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Strength & Conditioning and swimming performance
The effects of strength and conditioning training programs in age group swimmers

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“It always seems impossible until it's done.”

Nelson Mandela

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List of Publications

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- **Amaro, NM,** Marinho, DA, Batalha, NM, Marques, MC, and Morouço, PG. Reliability of Tethered Swimming Evaluation in Age Group Swimmers. *Journal of Human Kinetics* 41: 155-162, 2014.

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Abstract

The ability to apply force is crucial in competitive swimming, particularly in short distances. Accordingly, literature has shown that high values of upper-body strength and power are determinant to succeed in competitive swimming. Thus, dry-land Strength and Conditioning (S&C) is a common practice in swimming prescription in order to improve performance or prevent injuries. Nevertheless, research over the effects of S&C training in swimming performance is scarce and far from consensus. The main purpose of this thesis was to analyze the effect of S&C training programs on swimming performance in age group swimmers. Additionally, the reliability of tethered swimming evaluation with age group swimmers was verified, as a methodology to evaluate S&C training effects in swimming performance. For the accomplishment of these purposes the following sequence was used: (i) reviewing the available literature; (ii) examination of the reliability of tethered swimming evaluation; (iii) analyzing the effects of S&C programs in dry-land strength and swimming performance; (iv) proposing a practical S&C program to swimming prescription. The main conclusions drawn were: (i) there is limited research on S&C training effects in competitive swimming and the existent was mainly conducted with older and experienced swimmers; (ii) tethered swimming is a reliable test to evaluate force exerted in water by swimmers familiarized with the test; (iii) tethered swimming evaluations throughout the season may allow coaches to control swimmers' ability to exert in-water force and evaluate the effects of S&C training programs, in age group swimmers; (iv) 6 weeks of a complementary S&C training allow improvements in dry-land strength, in age group swimmers; (v) a 4-week adaptation period is suggested to allow transferability of S&C improvements to swimming performance; (vi) explosiveness should be the goal of S&C training in order to allow swimming performance enhancement in short distance swimming, with age group swimmers. These findings can be used by coaches and researches as a starting point to future S&C training programs in age group swimmers.

Key words: swimming; front crawl; strength and conditioning; dry-land; training and testing; youth

Resumo

Em Natação, a capacidade de aplicar força é crucial, especialmente em provas mais curtas. A investigação mostrou-nos ainda que, elevados valores de força e potência nos membros superiores são fundamentais. Assim, o treino de força e condição física em seco é uma prática comum no planeamento, tendo como objetivo o incremento do rendimento ou a prevenção de lesões. Ainda assim, a investigação sobre os efeitos do treino de força e condição física em seco no rendimento dos nadadores é escassa e inconclusiva. Assim, o objetivo principal desta tese foi analisar os efeitos de um programa de treino de força e condição física em seco no rendimento do estilo crol, em nadadores jovens. Adicionalmente, foi analisada a fiabilidade das avaliações do nado amarrado em nadadores jovens, de forma a validar o nado amarrado como uma metodologia de avaliação de força. Para atingir estes objetivos foi seguida a seguinte sequência: (i) revisão de literatura disponível; (ii) verificação da fiabilidade do nado amarrado em nadadores jovens; (iii) análise dos efeitos de dois treinos de força e condição física em seco no rendimento de nadadores jovens; (iv) apresentação de uma proposta prática de treino de força e condição física em seco. As principais conclusões alcançadas foram: (i) há pouca investigação sobre os efeitos de programas de treino de força e condição física em seco em natação e os que existem foram, na sua maioria, conduzidos com nadadores mais velhos e experientes; (ii) o nado amarrado é uma metodologia fiável para avaliar a aplicação de força em nadadores jovens familiarizados com o teste; (iii) avaliações de nado amarrado ao longo da época podem auxiliar os treinadores no controlo da capacidade de aplicação de força dos nadadores, bem como na avaliação dos efeitos de programas de treino de força e condição física em seco; (iv) 6 semanas de um treino complementar de força e condição física em seco permitiram o incremento da força em seco; (v) um período de 4 semanas é necessário para permitir a transferência dos ganhos de força em seco para a capacidade de aplicação de força na água e consequente melhoria do rendimento; (vi) em nadadores jovens e em distâncias de nado curtas, a potência máxima deve ser a base do treino de força e condição física em seco para permitir o incremento do rendimento. Os resultados desta tese podem configurar-se como um ponto de partida para futuros programas de treino de Força e Condição Física em seco, em nadadores jovens.

Palavras-chave: natação; estilo livre; força e condição física; treino em seco; treino e avaliação; jovens.

Resumen

En natación, la capacidad de aplicar fuerza es crucial, en particular en pruebas más cortas. Además, la investigación pone de relieve que elevados valores de fuerza y de potencia en los miembros superiores son determinantes. El entrenamiento de fuerza y condición física en seco es habitual en la planificación de la natación, siendo su objetivo el incremento del rendimiento en la prevención de lesiones. Con todo, se puede afirmar que los estudios sobre los efectos del entrenamiento de fuerza y condición física en el rendimiento de los nadadores no son concluyentes. Así, el objetivo principal de esta tesis ha sido de analizar los efectos de programas de entrenamiento de fuerza y condición física en el rendimiento de los nadadores jóvenes. Además, se ha analizado la fiabilidad de las evaluaciones del nado amarrado, de modo a confirmar la validez del nado amarrado en tanto que metodología de evaluación de fuerza. Afín de alcanzar estos objetivos, se ha seguido la secuencia siguiente: (i) revisión de la literatura disponible; (ii) comprobación de la fiabilidad del nado amarrado en nadadores jóvenes; (iii) análisis de los efectos de dos entrenamientos de fuerza y condición física en el rendimiento de nadadores jóvenes; (iv) presentación de una propuesta práctica de un programa de entrenamiento de fuerza y condición física. La principales conclusiones a las que se ha llegado son: (i) la escasa investigación en cuanto a los efectos de lo entrenamiento de fuerza y condición física en la natación - los existentes, en su mayoría, se han llevado a cabo con nadadores con más edad y experimentados; (ii) el nado amarrado constituye una metodología fiable para evaluar la aplicación de la fuerza en nadadores jóvenes familiarizados con la prueba; (iii) evaluaciones de nado amarrado a lo largo de la temporada pueden ayudar a los entrenadores para controlar la capacidad de aplicación de la fuerza de los nadadores; (iv) 6 semanas de un entrenamiento complementario de fuerza y condición física han permitido el incremento de la fuerza en seco de nadadores jóvenes; (v) se necesita un período de 4 semanas para poder transferir el aumento de fuerza en seco hacia la capacidad de aplicación de fuerza en el agua y la consecuente mejoría del rendimiento; (vi) en nadadores jóvenes, y en distancias de nado cortas, la potencia máxima debe constituir la base del entrenamiento de fuerza y condición física, para permitir el incremento del rendimiento. Estos resultados podrán ser utilizados por entrenadores e investigadores como un punto de partida para la aplicación de programas de entrenamiento de fuerza y condición física en nadadores jóvenes.

Palabras-clave: natación; estilo crol; fuerza y condición física; entrenamiento en seco; entrenamiento y evaluación; jóvenes.

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List of Abbreviations

1RM	One repetition maximum
BTS	Bartlett's test of Sphericity
CG	Control group
CMJ	Countermovement jump
cV%	Coefficient of variation
ES	Eletrical stimulation
GR1	Group 1
GR2	Group 2
FW	Free – Weights
HIIT	High-intensity interval training
HT	Habitual training
ICC	Intraclass Correlation Coefficient
impF	Mean impulse of force
max	Maximum measure value
maxF	Maximum force
mean	Mean values
meanF	Mean force
min	Minimum measure value
MS	Maximal strength
PT	Plyometric training
RAS	Resisted – and assisted - sprint
S	S&C training
SD	Standard deviation
SJ	Squat jump
SW	Shapiro Wilk tests
S&C	Dry-land Strength and Conditioning
T1	At the beginning of the experimental period
T2	After 6 weeks of the dry-land S&C program
T3	After 4 weeks of an adaptation period to strength gains
V25	25-m front crawl performance

Chapter 1. General Introduction

In competitive swimming the main goal is to complete the race as fast as possible. For that purpose, an optimal interaction of several domains, such as energetics, kinematics, kinetic, strength and conditioning, motor control and anthropometrics must occur (Barbosa et al., 2013). Accordingly, literature over the interaction of these domains and their effects in swimming performance is extensive. For instance, Barbosa et al. (2010b) analyzed the number of papers published in the "Biomechanics and Medicine in Swimming" Proceedings Book from 1971 to 2006. Authors reported a significant increase of publications between 1996 and 2006. Furthermore, a trend in "interdisciplinary assessment" was noted since 2003. A quick search in scientific databases shows about 4.000 academic works within the domain "swimming", over the past ten years (2006 – 2016). However, the domain of dry-land Strength and Conditioning (S&C) has not been widely investigated and the existent literature is not unanimous. This is even more important as swimming performance is highly dependent on strength and muscular power (Barbosa et al., 2015; Girold et al., 2007; 2012; Keskinen et al., 1989; Newton et al., 2012), being the ability to exert force in water determinant over short distances (Morouço et al., 2014; Stager & Coyle, 2005). Moreover, upper body strength has shown to be well correlated with swimming velocity (Aspenes et al., 2009; Costill et al., 1986; Hawley et al., 1992; Morouço et al., 2011a; Sharp et al., 1982; Tanaka & Swensen, 1998). Thus, it is suggested by deterministic models (Barbosa et al., 2010b) that muscular strength may have a positive influence in technique and, ultimately, in performance.

Despite the lack of consensus on the specific benefits to swimming performance, S&C training is a common practice in swimming training prescription. Its' main purpose is to enhance swimming performance and/or prevent injuries (Barbosa et al., 2013; Faigenbaum et al., 2009; Folland & Williams, 2007; Leveritt et al., 1999). Nevertheless, some coaches assume that S&C training may negatively affect swimmers' performance, through the increase of hydrodynamic drag forces (Newton 2002). Muscular hypertrophy and flexibility decrease are some of the S&C training outputs believed to impair performance. As far as muscular hypertrophy is concerned, this is not the primary factor for strength improvement in prepubescent subjects (Tolfrey et al., 2007). In fact, neuromuscular adaptations have been identified as the main justification for strength improvements, within prepubescent stages (Faigenbaum et al., 2009; 2015). However, there is a scarce number of investigations able to clarify this topic. Additionally, investigations with age group swimmers are even scarcer, mostly due to ethical and financial issues (Barbosa et al., 2010a).

As above-mentioned, S&C training is a significant part of swimming training prescription. Hence, it would be expected to find extensive and conclusive research over this domain.

Nevertheless, it is a domain requiring further and deeper concern by the swimming research community. Previous experiments have stated positive effects of S&C programs in swimming performance (Aspenes et al., 2009; Bishop et al., 2009; Girold et al., 2007, 2012;Hong-Sun et al., 2009; Potdevin et al., 2011; Strass, 1988; Weston et al., 2015), in tethered swimming force (Aspenes et al., 2009; Sadowski et al., 2012) and in technical parameters, like stroke length (Girold et al., 2012; Strass, 1988) and stroke rate (Strass, 1988). On the other hand, other experiments have stated no positive effects in swimming performance (Breed & Young, 2003; Cossor et al., 1999; Sadowski et al., 2012).

There are some general issues suggested to be associated with the absence of positive results. Firstly, the lack of transferability from dry-land strength improvements to in-water actions is suggested to impair results (Barbosa et al., 2013). Secondly, tests and procedures with different demands from swimming actions and context are also reported. For instance, assessments or exercises performed in isometric conditions may not be related to swimming actions which are dynamic. Finally, and probably the major constraint: specificity. Swimming environment is impossible to reproduce in dry-land conditions, which may affect exercises' specificity (Tanaka et al., 1993). Muscular tension in tests and exercises should be as similar as possible to in-water actions (Barbosa et al., 2013). Additionally, S&C training depends on other factors such as: type of training; methods; materials, periodization; and swimmers' maturation or competitive level.

Estimation of propulsive forces is crucial to identify determinant factors for swimming performance enhancement (Marinho et al., 2011). Until now, there is no direct measurement procedure able to assess the exact propulsive force of a swimmer. The particular characteristics of the aquatic environment make this task complex (Akis & Orkan, 2004). Nevertheless, researchers have been assessing propulsive force through video analysis (Schleihauf et al., 1983; 1988), measurement of active drag system (Toussaint et al., 1988), pressure differences (Takagi & Wilson, 1999), semi-tethered (Costill et al., 1986) and tethered system (Kjendlie & Thorsvald, 2006), and numerical analysis (Marinho et al., 2011; Vilas-Boas et al., 2015). Each of the referred methods has advantages and disadvantages.

Tethered swimming allows swimmers to mimic free-swimming movements, with low constrains (Morouço et al., 2014). Theoretically, the maximum tethered force corresponds to the propelling force that a swimmer must produce to overcome the water resistance at maximum free-swimming velocity (Magel, 1970; Yeater et al., 1981; Keskinen, 1997; Dopsaj et al., 2000; Morouço et al., 2011b; Gatta et al., 2016). Furthermore, it is a reliable methodology (Dopsaj, et al. 2003; Kjendlie and Thorsvald, 2006; Psycharakis et al., 2011; Gatta et al., 2016) suitable to evaluate aerobic (Pessôa-Filho and Denadai, 2008) and anaerobic (Ogonowska, et al. 2009; Morouço, et al. 2012) energetic profiles. Complementarily, it has similar muscular activity (Bollens et al., 1988) and oxygen consumption (Lavoie & Montpetit, 1986) to free-swimming.

Apart from being an easy, operative and inexpensive methodology (Morouço et al., 2012), there are some limitations associated to tethered swimming. Kinematical changes have been reported (Maglischo, et al. 1984; Psycharakis et al., 2011), although changes in stroke patterns are not significant and the physiological responses are equivalent to free-swimming (Morouço et al., 2014; Morouço et al., 2015). Therefore, it is recommended that evaluations should be conducted with swimmers experienced in tethered swimming drills (Psycharakis et al., 2011), otherwise, results of inexperienced swimmers can be compromised (Kalva-Filho et al., 2016). On the other hand, the absent of displacement leads to different interactions between the swimmer and the fluid in relation to free swim (Barbosa et al., 2013).

Available literature is unanimous over the importance of force exertion in swimming, particularly in short distances. As well, tethered swimming is considered a reliable and useful tool to assess force production in-water. However, in age group swimmers there is a gap in literature over these domains. Considering the aforementioned, the main purpose of this thesis was to analyze the effects of an S&C training program on front crawl swimming performance in age group swimmers, allowing coaches to improve their S&C training programs in age group swimmers. Previously, the reliability of tethered swimming evaluation with age group swimmers was verified as a methodology to evaluate S&C training effects in swimming performance.

The thesis is developed according to the following sequence:

Chapter 2 presents a systematic review over the effects of S&C training in swimming performance.

Chapter 3 presents a qualitative review over tethered swimming as a methodology to evaluate swimmers, regarding biomechanical and bioenergetical domains.

Chapter 4 presents a study with the aim to examine the reliability of tethered swimming in the evaluation of age group swimmers.

Chapter 5 presents a study with the aim to investigate the effects of S&C programs in dry-land strength and swimming performance of age group swimmers.

Chapter 6 presents a study with the aim to provide coaches a practical proposal to enhance swimming performance through the addition of an S&C program to swimming prescription, in age group swimmers.

Then, main conclusions and limitations of the thesis are presented (**Chapter 7**), as well as suggestions for future research (**Chapter 8**).

Chapter 2.

A Systematic Review on Dry-land Strength and Conditioning Training on Swimming Performance

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Science & Sports (submitted)

Abstract

Objectives. – The objective of this review was to examine the effects of S&C training on swimming, and starts and turns performances.

News. – Dry-land strength and conditioning (S&C) training is a common practice in swimming aiming to enhance performance or to prevent injuries. However, studies regarding the effects of S&C on swimming performance are scarce; the influence of age, gender or competitive level is even scarcer.

Prospects and projects. - After a structured literature search, fifteen studies were included in the current review. Of those, seven did not report any positive or negative effects on swimming performance. Contrarily, most studies with positive effects were conducted with older swimmers whereas maximal strength was the most effective methodology for improving swimming performance. S&C plyometric training is suggested to be the most effective method to improve starts and turns. Future Randomized Controlled Trials should be conducted to explore the effects of S&C induced by age and gender, on different swimming distances and techniques, and long-term training effects.

Conclusion. - It is recommended that S&C training should be based on maximal strength, ranging from six to twelve weeks of 2 to 4 sessions per week (approximately 24 sessions altogether). In each session, coaches should vary from 2 to 3 sets and 3 to 5 repetitions, according to prescribed intensity. Rest intervals should range between 2 to 5 minutes and the intensity should be from 80 to 90% of 1RM. Particularly regarding improving starts and turns, a S&C training regime ranging from 6 to 8 weeks and with 2 sessions per week is suggested. In each session, swimmers should perform between 1 and 6 sets and 1 and 10 repetitions, according to the established intensity. Rest between sets should range from 60 to 90 seconds.

Key words: swimmers; performance; starts; turns; plyometric

1. Introduction

The ability to apply force in water is crucial in competitive swimming (Girold et al., 2007; Haycraft & Robertson, 2015; Keskinen et al., 1989; Newton et al., 2002), particularly in short distances events (Morouço et al., 2011; Stager & Coyle, 2005). High values of strength and power, mostly in the upper-body, have been identified as a determinant factor for success in competitive swimming (Aspenes et al., 2009; Bishop et al., 2009; Garrido et al., 2010). Dry-land strength and conditioning (S&C) training can improve swimming performance (Aspenes et al., 2009; Bishop et al., 2009; Girold et al., 2007, 2012; Hong-Sun et al., 2009; Potdevin et al., 2011; Strass, 1988; Weston et al., 2015), increase tethered swimming force (Aspenes et al., 2009; ;Sadowski et al., 2012;) and technical parameters such as increased stroke length (Girold et al., 2012; Strass, 1988) and stroke rate (Strass, 1988). Therefore, S&C training is a common swimming practice, dry-land S&C being an alternative to in-water procedures, even if its specificity is questioned (Tanaka et al., 1993).

Coaches have prescribed S&C training programs for decades in order to enhance swimming performance and/or prevent injuries (Barbosa et al., 2013; Folland & Williams, 2007; Leveritt et al., 1999). Despite being a common practice, some coaches assume that S&C training can negatively affect the swimmer's technical ability and consequently increase drag forces (Newton et al., 2002). This is mostly due to the muscular hypertrophy and the decrease in flexibility commonly associated with S&C training. Nevertheless, several improvements were associated with S&C training, leading to an increase in maximum force, power and muscular endurance and optimization of performance (Newton et al., 2002; Toussaint & Truijens, 2006).

Studies examining the effects of S&C on swimming performance have been conducted over the last 30 years, but its overall impact remains inconclusive (Garrido et al., 2010; Sadowski et al., 2012; Tanaka et al., 1993; Trappe & Pearson, 1994). While some of these investigations showed improvements in swimming starts and turns and 25m, 50m, 400m and turn in freestyle swimming races after a S&C training program (Aspenes et al., 2009; Bishop et al., 2009; Girold et al., 2007, 2012; Hong-Sun et al., 2009; Potdevin et al., 2011; Strass, 1988; Weston et al., 2015), others did not (Breed & Young, 2003; Cossor et al., 1999; Garrido et al., 2010; Manning et al., 1986; Sadowski et al., 2012; Tanaka et al., 1993; Trappe & Pearson, 1994). The transferability of dry-land S&C gains to swimming performance remains unclear and it is suggested to be a crucial factor for the absent of positive results.

The success of a S&C program depends on several factors such as the type of training, methods, materials, periodization, and swimmers' maturation or competitive level. The optimal combination of these factors requires clarification and further investigation. In fact, few studies have focused on youth swimmers (Bishop et al., 2009; Cossor et al., 1999; Garrido et al., 2010; Potdevin et al., 2011; Sadowski et al., 2012), perhaps because of ethical issues (Barbosa et al., 2010a). Nevertheless, S&C and in-water power output seem to have a determinant influence on youth swimmers' performance and should be part of their training (Barbosa et al., 2015; Morais et al., 2016). Additionally, S&C training could also be crucial in preventing injuries (Batalha et al., 2015), which are one of the major concerns of coaches in age group swimmers.

Hence, scientific research has not reached a consensus on the methodologies and benefits of S&C training programs in swimming. The variability of research designs (e.g. protocols, outcomes selected, swimming events, and swimmers' competitive level) makes it difficult to compare data and come to practical conclusions. Therefore, the purpose of the present study was to examine possible effects of S&C training on swimming performance, as well as on starts and turns performances. A systematic review was done, summarizing evidence related to the effect of S&C training on swimming performance.

2. Methods

2.1. Literature search

An extensive literature search was conducted to identify studies from January 1st, 1985 until December 31st, 2016 in which S&C training programs effects on swimming were investigated. This was done through computer searches (ISI Web of Knowledge, PubMed, Scopus and SPORTDiscus) using the keywords "swimming", "swimmer", "swim", "strength and conditioning", "strength", "strength training", "weight training", "resistance", "dry-land", "performance" and "longitudinal", with multiple combinations. In addition, the bibliographies of the located studies were extensively searched and cross-referenced. Those articles with restricted full text online were found in hardcopy form in library archives.

Studies selected for this review fulfilled the following selection criteria: (i) the studies were written in English; (ii) they were published in a peer-reviewed journal; (iii) they contained research questions on the effects of S&C training programs on competitive swimming; (iv) the main outcome reported was a performance measure (e.g. time or velocity); and (v) healthy human participants were used. Review articles (qualitative review, systematic review, and meta-analysis) were not considered. The included studies focused on longitudinal interventions in S&C training on competitive swimming. Studies based on other populations (e.g. Paralympic swimmers) were excluded. Studies that did not present a complete description of their methods and/or results were excluded.

Our initial search identified 360 studies. After reading the titles and abstracts, fifteen articles were chosen for further analysis (Tables 1 and 2). Of these, four studies focused on the effects of S&C training programs interventions on starts and turns performance and eleven studies on overall swimming performance. Those that were clearly not relevant or did not meet inclusion criteria were eliminated.

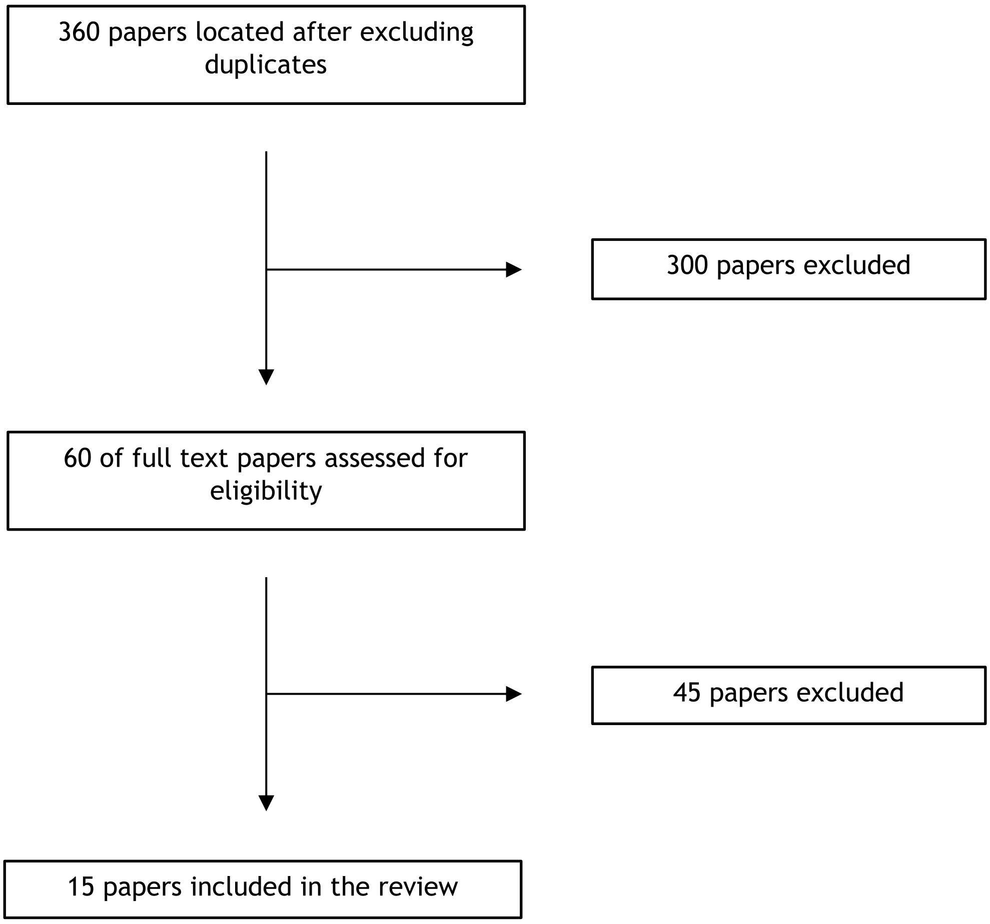

Figure 1. Flow of information through the different phases of paper selection for the systematic review

3. Results

Since S&C programs are common in swimming training, it seems that researchers should conduct more research into this area. The earliest study was published in 1986 (Manning et al., 1986) and since then only fourteen studies have been conducted. Despite interest in this domain rising over the last 15 years, with ten of the studies appearing after 2000, literature remains scarce on this subject. Several investigations showed improvements in 25m (Strass, 1988), 50m (Girold et al., 2007, 2012; Strass, 1988; Weston et al., 2015) and 400m (Aspenes et al., 2009) freestyle swimming performance, in stroke length (Girold et al., 2012; Strass, 1988), in stroke rate (Strass, 1988), in starts (Bishop et al., 2009) and turns (Potdevin et al., 2011) performance.

Concerning samples, 8 in 15 studies did not randomly allocate subjects to group. Other investigations did not include a control group (Hong-Sun et al., 2009; Manning et al, 1986; Trappe & Pearson, 1994). Samples size ranged from 7 (Manning et al., 1986) to 38 subjects (Potdevin et al., 2011), with the age of participants being around 16 years old (16.4±3.1 years). Seven studies assessed adolescent subjects (Bishop et al., 2009; Girold et al., 2007; Manning et al., 1986; Potdevin et al., 2011; Sadowski et al., 2012; Strass, 1988; Weston et al., 2015), six studies were conducted with young adults (Aspenes et al., 2009; Breed & Young, 2003; Girold et al., 2012; Hong-Sun et al., 2009; Tanaka et al., 1993; Trappe & Pearson, 1994) and only two studies assessed prepubescent swimmers (Cossor et al., 1999; Garrido et al., 2010). In terms of gender, only one study focused exclusively on female swimmers (Breed & Young, 2003), while seven studies evaluated male swimmers (Bishop et al., 2009; Hong-Sun et al., 2009; Manning et al., 1986; Sadowski et al., 2012; Strass, 1988; Tanaka et al., 1993; Trappe & Pearson, 1994). The remaining were conducted with mixed samples, coupling male and female subjects (Aspenes et al., 2009; Garrido et al., 2010; Girold et al., 2007, 2012; Potdevin et al., 2011; Weston et al., 2015) and only one compared the gender effect (Aspenes et al., 2009).

The intervention programs varied between four and twenty-four weeks, with six weeks being the most chosen length (n=4). The frequency of sessions per week was between 2 and 4, and from 30 to 60 min per session. Volume per session varied between 10 and 36 repetitions. Sets varied from 2 to 3 sets per session. In studies using time instead of number of repetitions, the length of exercise execution varied from 30 to 120 seconds, with 2 to 6 sets per session. Intensity was expressed as a % of 1RM, ranging from 30% to 100% of 1RM + 1kg. Some studies reported an intensity of exercises from 1 to 7kg while others did not present intensities at all. Five studies examined the effect of maximal strength (Aspenes et al., 2009; Girold et al., 2007, 2012; Hong-Sun et al., 2009; Strass, 1988), four studies were on power training (Breed & Young, 2003; Garrido et al., 2010; Manning et al., 1986; Sadowski et al., 2012), and four tested general strength (Breed & Young, 2003; Tanaka et al., 1993; Trappe & Pearson, 1994; Weston et al., 2015). In addition, plyometric training was used in five studies (Bishop et al., 2009, Cossor et al., 1999; Girold et al., 2007; Hong-Sun et al., 2009; Potdevin et al., 2011).

Weight lifting equipment was the most common material used (Aspenes et al., 2009; Breed & Young, 2003; Garrido et al., 2010; Girold et al., 2007, 2012; Hong-Sun et al., 2009; Manning et al., 1986; Tanaka et al., 1993; Trappe & Pearson, 1994). Free weights were used in three studies (Strass, 1988; Tanaka et al., 1993; Trappe & Pearson, 1994) and bodyweight exercises were used in seven studies (Bishop et al., 2009; Cossor et al., 1999; Garrido et al., 2010; Girold et al., 2007; Hong-Sun et al., 2009; Potdevin et al., 2011; Weston et al., 2015). Other materials such as medicine ball (Garrido et al., 2010), ergometer bicycle (Manning et al., 1986) and a hydro isokinetic ergometer (Sadowski et al., 2012) were also used.

These S&C programs were implemented and their effects on swimming were tested by analyzing 25 yards (Tanaka et al., 1993; Trappe & Pearson, 1994), 25m (Garrido et al., 2010; Potdevin et al., 2011; Sadowski et al., 2012; Strass, 1988), 50 yard (Manning et al., 1986), 50m (Aspenes et al., 2009; Garrido et al., 2010; Girold et al., 2007, 2012; Potdevin et al., 2011; Strass, 1988; Weston et al., 2015), 100 yard (Manning et al., 1986), 100m (Aspenes et al., 2009), 200 yard (Manning et al., 1986), 400 yard (Tanaka et al., 1993; Trappe & Pearson, 1994) and 400m (Aspenes et al., 2009; Potdevin et al., 2011) freestyle (front crawl stroke) swimming performances. Only one investigation analyzed the effects on other swimming techniques (Hong-Sun et al., 2009).

Table 1. Summary of the studies concerning the influence of S&C programs on swimming performance

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Manning et al. (1986)	To evaluate the effects of an upper and lower body power circuit weight training on power measures and sprint freestyle swim times	Male competitive swimmers Experimental group (n=7, age: 16.49±0.81 years)	Power training with weight lifting equipment 9 weeks (3 sessions per week) 2 sets and the highest repetitions possible in 1 minute 30% of 1RM - first 3 weeks 40% of 1RM - second 3 weeks 50% of 1RM - last 3 weeks Exercises: Leg extension; bench press; sit-ups with weight on chest; shoulder press; jump rope; lat pull-down; leg flexion; arm curl; ergometer bicycle; shoulder shrug; and the side bend	50, 100 and 200 yard freestyle times obtained during swim competitions	Non-significant Improvements for the 3 measurements ($p>0.05$) 50 yard test -0.98 seconds 100 yard test -0.06 seconds 200 yard test -1.30 seconds
Strass (1988)	To evaluate the effects of a heavy explosive strength training regimen in the 50m freestyle performance	Adult swimmers Experimental group (n = 10, age:16.6 years) Control group (n=9, age: 17.8 years)	Heavy explosive training with free weights 6 weeks (4 sessions per week) 3 repetitions per 3 sets at 90% of 1RM 2 repetitions per 2 sets at 95% of 1RM 1 repetition at 100% of 1RM 1 repetition attempted at 100% of 1RM+1kg Exercise: elbow extensions	50 and 25m freestyle time	Significant improvements of 4.4 and 2.1% over 25 and 50 m freestyle performance
Tanaka et al. (1993)	To examine the contribution of swimming-specific resistance training in male competitive swimmers	Intercollegiate male swimmers Experimental group (n=12, age:19.17±0.32 years) Control group (n=12, age: 19.50±0.26 years)	General strength training with weight lifting equipment and free weights 8 weeks (3 sessions per week) 3 sets of 8 to 12 repetitions Exercises: Dips, chin-ups, lat pull-downs, elbow extensions, bent arm flys	22.9m freestyle velocity (m.s-1) 365.8m freestyle velocity (m.s-1) Distance per stroke (m)	No improvements Non-significant difference between experimental group and control group in any measure
Trappe & Pearson (1994)	To compare the effects of 6 weeks of weight assisted training (WAT) to free-weight training (FWT) on swimming performance	Highly trained collegiate male swimmers WAT group (n=5) FWT group (n=5)	General strength training with weight lifting equipment and free weights 6 weeks (2 sessions per week) WAT group: 1 x set until volitional fatigue - no assistance 1 x set until volitional fatigue - 13.6kg assistance 1 x set until volitional fatigue - 22.7kg assistance Exercises: dips and pull-ups FWT group: 3 sets x 8-12 repetitions - progressive load until exhaustion Exercises: Elbow extension and flexion, lat pull downs, bent arm flys, quadriceps extension, hamstring flexion	22.9m front crawl sprint time 365.8m front crawl sprint time Stroke rate Distance per stroke	No variation ($p>0.05$) between groups in 22.9m front crawl sprint time No observed changes occurred in stroke rate and distance per stroke

Table 1. Continued.

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Girold et al. (2007)	To compare the effects of combined dry-land strength (S) with a swimming program with those of a combined resisted - and assisted-sprint (RAS) with the same swimming program.	Regional to national level swimmers (n= 21; 10 men, 11 women) Strength group (n=7, age:16.5±2.5 years) Resisted- and assisted-sprint group (n=7, age:16.5±2.5 years) Control group (n=7, age: 16.5±1.5 years)	Maximal strength Weight lifting equipment and plyometric 12 weeks (2 sessions per week) S group: 3 sets of 6 repetitions at 80 % to 90% of 1RM Exercises: press, pull-up, draw with barbells, abdominal, different types of squat and plyometric jumps RAS group: 3 x 2 sets of 3 repetitions per program (1 set in front crawl and 1 set in swimmers' specialty)	50m Freestyle (s) Stroke length (m) Stroke rate (cycle.min-1) Stroke depth (m)	A significant improvement ($p < 0.05$) in 50 m time (s) was reported for the S (2.8±2.5%) and RAS (2.3±1.3%) groups compared to control group (0.9±1.2%). No significant difference ($p > 0.05$) between S and RAS groups in 50 m time. Significant ($p < 0.05$) decrease in stroke depth for S (0.03 m) and RAS (0.02 m) groups. Significant increase in stroke rate (1.3 cycle.min-1, $p < 0.05$) for RAS group.
Hong-Sun Song et al. (2009)	To examine the efficacy of the application of a periodized strength training in improving swimmer's records	National team male swimmers Experimental group (n=10; age: 18.50±2.07 years)	Maximal Strength, Plyometric and Power with weight lifting equipment and free weights 2 cycles - June and December competitions 1st cycle (18 weeks - 4 sessions per week): - 10 weeks of adaptation, peak muscle strength - 8 weeks of power or muscle endurance maintenance 2nd cycle (20 weeks - 4 sessions per week): - 12 weeks of maximal strength - 8 weeks of power or muscle endurance maintenance	Swimming records	6 official personal records broken 2 Korean records broken 4 personal records broken 2 Korean records broken 2 Asian records broken During Asian Games in December, they established 8 personal records broken 4 Korean records broken 2 Asian records broken

Table 1. Continued.

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Aspenes et al. (2009)	To investigate the effect of a combined intervention of maximal strength training and high-intensity interval training (swimming) on swimming performance	Competitive swimmers Experimental group (n=11, 6 male, 5 female; age: 17.5±2.9 years) Control group (n=9, 2 male, 7 female; age:15.9±1.1 years)	Maximal strength (MS) and high-intensity interval training Weight lifting equipment 11 weeks (2 sessions per week) MS - 3 sets of 5 maximal repetitions HIIT - 4 x 4 minutes (90-95% of HRmax)	Maximal Swimming Force (N) 50m Freestyle (s) 100m Freestyle (s) 400m Freestyle (s) Max Swim Velocity (m.s-1) Stroke Length (m) Stroke Rate (Hz)	Improvements in tethered swimming force (+15.4N, $p<0.05$) between experimental and control group. Strong correlation between 400m improvements and tethered swimming force improvement, for the female group ($r= -0.975$, $p < 0.01$) Improvements for the experimental group in the 400m freestyle time (mean -4 s, $p <0.05$).
Garrido et al. (2010)	To examine the effects of 8 weeks of combined dry-land strength and aerobic swimming training for increasing swimming performance in young competitive swimmers. To assess the effects of a detraining period (strength training cessation) on strength and swimming performance.	Young competitive swimmers Experimental group (n=12, 8 male, 4 female; age: 12.0±0.78 years) Control group (n=11, 6 male, 5 female; age: 12.18±0.75)	Power and general strength Weight lifting equipment 8 weeks (2 sessions per week) 2 to 3 sets and 6 to 8 repetitions 50 to 75% of 6RM Exercises: Leg extension; Countermovement jumps; Countermovement jump to box; Medicine ball throws (1kg); Bench press	25m Freestyle Velocity (m.s-1) 50m Freestyle Velocity (m.s-1) Drag Force (N)	No differences between experimental and control groups in the 25 m and 50 m swim velocity ($p >0.05$). Experimental group significantly increased 25 m and 50 m swim velocity (25 m: 6.95%; 50 m: 4.77%, $p <0.01$). Significant increases in control group in the 25 m and 50 m swim velocity (25 m: 6.44%; 50 m: 3.16%, $p <0.05$).
Girold et al. (2012)	To compare the effects of dry-land strength training vs. an electrical stimulation program on swimmers	Competitive swimmers Strength (S) group (n=8, 4 male, 4 female; age: 21.1±1.4 years) Electrically stimulated (ES) group (n=8, 4 male, 4 female; age: 19.5±1.5 years) Control group (n=8, 4 male, 4 female; age: 24.2±4.6 years)	Maximal strength Weight lifting equipment 4 weeks (3 sessions per week) Dry-land Strength Training: 3 sets of 3 exercises (maximum of 6 repetitions per exercise) 80 to 90% of 1RM Exercises: pull-ups and draws with pulleys Electric Stimulation: Latissimi dorsi muscles Pulse currents of 100 Hz in frequency lasting 300 microseconds Average of 80-90% of the 1RM	50-m front crawl performance (s) Stroke length (m) Stroke rate (cycle·min-1)	A significant increase in swimming velocity was observed for both S and ES ($p <0.05$). Stroke length was significantly ($p<0.05$) increased during the 50 m in S.

Table 1. Continued.

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Sadowski et al. (2012)	To evaluate the effects of the dry-land power training on swimming force, swimming performance and strength in youth swimmers.	Youth male swimmers Experimental group (n=14; age: 14.0±0.5 years) Control group (n=12; age: 14.1±0.5 years,	Power Hydro isokinetic ergometer 6 weeks (3 sessions per week) 6 sets x 50 seconds of work	25-m front crawl performance (V25), Strength during tethered swimming (TS)	Significant improvement of TS force for the experimental group (9.64%, p<0.02)
Weston et al. (2015)	To quantify the effects of a 12-week isolated core-training program on 50-m front-crawl swim time and measures of core musculature functionally relevant to swimming.	National-level junior swimmers Experimental group (n=10, 5 male, 5 female; age: 15.7 ± 1.2 years) Control group (n=10, 5 male, 5 female; age: 16.7 ± 0.9 years)	General strength 12 weeks (3 session per week) 2 to 3 sets and 30 to 120 seconds hold 10 to 30 repetitions and 3 to 7kg load Exercises: Prone bridge; Side bridge; Bird dog; Leg raise; Overhead squat; Sit twist; Shoulder press	50-m front crawl swim time (s)	Compared with the control group, the core-training intervention group had a possibly large beneficial effect on 50-m swim time (-2.0%; 90% confidence interval -3.8 to -0.2%).

Table 2. Summary of the studies concerning the influence of S&C programs on swimming performance (starts and turns)

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Cossor et al. (1999)	To examine the effects of a plyometric training program on freestyle tumble turns by age-group swimmers	Age group male swimmers (n=38; age: 11.7±1.16 years) Plyometric group (n=19) Control group (n=19)	Plyometric 20 weeks (3 sessions of 30 minutes per week) 2 sets x 10-15 repetitions 15 exercises (not described)	2.5m round trip time 5m round trip time 50m freestyle time	No significant differences occurred between the 2 groups, for any measure
Breed & Young (2003)	To determine if a resistance-training program designed to increase vertical jumping ability could enhance various performance parameters in the grab, swing and track starts.	Female students of physical education/ human movement courses [n= 23; age:18.9 years (s = 1.5)] Experimental group (n=12) Control group (n=11)	General strength and power Weight lifting equipment 9 weeks (3 sessions per week) Weeks 1-3: Clean pull; barbell jump squat; barbell press (behind neck); back extension; parallel squat (Smith mach); prone hold; back extension Weeks 4-6: barbell jump squat; weighted belt jump; dumbbell overhead press; back extension; barbell half squat; twisting crunch; back extension; twisting crunch Weeks 7-9: drop jump; barbell half squat; cable arm drive; barbell jump squat; weighted belt jump; dumbbell arm drive; side hold	Flight distance Take-off velocity Take-off angle Total horizontal impulse Horizontal impulse of hands	No improvements in flight distance Significant improvements in take-off velocity in track starts ($p<0.05$) Significant improvements in take-off angle in track starts ($p<0.01$) Significant improvements in total horizontal impulse in track starts ($p<0.05$) Significant improvements in hands horizontal impulse in track starts ($p<0.01$)

Table 2. Continued.

Author's reference	Purpose	Sample characteristics	S&C intervention	Swimming performance measured	Findings
Bishop et al. (2009)	To identify the effect of plyometric training (PT), when added to habitual training (HT) regimes, on swim start performance.	Adolescent competitive swimmers Experimental group (n=11; age: 13.1±1.4 years) Control group (n=11; age: 12.6±1.9 years)	Plyometric 8 weeks (2 sessions per week) Plyometric training 1 to 4 sets and 1 to 5 repetitions Intensity: Low (3 weeks); Medium (3 weeks); High (2 weeks) Exercises: Two-foot ankle hop; Tuck jump with knees up; Squat jump; Split squat jump; Standing jump over barrier; Front cone hops; Hurdle hops; Single leg bounding; Single leg push-off; Multiple box-to-box jumps; Box skip; Alternate bounding with double arm action; Double leg hops; Depth jump; Depth jump to standing long jump; Jump to box; Standing jump and Standing long jump; Standing long jump with hurdle hop.	Angle out of blocks (°) Distance to head contact (m) Swim Block Start velocity (m.s-1) Time to head contact (s) Angle of entry into water (°) Performance time to 5.5m (s)	Significant differences (p <0.01) between baseline and post-trial swimming block starts for experimental group compared to control group in swim time over 5.5 m (-0.59 s vs. -0.21s) and velocity of take-off to water contact ($0.19\ ms^{-1}$ vs. $-0.07\ ms^{-1}$). No significant difference was found between groups for angle out of blocks (p = 0.023), and angle of entry into water (p = 0.27).
Potdevin et al. (2011)	To examine the effects of a 6-week plyometric training (PT) on front crawl performances in pubescent swimmers	Pubescent swimmers Experimental group (n=12, 5 male, 7 female; age: 14.3±0.2 years) Control group (n=11, 5 male, 6 female; age: 14.1±0.2 years)	Plyometric 6 weeks (2 sessions per week) 1 to 6 sets and 1 to 10 repetitions Intensity: Height jump from 0.21 to 1 m Exercises: Standing Jump over barrier; Standing Jumps over barrier with single leg; Standing long Jump; Standing long Jump with squat jump position; Single leg bounding; Two foot ankle Jump; Double leg lateral hop; Single leg lateral hop; Depth Jump; Depth Jump with single leg; Drop Jump; Multiple step to step Jump; Static jump with tuck jump with knees up; Combined standing high, depth and long Jumps.	Gliding test Front crawl swimming test with a diving start (400-m, 50-m) 2 tests with a water start without push-off on the wall (25-m in front crawl and 25-m only with kicks)	Improvements for the experimental group in the front crawl tests (Δ= 0.04 ± 0.04 m.s-1; Δ= 0.04 ± 0.05 $m.s^{-1}$; for V50 and V400 respectively; p<0.05) Significant correlations were found for experimental group between improvements in Squat Jump and V50 (R=0.73, p<0.05).

4. Discussion

4.1 Effects of S&C om swimming performance according to age

Most investigations until now have been conducted with adolescents and young adults. In fact, only one investigation (Garrido et al., 2010) focused on prepubescent swimmers, with the authors reporting similar improvements in swimming velocity gains between experimental and control group (4.8% vs. 3.2%, respectively). The lack of studies may be due to financial and ethical issues (Barbosa et al., 2010a) or the assumption by coaches that technical training is more important than S&C training (Aspenes et al., 2009; Barbosa et al., 2010a; Garrido et al., 2010; Kjendlie et al., 2004). Coaches usually assume that muscular hypertrophy and consequent decreases in flexibility may affect the swimmer's ability and increase drag forces (Newton et al., 2002). Nevertheless, during the prepubescent stage, muscle hypertrophy is not believed to be the primary factor in strength improvement (Tolfrey, 2007), with neuromuscular adaptations identified as the main explanation for strength gains (Faigenbaum et al., 2009, 2015). It is indeed recommended that young athletes engage in resistance training, not only to enhance health, fitness and performance, but also to prevent sports-related injuries (Faigenbaum et al., 2009, 2015).

Studies conducted with adolescent swimmers showed that the effects of S&C training may not be as clear as thought. Positive effects were reported in four studies (Manning et al., 1986; Girold et al., 2007; Strass, 1988; Weston et al., 2015) and no influence was reported in one study (Sadowski et al., 2012). Within the adolescent age group, caution must prevail when analyzing results. Biological maturity is related to chronological age, and has a major impact on the physical performance of youth athletes (Engebretsen et al., 2010). Nevertheless, athletic performance may be influenced not only by training but also by growth and maturation (Meylan et al., 2014), which can cause morphological and neural changes (Malina et al., 2004). Maturity status was not provided in the aforementioned investigations. Therefore, with subjects ranging from 13 to 19 years old, and morphological characteristics being considered one of the main reasons for the differences in energetic profiles after puberty (Seifert et al., 2010), the results may not be as clear as expected.

Three studies conducted with swimmers after puberty reported positive effects (Aspenes et al., 2009; Girold et al., 2012; Hong-Sun et al., 2009) and no effects were reported in two other studies (Tanaka et al., 1993; Trappe & Pearson, 1994). In both investigations where no positive effect was reported, the swimmers competed in collegiate teams. The lower competitive level of these swimmers could influence the results, since the energetic and biomechanical profiles of swimmers were different (Barbosa et al., 2010a). Swimming performance depends on the good relationship between bioenergetics and biomechanical parameters (Barbosa et al., 2010b). Thus, the transferability of dry-land strength gains to swimming performance could

depend on the interaction of several parameters such as strength (dry-land and in-water) and biomechanics (kinematics and kinetic) (Barbosa et al., 2010b), determined by competitive level.
Investigations have, so far, focused on adolescence and early adulthood. Investigations with age group swimmers must be conducted as a means of potentially enhancing swimming performance not only in the short term, but also in the long term, and at different competitive levels.

4.2. Effects of S&C on swimming performance according to gender

As it occurs with competitive level, differences in muscular strength and anthropometrics emerge (Seifert et al., 2004, 2010; Seifert & Chollet, 2008) between genders, particularly after puberty. However, there are few studies with samples separated according to gender. Results with mixed samples (male and female) must be analyzed with extra caution due to a possible gender effect. Even though during prepubescence strength improvements are quite similar between boys and girls (Faigenbaum et al., 2015), after this period boys have a tendency to exhibit higher muscle strength levels than girls (Bencke et al., 2002; Bergeron et al., 2015). Thus, coupling data from both sexes in research focused on S&C may be misleading. Within the analyzed studies, only one study presented separated results between females and the whole group (male plus female) (Aspenes et al., 2009). However, 7 out of 9 subjects were female in the control group and 5 out of 11 subjects were female in the intervention group, which may have led to heterogeneity between groups. For instance, the authors reported a significant correlation (r= -0.975, $p < 0.01$) between strength and 400m swimming performance in the female group but not in the whole group results. The authors also reported significant improvement in tethered swimming force in both the female group and the whole group. On the other hand, in terms of swimming performance, only the whole group experienced significant improvements in the 400m freestyle (-4 s mean). In adulthood differences in swimming performance between genders tend to be greater over short distances and less over higher distances (Tanaka et al., 1993). Additionally, through having more fat mass than males, females can adopt a better body position, thereby increasing swimming economy (Seifert et al., 2010).

By contrast, the remaining investigations with mixed samples did not present separated results, which may lead to misleading results. Yet, improvements in swimming time were reported in the 50m (Girold et al., 2007, 2012; Weston et al., 2015). Whereas no significant differences between sexes were reported in two investigations (Girold et al., 2007, 2012), Weston et al. attempted to balance groups by sex (5 males and 5 females). However, the results of the latter paper were coupled and so a gender effect could not be determined. The only study that did not report positive effects was conducted with age group swimmers (Garrido et al., 2010), where differences in swimming performance between the sexes do not exist or tend to be nonrelevant. Nevertheless, the study of heterogeneous groups in investigations of swimming performance can lead to ambiguous conclusions (Costill et al., 1983; Rohrs et al., 1990).

Most of these studies were conducted with exclusively male samples (Hong-Sun et al., 2009; Manning et al., 1986; Sadowski et al., 2012; Strass, 1988; Tanaka et al., 1993; Trappe & Pearson, 1994). Of those already mentioned, only two reported improvements in swimming performance (Hong-Sun et al., 2009; Strass, 1988). On the other hand, there were no investigations conducted with an exclusively female sample, up to the date.

Thus, further investigations with separated samples must be conducted in order to draw conclusions on a possible gender effect. Yet, the available literature suggests a tendency for swimming performance to improve in investigations on the effects of S&C training on mixed samples. Additionally, it is also crucial to cross compare information with age and consequently with the theoretical maturational development of swimmers.

4.3. Effects of S&C on swimming performance according to training protocol

Maximal strength training is the most regularly applied methodology in S&C training programs. Furthermore, all investigations that have used maximal strength reported improvements of between 2 and 4% in swimming performance (Aspenes et al., 2009; Girold et al., 2007, 2012; Hong-Sun et al., 2009; Strass, 1988).

Six weeks of S&C training with 4 sessions per week using intensities from 90 to 100% of 1RM showed gains of between 20 and 40% of dry-land muscular strength (Strass, 1988). These measurements occurred in isometric conditions that may not be related to swimming actions. Swimming actions are dynamic and isometric testing may therefore represent a lack of specificity (Baker et al., 1994). Nonetheless, dry-land muscular strength gains allowed significant improvements in swimming performance over 25 and 50m (4.4 and 2.1%, respectively). In this investigation, only the upper body was exercised through elbow extension exercises and the use of free weights through maximal strength S&C methodologies. Weight lifting equipment was used in the remaining investigations (Aspenes et al., 2009; Girold et al., 2007, 2012; Hong-Sun et al., 2009).

S&C training (S) based on maximal strength was applied for twelve weeks (2 sessions per week) and compared to resisted – and assisted – sprint (RAS) training (Girold et al., 2007). These authors found improvements in the 50m time of the S (2.8±2.5%) and RAS (2.3±1.3%) groups compared to the control group (0.9±1.2%). Improvements in muscle strength were more significant in the S group than in the RAS group. In contrast, the RAS group presented an increase in stroke rate in their 50m freestyle performance. It was suggested that the application of S or RAS training was more effective than swimming training alone. These results were then corroborated by other researchers (Aspenes et al., 2009; Girold et al., 2012). After eleven weeks (2 sessions per week) of combining maximal strength training and high-intensity interval swimming training (HIIT) the results were positive in strength, tethered swimming force and 400m freestyle performance (Aspenes et al., 2009). However, no improvements occurred in short distance performance (50m or 100m) and biomechanical variables (stroke length and stroke rate). With the ability to exert force in the water a decisive factor over short distances (Morouço et al., 2011; Stager & Coyle, 2005), it would be of great importance to clarify the lack of effect in sprint distances. Moreover, the positive effects on tethered swimming and 400m freestyle were correlated in the female subjects of the intervention group. These results appeared to suggest that in-water force exertion may be important in middle swimming distances for female swimmers. However, it was not determined if the positive effects in swimming performance were a result of the combined methodologies or if a crossover between HIIT and S&C sessions occurred. HIIT sessions were composed of 4 × 4 min of high intensity interval training. These efforts and durations may be better associated with the 400m improvements.

An investigation compared the effects of a S&C program (S) with those of an electrical stimulation (ES) program, both combined with a swimming program, over four weeks, on adult swimmers (Girold et al., 2012;). Additionally, the authors tried to verify if training effects lasted four weeks after the training period ended. The S&C training sessions were performed 3 times per week. The authors reported an increase in swimming velocity for both S and ES group (2% and 1.7%, respectively), at the end of the four-week intervention. Stroke length was increased only for the S group. Improvements in swimming velocity were maintained four weeks after the end of the program in both groups and no differences were reported between male and female swimmers. It seems that both methods were more efficient in improving swimming velocity than swimming training alone. However, electrical stimulation demands a higher investment from most swimming clubs than a S&C program. Yet, this investigation only analyzed sprint performance (50m freestyle) in high-level swimmers. Further investigations must be conducted with middle and long swimming distances as well as with swimmers operating at different competitive levels and with varying amounts of swimming expertise.

Interestingly, only four weeks and 12 sessions (18 repetitions per session) were sufficient to verify a positive effect in swimming performance. This volume was clearly less than that reported by other studies: 24 sessions with 15 repetitions per session (Strass, 1988), 24 sessions with 18 repetitions per session (Girold et al., 2007), 22 sessions and 15 repetitions per session (Aspenes et al., 2009), and 72 sessions in the first cycle of S&C training and 80 sessions in the second cycle (Hong-Sun et al., 2009). This may indicate that lower volumes and high intensity S&C training may induce less neuromuscular fatigue and therefore improvements, leading to subsequent improved swimming performance.

S&C training for a national team of male swimmers (18.50±2.07 years) was divided into two cycles applied according to the periodization of their main competitions (June and December) (Hong-Sun et al., 2009). The first cycle lasted eighteen weeks with 4 sessions per week, emphasizing peak muscle strength, power and muscle endurance maintenance. The second cycle lasted for twenty weeks with 4 sessions per week of maximal strength, power and muscle endurance maintenance. Although several dry-land tests were performed, no swimming tests were performed to assess effectiveness of this S&C training program. Yet, the authors reported 18 personal records, 8 Korean records and 3 Asian records in those two main competitions. Nevertheless, there was no statistical analysis of the influence of the S&C training on swimming performance and there was no control group. Authors concluded that S&C training program enhanced muscular functions and swimming performance, nevertheless with a significant decrease in flexibility. Although this was the investigation carried out over the largest number of weeks, the lack of swimming tests, some dubious procedures and reports (contradictory information on the number of subjects and weeks throughout the text) necessitates caution when analyzing its conclusions.

It is common to use the 1RM methodology to define the external load of exercises. However, when analyzing the influence of S&C training in short distances, where power is crucial (Barbosa et al., 2015; Morouço et al., 2011; Stager & Coyle, 2005; Toussaint, 2007), it is questionable whether 1RM is the force parameter with the higher association with power. For instance, the velocity with which exercises are performed at is crucial to increasing the specificity of S&C exercises (González-Badillo & Sánchez-Medina, 2010) and overall power output. S&C training based on power (generation of force over a very short period of time) was applied in three investigations (Garrido et al., 2010; Manning et al., 1986; Sadowski et al., 2012). However, no positive effects in swimming performance were reported by any of those investigations. A S&C training program based on speed and explosiveness (power) was applied to adolescent swimmers (16.49 ± 0.84 years) (Manning et al., 1986). Each training session consisted of 11 exercises (upper and lower body exercitation), performed in 2 sets of the maximum number of repetitions during one minute. This was performed 3 times a week over nine weeks, using weight lifting equipment and an ergometer bicycle. Intensities varied from 30 to 50% of 1RM with a progressive increase of 10% every three weeks. Although there were no significant differences, authors presented improvements of -0.98 s, -0.06 s and -1.30 s for the 50, 100 and 200 yard tests, respectively. In swimming, these small improvements can be remarkable, particularly in short swimming distances.

A S&C program of circuit training over six weeks (3 sessions per week), comprising 6 sets of 50 s exercitation and 10 s of rest on a specific hydro isokinetic ergometer device each session, led to improved tethered swimming propelling force but not different values of dry-land strength, stroke kinematics and swimming performance (25m front crawl) (Sadowski et al., 2012). In spite of the effort to mimic underwater movement, it was concluded that S&C training was not specific enough to improve swimming performance. Isokinetic conditions are not related to in-water actions that are performed with different velocities along the stroke. It is crucial that S&C exercises and tests stimulate the muscles used in swimming and that muscle tension be related to in-water conditions (Barbosa et al., 2013). In addition, only 3 swimmers were sprinters (n = 26), which could have influenced the results, as swimming performance was measured in a 25m front crawl test.

The other study on power training program was the only one applied to prepubescent swimmers and combined dry-land S&C training and aerobic swimming training (Garrido et al., 2010). The swimming training program was complemented with 2 sessions per week of S&C training (bench press and leg extension, medicine ball throwing with 1kg, countermovement jump alone and with a 30cm box) over eight weeks. Although dry-land improvements were reported, no swimming performance improvement was found. The authors suggested that swimmers' competitive level could affect performance improvements. Yet, a detraining period (S&C training cessation and maintenance of swimming training) of six weeks showed that, although strength parameters remained stable, swimming performance still improved. It is reasonable to wonder if swimmers benefit from an adaption period to S&C gains, while performing swimming training. The literature showed that there was no risk of losing strength and power during short cessation periods of a S&C training program (Häkkinen et al., 1990; Wilmore & Costill, 1988), and the effect on maximal power was smaller than that observed for maximal force (Bosquet et al., 2013). So, it seems reasonable to investigate whether specific in-water training can be useful in taking effective advantage of S&C program improvements, after cessation (Garrido et al., 2010). This continuous stimulation could be the bridge between S&C gains and swimming performance. However, further investigations with different ages, competitive levels and post-evaluation periodization must be conducted to clarify this issue.

Finally, three studies based their investigations on different protocols from those already discussed. S&C training with weight lifting equipment and free weights was conducted over eight weeks (3 sessions per week) (Tanaka et al., 1993). Even though volume per session was presented (3 sets of 8-12 repetitions), intensity was not. The authors only reported an increment of 25-35% in the resistance used over the eight weeks of S&C. There were no improvements in swimming performance after the S&C training period, possibly due to the overload of a cycle of competitions during the S&C training. The potential lack of control of the load and swimming competitions could have jeopardized results. However, the authors concluded that the lack of specificity of S&C training in relation to in-water actions (swimming) was the main reason for the absence of positive transferability of strength gains. These results were later corroborated (Trappe & Pearson, 1994) through the comparison of S&C weight assisted training (WAT) and S&C free weights training (FWT). The investigation was carried out over six weeks (2 sessions per week). In every session both groups were instructed to reach volitional fatigue (WAT) and exhaustion (FWT). No differences in short (22.9m) and medium

(365.8m) distance swimming performance were found between experimental groups. However, results from this study may be misleading, since there was no control group and groups were composed of only a small number of swimmers (5 in each group). In addition, S&C training was implemented over six weeks out of a total of twelve weeks' follow-up, and the evaluation was performed in weeks 4 and 12. These confounding factors did not allow for a consistent interpretation of results.

Recently, an investigation tried to quantify the effects of an isolated core-training program on 50m front-crawl (Weston et al., 2015). A S&C program was implemented 3 times per week over twelve weeks and included exercises which aimed to work out the lumbopelvic complex and upper region extending to the scapula. Each session comprised isometric (prone bridge and side bridge) and dynamic (bird dog; leg raise; overhead squat; sit twist and shoulder press) exercises. Every two weeks, volume per session was increased and varied between 60 s to 360 s hold; 30 to 90 repetitions and 3 to 7kg of load. A large beneficial effect on 50m swim time (-2.0%; 90% confidence interval -3.8 to -0.2%) was found after the training period. Good core stability is supposed to have a positive influence on the efficient relationship of force production between upper and lower limbs (Willardson, 2007). A question to be raised relies on the isometric conditions of most included exercises in S&C training. Swimming actions are dynamic and so it was expected that swimming specificity could be negatively affected. To the best of our knowledge, this is the first investigation on the effects of S&C core training on swimming performance and further investigation is needed.

In a brief analysis, it seems that maximal strength is the most effective methodology for improving performance, mainly in short distances. However, different low-volumes training programs seem to induce positive effects. In adolescent swimmers, S&C training ranging from six to twelve weeks and with 2 to 4 (approximately 24 sessions) sessions per week, is suggested to improve swimming performance. In adulthood and at a high competitive level, a S&C training program of four weeks (3 sessions per week) is suggested to improve swimming performance. In each session, the volume should vary from 2 to 3 sets of 3 to 5 repetitions, according to the chosen level of intensity. Rest intervals should vary between 2 to 5 minutes. Concerning the intensities, high velocities and loads ranging from 80 to 90% of 1RM are associated eith improvements. Nevertheless, there should be caution when applying S&C programs near competitions or over high volumes of swimming training, in order to avoid overreaching and overuse injuries. S&C based on maximal strength requires adjustments in swimming to avoid overloading of the peripheral and central fatigue mechanism (Linnamo et al., 1997). Most of the studies reporting improvements used weight lifting equipment that may not be affordable for many swimming clubs due to financial constrains. With regard to prepubescent swimmers, there were no positive effects in swimming performance associated with S&C training programs. Nevertheless, S&C training based on power reported a tendency to improve swimming performance in this age range. However, conclusions are not easy to draw as many confounding factors seem to exist in the available investigations.

4.4. Effects of S&C on starts and turns

Starts and turns are explosive actions usually associated by coaches and swimmers with the strength of the swimmer or to dry-land S&C training, despite the scarcity of scientific evidence. These actions in swimming require high values of power output. Therefore, explosiveness is usually thought of as the main aim of S&C training and supports the greater use of plyometric S&C training. In fact, three of the four investigations analyzed the use of plyometric training to improve starts and turns performance (Bishop et al., 2009; Cossor et al., 1999; Potdevin et al., 2011). Positive effects of plyometric training were reported in two studies (Bishop et al., 2009; Potdevin et al., 2011), while the third did not find a positive result (Cossor et al., 1999).

A study examined the effects of a plyometric training program on freestyle tumble turns, in age group male swimmers (Cossor et al., 1999). The subjects performed from 300 to 450 ground contacts per session, 3 times per week, over twenty weeks. There were no significant differences between experimental and control groups, for any measure. Despite the adoption of low to moderate intensities, one can assume that overload may have impaired results. Moreover, the control group performed 90 minutes of swimming training and the experimental group performed 75 minutes, adding 15 minutes of S&C training. Although there were no significant differences between the experimental and control group, in most of the parameters assessed, improvements (%) in the control group were higher than those in the plyometric group. Moreover, no differences in turning performance were found between swimmers who attended fewer S&C sessions (<49%) when compared to those who attended more S&C sessions (>75%). This raises questions over the efficiency of a plyometric program, in early ages, and indicates that swimming training seems to be enough to improve freestyle turns. Moreover, the authors claimed that some maturational and growth changes could positively influence performance (Malina et al., 2004; Meylan et al., 2014), rather than plyometric training.

Plyometric training program was also tested with regard to starts, showing some positive results (Bishop et al., 2009; Potdevin et al., 2011). First, an investigation aimed to identify the effect of plyometric training, when added to habitual training regimes, on swim start performance (Bishop et al., 2009). Significant improvements were found between baseline and post-evaluations for plyometric training group when compared to the control group, in the time taken to reach 5.5m (-0.59 s vs. -0.21 s; $p<0.01$) and velocity of take-off to water contact (0.19 ms-1 vs. -0.07 ms-1; $p<0.01$). These results can be determinant for a race performance; however, there should be some caution in assessing these effects as no information was provided regarding maturation level or even the sample’s gender. The latter investigation mentioned (Potdevin et al., 2011) corroborated these positive results (Bishop et al., 2009), presenting the effects of the maturational status (Tanner stages of 3 and 4) and finding no differences between groups. Investigations were carried out over eight (Bishop et al., 2009) and eleven (Potdevin et al., 2011) weeks, with total volume per session higher in the most recent one (Potdevin et al., 2011). Both investigations increased the intensity from low to high, increased the height, from 0.22 to 0.79m (Bishop et al., 2009), and from 0.21 to 1m (Potdevin et al., 2011), and increased the number of jumps per session from 37 to 192 (Bishop et al., 2009), and from 100 to 264 (Potdevin et al., 2011).

Improvements reported in the 50 and 400m front crawl velocity (Potdevin et al., 2011), suggest a positive influence on starts and turns within overall swimming performance. This positive influence was, according to the authors, explained by the significant correlation between improvements in Squat Jump (SJ) and velocity in 50m front crawl. As SJ mechanical and muscular requirements are similar to those of starts, the authors concluded that improvements in swimming velocity were due to this phase of the race. Despite this idea of "transferability", there were no specific results on starts and turns of the swimmers.

Only one study on starts was focused on power and general strength training (Breed & Young, 2003). The goal was to improve vertical jump ability, on the grab, swing and rear-weighted track starts in swimming. For that purpose, 16 exercises were performed over nine weeks. Vertical jump was emphasized, as well as upper and lower body strength and power maintenance. The training program consisted of higher volumes and intensities in the first and third sessions of the week (3 sessions per week). Adjustments were made every three weeks, increasing volume and intensity on the first and third session and decreasing on the second session of the week, until nine weeks of training were completed. Despite significant improvements in dry-land strength (leg power and jumping ability), no significant improvements were found for flight distance when using any start technique. The authors suggested that improvements in jumping ability were not transferred to diving skills. Information on the periodization of different moments of this investigation was not provided. It would be of interest to know whether the teaching period of starts or the starts training were concurrent or not to the S&C program. Nevertheless, the conclusions of this investigation must be analyzed with caution as the sample comprised non-swimmer subjects.

Summarizing the evidence of S&C training on starts and turns, we could conclude that plyometric training is the most effective in improving starts and turns. S&C training ranging from six to eight weeks and with 2 sessions per week is suggested to improve performance. In each session subjects are allowed to perform between 1 to 6 sets and 1 to 10 repetitions, according to the chosen level of intensity. Rest between sets should vary from 60 to 90 seconds. This training program should be progressive, starting with low volumes and intensities to allow swimmers to adapt to plyometric training specificities. Moreover, exercises should be performed in as similar a way as possible to in-water movements. It would be of interest to analyze S&C effects in older and more skilled swimmers. Transferability of S&C gains to swimming performance remains controversial. Therefore, it would be of interest to compare plyometric training to other methods of S&C training, and thus analyze the efficiency of different methods.

5. Conclusions

S&C training in swimming is a common practice used by coaches and swimmers to enhance performance and to prevent injuries. Nevertheless, there is no consensus on the effectiveness of S&C programs on swimming performance. Some limitations were found in the literature regarding this issue. Most investigations involved adolescent and adult swimmers, and S&C programs with prepubescent swimmers are scarce and do not allow for valid conclusions. Younger swimmers should participate in S&C programs, not only to enhance performance but also to build a solid foundation for preventing sports-related injuries. Moreover, few studies separated the samples and compared the gender effect, and those that did gave no clear results. With regard to the type of S&C training, maximal strength training is associated with swimming performance improvements in the oldest swimmers, particularly in relation to short distance (25 and 50m) races. However, it is questionable whether this is an adequate methodology to apply to younger swimmers and those at a lower competitive level. Weight lifting equipment is the most used training tool in research, nonetheless we must be aware that most swimming clubs may not have access to these resources. Additionally, young swimmers may not have the expertise and experience to use this equipment.

The influence of force exertion cannot be determined, as there were few investigations analyzing techniques other than freestyle. Likewise, the influence of S&C in swimming distances above 200m was not determined. Only one investigation assessed a middle distance (400m) and presented positive results.

Based on this review, it is suggested low-volume S&C training based on maximal strength, ranging from six to twelve weeks of 2 to 4 (approximately 24 sessions) sessions per week, for improving swimmers' performances. In each session, coaches should vary from 2 to 3 sets and with 3 to 5 repetitions, according to prescribed intensity. Rest intervals should vary between 2 to 5 minutes and the intensity should vary from 80 to 90% of 1RM.

To improve starts and turns, a S&C training ranging from six to eight weeks and with 2 sessions per week is suggested. In each session, swimmers should perform between 1 to 6 sets and 1 to 10 repetitions, according to the chosen level of intensity. Rest between sets should vary from 60 to 90 seconds. Volume should be progressive, such as raising intensity from low to high within the S&C training program. It is recommended to start with low volumes and intensities to allow swimmers to adapt to plyometric training specificities. Only recommendations for adolescent swimmers were presented, since no studies with older swimmers were included in this review.

Although there is a lack of coherent scientific evidence, S&C training remains a commonly prescribed swimming practice. So, it seems fair to argue that further investigations should be carried out. To control for some gaps in protocols and to enable the generalizability of conclusions, randomized controlled trials (RCT) should be conducted. Future investigations should explore the following topics:

(i) differences in S&C training effects induced by age and gender;
(ii) effects of S&C training in relation to different swimming techniques;
(iii) effects of S&C training in middle and long swimming distances;
(iv) effects of S&C training experimental periods over a season, to evaluate long-term effects;
(v) effects of a swimming adaption period after S&C cessation to allow transferability of strength gains to swimming.

Chapter 3.

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 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

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). 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 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; Gatta et al., 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 et al., 2003; Kjendlie & Thorsvald, 2006; Psycharakis et al., 2011; Amaro et al., 2014; Gatta et al., 2016) suitable to evaluate aerobic (Pessôa-Filho & Denadai, 2008) and anaerobic (Ogonowska et al., 2009; Morouço et al., 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 et al., 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 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 et al.,1986; Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006), although some kinematical changes have been reported (Maglischo et al., 1984; Psycharakis et al., 2011).

In the most common apparatus, fully-tethered and non-elastic cables are employed (Magel, 1970; Yeater et al., 1981; Christensen & Smith, 1987; Ria, Falgairette, & Robert, 1990; Sidney et al.,1996; Taylor et al., 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 et al., 1983) or a force transducer (e.g. Dopsaj et al., 2000; Morouço, Keskinen et al., 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 et al., 2014; Morouço et al., 2015a). 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 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 (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 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 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 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), 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 & 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 (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 regards 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 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 et al. (2011b) 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 et al., 1988; Deschodt et al., 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 et al. (1996) also noted this fact in terms of energy consumption in front crawl swimming. Recently, Morouço et al. (2015b) 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 et al., 2009; Sanders et al., 2011). Tethered swimming could also be used to identify bilateral upper limb asymmetries (dos Santos et al., 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. (2015a) 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 et al., 2010; Formosa et al., 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 et al., 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 et al., 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. (2016) 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 males and 15 females) 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.

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 et al. (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 et al. (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 (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 et al., 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 et al., 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 et al., 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 et al. (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 et al. (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.

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.

Chapter 4.

Reliability of tethered swimming evaluation in age group swimmers

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Abstract

The aim of the present study was to examine the reliability of tethered swimming in the evaluation of age group swimmers. The sample was composed of 8 male national level swimmers with at least 4 years of experience in competitive swimming. Each swimmer performed two 30 second maximal intensity tethered swimming tests, on separate days. Individual force-time curves were registered to assess maximum force, mean force and the mean impulse of force. Both consistency and reliability were very strong, with Cronbach's Alpha values ranging from 0.970 to 0.995. All the applied metrics presented a very high agreement between tests, with the mean impulse of force presenting the highest. These results indicate that tethered swimming can be used to evaluate age group swimmers. Furthermore, better comprehension of the swimmers ability to effectively exert force in the water can be obtained using the impulse of force.

Key words: swimming, training and testing, propulsive force, front crawl.

Introduction

There are several factors that affect swimmers' performance such as: swimming technique, strength and physiological measures. Among these, force exerted in water is a major factor that influences success in swimming (Keskinen et al., 1989; Girold et al., 2007; Barbosa et al., 2010) and its importance is higher as the swimming distance diminishes (Stager and Coyle, 2005; Morouço et al., 2011a). Thus, the measurement of swimming propulsion is of great interest to sports biomechanics, therefore its evaluation is highly complex (Payton et al., 2002; Marinho et al., 2011). In order to determine the force exerted by a swimmer in an identical context to the competition (i.e. in water), tethered swimming has been one of the most frequently used methodologies in the field of biomechanics (Akis and Orcan, 2004).

In the study by Magel (1970), a polygraph was used to characterize the four swimming techniques of 26 highly trained college swimmers along a tethered swimming test of 3 minutes. The author found that high levels of force production could be achieved in shorter durations of tethered swimming and that the measurement of these forces could be a reliable indicator to estimate the force produced during free swimming. Furthermore, Yeater et al. (1981) conducted an experiment using fully tethered swimming with 18 male athletes. Positive correlations were found between mean tethered force and velocity in front crawl and negative correlations between crawl velocity and the peak/mean force ratio. Since the study of Yeater et al. (1981), several investigations have shown significant relationships between tethered forces and swimming velocity (e.g. Keskinen et al., 1989; Dopsaj et al., 2000; 2003), differing according to age and maturity (Vorontsov et al., 1999; Taylor et al., 2001), competitive level (Sidney et al., 1996) and swimming distance (Yeater et al., 1981; Morouço et al., 2011a).

Nowadays, technological improvements allow an easy and operative way of assessing individual force - time curves (Toubekis et al., 2010), which seems to be a reason for considering tethered swimming as a useful and reliable methodology for the evaluation and control of swimmers training (Dopsaj et al., 2003; Kjendlie & Thorsvald, 2006). It evaluates aerobic (Pessôa-Filho & Denadai, 2008) as well as anaerobic (Ogonowska et al., 2009; Morouço et al., 2012) energetic profiles, with similar muscular activity (Bollens et al., 1988) and oxygen consumption (Lavoie & Montpetit, 1986) as in free swimming. Although it may induce some kinematic changes (Maglischo et al., 1984; Psycharakis et al., 2011), it is assumed that the force produced in this test is similar to the force required to overcome the drag in freestyle swimming (Dopsaj et al., 2000; 2003; Morouço et al., 2014). However, swimming with no displacement and the effort induced by this test could affect the results. Hence, it is recommended that swimmers have some experience in tethered swimming and they should be given the opportunity to be familiarized with the test procedures before an evaluation (Psycharakis et al., 2011). Evidence about the familiarization with the test procedures in previous studies is scarce. Thus, those results could have been underestimated by the initial difficulty of familiarization with the test.

Several studies have used different measures of force production in tethered swimming tests such as: average force (Ria et al., 1990; Taylor et al., 2001; Morouço et al., 2011a), average of maximum force (Yeater et al., 1981; Fomitchenko, 1999), peak maximum force (Christensen & Smith, 1987; Keskinen et al., 1989), impulse of force (Dopsaj et al., 2000; Dopsaj et al., 2003; Morouço et al., 2014) and fatigue index (Morouço et al., 2012) which has spawned controversy about which one could be more associated with performance. Taylor et al. (2001) concluded that only average force was a reliable parameter to associate with swimming velocity in age group swimmers. On the opposite, Dopsaj et al. (2000) and Morouço et al. (2014) concluded that the impulse of force had a better relationship with swimming performance. These discrepancies led us to question whether the measures to be assessed could differ depending on the swimmers' level or if they were a result of the lack of evaluation of the impulse of force (Taylor's et al., 2001). If one considers that propulsion may occur along the whole underwater phase of the stroke (Marinho et al., 2011) and not only in one specific moment (maximum force) and if a lower amount of force applied during a longer period can mean equal or further advancement of the swimmer, then the impulse of force should be considered. These inconsistencies reveal the need for further studies to clarify the methodological options. Additionally, it is clear in the literature that most studies with tethered swimming tested high level or elite swimmers. Thus, it is crucial to understand whether this methodology is reliable and provides benefits to age group swimmers whose technique development is still scarce.

Therefore, the aim of the present study was to examine the reliability of tethered swimming evaluation with age group swimmers. It was hypothesized that, as in adult swimmers, tethered swimming can be used as a reliable methodology to evaluate age group swimmers.

Material and Methods

Participants

The study involved 8 male swimmers that volunteered for the experiment (age 15.3 ± 1.17 years; body height 1.68 ± 0.06 m; body mass 57.2 ± 9.93 kg; span 1.70 ± 0.06 m. The personal best for the 50 m freestyle long course was 28.59 ± 1.47 s. The subjects had at least 4 years of experience in competitive swimming participating in national level competitions. No swimmer suffered from any illness or any other restrictions that could hinder their performance during the tests. All procedures were in accordance with the Declaration of Helsinki in respect to human research. All subjects and their parents gave their consent and the study was approved by the Scientific Committee of the University of Beira Interior.

Apparatus

The testing apparatus consisted of a load-cell system (Globus™, Codognè, Italy) recording at 100 Hz with a measurement capacity of 4903 N. The load-cell was connected by a cable to a Globus Ergometer data acquisition system (Globus™, Codognè, Italy) that exported the data in ASCII format to a PC. The load-cell was attached to the starting block (Figure 1) through a chain locked with a certified aluminum carabiner (Petzl CE EN 362, CE EN 12275, type K - major axis strength: 28 kN). It was proofed and tested prior to testing and between tests. The load-cell calibration was verified with the use of 5 kg, 10 kg and 20 kg standard weights. Subjects were wearing a nylon belt attached to a steel cable with a certified aluminum carabiner (Petzl CE EN 362, CE EN 12275, type K - major axis strength: 28 kN) with 3.5 m length (0.5 cm diameter). The attachment of the load-cell to the starting block created a 5.7° angle in relation to the water surface.

Figure 1. Experimental apparatus of the tethered swimming tests

Procedures

Before tests and aiming to familiarize subjects with the methodology, several training sessions had been conducted during which the subjects engaged in different tethered swimming exercises with various intensities and durations.

For test 1, after a 1000 m moderate intensity warm-up (400 m swim, 100 m pull, 100 m kick, 4 x 50 m at increasing speed, 200 m easy swim) each subject executed a maximal intensity front crawl tethered swimming test. Preceding the starting signal, swimmers adopted a horizontal position with the cable fully extended starting the data collection only 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 (Morouço et al., 2011a). The duration of the exercise was 40 s with an initial phase of 10 s with moderate intensity and 30 s at maximum intensity. Participants were told to follow the breathing pattern they would normally apply during a 50 m front crawl event, and were verbally encouraged throughout the tests to maintain maximal effort over the duration of the tests. The end of the test was marked through an acoustic signal. Twenty four hours later, for test 2, the same experimental procedures were conducted with the same conditions.

Experiments were carried out during a competitive period to ensure that the subjects were in a prime training period. All tests occurred in the same 25 m indoor swimming pool (27 - 28° C of water temperature).

Data Analysis

Tethered swimming data were exported to a signal processing software (AcqKnowledge v.3.7. Biopac Systems, Santa Barbara. USA) to assess the individual curves of force (y axis) along time (x axis). Data were filtered with a 4.5 Hz cut-off low-pass according to residual analysis (residual error versus cut-off frequency). As the force vector in the tethered system presented a small angle in relation to the water surface, data were corrected computing the horizontal component of force (Taylor et al., 2001). The following measures were estimated for each participant: maximum force (maxF) as the higher value obtained in individual force-time curve; mean force (meanF) as the mean of F values registered along the 30 s; mean impulse of force (impF) as the quotient of the sum of single-stroke impulse and the number of strokes performed in the 30 s.

Statistical analysis

Descriptive statistical analysis was used for the calculation of test/retest mean values (mean), standard deviation (SD), minimum measure value (min), maximum measure value (max) and coefficient of variation (cV%) for all measures. The normality assumption was checked by Shapiro Wilk tests (SW), thus parametrical statistics analyses were applied. Relative and absolute reliability were calculated through the Intraclass Correlation Coefficient (ICC) and Coefficient of Variation (cV%), respectively. General reliability was calculated using Cronbach's alpha for internal consistency of measures and the Bartlett's Test of Sphericity as a measure that determines the homogeneity of variances. SPSS for Windows¤ (version 20.0, Chicago, IL, USA) was used for all statistical procedures. The level of statistical significance was set at $\rho < 0.05$.

Results

Table 1 contains the basic descriptive statistics results of both tests. Results of the 3 assessed measures were similar between the test and retest. The coefficient of variation which can be considered as a measure of descriptive homogeneity of raw results, ranged between 14.7% and 23.1%, and 17.6% and 24.4% for the test and retest, respectively.

Distribution of used measures did not differ from the model of hypothetically normal p values from 0.21 (Fmax) to 0.78 (ImpF) for the test, and 0.26 (meanF) to 0.71 (impF) for the retest.

Table 1. Basic descriptive statistics

Measures	Test	Mean	SD	Min	Max	cV%	SW Z ratio	SW p value
maximum force (N)	1	220.66	50.94	165.69	300.99	23.08	0.886	0.214
	2	217.86	53.07	162.81	306.29	24.35	0.913	0.372
mean force (N)	1	86.10	12.62	71.47	105.95	14.66	0.908	0.338
	2	86.92	16.15	68.93	111.62	18.58	0.895	0.261
impulse of force (N.s)	1	77.68	12.77	61.11	96.43	16.44	0.957	0.783
	2	75.71	13.31	58.64	95.86	17.58	0.950	0.708

SD=standard deviation; Min=minimum; Max=maximum; cV%= Coefficient of variation; SW=Shapiro Wilk

Table 2 presents the results of single reliability of used measures. Cronbach's alpha for the reliability among the used measures ranged from 0.970 for maximum force to 0.995 for the impulse of force. Results of the Bartlett's Test of Sphericity showed that x^2 was statistically significant in all measures (p<.0001). Intraclass Correlation Coefficient was excellent for all measures ranging from 0.942 for maximum force to 0.990 for the impulse of force

Table 2. Results of single reliability of used measures

Measures	Cronbach's alpha	BTS	ICC
maximum force	0.970	x^2 = 12.038; p = 0.001	0.942
mean force	0.977	x^2 = 19.135; p = 0.000	0.955
impulse of force	0.995	x^2 = 22.060; p = 0.000	0.990

BTS = Bartlett's Test of Sphericity; ICC = Intraclass Correlation Coefficient

Discussion

The aim of the present study was to examine the reliability of tethered swimming evaluation with age group swimmers. Overall results showed that tethered swimming was a highly reliable methodology to evaluate age group swimmers in the water.

In regard to internal consistency of measures, results showed a very high agreement for all metrics. These data may be considered excellent, which is in accordance with previous studies conducted with older and more skilled swimmers (Kjendlie & Thorsvald, 2006; Dopsaj et al., 2003). For instance, Dopsaj et al. (2003) evaluated 10 high-level swimmers and obtained similar reliability values. Small biases may be due to the swimmers level, but also to the duration of the tests. With an increased duration (60 s), these authors emphasized the importance of swimming technique devaluing the importance of force. On the other hand, with a smaller duration, our swimmers were able to keep the effort closer to maximal intensity throughout all test duration. Aiming to investigate the test-retest reliability in a 10 s maximal tethered swimming test, Kjendlie & Thorsvald (2006) assessed the maximum force of 32 swimmers. These authors stated that subject variations were very small, obtaining Cronbach's alpha of 0.992. This value is in accordance with the obtained data in the present study that also assessed the reliability of other measures (mean force and impulse of force). Thus, tethered swimming, which has been used with high-level swimmers, seems to be also a highly reliable procedure to evaluate age group swimmers.

Technique development and strength improvement have been two issues of major concern for swimming biomechanics over the years. For instance, Newton et al. (2002) reported that an optimum level of strength and swimming power is necessary for good performance. Vorontsov (2010) proposed that during the pubescent period (12-14 years for girls and 14-16 years for boys) maturation and all its implications provide an optimal biological background for development of the anaerobic energy system, maximal power, specific muscular endurance, and speed-strength abilities. However, in the development of youth swimmers, especially at younger ages (12 and 14 years old) training focuses specifically on improving swimming technique (Barbosa et al., 2013), relegating the physical condition to later stages. We could state that from this age on swimmers begin the stage of specialization in a swimming technique and/or in a swimming distance (Morouço et al., 2011b). As a result, it is relevant to emphasize other measures, which include strength, seeking balance between the development of technique and the ability to effectively exert force in the water. Thus, tethered swimming may emerge as a support tool for coaches and researchers in this crucial stage of the swimmers' career.

It is well known that force exerted in water is a major factor to enhance swimming performance (Barbosa et al., 2010). Therefore, several methodologies have been used to evaluate the force exertion that a swimmer can produce in the water. One of those methodologies uses a load-cell to register the forces that a swimmer exerts when tethered. However, the question about which measures should be considered in tethered swimming evaluations remains open. On the one hand, Taylor et al. (2001) concluded that only average force was a reliable parameter to associate with swimming velocity in age group swimmers, to the detriment of maximum force peaks. On the other hand, Dopsaj et al. (2000) stated that the average impulse of force had a better relationship with swimming performance in elite sprinters. In our experiment, consistency of the impulse of force was higher than consistency of maximum or mean force. As aforementioned, propulsion may occur along the whole underwater phase of the stroke (Marinho et al., 2011). In a recent study, Morouço et al. (2014) have showed that the impulse of force presents a linear relationship with free-swimming velocity. These authors indicated previous studies that only assessed the maximum force that a swimmer exerts in the water, underestimated the role of stroke force mechanics in swimming performance. Indeed, maximum force comprises information about a single point per stroke: when maximum force is reached. However, according to the integral of force with respect to time, propulsion can occur throughout the underwater 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. Our results indicate that, also for age group swimmers, the impulse of force is a feasible measure and should be taken in consideration.

This study has some limitations. First, a sample size of 8 swimmers does not assure an extensive generalizability. Second, swimmers had to be attached to the starting block by a steel cable, which produced a small angle in relation to the water surface. This clearly could lead to a change in the swimmer streamline. And third, the swimmers might have inhibited their leg kicking in an attempt not to touch the cable with their feet.

In conclusion, according to our results, the 30 s maximal intensity tethered swimming provides a reliable tool to evaluate age group swimmers. Thus, the current study provides promising results for the application of tethered swimming to the evaluation of age group swimmers, as well as remarks for future research in this area. Systematic evaluations throughout the season may be an operational procedure for coaches to examine the ability of their swimmers to exert force in the water. Finally, it is suggested to assess the impulse of force as a more reliable metric to analyze the tethered forces.

Chapter 5.

Effects of dry-land strength and conditioning programs in age group swimmers

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Abstract

Even though dry-land S&C training is a common practice in the context of swimming, there are countless uncertainties over its effects in performance of age group swimmers. The objective was to investigate the effects of dry-land S&C programs in swimming performance of age group swimmers. A total of 21 male competitive swimmers (12.7 ± 0.7 years) were randomly assigned to the Control group (n = 7) and experimental groups GR1 and GR2 (n = 7 for each group). Control group performed a 10-week training period of swim training alone, GR1 followed AU3 a 6-week dry-land S&C program based on sets/repetitions plus a 4-week swim training program alone and GR2 followed a 6-week dry-land S&C program focused on explosiveness, plus a 4-week program of swim training alone. Results for the dry-land tests showed a time effect between week 0 and week 6 for vertical jump ($p < 0.01$) in both experimental groups, and for the GR2 ball throwing ($p < 0.01$), with moderate to strong effect sizes. The time X group analyses showed that for performance in 50 m, differences were significant, with the GR2 presenting higher improvements than their counterparts ($F = 4.156$; $\rho = 0.007$; $\eta^2_p = 0.316$) at week 10. Concluding, the results suggest that 6 weeks of a complementary dry-land S&C training may lead to improvements in dry-land strength. Furthermore, a 4-week adaptation period was mandatory to achieve beneficial transfer for aquatic performance. Additional benefits may occur if coaches plan the dry-land S&C training focusing on explosiveness.

Key words: swimming, exercise testing, sprint performance, explosiveness.

Introduction

Strength and conditioning (S&C) training is a common practice in most sports, aiming to enhance performance and/or prevent injuries (Leveritt et al., 1999; Barbosa et al., 2013; Faigenbaum et al., 2009, 2015). Yet, the S&C training design should be specific for the requirements of the concerned sport. In swimming, performance is highly dependent on strength and muscular power (Keskinen et al., 1989; Newton et al., 2002; Girold et al., 2007; Barbosa et al., 2015), being the ability to exert force in the water a decisive factor over short distances (Stager & Coyle, 2005; Morouço et al., 2011). Thus, swimming coaches traditionally apply dry-land S&C programs in their training sessions (Aspenes et al., 2009; Garrido et al., 2010; Sadowski et al., 2012; Barbosa et al., 2013) even if consensus on the specific benefits to a swimmer's performance has not yet been corroborated in literature (Tanaka et al., 1993; Trappe & Pearson, 1994; Girold et al., 2007; Sadowski et al., 2012). It is suggested that transferability of dry-land strength gains to swimming performance depends on the interaction of several parameters such as strength (dry-land and in-water) and biomechanics (kinematics and kinetic) (Barbosa et al., 2010b). There are many coaches who assume that strength training could negatively affect a swimmer's ability and, consequently, increase drag forces (Newton et al., 2002). This is mostly due to the muscular hypertrophy and flexibility decrease, commonly identified as outputs of strength training. Nevertheless, during the prepubescent stage, muscle hypertrophy is not believed to be the primary factor in strength improvement (Tolfrey, 2007), as neuromuscular adaptations are identified as the main explanations for strength gains (Faigenbaum et al., 2009, 2015). However, the number of investigations able to clarify this subject is scarce, most likely due to financial and ethical issues, particularly if we look for research with age group swimmers (Barbosa et al., 2010a).

Apart from the above-mentioned need of clarification, it is suggested by deterministic models (Barbosa et al., 2010b) that muscular strength may influence technique and, therefore, performance. Additionally, if it is considered that swimming techniques can be improved due to dry-land S&C training (Maglischo, 2003) and that it is common to apply dry-land S&C training programs to swimming, understanding the effects that the dry-land S&C training programs may induce is mandatory. On one hand, several investigations have shown improvements in swimming performance (Strass, 1988; Aspenes et al., 2009; Girold et al., 2007, 2012) after a dry-land S&C training program intervention. For instance, a recent investigation (Girold et al., 2012) presented an increase of 2.0 ± 1.3% in the 50 m freestyle performance after the application of a dry-land S&C program for 4 weeks (three sessions per week, of 15 minutes each) with an intensity between 80 to 90% of one repetition maximum (1RM). On the other hand, other investigations stated that a dry-land S&C program intervention promotes strength gains, but that these gains have no significant direct transfer for swimming performance improvements (Tanaka et al., 1993; Trappe & Pearson, 1994; Garrido et al., 2010; Sadowski et al., 2012). The reasons for these differences may be different protocol interventions/design, time-period applications and/or sample size. For instance, some studies pooled together both genders in one single group. Despite the fact that during preadolescence, strength improvements are quite similar between boys and girls (Faigenbaum et al., 2015), after this period boys have a tendency to exhibit higher muscle strength levels than girls (Bencke et al., 2002). Thus, coupling data from both genders in research focused in dry-land S&C may be misleading. Furthermore, even if no statistically significant improvements were stated, recent investigations with young swimmers found a tendency to improve sprint performance in the 25 and 50 m freestyle, due to dry-land S&C programs (Garrido et al., 2010; Sadowski et al., 2012). These investigations, whether with significant results or only with a tendency to enhance performance, have a common point: short swimming distances. Thus, the ability to exert high levels of force for a short period of time seems relevant for an appropriate training prescription and demands further investigations.

It is well stated in the literature that movements performed when swimming are difficult to replicate on dry-land, as water drag is impossible to reproduce in dry-land exercises (Tanaka et al., 1993; Toussaint & Hollander, 1994; Maglischo, 2003; Sadowski et al., 2012). So, a dry-land S&C program design should try to mimic the in-water movements as much as possible. Perhaps some of the previous investigations, which did not accomplish improvements in swimming performance, could have used exercises with low mimicking or did not use as much muscular tension as in the water (Barbosa et al., 2013). Another decisive factor could be the minor importance to overall swimming performance of the muscles worked out in dry-land S&C programs (Barbosa et al., 2015). Moreover, the velocity with which exercises were performed could have been different from the in-water performance (Toussaint et al., 1988; Tanaka et al., 1993; Maglischo, 2003; Lucero, 2011; Barbosa et al., 2013). Several studies followed a 1RM methodology to define the exercises' external load. Nevertheless, it is questionable whether maximum force is the force parameter with a higher association with swimming performance, as swimming power has proven to be of major importance in shorter distances (Strass, 1988; Toussaint, 2007; Morouço et al., 2011; Barbosa et al., 2015). Thus, it may be expected that movement velocity plays an important role in increasing the specificity of dry-land S&C exercises (González-Badillo & Sánchez-Medina, 2010) and overall power output. Still, the strength programs analyzed are not explicit about the exercise movement velocity.

One last point regarding dry-land S&C programs for swimming is related to the moments when evaluations are carried out after the dry-land S&C program interventions. Commonly, research is interested in knowing the effects of a designed intervention, thus, making evaluations before and after the application period. However, it has been hypothesized that swimmers could benefit from an adaptation period to the strength gains (Maglischo, 2003). That is, after increasing strength levels, swimmers should go through a period to adapt their ability to apply new levels of force in the water. To the best of our knowledge, only two studies have investigated detraining or delayed effects after dry-land S&C programs interventions (Garrido et al., 2010; Girold et al., 2012). Both investigations reported that training effects were maintained after 6 and 4 weeks, respectively. So, it seems reasonable to investigate if a period where swimmers could perform this specific in-water training would be useful to effective take advantage of dry-land S&C programs improvements (Garrido et al., 2010).

The above-mentioned uncertainties regarding the benefits of dry-land S&C training programs and their effect on swimming performance highlight the need for more investigations on this matter. In fact, being able to clarify the role of dry-land S&C training and its prescription would be of major value for swimming coaches. Therefore, this study aimed to analyze the effects of a period of swim training alone, a dry-land S&C program based on sets/repetitions according to current guidelines, plus swim training alone or a dry-land S&C program that focused on explosiveness plus swim training alone, in age group swimmers. It was hypothesized that (a) a dry-land S&C training program would be able to enhance both dry-land strength and swimming performance, if adaptation for strength gain occurs; and (b) that a dry-land S&C program focused on explosiveness development would be more suitable to increasing swimming performance in short distance events.

Methods

Experimental approach to the problem

A randomized controlled trial, with balance randomization, parallel-group was conducted at the competitive period of the spring training, thus ensuring that the subjects were in a prime training period cycle and was performed in an on-field setting. 21 participants were randomly assigned into two experimental and one control group according to the random number table (n = 7 for each group). The study was conducted in accordance with the ethics committee of the host institution and with the Declaration of Helsinki for research involving human participants. All parents gave their consent and under-age subjects their assent.

Subjects

Twenty-one male prepubescent swimmers (2.1 ± 0.4 Tanner stages by self-evaluation) were recruited by convenient sampling to take part in the study, as observed in Table 1. Eligible participants were age group swimmers of teams competing in the first national division (Portugal). Inclusion criteria required that swimmers had at least 2 years of experience in swimming competition. Participants were excluded if they had an injury or had regularly participated in any kind of strength training before this investigation. Swimmers were randomly assigned using computerized randomization and allocated into three groups (GR1; GR2 and CG) based on similar swimming performance (1:1:1). None of the groups was aware of the existence of other groups in the experiment. Since the sample size comprises a low number of subjects, statistical analyses were performed in order to assess the sample's power. The results showed an effect size of 0.3, α=0.05 and β=0.7. All groups had 5.8 training sessions per week with an average of 4.075 ± 0.2 km per training unit.

Table 1. Main physical characteristics of the subjects, according to the group.

	age (y)	**height (m)**	**body mass (kg)**
Group 1 (*n*= 7)	12.7 ± 0.8	1.57 ± 0.07	47.9 ± 7.2
Group 2 (*n*= 7)	12.7 ± 0.8	1.58 ± 0.09	47.4 ± 10.0
Control group (*n*= 7)	12.6 ± 0.8	1.55 ± 0.07	47.8 ± 12.8

Procedures

The experimental period for the present study was 10 weeks, divided into two periods: the dry-land S&C implementation period (6 weeks) and an adaptation period (4 weeks). Previous investigations using subjects with similar age were conducted through 8 weeks (Garrido et al., 2010). Additionally, and in order to fit in one available planning meso-cycle, the duration of 6 weeks (two meso-cycles of 3 weeks each) of dry-land S&C training intervention was chosen.

Dry-land S&C training sessions (two sessions per week of 30 min each, prior to in-water training) took part in addition to regular swimming training sessions. Table 2 presents a detailed description of the dry-land S&C training program. Sessions were conducted by two S&C coaches, always with the presence of the head coach. S&C training was planned and supervised by an NSCA Certified Strength and Conditioning Specialist. Preceding the dry-land S&C training exercises, a warm-up of approximately 10 minutes was completed in each session. The goal was to elevate body temperature and enhance motor unit excitability. Rope skipping and similar articular mobilization to S&C exercises were used (Faigenbaum et al., 2015). The program consisted of five different exercises: medicine ball throw down; countermovement jump; dumbbell flys; Russian twist; and push-ups. For the medicine ball throw down, participants started in an upright position with the ball (1 kg) above the head, with upper limbs fully extended and threw it to the ground, as fast as they could. The countermovement jump was made to a higher surface (box) with 30 cm height. Dumbbell flys were performed with participants lying on the ground. The exercise started with upper limbs in a vertical position where dumbbells weighing 1.5 kg had to reach the minimum distance to the ground, without contact on it. Upper limbs were fully extended during the exercise. Russian twists were performed with a medicine ball that weighed 3 kg. Participants started in a seated position with arms fully extended in the front of their chest and with feet off the ground. The ball had to be displaced from the right hip to the left hip, with precision. Push-ups were performed with upper limbs in adduction, close to upper body during the duration of exercise. The body had to remain in plank during the exercise. Strength training followed two different dry-land S&C programs as shown in Table 2.

Experimental GR1 performed exercises following a sets/repetitions methodology with no restrictions on the time of execution (Table 2). A rest period between sets was incremented every 2 weeks of intervention (40 s; 60 s and 1 m 30 s). This methodology is similar to previous studies (Garrido et al., 2010) and is traditionally used in S&C training programs (Faigenbaum et al., 2015). Instead, experimental GR2 followed an explosiveness methodology, where subjects had to perform as many repetitions as they could in a specific time (Table 2). Swimmers were told to perform the repetitions as rapidly as possible. A rest period between sets was always calculated by the multiplication of the execution time by 4. This methodology was chosen to allow each participant to perform as many repetitions as possible. The time of each set tried to approach the time spent in short distances swimming. This way, and controlling fatigue, participants performed a similar number of actions as in swimming, attempting to be more specific for swimmers. In addition to technical follow-up, posters with images and execution criteria were printed and fixed in the gym. The quality of movement and fatigue were the two main aspects controlled by coaches.

Table 2. Strength and conditioning training programs, according to group.

	Group 1			**Group 2**		
	weeks 1-2	weeks 3-4	weeks 5-6	weeks 1-2	weeks 3-4	weeks 5-6
Medicine ball throw down 1kg	3x8	3x12	3x15	3x15s	3x20s	3x25s
CMJ to box 30cm	3x10	3x14	3x18	3x15s	3x20s	3x25s
Dumbbell Flys 1.5kg	3x6	3x10	3x15	3x10s	3x15s	3x20s
Russian twist 3kg	3x10	3x14	3x18	3x15s	3x20s	3x25s
Push-ups	3x10	3x14	3x18	3x10s	3x15s	3x20s

Finally, the CG followed the regular swimming training. During the 10 weeks of the experimental period, subjects performed 58 swimming training sessions (5.8 per week). The participants swam 236.4 km, the equivalent to a mean value of 23.64 ± 2.4 km per week and

4.08 ± 0.21 km per training unit. A volume of 23.7 km was performed at an intensity equivalent to their critical velocity (2.37 ± 0.85 km per week) and 13.3 km at an intensity equivalent to their aerobic power (1.33 ± 1.16 km per week). The remaining training program contained low aerobic (~70% of total volume), technical (~14%) and velocity (~1%) sets. Throughout the 4 weeks after the implementation of the S&C programs, sets focused on velocity increased to ~2%.

Assessment

Test procedures occurred at three different moments: (a) before the experimental procedure – pre-test, (b) after 6 weeks of a strength training program – mid-test, and (c) 4 weeks after the end of the strength training program – post-test.Tests were performed at the same time of the day to avoid any effect of circadian rhythms. The two experimental and the CG were evaluated at the same moment in the procedures schedule. The evaluations were conducted for 3 days for each moment. All subjects were informed of and familiarized with all test procedures 4 weeks before the first evaluation.

A maximal intensity front crawl tethered swimming was conducted to measure force produced in water, as previously described (Morouço et al., 2014). After an 800 m moderate intensity warm-up (300 m swim, 50 m pull, 50 m kick, 4 x 50 m at increasing speed, 200 m easy swim) each participant performed the test. Prior to the starting signal, participants assumed a horizontal position with the cable fully extended. Data collection began after the first stroke cycle was completed. This procedure was used to avoid the inertial effect of the cable extension usually created immediately before or during the first arm action (Morouço et al., 2011). The duration of the exercise was 40 s with an initial phase of 10 s with moderate intensity and 30 s at maximum intensity. Participants were told to use the breathing pattern they would normally apply during a 50 m front crawl event. They were also verbally encouraged throughout the test to maintain maximal effort. An acoustic signal marked the end of the test. Values of mean force (MF) as the mean of force values recorded during the 30 seconds, and mechanical impulse (MI) as the mean impulse determined as the quotient of the sum of the single-stroke impulse and the number of strokes performed during the 30-second tethered swim were estimated.

Dry-land strength tests were performed after a standard warm-up of articular mobilization and rope skipping of approximately 10 minutes. Ball thrown (BT) distance (in m) was measured through a maximal throwing velocity test using a 1 kg medicine ball with rough surface and circumference of 0.59 m (Garrido et al., 2010). Preceding the tests, each participant executed several throws for warm-up. Each participant executed three throws with 2 minutes rest between attempts. The subjects were seated with their back against the wall holding the ball with both hands, resting it against the chest. Participants were told to throw the medicine ball for the maximum possible distance, as far and fast as possible. Three technical valid attempts were used to calculate the average for analysis (ICC values were always higher than 0.97). Throwing distance was measured using a measuring tape.

Vertical jump height (in cm) was obtained with the use of countermovement jump (CMJ) (Garrido et al., 2010). For that purpose, a contact mat connected to an electronic power time (Ergojump, Globus, Italy) was used. Each subject started in the upright position with feet shoulder-width apart and squatted down until a 90 degrees angle of knees. Immediately after this moment, they jumped as high as possible, always with hands on the hips. Landing was made with both feet at the same time and with extended lower limbs. A 2-minute rest was accomplished between each of the three jumps. The average of three valid attempts was taken to analysis (ICC values were always higher than 0.95).

Swimming performance tests were executed after a standard warm-up (equal to the tethered swimming test) in a 25 m indoor swimming pool. A short distance time trial was chosen due to the influence of force application over these distances (Stager & Coyle, 2005; Morouço et al., 2011). All subjects completed two maximal tests of 50 m in front crawl in order to access their best time (in s) in each test (Girold et al., 2007, 2012) (ICC values between 0.93 and 0.98). The beste time was used to analysis. A 15 min active recovery period between the two trials was respected. The starts were performed in the starting block. Time was measured by two experienced researchers with a chronometer (SEIKO S120-4030, Japan).

Statistical analyses

Variables were expressed as means and standard deviations. After normality and homoscedasticity assumption were checked (Shapiro-Wilk and Levene tests, respectively), parametric tests were conducted. One-way ANOVA was performed to analyze possible differences over the groups at baseline. Repeated measures (within-subjects ANOVA) analysis of the variables according to the groups was performed. Following this, a repeated measures factorial analysis (2-way ANOVA: moments X groups) was conducted. ANOVA repeated measures were followed by Bonferroni tests. The level of statistical significance was set at $\rho < 0.05$. The effect size was computed based on the partial eta-squared (η^2) procedure, and values interpreted as: 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

A total of 21 participants (7 in GR1, 7 in GR2 and 7 in CG) were measured at baseline and post intervention. Outcomes were attained for all variables and there were no dropouts. At baseline, there were no significant differences between any of the analyzed variables (table 1), thus, presenting acceptable homogeneity between groups.

Table 3 presents the results for the tethered swimming and dry-land tests, at the beginning of the experimental period (T1), after 6 weeks of the dry-land S&C program (T2) and after 4 weeks of an adaptation period to strength gains (T3) for the three groups. Both mean force and mechanical impulse did not present a time or group effect, nor a time X group interaction. For the dry-land tests a time effect was observed between T1 and T2 for the GR1 and GR2 in the vertical jump (ρ <0.01), and for the GR2 in the ball throwing (ρ <0.01), with moderate-strong effect sizes. No group effect or time X group interaction were observed.

Table 3. Mean force, mean mechanical impulse, vertical jump and ball throwing mean values (± SD), differences (%), significance (ρ) and effect sizes ($\eta^2{}_\rho$) throughout the experimental period.

		T1	T2	T3	T1 - T2	T2 - T3	ρ	η^2
Mean force (N)	GR1	59.86 ± 9.74	58.57 ± 11.26	60.97 ± 9.73	- 2.2%	+ 4.09%	0.150	0.271
	GR2	63.82 ± 17.20	64.12 ± 17.92	66.36 ± 17.32	+ 0.47%	+ 3.5%	0.126	0.292
	CG	55.79 ± 15.80	56.93 ± 16.68	57.13 ± 16.87	+ 2.04%	+ 0.035%	0.335	0.167
Mean mechanical impulse (N.s)	GR1	71.49 ± 15.51	70.06 ± 14.32	72.97 ± 20.88	- 2.04%	+ 4.15%	0.469	0.119
	GR2	71.51 ± 23.62	73.95 ± 26.97	77.52 ± 25.81	+ 3.41%	+ 4.82%	0.255	0.204
	CG	68.72 ± 24.08	69.26 ± 20.93	68.73 ± 20.87	+ 0.78%	- 0.77%	0.921	0.014
Vertical jump (cm)	GR1	25.70 ± 3.29	29.28 ± 3.06[a]	29.18 ± 4.70	+ 13.92%	- 0.34%	0.003	0.617
	GR2	29.70 ± 4.73	31.85 ± 4.78[a]	31.91 ± 5.51	+ 7.44%	+ 0.18%	0.018	0.487
	CG	25.44 ± 4.47	27.32 ± 6.94	26.88 ± 5.48	+ 7.38%	- 1.63%	0.377	0.150
Ball throwing (m)	GR1	4.53 ± 0.61	4.81 ± 0.59	4.87 ± 0.42	+ 6.18%	+ 1.24%	0.051	0.391
	GR2	4.07 ± 0.54	4.78 ± 0.49[a]	5.18 ± 0.77	+ 17.44%	+ 8.36%	0.000	0.856
	CG	3.98 ± 0.89	4.25 ± 0.78	4.40 ± 0.86	+ 6.78%	+ 3.52%	0.056	0.481

[a] - significantly different from T2 (p=0.03).

Table 4 presents the front crawl swimming performance, at the beginning of the experimental period (T1), after 6 weeks of the dry-land S&C program (T2) and after 4 weeks of an adaptation period to strength gains (T3) for the three protocol groups. The 6 weeks of the dry-land S&C program did not improve swimming performance for any group. However, the 4-week adaptation period allowed GR2 to significantly improve swimming performance (ρ = 0.03), with a moderate effect size. With regard to the group effect within the three moments, no differences between groups were identified. The time X group analyses showed that for performance in the 50 m, differences were significant, with the GR2 presenting higher improvements than their counterparts (F=4.156; ρ=0.007; η^2=0.316).

Table 4. Front crawl swimming performance mean values (± SD), differences (%), significance (ρ) and effect sizes (η^2_ρ) throughout the experimental period.

		T1	T2	T3	T1 - T2	T2 - T3	ρ	η^2
Swimming performance (s)	GR1	33.92 ± 1.47	34.52 ± 1.52	34.02 ± 1.61	+ 1.76%	- 1.46%	0.315	0.175
	GR2	33.43 ± 2.83	32.35 ± 2.36	31.65 ± 2.53[a]	- 3.33%	- 2.21%	0.003	0.616
	CG	33.76 ± 3.14	33.63 ± 3.71	33.64 ± 3.04	- 0.38%	+ 0.02%	0.925	0.156

[a] – significantly different from T2 (p=0.03).

Discussion

The aim of this investigation was to examine the effects of a 10-week training period of swim training alone, a 6-week dry-land S&C training program based on sets/repetitions according to current guidelines, plus 4 weeks of swim training alone or a 6-week dry-land S&C training program focused on explosiveness, plus 4 weeks of swim training alone, in age group swimmers. The main results showed that dry-land S&C training at these ages induces gains in dry-land measurements, but improvement in swimming performance only occurs after an adaptation period, thus confirming hypothesis one. By allowing an adaptation period of 4 weeks, an improvement in swimming performance was noted for the group that engaged in the dry-land S&C program with a focus on explosiveness, thus confirming hypothesis two.

Improvements in swimming performance have been associated with increases in power output (Sharp et al., 1982; Toussaint & Vervoorn, 1990; Toussaint, 2007; Barbosa et al., 2015), which are elucidated by higher force application in the water (Barbosa et al., 2010b). One of the available procedures to assess in-water propulsive forces and that can be used to evaluate force contribution for short-distance swimming performance is tethered swimming (Morouço et al., 2014). Therefore, it was expected that dry-land strength gains would lead to higher levels of in-water force exertion (Sadowski et al., 2012). However, for these swimmers that did not occur. The increases in mean force and mechanical impulse were lower than the ones obtained with older swimmers (Sadowski et al., 2012), who, with 9% increase, also were not able to enhance their swimming performance. Stroke kinematics and propulsive efficiency can be a decisive factor to explain this bias, thus, further studies controlling stroke efficiency are mandatory to clear the relationship between strength gains and the ability to exert force in the water. Moreover, competitive level (Garrido et al., 2010) and age may have influenced the transferability of dry-land strength training gains to in-water force production. It could be interesting to explore whether a similar bias would occur with more experienced and higher level swimmers. Still, after the 4 weeks of adaptation, a tendency to increase mean force and mechanical impulse was noticed, in both experimental groups. In fact, of those 14 swimmers, only three did not increase their mechanical impulse, suggesting that this period led to a cascade of events linking dry-land strength to aquatic performance.

For dry-land strength assessments, both experimental groups obtained significant improvements in jumping height, whereas the control group did not. This is in accordance with previous results (Garrido et al., 2010), suggesting that a dry-land S&C program in age group swimmers could lead to higher levels of strength in the lower limbs. This may be of high importance for short distance events, as the swimming start is known to be a determinant factor for success (Vantorre et al., 2014). Furthermore, swimmers were able to maintain their jumping height after the dry-land S&C program cessation, confirming that 4 weeks were not enough for losing strength gains (Wilmore & Costill, 1988). For the upper limbs, only GR2 obtained significant improvements in the medicine ball throw. This group had a dry-land S&C program focused on explosiveness, which may have led to higher specificity transferable for swimming, as adolescent male swimmers obtain higher swimming velocities due to the high force exertion with their arm stroke (Morouço et al., 2015). Even though literature about the detraining period in prepubescence is not extensive, it is suggested that strength and power training-induced gains tend to revert during detraining (Faigenbaum et al., 2009), mainly explained by neuromuscular forgetting (Wilmore & Costill, 1988). Available literature claims that a multidimensional S&C training in young athletes is crucial in several domains (Faigenbaum et al., 2009, 2015). For instance, it can improve athletic performance and prevent sports related injuries. On the other hand, stronger young athletes will be able to succeed in the long-term demands of their sports careers (Faigenbaum et al., 2009).

Previous investigations stated that the risk of losing strength gains is not present until 6 weeks after the cessation of a strength training program (Wilmore & Costill, 1988). Furthermore, dry-land strength and power gains are maintained with a minimal stimulus contrarily to water strength and power gains, which require a more frequent and consistent stimulus, due to water-action specificity (Wilmore & Costill, 1988). In our investigation swimmers were tested not only at the end of the dry-land S&C program, but also 4 weeks afterwards. During this latter period, swimmers only performed their regular swimming training, aiming technical and/or propulsive adaptations to their new strength gains. Results showed that swimmers from GR2 had benefits from that period, improving swimming performance; before that, dry-land strength gains were not transferable to swimming performance, as stated by Garrido et al. (2010). These outputs may suggest that this group followed a dry-land S&C training methodology more specific to sprint swimming events. Additionally, a period of overload decrement (strength training cessation) may induce a positive delay transformation to enhanced specific performance (Zatsiorsky, 1995). Thus, swimming coaches should take into consideration both a suitable methodology for dry-land S&C prescription, as well as a proper time window to adapt swimmers to new force levels.

We believe that the main limitation of this study was the sample size. A sample size of 7 swimmers in each group does not assure an extensive generalizability, thus, further studies should engage more swimmers per group. Secondly, future investigations should try to extend experimental design during the season, attempting to evaluate longer term effects. This, may provide clearer insights for training prescription.

Among several dry-land and in-water methodologies used by coaches and practitioners, dry-land S&C training programs are common in swimming, and positive results have been reported in previous investigations. To the best of our knowledge, this is the first investigation with age group swimmers that examined (a) two different approaches for dry-land S&C training and (b) an adaptation period to dry-land strength gains, regarding to swimming performance. Previous studies were conducted with older and more skilled swimmers than the ones who participated in this investigation. At these ages, swimmers do not have a specialization in a swimming technique, what may suggest that benefits of dry-land strength programs in swimming performance can be achieved at younger ages. Despite performing the same dry-land exercises, only GR2 obtained significant improvements in swimming performance. These results suggest that being able to perform the repetition rapidly had higher benefits for achieving higher swimming speed. It is known that swimming power is a critical factor to achieve swimming success (Newton et al., 2002; Barbosa et al., 2010b), particularly in short distances (Stager & Coyle, 2005; Toussaint, 2007; Morouço et al., 2011; Barbosa et al., 2015). Nevertheless, several dry-land S&C training programs followed a 1RM, which is more related to maximum force than to power. This may constrain the specificity of the movement concerning to the velocity and may jeopardize swimming performance enhancement (González-Badillo & Sánchez-Medina, 2010). In fact, not giving so much importance to the velocity of the movement could have been the factor that constrained swimming performance enhancement in GR1. Furthermore, in-water muscular tension (Barbosa et al., 2013) could have been more replicated in GR2 exercises. Actually, power depend on the quick and large activation of muscle fibers and its synchronization. Thus, neural adaption happened as far as swimmers got stronger and body weight did not alter significantly—a process suggested to improve work economy (Hoff et al., 2002). Additionally, it was shown that muscular recruitment was higher for maximal swimming speed than for low speed (Rouard et al., 1992). This should reinforce the properness of using explosiveness in training sessions and evaluations.

Practical applications

It is known that dry-land S&C programs are a common practice in swimming, independent of age or competitive level. First, dry-land S&C programs for age group swimmers with a small investment in materials and easy transportability are presented. Secondly, 6 weeks of complementary dry-land S&C training led to improvements in dry-land strength, which were beneficial for aquatic performance only after a 4-week adaptation period. That will lead to higher probabilities of being able to efficiently apply force in the water. Furthermore, it seems that additional benefits may occur if coaches plan the dry-land training focusing on explosiveness.

Chapter 6.

Dry-Land Strength and Conditioning for Prepubertal and Peripubertal Swimmers

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Abstract

Swimming performance depends on the optimal interaction of several factors. Strength is one of those factors, being the ability to apply in-water force determinant in short swimming distances. So, dry-land Strength and Conditioning (S&C) training is usual in swimming prescription where the goal is to enhance performance and/or prevent injuries. However, there is a lack of investigations over this matter, particularly with age group swimmers. Thus, the objective of this article is to provide coaches a practical proposal to enhance swimming performance through the adding of an S&C program to their swimming prescription, in age group swimmers.

Key words: swimming; dry-land; strength and conditioning; training and testing; youth

Introduction

Swimming success depends on several factors. The ability to apply in-water force crucial, particularly in short distances (Stager & Coyle, 2005; Morouço et al., 2011). Among others methodologies, dry-land strength & conditioning (S&C) training is a common practice in competitive swimming. There are two main goals in S&C training: to improve swimming performance and to prevent injuries (Aspenes et al., 2009; Batalha et al., 2015; Bishop et al., 2009; Potdevin et al, 2011; Girold et al., 2012) . Although training is often recommended to improve strength and power outputs, the swimming community has yet to reach a concensus regarding specific benefits on swim performance. Still, no negative effects over swimming performance were reported in the available literature, till date.

Lack of specificity of S&C training is one of the main reasons concluded to impair results in some of the conducted investigations. Several exercises have been used to mimic in-water movement; the bench press being one of the most commonly applied. Yet, results are not convincing because in-water movement has particular characteristics that are impossible to replicate in dry-land, such as water tension and drag (Barbosa et al., 2010). For instance, neuromuscular demands are far from being similar in both conditions. The more a swimmer mimics an in-water movement in a dry-land condition with resistance, the more the swimmer could be potentially disrupting motor patterns acquired in-water. Thus, in order to promote transferibility of dry-land strength gains to swimming performance, it is suggested to concurrently implement technical swimming training (Aspenes et al., 2009). Strength and conditioning coaches should focus on strengthen muscles involved in swimming with the intent of increasing force production and to prevent muscular imbalances, according to each swimmer's needs (Batalha et al., 2015).

The ability to produce a high rate of force development is crucial in short distances and decreases as the distance increases. Training with heavy loads (maximal strength) requires low execution velocity and likely is not related with swimming demands, particularly in short-distances bouts. Thus, dry-land training should be performed with a velocity similar to in-water movements, trying to fulfil similar neuromuscular demands. When adding strength and conditioning training for short-distance swimming, explosiveness should be the main goal. Therefore, it is expected that movement velocity increases specificity of strength and conditioning exercises and overall power output (González-Badillo and Sánchez-Medina, 2010).

Previous Investigations have focused on older and high competitive level swimmers. Very few studies have been published regarding prepubertal (before puberty) and peripubertal (during puberty) swimmers. This could be due to ethical issues or unclear information available to coaches, making them skeptical toward strength and conditioning training swimmers in those age groups (Barbosa et al., 2010). Nevertheless, dry-land and in-water power outputs and strength have a determinant influence in youth swimming performance (Morais et al., 2016; Morouço et al., 2011). It is recommended that youth athletes engage in resistance training, not only to enhance health, fitness, and performance, but also to prevent sports-related injuries (Faigenbaum et al., 2015; Morais et al., 2016). Therefore, it seems reasonable that strength and conditioning can aid performance of prepubertal and peripubertal swimmers. The objective of this article is to provide strength and conditioning coaches with practical training recommendations to improve performance through the addition of a strength and conditioning program to prepubertal and peripubertal swimmers.

Training recomendations

There are several aspects of strength and conditioning training: type, frequency, intensity, volume, recovery, and progression. The following training recommendations are intended to follow the National Strength and Conditioning Association (NSCA) guidelines, as well as the relevant literature on strength and conditioning training with youth athletes (Faigenbaum et al., 2015; Haff & Triplett, 2016). Therefore, strength and conditioning training based on power is presented. The strength and conditioning program is designed for six weeks with two sessions per week. After the six weeks of strength and conditioning training, swimmers are allowed a four-week adaptation period. The goal is to allow the transferability of new strength levels acquired in the strength and conditioning training to in-water actions. In this period, swimmers continue in their normal swimming training prescription and cease strength and conditioning training. Prior to the implementation of the strength and conditioning program, a pre-test is recommended to assess each subject's tolerance to the prescribed loads, always maintaining the goal of power-based training.

In each session, a warm-up of about 10 min should be performed. The goal of the warm-up is to elevate body temperature and enhance motor unit excitability. Rope skipping and similar mobilization to strength and conditioning exercises are recommended. Based on previous observations, swimmers should follow a sets/time scheme instead of sets/repetitions for the strength and conditioning program, as seen in Table 1 (Amaro et al., 2016). The goal is to perform the repetitions as rapidly as possible, maintaining high-quality movements. The time spent in each set should approach the time spent in short-distance swimming. Through controlling fatigue, participants should perform a similar number of actions as in swimming competitions, in order to be sportspecific. Rest periods between sets should be calculated by the multiplication of the execution time by four (Amaro et al., 2016; Haff & Triplett, 2016).

The strength and conditioning training presented consists of five exercises: medicine ball throw down, countermovement box jump, dumbbell fly, Russian twist, and triceps push-ups. The main goal is to workout muscles involved in swimming, especially in front-crawl stroke. It is intended to use bodyweight and materials with easy transportability, aiming to reduce time transporting training equipment. It is recommended that swimmers engage in familiarization sessions to enhance exercise technique before program implementation.

Table 1. S&C training programs between week 1 and 6

	weeks 1 and 2 (recovery time)	weeks 3 and 4 (recovery time)	weeks 5 and 6 (recovery time)
Medicine ball throw down (1Kg)	3x15s (60s)	3x20s (80s)	3x25s (100s)
CMJ to box (30 cm)	3x15s (60s)	3x20s (80s)	3x25s (100s)
Dumbbell Flys (1,5Kg)	3x10s (60s)	3x15s (80s)	3x20s (100s)
Russian twist (3Kg)	3x15s (60s)	3x20s (80s)	3x25s (100s)
Push-ups	3x10s (60s)	3x15s (80s)	3x20s (100s)

Medicine ball throw down (figure 1)

Execution: The swimmer starts in an upright position with the medicine ball (1 kg) above their head and the upper limbs fully extended. Then throw the medicine ball to the ground as fast as possible.

Muscle involvement: pectoralis major, pectoralis minor, anterior deltoid, medial deltoid, serratus anterior, latissimus dorsi, posterior deltoid, teres major, teres minor, and infraspinatus.

FIGURE 1. MEDICINE BALL THROW DOWN (WITH PRIMARY MUSCLES RECRUITED IN RED)

Countermovement jump to box (figure 2)

Execution: The swimmer starts in an upright position, squats down until the knees are bent at 90 degrees, then immediately jumps vertically as high and fast as possible, landing on the box (30 cm) on both feet at the same time.

Muscle involvement: rectus femoralis, vastus lateralis, vastus medialis, gluteus medius, gluteus maximus, biceps femoris, semitendinosus, semimembranosus, and gastrocnemius.

FIGURE 2. COUNTERMOVEMENT BOX JUMP (WITH PRIMARY MUSCLES RECRUITED IN RED)

Dumbbell fly (figure 3)

Execution: The swimmer should lay on the ground and start with the upper limbs in a vertical position holding dumbbells. Then the dumbbells (1.5 kg) should be moved outward and downward, utilizing the minimum distance needed to reach to the ground without contacting it.

Muscle involvement: pectoralis major, pectoralis minor, anterior deltoid, medial deltoid, trapezius, teres major, teres minor, infraspinatus, rhomboids, posterior deltoid, and triceps brachii

FIGURE 3. DUMBBELL FLY (WITH PRIMARY MUSCLES RECRUITED IN RED)

Russian twist (figure 4)

Execution: The swimmer starts in a seated position on the floor with the hands grasping a medicine ball (3 kg) in the front of the chest with the feet off the ground. The ball should be displaced from the one hip to the other in a controlled motion.

Muscle involvement: rectus abdominis, external oblique, internal oblique, and external oblique

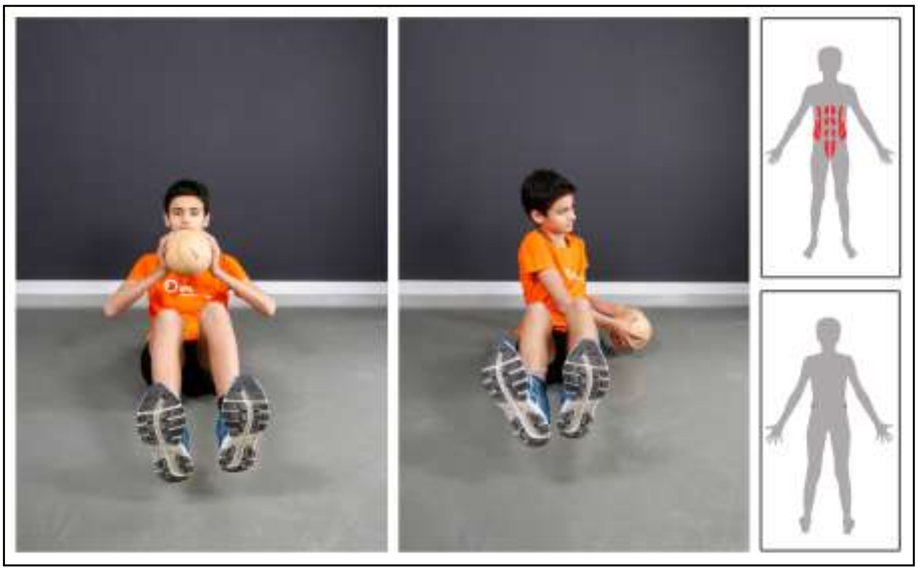

FIGURE 4. RUSSIAN TWIST (WITH PRIMARY MUSCLES RECRUITED IN RED)

Push-up (figure 5)

Execution: The swimmer starts with the upper limbs fully extended close to the upper body and in adduction. The swimmer should lower their body until the chest almost touches the floor and return to the initial position by extending the upper limbs. The body must remain in a plank position with the upper limbs close to the upper body during the entire exercise.

Muscle involvement: Pectoralis Major, Pectoralis Minor, Anterior Deltoid, Medial Deltoid, Posterior Deltoid, and Triceps Brachii

FIGURE 5. PUSH-UP (WITH PRIMARY MUSCLES RECRUITED IN RED)

Conclusion

The current strength and conditioning program for prepubertal and peripubertal swimmers provides an evidence-based strength and conditioning prescription for youth swimmers that is affordable, portable, and uses minimal equipment. It is imperative that strength and conditioing coaches control swimmers' execution and fatigue in each strength and conditioning session. Additionally, strength and conditioing coaches should apply strength and conditioning programs adjusted to each swimmer's ability to avoid overreaching and prevent injuries. Finally, it is important that strength and conditioing coaches allow swimmers to have a period to adapt to new strength levels acquired in the strength and conditioning program.

Chapter 7. Overall conclusions

The main findings of this work emphasize the importance of S&C training for swimming performance enhancement, in age group swimmers. Data also showed that tethered swimming is a reliable methodology for evaluation of age group swimmers.

Literature research showed that:

1. There is a lack of research on the effects of S&C training in swimming performance, and most investigations occurred with older and experienced swimmers.
2. Moreover, the influence of S&C in other techniques rather than front crawl cannot be determined as well as its influence on swimming distances above 100m, due to the absence of research.
3. Nevertheless, some studies presented data suggesting that S&C training based on maximal strength is associated with improvements in older and experienced swimmers, particularly in short distance races (25 and 50m) and S&C training based on plyometric is associated with improvements on starts and turns, in young swimmers.
4. Additionally, tethered forces present moderate to strong relationships with swimming velocity and associations between forces diminish as swimming distance increases.

According to our experiments:

1. Tethered swimming is a reliable test to evaluate force exerted in water by swimmers familiarized with the test.
2. Tethered swimming evaluations throughout the season may allow coaches to control swimmers' ability to exert in-water force and evaluate the effects of S&C training programs, in age group swimmers.
3. 6 weeks of a complementary S&C training with appropriate and systematic planning allow improvements in dry-land strength, in age group swimmers.
4. A 4-week adaptation period is suggested to allow transferability of S&C improvements to swimming performance.
5. Explosiveness should be the goal of S&C training in order to allow swimming performance enhancement in short distance swimming, with age group swimmers.

Some main limitation of this thesis can be addressed:

1. This study only analysed front crawl swimming, male swimmers and short swimming distances;
2. Larger samples could allow more consistent results; yet, it is difficult to find age group swimmers available and committed to an S&C program;
3. This investigation did not analysed the effects of S&C training in starts and turns.

Chapter 8. Suggestions for future research

It seems evident that there is a lack of scientific knowledge about S&C training in swimming. Furthermore, a more practical approach is mandatory in order to fulfill coaches and swimmers needs. Hence, a few topics for possible future investigations are listed below:

- To explore differences in S&C training effects induced by age, gender and competitive level;
- To analyze the effects of S&C training in different swimming techniques as well as in middle and long swimming distances;
- To evaluate long-term effects of S&C training in swimming performance, throughout the seasons.
- To investigate the effects in swimming performance of different time periods to adapt swimmers to new force levels acquired in S&C programs, including also the detraining phase.

Chapter 9. References

Chapter 1

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