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Original Article

Biomechanical and bioenergetical evaluation of swimmers using fully-tethered swimming: A qualitative review

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ABSTRACT

It is presented a qualitative review of the specialized literature on fully-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; (vi) Tethered swimming is a valid methodology to evaluate aerobic energy contribution in swimming and recent investigations concluded that it can also provide information on the anaerobic contribution. Based on and stimulated by current knowledge, further research should focus on the following topics: (i) the usefulness of tethered swimming as a valid tool to evaluate other swimming techniques; (ii) differences in force parameters induced by gender or competitive level; (iii) defining accurate variables for estimation of anaerobic power and/or capacity using tethered

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swimming; (iv) bilateral asymmetries in exerted forces, and corresponding influence of breathing; (v) relative contribution of arms and legs for whole-body propelling forces. **Key words:** TRAINING; TESTING; PERFORMANCE; FORCE.

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INTRODUCTION

The improvement of swimming performance requires the control of multiple variables (e.g. biomechanical, bioenergetical and psychological), which positive or negative influences the four phases of a swimming competition: the 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 should performance parameters be evaluated? The responses to those questions are complex, but they may lead to an increase in the efficiency of the training process and performance prediction (Maglischo, 2003). T. 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 or the drag force, or; (ii) a consequence of an increased (or decreased) added mass effect during a given swim cycle (Vilas-Boas, Barbosa, & Fernandes, 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, Matkovic, & Zdravkovic, 2000; Gatta, Cortesi, & Zamparo, 2016). Magel (1970) was one of the first authors to emphasize the potential of tethered swimming as an evaluation tool for swimmers, and he suggested that measuring the propelling forces at zero velocity could provide a good estimate of the force that can be developed during free swimming. Recently, Gatta et al. (2016) concluded that swimmer’s thrust force (tethered swimming) is equivalent to the force required to overcome swimmer’s drag in active conditions (clean swimming), in front crawl swimming. Furthermore, tethered swimming is considered a reliable methodology (Dopsaj, Matkovic, Thanopoulos, & Okicic, 2003; Kjendlie & Thorsvald, 2006; Psycharakis, Paradisis, & Zacharogiannis. 2011; Amaro, Marinho, Batalha, Marques, & Morouço, 2014; Gatta et al., 2016) suitable to evaluate aerobic (Pessôa-Filho & Denadai, 2008) and anaerobic (Ogonowska, Hübner-Woźniak, Kosmol, & Gromisz, 2009; Morouço, Vilas-Boas, Fernandes, 2012) energetic profiles.

More than four decades after Magel’s (1970) suggestions, tethered swimming is being used with fully-tethered (with elastic or non-elastic cable) and semi-tethered procedures (Dominguez-Castells, Izquierdo, Arellano, 2013) with an effort duration from 5 s to 12 min, which should be taking in consideration when comparing results. In the current manuscript a qualitative review it is presented of the specialized literature on fully-tethered swimming as a tool to evaluate competitive swimmers, which aims 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 into four sections: the apparatus and procedures used to measure tethered forces, an analysis over available experiments conducted under a biomechanical perspective, studies that use tethered swimming with a bioenergetical perspective, and main research findings.

Experiments available in the literature were gathered by research using databases (SportDiscus, PubMed, and Scopus). The research 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

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analyzed, referred words were occasionally coupled. In addition, references from relevant proceedings were taken into consideration and added to the review.

APPARATUS AND PROCEDURES

Tethered swimming allows the measurement of exerted forces assessing individual Force-time curves during the exercise. Consequently, its use improves the possibility of analysis and comparison of swimming technique profiles and allows to accurately know 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 structures in a similar way to the form used in competitive swimming (Costill, Rayfield, Kirwan, & Thomas, 1986; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), although some kinematical changes have been reported (Maglischo, Maglischo, Sharp, Ziera & Katz, 1984; Psycharakis et al., 2011).

In the most common apparatus, fully-tethered and non-elastic cables are employed (Magel, 1970; Yeater, Martin, White, & Gilson, 1981; Christensen & Smith, 1987; Ria, Falgairette, & Robert, 1990; Sidney, Pelayo, & Robert, 1996; Taylor, Lees, Stratton, & MacLaren, 2001), with 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, Hadley, Piva, & Bambauer, 1983) or a force transducer (e.g. Dopsaj et al., 2000; Morouço, Keskinen, Vilas-Boas, & Fernandes, 2011). The force transducer can be fixed on the pool wall with the advantage of minimizing any interference with the swimmers normal technique as the rope is aligned with the direction of swimming (Psycharakis, et al. 2011), but it presents the disadvantage of the feet touching the cable producing alterations to assessed values. It could also be fixed onto the starting block (the most usual procedure) which 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 component of the force exerted) (Taylor et al., 2001). These calculations were not referred to 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 for the signal of the measurement system to be amplified and acquired through an analogue-to-digital converter, which was directly recorded on a computer (Dopsaj et al., 2000; 2003; Morouço et al., 2011a), thus, considerably reducing time consumption.

The absent of displacement during tethered swimming test can create mechanical constraints to swimmers, in relation to free swimming. So, tethered swimming could cause changes to stroke pattern (Maglischo et al., 1984; Psycharakis et al., 2011). However, changes in stroke patterns are not significant and the physiological responses are equivalent to free swimming (Morouço, Marinho, Keskinen, Badillo, & Marques, 2014; Morouço, Marinho, Fernandes, & Marques, 2015). Nevertheless, it is suggested that evaluations should be performed with swimmers experienced in tethered swimming drills (Psycharakis et al., 2011). Otherwise, results of inexperienced swimmers can be compromised (Kalva-Filho et al., 2016). In addition, 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, Tilli, & Komi, 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 (Morouço et al., 2011a).

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 relationship 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, and 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, latter, Cortesi, Cesaracciu, Sawacha, & Gatta (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 tests use the same amount of time. Furthermore, some researchers suggest the use of the 30 s at maximum intensity as an adaptation of the Wingate test for swimmers evaluation (Papoti, Martins, Cunha, Zagatto, & Gobatto, 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), average force (e.g. Ria et al., 1990; Morouço et al., 2011a), minimum force (e.g. Dopsaj et al. 2003), impulse of force (e.g. Dopsaj et al., 2000; Morouço et al., 2014) and fatigue index (e.g. Morouço et al., 2012) are the most common in literature. There is no clear evidence suggesting 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 more recent experiments (Dopsaj et al., 2000; Morouço et al., 2014; Amaro et al., 2014) who stated that impulse is the most accurate parameter. Additionally, investigations have commonly used absolute values (e.g. Christensen & Smith, 1987; Kjendlie & Thorsvald, 2006; Pessôa-Filho and Denadai, 2008) and not relative values (normalized to body mass). Tests are performed in the water being the body weight counterbalanced by the buoyancy (Taylor et al., 2001) and the use of relativized values does not enhance accuracy in relationships between variables (Yeater et al., 1981; Morouço et al., 2011a).

BIOMECHANICAL PERSPECTIVE

Swimming biomechanics aims to define the fundamental parameters that characterize and describe the movement of the swimmer using mechanical principles and approaches (T. Barbosa et al., 2010). Its purpose is to obtain results of the causes and consequences processed in the swimmers' body and the resultant movement on specific environment: through kinematics for the visible result and kinetics for the non-visible. Thus, the fundamental goal is to quantify the propulsive and drag forces, and their relationship to a swimmer's 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).

In regard to 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. This made it possible to collect individual force-time curves sensitive to the variations of propelling force within a stroke: an upward trace indicated a positive acceleration or propulsive moment, and a downward trace indicated 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. As regards to the role of arms and legs, it was stated that: for the 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.

Later, 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 higher peak forces, once

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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., 2011a). 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. Morouço, Neiva, Garrido, Marinho, Marques, & González-Badillo (2011) tested 32 swimmers of international level during a 30 s maximum tethered swimming, and observed different profiles for each swimming technique: breaststroke and butterfly obtained both higher and lower values of force production than front crawl and backstroke, resultant from the simultaneous actions of both arms and legs, and consequently leading to a higher intracycle velocity variation (Barbosa 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 the role of the legs for these swimming techniques has been neglected as a secondary factor (Hollander, De Groot, Van Ingen Schenau, Kahman, & Toussaint, 1988; Deschodt, Arsac, & Rouard, 1999). However, these results may be uncertain due to the calculation of the contribution of legs 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, Har, & Tabata (1996) also noted this fact in terms of energy consumption in front crawl swimming. Recently, Morouço, Marinho, Izquierdo, Neiva, & Marques (2015) evaluated relative contributions of arms and legs of 23 postpubescent swimmers (12 females and 11 males) in 30 s front crawl tethered swimming. These authors raised the question about the legs contribution to sprint performance. It seems that both arm stroke and leg kicking play a crucial role. In male swimmers maximum force exerted by upper limbs is highly related with short distances swimming performance. For female swimmers, the average force resulting from coordination between arms and legs (whole body) is highly related with short distances swimming performance. 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 during the front crawl and backstroke.

Knowing that during the front crawl and backstroke swimming techniques, the symmetry between the right and left arms may positively affect the average speed of a swimmer and contribute to a more appropriate posture minimizing the resistive drag (Tourny-Chollet, Seifert, & Chollet, 2009; Sanders, Thow, Fairweather, 2011). Tethered swimming could also be used to identify bilateral upper limb asymmetries (dos Santos, Pereira, Papoti, Bento, & Rodacki, 2013; Morouço et al., 2015b). In a pioneer experiment with 2 male swimmers, asymmetries between the tethered forces of left and right strokes were noticed (Goldfuss & Nelson, 1970). Recently, dos Santos et al. (2013) found asymmetries evaluating 18 adult national level swimmers in tethered swimming tests. Breathing preference (unilateral versus bilateral) did not influence symmetry. Nevertheless, a snorkel minimized the breathing effect requiring further investigations on the subject. Even though without significance, asymmetries were higher in swimmers with worst performance. However, caution must prevail when interpreting these results as some gaps can be identified. Authors ignored the possible overlap between upper limbs, no symmetry index was provided and lateral dominance was not taken into consideration. Morouço et al. (2015b) identified asymmetries in the majority (67.7%) of the 18 male swimmers evaluated in front crawl tethered swimming. Contrarily to previous studies, force asymmetries did not lead to a worst swimming performance. In fact, authors concluded that a certain force asymmetry may not be critical in short swimming performance. Likewise, kinematical (Tourny-Chollet, et al. 2009) and kinetic asymmetries (Toubekis, Gourgoulis, & Tokmakidis, 2010; Formosa, Mason, & Burkett,

2011) have been reported, inducing that an arm is mostly used for propulsion and the other primarily used 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.

Within the season coaches prescribe different training loads according to competition's moments, which makes training evaluation crucial to achieve success. Tethered swimming allows for the evaluation of forces production created by swimmers, independently of the technique performed, which is useful to the evaluation of swimmers and respective training control. For instance, tethered swimming test was used as a tool to evaluate training load before and during tapering in young swimmers (Toubekis, Drosou, Gourgoulis, Thomaidis, Douda, & Tokmakidis, 2013). With the same purpose, tethered swimming tests were applied to assess the effects of different hand paddles sizes training on front-crawl swimming (Barbosa, Castro, Dopsaj, Cunha, & Júmior, 2013). It is accepted that more important than increasing the strength of a swimmer is to enhance his ability to effectively use muscular force production in water (Keskinen et al., 1989). So, high values of dry-land strength production do not necessary mean higher in-water force production (measured trough tethered swimming) or improved swimming performance. Morouço et al. (2011b) analyzed the relationships between dry-land strength and power measurements and average tethered swimming forces and swimming performance. Main conclusions of this study revealed that work during countermovement jump (CMJ) is a better estimator of in-water force production (r = 0.75), than height. Lat pull down back was the most related dry-land test with swimming performance (r = 0.68); bench press presented the higher relation with only arms tethered swimming (r = 0.73) and work during CMJ with only legs tethered swimming. Recently, Loturco et al. (2015) confirmed the strong relationship between dry-land power, tethered swimming and sprint performance. However, these associations were only observed in 50 and 100 m front-crawl performance, whereas the 200 m front-crawl performance had weak/poor relationship. The short duration of the tethered swimming test (10 s) is not related with the 200 m front crawl distance/time, what may have influenced results. Thus, relationships between dry-land tests, 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 with the front crawl swimming technique (e.g. Costill et al., 1986; Christensen & Smith, 1987), 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). For example, Christensen & 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. Dopsaj et al., 2000; Morouço et al., 2011a) proposing that to improve maximum velocity the swimmer must improve maximum stroking force.

The studies referred above 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 was explained on the force-velocity relationship of the skeletal muscle, inducing that at a very high velocity it is not easy to produce very high force values (Keskinen et al., 1989). While it is understood that an association does exist, the nature and strength of this relationship remains inconclusive.

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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 supported for a more homogeneous sample cohort by Morouço et al. (2011a) that observed that for all swimming techniques stroking force measured through a tethered system may estimate free swimming velocities. Barbosa, Dopsaj, Okicic, & Andries (2010) evaluated fourteen high-competitive male swimmers through a tethered swimming test with the aim to predict breaststroke performance. Authors concluded that breaststroke swimming velocity was high related with tethered swimming variables such as impulse of force, average force and stroke duration.

Wilke & Madsen (1990) specified 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 & 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 & Costill (1998) tested 17 breaststroke swimmers and obtained significant correlations for both 91.4 and 365.8 m. A clear evidence of higher relationships between short competitive distances and tethered swimming forces was found (Morouço et al., 2011a). Recently, Santos, Bento, Pereira, & Rodacki (2016) reported moderate correlations (r = 0.61) between peak force obtained through a 2 m tethered swimming test and swimming velocity of 200 m front-crawl. This moderate correlation obtained may be another confirmation of the decrease of force importance as swimming distances increase. 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 (T. 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 (Papoti et al., 2009). 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, Wakayoshi, & Nomura, 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). It suggested that critical force determined in tethered swimming may correspond to the swimming intensity at maximal lactate steady-state. Papoti et al. (2009) supported these results and concluded that critical force presented a significant correlation with lactate anaerobic threshold (Papoti et al., 2013). Recently, critical force of a 3-minute all-out tethered swimming was concluded as a valid parameter to estimate aerobic capacity of swimmers (Kalva-

Filho et al., 2014). Although these results, its reliability as an index of performance raised some doubts (Pessôa-Filho & Denadai, 2008; 2010).

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, Norris, & Hogg, 2002; Stager & Coyle, 2005). 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; Kalva-Filho et al., 2016), (ii) the Wingate arm cranking test (e.g. Vandewalle, Pérès, Sourabié, Stouvenel, & Monod, 1989), (iii) the force-velocity test (e.g. Vandewalle et al., 1989); and (iv) tethered swimming test (e.g. Papoti et al., 2007; Ogonowska et al., 2009; Morouço et al., 2012). For instance, it has been proven that Anaerobic Impulse Capacity is a good indicator of Anaerobic Fitness (Papoti et al., 2013). Among these various approaches, it seems that tethered swimming stands out as being operational, with easy application and a low cost procedure. Moreover, tethered swimming does not significantly alter stroke and the physiological responses are similar to free swimming (Morouço et al., 2014; Morouço et al., 2015a) and has similar muscle activity (Bollens, Annemans, Vaes, & Clarys, 1988) and oxygen consumption (Lavoie & Montpetit, 1986).

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 phosphates 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 & 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 evaluating the capacity and/or anaerobic power 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 the Wingate arm cranking test. Moreover, the relationship between the decrease in force output and performance in sprint events shows a high correlation (Morouço et al., 2012), inducing that tethered swimming energetic demands are similar to free swimming events of equal duration (Morouço et al., 2015a). This assumption was corroborated by Thanopoulos , Rozi, & Platanou (2010) that reported similar values of net blood lactate concentrations between 100 m free swimming and tethered swimming with equal duration, at maximal intensity. Neiva, Morouço, Silva, Marques, & Marinho, (2011) evaluated the effect of warm-up on tethered front crawl swimming forces and confirmed the high anaerobic contribution in the 30s test. Warm-up improved maximum and mean force suggesting a positive effect also in swimming performance, due to the high relationship between the 30 s tethered swimming and swimming performance (Morouço et al., 201a). Peyrebrune, Toubekis, Lakomy, & Nevill (2014) corroborate the high anaerobic contribution in the 30 s tethered swimming test (67%) in relation to aerobic energy (33%). Nevertheless, authors found that aerobic contribution progressively increased to 52% after the first 30 s test and during 4 repeated 30 s tethered swimming tests.

Being aware that the evaluation of a swimmer's anaerobic capacity and/or power are questionable, emerging methodologies that are easy to operate and that bring direct results are one of the main purposes of swimming science (Stager & Coyle, 2005) and should be further investigated in the future.

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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 useful and valid, as well as easy, simple and a 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 assets 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 familiarized with the test;
- 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 they affect swimming performance;
- Tethered swimming is a valid methodology to evaluate aerobic energy contribution in swimming and recent investigations concluded that it can also provide information on the anaerobic contribution.

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:

- The usefulness of tethered swimming as a valid tool to evaluate other swimming techniques;
- Differences in force parameters induced by competitive level or gender;
- Defining accurate variables for estimation of anaerobic power and/or capacity using tethered swimming;
- Bilateral asymmetries in exerted forces, and correspondent influence of breathing;
- Relative contribution of upper-limbs and lower-limbs for whole-body propelling forces.

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REFERENCES

1. Akis T, Orcan Y. Experimental and analytical investigation of the mechanics of crawl stroke swimming. Mech Res Comm, 2004; 31: 243–261. https://doi.org/10.1016/j.mechrescom.2003.07.001

2. Amaro N, Marinho D, Batalha N, Marques M, Morouço P. Reliability of Tethered Swimming Evaluation in Age Group Swimmers. J Of Hum Kin.2014;41:155-162. https://doi.org/10.2478/hukin-2014-0043
3. Dominguez-Castells, R., Izquierdo, M., & Arellano, R. (2013). An updated protocol to assess arm swimming power in front crawl. International Journal of Sports Medicine, 34(4), 324–329. http://doi.org/10.1055/s-0032-1323721
4. Barbosa AC, Dopsaj M, Okicic T, Andries O. The usefulness of the fully tethered swimming for 50-m breaststroke performance prediction. Xith International Symposium For Biomechanics & Medicine In Swimming, 2010;(11):47-49.
5. Barbosa A, Castro F, Dopsaj M, Cunha S, Júnior O. Acute responses of biomechanical parameters to different sizes of hand paddles in front-crawl stroke. J Of Sports Sciences, 2013;31(9):1015-1023. https://doi.org/10.1080/02640414.2012.762597
6. Barbosa, T., Fernandes, R., Keskinen, K., Colaco, P., Cardoso, C., Silva, J., & Vilas-Boas, J. (2006). Evaluation of the Energy Expenditure in Competitive Swimming Strokes. Int JOf Sports Med, 27(11), 894-899. Barbosa TM, Bragada JA, Reis VM, Marinho DA, Carvalho C, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sport, 2010; 13: 262–269. https://doi.org/10.1055/s-2006-923776
7. Bollens E, Annemans L, Vaes W, Clarys JP. Peripheral EMG comparison between fully tethered and free front crawl swimming. In BE Ungerechts, K Wilke, K Reischle (Eds.), Swimming Science V. London, Spon Press, 173-181; 1988.
8. Christensen CL, Smith GW. Relationship of maximum sprint speed and maximal stroking force in swimming. J Swim Res, 1987; 3: 18–20.
9. Cortesi M, Cesaracciu E, Sawacha Z, Gatta G. Which is the recommended duration for the tethered swimming test? In K.L. Kjendlie, R.K. Stallman, & J. Cabri (Eds.), Biomechanics and Medicine in Swimming XI. Oslo: Norwegian School of Sport Science, 2010: 91.
10. Costill DL, Rayfield F, Kirwan J, Thomas RA. A computer based system for the measurement of force and power during front crawl swimming. J Swim Res, 1986; 2: 16–19.
11. D'Acquisto LJ, Costill DL. Relationship between intracyclic linear body velocity fluctuations, power, and sprint breaststroke performance. J Swim Res, 1998; 13: 8–14.
12. Deschodt VJ, Arsac LM, Rouard AH. Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. Eur J Appl Physiol, 1999; 80: 192–199. https://doi.org/10.1007/s004210050581
13. Dominguez-Castells, R., Izquierdo, M., & Arellano, R. (2013). An updated protocol to assess arm swimming power in front crawl. International Journal of Sports Medicine, 34(4), 324–329. https://doi.org/10.1055/s-0032-1323721
14. Dopsaj M, Matkovic I, Zdravkovic I. The relationship between 50m – freestyle results and characteristics of tethered forces in male sprinters: a new approach to tethered swimming test. Phys Ed Sport, 2000; 1: 15–22.
15. Dopsaj M, Matkovic I, Thanopoulos V, Okicic T. Reliability and validity of basic kinematics and mechanical characteristics of pulling force in swimmers measured by the method of tethered swimming with maximum intensity of 60 seconds. Phys Ed Sport, 2003; 1: 11–22.
16. dos Santos KB, Pereira G, Papoti M, Bento P C, & Rodacki A. Propulsive force asymmetry during tetheredswimming. International Journal of Sports Medicine, 2013;34, 606–611. https://doi.org/10.1055/s-0032-1327575
17. Formosa DP, Mason B, Burkett B. The force–time profile of elite front crawl swimmers. J Sports Sci, 2011; 29: 811–819. https://doi.org/10.1080/02640414.2011.561867

 © 2017 University of Alicante

18. Gatta G, Cortesi M, Zamparo P. The Relationship between Power Generated by Thrust and Power to Overcome Drag in Elite Short Distance Swimmers. PLoS ONE, 2016; 11(9): e0162387. https://doi.org/10.1371/journal.pone.0162387
19. Goldfuss AJ, Nelson RC. A temporal and force analysis of the crawl arm stroke during tethered swimming. In L. Lewillie, & J.P. Clarys (Eds.), First International Symposium on Biomechanics in Swimming, Waterpolo and Diving. Brussels: Université Livre de Bruxelles, 1970: 129–142.
20. Hollander AP, De Groot G, Van Ingen Schenau GJ, Kahman R, Toussaint HM. Contribution of the legs to propulsion in front crawl swimming. In B.E. Ungherects, K. Wilke, & K. Reischle (Eds.), Swimming Science V. Champaign, Ill: Human Kinetics, 1988: 39–43.
21. Hopper RT, Hadley C, Piva M, Bambauer B. Measurement of power delivered to an external weight. In A.P. Hollander, P.A. Huijing, & G. Groot (Eds.), Biomechanics and Medicine in Swimming IV. Champaign, Ill: Human Kinetics, 1983: 113–119.
22. Ikuta Y, Wakayoshi K, Nomura T. Determination and validity of critical swimming force as performance index in tethered swimming. In J.P. Troup, A.P. Hollander, D. Strass, S.W. Trappe, J.M. Cappaert, & T.A. Trappe (Eds.), Biomechanics and Medicine in Swimming VII. London: E & Spon, 1996: 146–151.
23. Kalva-filho, C, Zagatto, A, Araújo, M, Santiago, P, Da Silva, A, Gobatto, C, & Papoti, M. Relationship between aerobic and anaerobic parameters from 3-minute all-out tethered swimming and 400-m maximal front crawl effort. Journal of Strength & Conditioning Research, 2014; 29 (1): 238-245. https://doi.org/10.1519/JSC.0000000000000592
24. Kalva-Filho, C, Araújo, M, Silva, A, Gobatto, C, Zagatto, A, Gobbi, R, & Papoti, M. Determination of VO2-Intensity Relationship and MAOD in Tethered Swimming. International Journal Of Sports Medicine, 2016; 37(9): 687-693. https://doi.org/10.1055/s-0035-1559696
25. Keskinen KL, Tilli LJ, Komi PV. Maximum velocity swimming: interrelationships of stroking characteristics, force production and anthropometric variables. Scand J Sport Sci, 1989; 11: 87–92.
26. Keskinen KL. Evaluation of technique performances in freestyle swimming. Kinesiology, 1997; 2(1); 30–38.
27. Kjendlie PL, Thorsvald K. A tethered swimming power test is highly reliable. Port J Sport Sci, 2006; 6: 231–233.
28. Lavoie JM, & Montpetit RR. Applied physiology of swimming. Sport Med, 1986; 3(3): 165-189. https://doi.org/10.2165/00007256-198603030-00002
29. Loturco, I., Barbosa, A. C., Nocentini, R. K., Pereira, L. A., Kobal, R., Kitamura, K., … Nakamura, F. Y. (2016). A Correlational Analysis of Tethered Swimming, Swim Sprint Performance and Dry-land Power Assessments. International Journal of Sports Medicine, 37(3), 211–218. http://doi.org/10.1055/s-0035-1559694
30. Magel JR. Propelling force measured during tethered swimming in the four competitive swimming styles. Res Q, 1970; 41: 68–74.
31. Maglischo CW, Maglischo EW, Sharp R, Zier D, Katz A. Tethered and nontethered crawl swimming. In J. Terauds, K. Barthels, E. Kreighbaum, R. Mann, & J. Crakes (Eds.), Proceedings of the ISBS: Sports Biomechanics. Del Mar: Academic Publication, 1984: 163–176.
32. Maglischo EW. Swimming fastest. Champaign, Ill: Human Kinetics, 2003.
33. Marinho, D. A., Silva, A. J., Reis, V. M., Barbosa, T. M., Vilas-Boas, J. P., Alves, F. B., & ... Rouboa, A. I. (2011). Three-Dimensional CFD Analysis of the Hand and Forearm in Swimming. J App Biomechanics, 27(1), 74-80. https://doi.org/10.1123/jab.27.1.74
34. Morouço PG, Keskinen KL, Vilas-Boas JP, Fernandes RJ. Relationship between tethered forces and the four swimming techniques performance. J Appl Biomech, 2011; 27: 161–169. https://doi.org/10.1123/jab.27.2.161

35. Morouço, P., Neiva, H., González-Badillo, J. J., Garrido, N., Marinho, D. A., & Marques, M. C. (2011). Associations Between Dry Land Strength and Power Measurements with Swimming Performance in Elite Athletes: a Pilot Study. Journal of Human Kinetics, 29A, 105–112. http://doi.org/10.2478/v10078-011-0065-2
36. Morouço PG, Vilas-Boas JP, Fernandes RJ. Evaluation of adolescent swimmers through a 30-s tethered test. Pediatr Exerc Sci, 2012; 24: 312–321. https://doi.org/10.1123/pes.24.2.312
37. Morouço Pedro G, Marinho Daniel A, Keskinen Kari L, Badillo Juan J, Marques Mário C. Tethered swimming can be used to evaluate force contribution for short-distance swimming performance. J Strength Cond Res, 2014. https://doi.org/10.1519/JSC.0000000000000509
38. Morouço PG, Marinho DA, Fernandes RJ, Marques MC. Quantification of upper limb kinetic asymmetries in front crawl swimming. Human Movement Science, 2015; vol. 40, pp. 185–192. https://doi.org/10.1016/j.humov.2014.12.012
39. Morouço PG, Marinho DA, Izquierdo M, Neiva H, and Marques MC. Relative Contribution of Arms and Legs in 30 s Fully Tethered Front Crawl Swimming. BioMed Research International, vol. 2015, Article ID 563206, 6 pages, 2015. https://doi.org/10.1155/2015/563206
40. Neiva, H., Morouço, P., Silva, A. J., Marques, M. C., & Marinho, D. A. (2011). The Effect 0f Warm-up on Tethered Front Crawl Swimming Forces. J Hum Kin, 113-119. https://doi.org/10.2478/v10078-011-0066-1
41. Ogita F, Hara M, Tabata I. Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole body swimming. Acta Physiol Scand, 1996; 157: 435–441. https://doi.org/10.1046/j.1365-201X.1996.490237000.x
42. Ogonowska A, Hübner-Woźniak E, Kosmol A, Gromisz W. Anaerobic capacity of upper extremity muscles of male and female swimmers. Biomed Hum Kin, 2009; 1: 79–82. https://doi.org/10.2478/v10101-009-0020-z
43. Papoti, M., Martins, L. E. B., Cunha, S. A., Zagatto, A. M., & Gobatto, C. A. (2007). Effects of taper on swimming force and swimmer performance after an experimental ten-week training program. Journal of Strength and Conditioning Research, 21(2), 538–542. http://doi.org/10.1519/R-14894.1
44. Papoti M, Vitório R, Araújo G, Silva A, Santhiago V, Martins B, Gobatto C. A Determination of force corresponding to maximal lactate steady state in tethered swimming. Int J Exerc Sci, 2009; 2: 269–279.
45. Papoti M, Silva A, Araujo G, Santiago V, Martins L, Cunha S, Gobatto C. Aerobic and Anaerobic Performances in Tethered Swimming. Int J Sports Med, 2013; 34(8): 712-719. https://doi.org/10.1055/s-0031-1291250
46. Pessôa-Filho DM, Denadai BS. Mathematical basis for modelling swimmer power output in the front crawl tethered swimming: an application to aerobic evaluation. Open Sport Sci J, 2008; 1: 31–37. https://doi.org/10.2174/1875399X00801010031
47. Pessôa-Filho DM, Denadai BS. Extending the Critical Force Model to Approach Critical Power in Tethered Swimming, and its Relationship to the Indices at Maximal Lactate Steady-State. Xith International Symposium For Biomechanics & Medicine In Swimming, 2010; 11: 151-153.
48. Peyrebrune, M. C., Toubekis, A. G., Lakomy, H. A., & Nevill, M. E. (2014). Estimating the energy contribution during single and repeated sprint swimming. Scandn J Med Sci Sports, 24(2), 369-376. https://doi.org/10.1111/j.1600-0838.2012.01517.x
49. Psycharakis SG, Sanders RH. Shoulder and hip roll changes during 200-m front crawl swimming. Med Sci Sports Exerc, 2008; 40: 2129–2136. https://doi.org/10.1249/MSS.0b013e31818160bc
50. Psycharakis SG, Paradisis GP, Zacharogiannis E. Assessment of accuracy, reliability and force measurement errors for a tethered swimming apparatus. Int J Perform Anal Sport, 2011; 11: 410–416. https://doi.org/10.1080/24748668.2011.11868560

 © 2017 University of Alicante

51. Reis VM, Marinho DA, Policarpo FB, Carneiro AL, Baldari C, Silva AJ. Examining the accumulated oxygen deficit method in front crawl swimming. Int J Sports Med, 2010; 31: 421–427. https://doi.org/10.1055/s-0030-1248286
52. Ria B, Falgairette G, Robert A. Assessment of the mechanical power in the young swimmer. J Swim Res, 1990; 6: 11–15.
53. Rohrs DM, Stager JM. Evaluation of anaerobic power and capacity in competitive swimmers. J Swim Res, 1991; 7: 12-16.
54. Santos, K. B., Bento, P. B., Pereira, G., & Rodacki, A. F. (2016). The relationship between propulsive force in tethered swimming and 200-m front crawl performance. J Of Strength & Conditioning Research, 30(9), 2500-2507. https://doi.org/10.1519/JSC.0000000000000410
55. Sanders RH, Psycharakis SG. Rolling rhythms in front crawl swimming with six-beat kick. J Biomech, 2009; 42: 273–279. https://doi.org/10.1016/j.jbiomech.2008.10.037
56. Sanders RH, Thow J, Fairweather MM. Asymmetries in swimming: where do they come from? J Swim Res, 2011; 18: 1–11.
57. Sidney M, Pelayo P, Robert A. Tethered forces in crawl stroke and their relationship to anthropometrics characteristics and sprint swimming performance. J Hum Mov Stud, 1996; 31: 1–12.
58. Smith DJ, Norris SR, Hogg JM. Performance evaluation of swimmers: scientific tools. Sport Med, 2002; 32: 539–554. https://doi.org/10.2165/00007256-200232090-00001
59. Soares, S., Silva, R., Aleixo, I., Machado, L., Fernandes, R. J., Maia, J., & Vilas-Boas, J. P. (2010). Evaluation of Force Production and Fatigue using an Anaerobic Test Performed by Differently Matured Swimmers. Xith International Symposium For Biomechanics & Medicine In Swimming, (11), 291-293.
60. Stager JM, Coyle MA. Energy Systems. In J. Stager, & D. Tanner (Eds.), Swimming – Handbook of Sports Medicine and Science. Massachusetts: Blackwell Science, 2005: 1–19. https://doi.org/10.1002/9780470698761
61. Taylor SR, Lees A, Stratton G, MacLaren DP. Reliability of force production in tethered freestyle swimming among competitive age-group swimmers. J Sports Sci, 2001; 19: 12–13.
62. Thanopoulos V, Rozi G, Platanou, T. Lactate concentration comparison between 100m freestyle and tethered swimming of equal duration. In K.L. Kjendlie, R.K. Stallman, & J. Cabri (Eds.), Biomechanics and Medicine in Swimming XI. Oslo: Norwegian School of Sport Science, 2010: 230–233.
63. Toubekis AG, Gourgoulis V, Tokmakidis SP. Tethered swimming as an evaluation tool of single arm-stroke force. In K.L. Kjendlie, R.K. Stallman, & J. Cabri (Eds.), Biomechanics and Medicine in Swimming XI. Oslo: Norwegian School of Sport Science, 2010: 296–299.
64. Toubekis A, Drosou E, Gourgoulis V, Thomaidis S, Douda H, Tokmakidis S. Competitive Performance, Training Load and Physiological Responses During Tapering in Young Swimmers. Journal Of Human Kinetics, 2013; 38:125-134. https://doi.org/10.2478/hukin-2013-0052
65. Tourny-Chollet CT, Seifert L, Chollet D. Effect of force symmetry on coordination in crawl. Int J Sports Med, 2009; 30: 182–187. https://doi.org/10.1055/s-0028-1104581
66. Toussaint HM. Strength power and technique of swimming performance: Science meets practice. In W. Leopold (Ed.), Schwimmen Lernen und Optimieren. Beucha, Deutschland: Schwimmtrainer – Vereinigung eV, 2007: 43–54.
67. Vandewalle H, Pérès G, Sourabié B, Stouvenel O, Monod H. Force-velocity relationship and maximal anaerobic power during cranking exercise in young swimmers. Int J Sports Med, 1989; 10: 439–445. https://doi.org/10.1055/s-2007-1024940

68. Vilas-Boas JP, Barbosa TM, Fernandes RJ. Speed fluctuation, swimming economy, performance and training in swimming. In L. Seifert, D. Chollet, & I. Mujika (Eds.), World Book of Swimming: From Science to Performance. New York: Nova Science Publishers, 2010: 119–134.
69. Wakayoshi, K., Yoshida, T., Udo, M., Kasai, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. IntJ Of Sports Med, 13(5), 367-371. https://doi.org/10.1055/s-2007-1021282
70. Wilke K, Madsen O. Coaching the Young Swimmer. Pittsburgh: Sports Support Syndicate, 1990.
71. Yeater RA, Martin RB, White MK, Gilson KH. Tethered swimming forces in the crawl, breast and back strokes and their relationship to competitive performance. J Biomech, 1981; 14: 527–537. https://doi.org/10.1016/0021-9290(81)90002-6

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