurement of tethered forces in separate conditions (whole-body, arms-only and legs-only) may diagnosis a weak arms action or leg-kicking, and lack of coordination according to equation 3 (**Chapter 6**), being low values representative of situations where an increase of arm and leg strength may not lead to a performance enhancement. But if this coordination is not lacking, then the increase of strength may improve swimming performance. For that purpose dry-land strength exercises are commonly used, but which exercises should be executed remains an unanswered question. Therefore, examining the relationships between dry-land strength exercises and swimming performance may provide indications of which exercises are more appropriate for swimmers training (**Chapters 7 and 8**). Nevertheless, some authors have stated that only the gain of force with in-water training is valuable for the enhancement of swimming performance; because the gain of force leads to hypertrophy that may alter body composition, affecting the hydrodynamic characteristics of the practitioner. However, hypertrophy is more related with maximum force training than with power.

As previously referred, dry-land strength training is a common component of swimming training, even if the scientific evidences about the benefits of this type of training are scarce. Bench press, squat or lat pull down are some of the exercises commonly performed by swimmers, but no studies have evaluated the transfer of their gains to swimming velocity (**Chapter 3**). Furthermore, most studies performed evaluated maximum repetitions, which are not the most appropriate methodology. It is understood that the execution of repetition(s) with high loads implies a low movement velocity; thus, not maximal power. By keeping a balance between load and velocity it is possible to attain higher power output values, which might be more associated with swimming performance, namely with arms stroking. Because of this, coaches should be aware that the velocity of a lift or exercise is as important as the load to be lifted.

Differences among genders are expected, as boys tend to reach higher values of strength, force and power. This was also verified for tethered swimming and dry-land exercises, being the boys more dependent of upper limbs strength than their counterparts, although force production values of the relative percentage contribution of arms and legs showed no significant difference between genders, both for maximum and mean values for tethered swimming (**Chapter 6**). Moreover, significant differences were found between absolute values of force parameters when comparing boys and girls, although these differences did not occur when considering force parameters relative to body mass during tethered swimming. However, when considering performance analysis, some interesting differences were observed both for tethered swimming and for dry-land tests: (i) for boys, maximum force presented higher correlations with swimming velocities, while for girls mean values produced higher correlations (**Chapter 6**), and (ii) lat pull down and squat are the most related dry-land exercises with swimming performance, for boys and girls, respectively (**Chapters 7 and 8**).

Some main limitation of this thesis can be addressed. This study only analysed front crawl swimming. Hence, it raises the question whereas this data would be applied in other swimming strokes, especially when considering the simultaneous strokes. For tethered swimming only 30 s time test was applied. It would be interesting to analyse different parameters of tethered swimming tests on different protocols of different time duration, and to relate this data to other swimming events. Although this thesis aimed to study swimmers of both genders, some tests were only carried-out in male swimmers (for instance, asymmetries between arms during tethered swimming).

Chapter 10. Conclusions

The main findings of this work emphasise the importance of strength for short distances front crawl performance, and the advantages of using tethered swimming as a biophysical methodology for swimmers evaluation:

i. tethered swimming enables the evaluation of balance between force and the ability to effectively apply force during swimming;
ii. impulse is a more accurate parameter to characterize stroking force;
iii. tethered swimming replicates free swimming of equal duration, in terms of kinematical and physiological parameters;
iv. swimmers present stroke asymmetries in a maximal tethered effort, that tend to diminish along the effort;
v. for both genders in maximal efforts, both arms and legs significantly contribute to performance;
vi. dry-land exercises are moderately related to swimming performance in short distances;
vii. mean power in dry-land exercises is highly related with forces exerted in-water with the same musculature;
viii. for boys lat pull down, and for girls squat, seems to be the most adequate dry-land exercises to enhance swimming performance.

Chapter 11. Suggestions for future research

Research purpose is to increase knowledge. However, it seems evident that there is a lack of scientific knowledge transfer to the ones who could more benefit with it: the swimmers. A practical approach of evaluations may provide new insights that can be applied in the training process. So, it seems important to continue with investigations in this field of work, in order to clarify some unanswered questions:

i. would tethered swimming replicate kinematical and physiological parameters of free swimming in other durations and distances?

ii. which is the magnitude of stroke kinematical differences between tethered swimming and free swimming, according to gender and level?

iii. do female swimmers present asymmetries in tethered forces?

iv. which is the relative contribution of arms and legs to whole-body tethered forces in other swimming techniques?

v. would a dry-land strength training program focused in maximum mean power enhance swimming performance?

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Appendix I.

Force production in tethered swimming: differences between hands in front crawl

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Abstract

In front crawl and backstroke swimming, propulsive actions are alternated between hands. Thus, it is useful to evaluate the differences of efficiency between upper limbs; however, studies conducted in this domain are scarce. Tethered swimming is a reliable methodology to evaluate the propelling force exerted by a swimmer in his/her real environment. Using a load cell system it is possible to assess individual F(t) curves improving the possibility of analysis and comparison of stroke patterns, and allowing to more accurately know the sequence of propulsive forces during swimming. PURPOSE: To compare the force produced by each upper limb of the swimmer and to correlate this force with swimming velocity (SV). METHODS: During the competitive period of spring macrocycle, after a 1000 m low intensity warm-up, 14 young male swimmers (14.20±1.09 yrs; 59.85±8.77 kg; 168±0.22 cm) performed one 30 s all-out tethered front crawl swimming test. A load-cell system (100Hz, máx. 500kg_f) was used to assess F(t) curves in ASCII code. Force production was calculated for preferred (P) and non-preferred (NP) hand for maximum, mean and minimum force values; in each stroke. Additionally, all subjects performed a 50 m front crawl maximum test to obtain SV. Student t-test for independent samples and Pearson's correlation coefficient were used. RESULTS: Differences were obtained between P and NP for maximum values in all swimmers (236.90±20.41 N vs. 170.92±17.95 N, $p<0.001$), for mean values in 11 swimmers (134.45±17.12 N vs. 126.27±19.34 N, $p<0.01$) and for minimum values in 12 swimmers (55.85±28.32 N vs. 49.17±23.77 N, $p<0.05$). P maximum force correlated significantly with SV ($r=0.92$, $p<0.001$) but not with NP ($r=0.48$, $p>0.05$). Additionally, it was verified that NP values present a less decrease in force production compared to P (11.36±3.66% vs. 27.44±6.36%, $p<0.01$). CONCLUSION: Differences in force production between hands may be a helpful tool for coach evaluation of swimmers propulsive force effectiveness.

Appendix II.

Tethered swimming as a useful tool to measure unbalance between arms and force production decrease

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Abstract

Our aim of present study was to investigate the differences in force production between arms during front crawl tethered swimming (TS). Firstly, 14 young male swimmers (14.2 ± 1.09 yrs; 168.3 ± 2.22 cm; 59.9 ± 4.77 kg) undertook a 30 s maximum front crawl TS test. It was observed that preferred arm (P_Fmax) produces a maximum force higher than non-preferred arm (NP_Fmax). Additionally, was verified that the decrease in maximum force was higher for P_Fmax than NP_Fmax. In the second part of the study, 6 elite male swimmers (19.8 ± 2.23 yrs; 183.6 ± 3.64 cm; 77.3 ± 3.64 kg) replicated the methodology, being the individual curves assessed trough polynomial curves, which allowed identifying the unbalance between arms. This methodology may detect a limiting factor of performance being a useful tool for coaches training prescription.

Key words: biomechanics, strength, training, front crawl.

Introduction

One of the main goals of swimming biomechanics is to determine the swimmer's propulsive force, identifying its relationship with swimming efficiency, in order to enhance performance (Akis & Orcan, 2004; Barbosa et al., 2010). However, to obtain the magnitude of these forces in the aquatic environment is highly complex. Tethered swimming (TS) is one of the reliable methodologies used to achieve part of this goal, particularly by measuring the propelling force exerted by a swimmer in water (Costill et al., 1986; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006; Filho & Denadai, 2008). In fact, by using a load cell system it is possible to assess individual force to time curves, improving the possibility of characterization and comparison of stroke patterns, and allowing a more accurate knowledge of the propulsive forces sequence during swimming (Morouço et al., 2010).

In addition, TS may help coaches, in real time, with technique prescription, and can provide answers to some practical issues that remain controversial. The unbalance between arms in terms of force production is one of these cases. Research on this topic is scarce, and some ideas are passed among members of the swimming community with little scientific (experimental or numerical data) support. Swimming performance is highly related to the propulsive forces (Rouard et al., 1996) and, in front crawl and backstroke, arm actions are alternated. Thus, it is useful to evaluate the differences of force production between arms. However, studies conducted in this domain are scarce.

Complementarily, Reischle (1998) indicated that specificity should be aimed in the training process. As a result, coaches may orientate their work with adequate strategies to a correct planning, control and evaluation. Special attention should be given to the role of the arms, as it is generally agreed that 85% of the total thrust is due to arms in front crawl stroke (Toussaint et al., 2000). Even though force production capacity is expected to be related to muscle mass, this particular relationship in swimming may be affected by specific swimming ability, traducing the subjects' capacity to apply force in water. Therefore, the main purpose of this study was to measure the differences of force production between arms in front crawl tethered swimming. Complementarily, the decrease in force production during a 30 s maximum effort was analysed.

Materials and methods

In the first part of the study (GR1), 14 young male swimmers of regional level were evaluated (age 14.2 ± 1.09 years; height 168.3 ± 2.22 cm; weight 59.9 ± 4.77 kg). In the second part (GR2), 6 elite swimmers were tested (age 19.8 ± 2.23 years; height 183.6 ± 3.64 cm; weight 77.3 ± 3.64 kg). The participants were primarily sprint and middle distance trained swimmers. Their personal best for 100 m freestyle averaged 63.32 ± 1.69 s and 51.86 ± 0.63 s, for GR1 and GR2, respectively. All tests were conducted in a 50 m indoor swimming-pool (27° C of water temperature) during the competitive period of the spring macrocycle to ensure that the subjects were in a high training stage. After an 800 m (GR1) or 1200 m (GR2) low intensity warm-up, each subject performed one 30 s all-out front crawl tethered swimming test. The subjects were wearing a belt attached to a non-elastic steal cable with 5 m length. A load-cell system connected to the cable was used as a measuring device, recording at 100 Hz with a measure capacity of 5000 N. The load-cell was connected to a Globus Ergometer data acquisition system (GlobusTM, Italy) that exported the data to a PC. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended; the data collection only started after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually produced immediately before or during the first arm action. The end of the test was set through an acoustic signal. The experiments conducted in normal swimming pool conditions, using an appropriate methodology (cf. Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), allowed real time access to data.

Individual force to time - F(t) - curves were assessed and registered to obtain the values of maximum force production for the preferred (PF_max) and non-preferred (NP_Fmax) arm. Preferred and non-preferred distinction was based in F(t) curve analysis visual inspection, being considered the preferred arm the one with higher maximum force production. Additionally, mean force production for each stroke cycle was calculated for GR2 being calculated correspondent polynomial curves. The swimming velocities (v) were obtained by the official electronic chronometric times of long course swimming competitions (100 m freestyle) within the 25 days following the tethered swimming experiments.

Statistical analysis was made using SPSS v15.0 package. To obtain the descriptive statistics (mean $\pm$ SD) standard statistical methods were used. The Kolmogorov-Smirnov normality test was applied to examine the distribution of variables. For the preliminary study, an independent samples t-test was performed in order to detect differences between the arms force production. In order to establish relationships between variables, a Pearson's correlation coefficient (r) was used for force production values and swimming velocity. In the second study, for the same analysis, Mann-Whitney test and Spearman correlation coefficient were applied. The level of statistical significance was set at $p < 0.05$.

Results and Discussion

The maximum force values collected for GR1 presented differences between arms (P_Fmax 169.85 ± 14.38 N vs. NP_Fmax 137.44 ± 26.32 N, $p < 0.01$), being possible to assume that the swimmers tested cannot produce the same levels of force with both arms. In this first study, the average swimming velocity for the 100 m correlated significantly with P_Fmax ($r = 0.92$, $p < 0.001$), but not with NP_Fmax ($r = 0.48$, $p > 0.05$). Relationship between swimming performance in sprint events and variables obtained trough TS is assumed in specialized literature (Costill et al., 1986; Keskinen et al., 1989; Morouço et al., 2010).

Concerning the second part of the study, no statistical differences in maximum force values were obtained between arms (P_Fmax 255.86 ± 15.31 N vs. NP_Fmax 228.83 ± 19.93 N, $p > 0.05$). The inexistence of statistical significance difference can be due to the small number of subjects evaluated. Therefore, an individual analysis of force pattern during the 30 s effort was carried. Two different patterns of polynomial curves of maximum force production according to arm are shown in Figures 1 and 2. In Figure 1 it is noticeable that the non preferred arm can maintain the same level of force production during the 30 s test, while the preferred arm presents a decrease of 34.76 %. In Figure 2 it is possible to diagnosis the lack of force production by the non-preferred arm, being compensated with higher values from the preferred arm. It is possible to infer that increasing the force production of the non-preferred arm, would enhance the swimming performance for both swimmers presented.

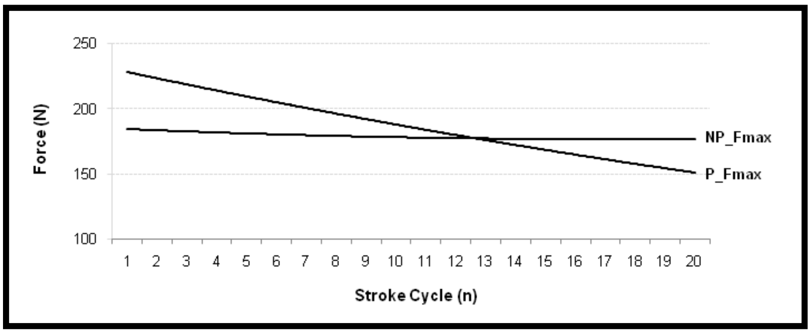

Figure 1: Polynomial curves of swimmer #2 maximum force production per stroke cycle. P_Fmax, maximum force produced by the preferred arm; NP_Fmax, maximum force produced by the non preferred arm.

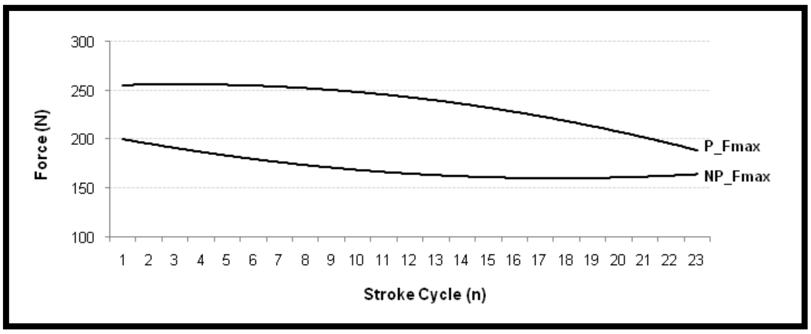

Figure 2: Polynomial curves of swimmer #3 maximum force production per stroke cycle. P_Fmax, maximum force produced by the preferred arm; NP_Fmax, maximum force produced by the non preferred arm.

Complementarily, average swimming velocity in the 100 m presented a significant correlation with P_Fmax and NP_Fmax ($r = 0.91$, $p < 0.05$ and $r = 0.86$, $p < 0.05$, respectively). This data suggest that higher level swimmers can approximate the levels of force production between arms. This fact may be due to the superior dry-land training that elite group does.

It has been suggested a decline in force production to be due to fatigue (Morouço et al., 2010; Soares et al., 2010). Figure 3 shows the patterns of mean force production for the elite swimmers. The average decrease of 5 swimmers is 32.5 ± 4.0 %. However it is possible to identify one of the swimmers (dashed line) that present a decrease of 47.5 %. Concerning that as the swimming distance diminish, the role of maximum force increases, and as the distance increase, the endurance force takes a major role (Wilke & Madsen, 1990), TS may be a useful tool to identify profiles particularly adapted to short or long distance swimming.

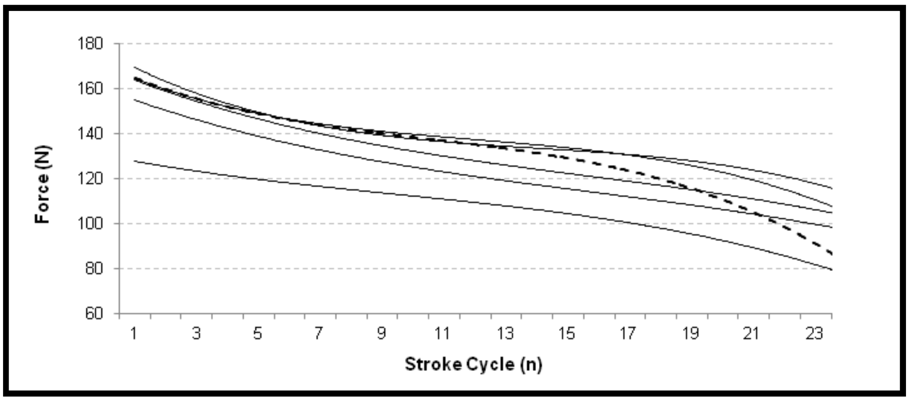

Figure 3: Polynomial curves of elite swimmers mean force production per stroke cycle.

Conclusion

The used methodology allowed gathering individual, easy to obtain and up to date information related with the force that swimmers can exert in the water. Differences between arms in force production can be assessed, as well as the percentage of force production decrease, identifying a tendency of each swimmer for short or longer swimming distances. Thus tethered force, as measured in this study, may be a useful methodology to identify factors that are related to swimming performance In future studies, an analysis of synchronized TS and underwater video may be able to identify the specific factors that limit performance.

Appendix III.

Tethered swimming as an estimator of anaerobic capacity

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Congress of the European College of Sport Sciences, accepted

Abstract

Relationships between tethered swimming (TS) and swimming performance have been previously studied. Nevertheless, most of these approaches studied heterogeneous groups. West et al. (2005) stated that to remain stationary, the swimmer relies mostly on fast glycolytic muscle fibers increasing the production of lactic acid. This was not verified in a recent study, reinforcing the importance of more studies under this scope.

Methods

3 homogeneous groups (variation of Personal Best 100-m Free < 2.5%) of 8 male swimmers (G1: 13.0±0.7y-of-age, 54.5±3.9kg, 164.8±6.8cm; G2:14.9±0.6y-of-age, 60.7±6.9kg, 172.1±6.6cm; G3: 19.9±1.7y-of-age, 75.6±7.6kg, 180.6±10.4cm) took part in the study. Maximum 30-s front crawl TS assessed maximum (Fmax) and mean force (Fmean). One day after, subjects performed 2 maximal front crawl swims (FS) with an underwater start (100- and 50-m) to obtain swimming velocity (v100 and v50). Blood samples from earlobe were taken after warm-up and at the terminus of the tests allowing the estimation of $\Delta[La^-]$. After Shapiro-Wilk normality test, parametric procedures were applied. The statistical significance was set at $p<0.05$.

Results

TS variables were higher in G3 than G2, than G1 (Fmax – 316.7±27.3N > 260.7±27.4N > 221.8±19.9N, $p<0.05$; Fmean – 126.6±10.9N > 102.9±11.3N > 93.9±12.1N, $p<0.001$). In $\Delta[La^-]$ higher differences were obtained between TS with 100-m ($p<0.0001$) than with 50-m FS ($p<0.05$). Fmax presented a high correlation with v50 in G3 ($r=0.87$, $p<0.001$). In G2 relationships were observed between v50 with Fmax ($r=0.77$, $p<0.001$) and Fmean ($r=0.73$, $p<0.05$). Fmean correlated significantly with

v50 ($r=0.63$, $p<0.05$) and v100 ($r=0.68$, $p<0.05$) for G1. $\Delta[La^-]$ presented moderate to high ($r=0.55$-0.86) correlations both with TS values and FS velocities.

Discussion

As expected upper level swimmers presented superior values of force exerted in water, corroborating the validity of the methodology used. In groups alike, $\Delta[La^-]$ in TS did not exceed the values of FS, contrasting the statement of West et al. (2005). For the different groups, correlations between force parameters and performance were estimated and differ according to age, force parameter and distance swam. These data could corroborate the idea that TS may be useful to discern between “sprinters” and “distance” swimmers profiles. The associations between $\Delta[La^-]$ with force exerted in water and swimming velocities support the idea that the capacity to obtain higher values of force production and swimming velocities, is related with an enhanced production of energy through the glycolytic system. Our data suggest that TS may be useful to monitor and evaluate anaerobic training.

Key words: Force, Blood Lactate, Anaerobic Training

Appendix IV.

Relationships between power in dry-land exercises and swimming performance

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Introduction

Swimming excellence can only be achieved with a specific and rigorous training process. Regarding specificity, dry land training exercises should be performed at the load that maximizes mechanical power output in order to achieve the most effective improvement in maximum muscle power (Kaneko et al., 1983). Secondly, at the age of adolescence most swimmers start to complement the water training with hours in the gym. However, the way to prescribe adequate loads is unclear as the relationship between load and intensity can be affected by different parameters (e.g. speed of execution; volume; rest periods; ...). Therefore, this study aims to point out a possible methodology to better evaluate the intensity of the dry land exercises, using average propulsive power.

Methods

Nineteen national level swimmers (10 male and 9 female; age: 15.3 ± 1.2 years; body mass: 57.9 ± 6.5 kg; height: 1.67 ± 0.08 m; 100 m long course front crawl PB: 62.3 ± 3.7 s) volunteered as subjects. Data collection was performed using a dynamic measurement system (T-Force System®, Ergotech, Murcia, Spain). Each participant executed n repetitions (5 min rest) in concentric-only bench press. Initial load was set at 10 kg and was gradually increased in 10 or 5 kg increments until mean propulsive velocity (MPV) got lower than 0.6 $m.s^{-1}$. Following a 30 min rest with active recovery, participants replicated the methodology for squat, until a MVP lower than 0.9 $m.s^{-1}$ was obtained. A detailed description of the measuring device used in this study has recently been reported elsewhere (Sanchéz-Medina & González-Badillo, 2011). A smith machine was used to ensure a smooth vertical displacement of the bar along a fixed pathway. In day two subjects executed the lat pull down back until MPV got lower than 0.6 $m.s^{-1}$. Average propulsive mechanical power was assessed

$$P = \frac{\delta(F \cdot x)}{\delta t} \qquad (1)$$

for each load and maximum value was registered for each exercise: squat (Psq); bench press (Pbp) and lat pull down back (Plpd). In day three, after a 1000 m low intensity warm-up, each subject performed 50 m maximal front crawl, with an underwater start. Spearman correlation coefficients (ρ) were calculated between power and velocity. Significance was accepted at $p < 0.05$.

Results

In table 1 it is perceptible the high relationships between the average propulsive mechanical power and swimming velocity, especially in the squat.

Table 1. Correlation coefficients (ρ) between 50 m velocity and power in dry land exercises.

	Psq	Pbp	Plpd
v50	0.91**	0.75*	0.81**

Figure 1 presents a load-power relationship for squat. The dashed-line represents minus 10% of maximum value achieved.

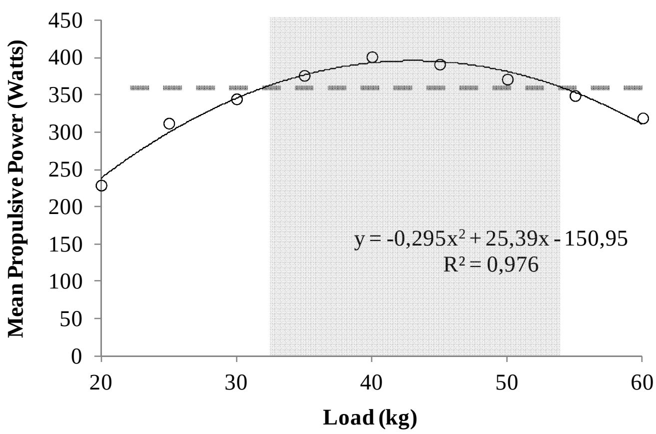

Figure 1. Load-power relationship in a representative swimmer for squat.

Discussion

Average propulsive mechanical power in the three exercises studied are related with swimming performance, being higher for squat, then lat pull down back and bench press. Moreover, as it is noticeable in figure 1, maximal power output is not reachable with high or low loads. Indeed, this methodology can be used to determine the adequate load to exert proper strength. More studies must be carried to clarify the role of power in swimming performance.