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Indirect assessment of young swimmers' anaerobic performance

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Abstract

In sports such as swimming, bioenergetics is critical in achieving maximum performance. Because of that, reliable tools must be used to measure its contribution to each kind of effort (aerobic and anaerobic). However, measuring anaerobic energy contribution is always more complex and less reliable, making it harder to determine the anaerobic potential of a swimmer. This thesis wanted to deepen scientific understanding and address practical needs within the swimming training environment, mainly focusing on the indirect assessment of the anaerobic potential. The primary aim was to define and apply a reliable tool for young swimmers' anaerobic performance evaluation. The research proceeded as follows: (i) literature review of anaerobic performance evaluation methods (ii) definition of a procedure for swimmers' anaerobic performance assessment and determination of its usefulness (iii) application of the procedure to evaluate young swimmers' anaerobic performance changes after a long and a short training period. The literature review allowed us to determine a tool for evaluating the swimmers' anaerobic performance based on determining anaerobic fatigue thresholds over a $v(t)$ curve obtained by a speedometer. Findings suggested that the procedure is proficient and reliable in gauging the anaerobic potential. The application of the procedure after long and short training periods revealed that more research is needed to overcome the limitations observed in this study to use the anaerobic fatigue thresholds to determine changes in young swimmers' anaerobic potential. The main limitations were the low number of subjects, its considerable heterogeneity, and, possibly, the absence of sprint specialists due to their young age.

Keywords: *swimming, training control, anaerobic performance, assessment, velocimetry*

Resumo

Em modalidades desportivas como a natação, a bioenergética é fundamental para o nadador alcançar o desempenho máximo. Por isso, são necessárias ferramentas fiáveis para medir a contribuição energética correspondente a cada tipo de esforço (aeróbio e anaeróbio). Contudo, medir a contribuição energética anaeróbia é sempre mais complexo e menos fiável, tornando mais difícil determinar o potencial anaeróbio de um nadador. Esta tese pretendeu aprofundar a compreensão científica e responder às necessidades práticas do ambiente de treino da natação, focando-se principalmente na avaliação indireta do potencial anaeróbio. O objetivo principal foi definir e aplicar uma ferramenta fiável para avaliação do desempenho anaeróbio de jovens nadadores. A pesquisa prosseguiu da seguinte forma: (i) revisão da literatura sobre métodos de avaliação do desempenho anaeróbio (ii) definição de um procedimento para avaliação do desempenho anaeróbio de nadadores e determinação da sua utilidade (iii) aplicação do procedimento para avaliar alterações de desempenho anaeróbio de jovens nadadores após um período longo e um período curto de treino. A revisão da literatura permitiu determinar uma ferramenta de avaliação do desempenho anaeróbio de nadadores baseada na determinação de limiares de fadiga anaeróbios em curvas de $v(t)$ obtidas com um velocímetro. Os resultados sugeriram que o procedimento é proficiente e confiável na medição do potencial anaeróbio. A aplicação do procedimento, após períodos de treino longo e curto, revelou que são necessários mais estudos para superar as limitações observadas nos desenvolvidos e utilizar os limiares de fadiga anaeróbios para determinar alterações no potencial anaeróbio de nadadores jovens. As principais limitações foram o baixo número de sujeitos, a sua considerável heterogeneidade e, possivelmente, a ausência de especialistas em velocidade devido à sua pouca idade.

Palavras-chave: *natação, controlo do treino, desempenho anaeróbio, avaliação, velocimetria*

Abbreviations and symbols

ANOVA	Analysis of variance
AFT	Anaerobic fatigue thresholds
ATP	Adenosine triphosphate
cm	Centimetres
°C	Degrees Celsius
CV%	coefficient of variation
D ⁻¹	Hydrodynamic drag force
d	Distance
ep	Propelling efficiency
E	Energy input from aerobic and anaerobic pathways
FI	Fatigue index
Hz	Hertz
ICC	Intraclass correlation coefficient
kg	Kilograms
[La ⁻]	Blood lactate concentration
[La ⁻]net	Net blood lactate concentration
LoA	Limits of agreement
m	Meters
ms ⁻¹	Meters per second

$\text{m}^2 \cdot \text{s}^{-1}$	Square meters per second
$\text{m} \cdot \text{week}^{-1}$	Meters per week
$\text{mmol} \cdot \text{l}^{-1}$	Millimoles per liter
min	Minutes
n	Number of subjects
p	p-value
PCr	Phosphocreatine
s	Seconds
sd	Standard Deviation
SEM	Standard error of measurement
SF	Stroke Frequency
SI	Stroke index
SL	Stroke Length
SPSS	Statistical package for the social sciences
SWC	Smallest worthwhile change
TE	Typical error
UL	Upper limbs
V	Velocity
V_{max}	Maximum velocity
V_{mean}	Mean velocity

Vmin	Minimum velocity
VC	Variation coefficient of the velocity
v(t)	Velocity/time curves
vs.	Versus
%	Percentage
2D	Two-dimensional
3D	Three-dimensional
95CI	95% confidence intervals

Chapter 1. General Introduction

*If I have seen further, it is by standing
on the shoulders of giants.*

Sir Isaac Newton

Since ancient times, human beings have felt the need to move in aquatic environments as a means of survival, while more recently, swimming has been used as a form of recreation, leisure, and competition (Pelayo & Alberty, 2011). As a sport, swimming has been practiced for more than a century worldwide, was one of the first to be included in the modern Olympic Games, and has received significant attention from the scientific community, evidenced by the vast amount of published research. The sport sciences community widely recognizes swimming for its technical and physical requirements. It is a cyclical, continuous, closed, and mixed sport (Barbosa et al., 2015; Fernandes & Vilas-Boas, 2012), with performance being influenced by contextual, genetic, energetic, biomechanical, and psychological variables (Fernandes et al., 2006; Figueiredo et al., 2013a; Ribeiro et al., 2017a).

Some authors argue that to enhance swimming performance and achieve high-standard competitive levels, it is necessary to excel in both energetical and biomechanical factors (Carvalho et al., 2023; Fernandes et al., 2010; Toussaint & Hollander, 1994; Vilas-Boas et al., 2015; Zamparo et al., 2005), which are essential determinants of performance (Fernandes et al., 2013). Since swimming technique is considered the crucial performance determinant in age group swimmers, it should be the primary concern in their training process (Barbosa et al., 2010a; Silva et al., 2012; Silva et al., 2013). The associated effect of energetic and biomechanical factors has been accepted for a long time. It is expressed by the $v = E * (ep * D^{-1})$ performance equation (Di Prampero et al., 1974), where v is the swimming velocity, E is the energy input from aerobic and anaerobic pathways, ep is the propelling efficiency, and D is the body drag. Those factors are highlighted as the most determinant in improving the performance of young

swimmers (Figueiredo et al., 2016; Lätt et al., 2010; Silva et al., 2019; Silva et al., 2022).

The above-referred performance optimization depends on the ability to generate maximum velocity during the clean swimming phase of a swimming event. This velocity depends on the previously described factors but is also influenced by swimmers' anthropometric characteristics, gender, and age (Geladas et al., 2005; Lätt et al., 2009; Saavedra et al., 2010). Increasing total mechanical power (Schreven et al., 2022) and propelling efficiency (Figueiredo et al., 2013a; Figueiredo et al., 2013b; Ribeiro et al., 2015a) while minimizing hydrodynamic resistance (Toussaint et al., 2006; Vilas-Boas et al., 2015; Zamparo et al., 2014), are also crucial factors for enhancing propulsion and, consequently, swim velocity. Swimming velocity is augmented by balancing energetic and biomechanical variables, mainly by reducing energy cost and improving swimming technique (Silveira et al., 2019). As swimming efficiency tends to increase with higher swimming velocities (Fernandes et al., 2005; Ribeiro et al., 2017b), probably, their anaerobic capacity is also a relevant parameter (Figueiredo et al., 2013b; Ribeiro et al., 2015b).

Pursuing optimal competitive swimming results is a clear objective for researchers, coaches, and swimmers alike. Achieving this goal is best accomplished by enhancing the efficiency of training planning and thorough training monitoring tasks (Fernandes et al., 2013; Olbrecht & Mader, 2006; Pyne et al., 2000; Smith et al., 2002; Zacca et al., 2020a) within a biophysical framework (Almeida-Coelho et al., 2016; Carvalho et al., 2020). The entire technical swimming community recognizes the importance of evaluation and training control. Still, sometimes, it must be remembered due to the lack of information or difficulty in assessing the necessary resources. Despite the acknowledged significance of evaluation and training monitoring for young swimmers, research on this topic remains scarce compared to studies focusing on adult and elite swimmers (Barbosa et al., 2010b; Barbosa et al., 2005; Fernandes et al., 2010; Figueiredo et al., 2016).

Emphasizing the early implementation of evaluation and training control to adjust the orientation in the preparation processes of young swimmers and prevent early dropout at very young ages is crucial (Costa et al., 2011; Fernandes et al., 2010).

Since the available evidence regarding how different determinant factors can affect youth swimming performance is insufficient (Costa et al., 2011; Morais et al., 2021), developing mechanisms to evaluate physiological factors to increase training efficiency is essential. One of the most relevant physiological factors in swimming is the anaerobic power expressing the amount of ATP (per unit time) required to perform a specific task (di Prampero et al., 2005). It explains more than 80% of performances in short-distance swimming (Vitor & Böhme, 2010) and, therefore, deserves particular attention (Ribeiro et al., 2017a; Soares et al., 2014).

To better understand anaerobic metabolism, it is essential to define and differentiate the concepts of anaerobic power and capacity, which requires expertise in the energetic processes generated by short-distance efforts (Green, 1994). The concept of anaerobic power (Van Praagh, 2000) is widely used in sports such as swimming and athletics. It is only meaningful when applied to the specific exercise or, more simply, when available. Furthermore, the power of a system refers to the maximum amount of energy produced per unit of time during maximum exercise, while capacity refers to the total amount of energy made available by that same system (Armstrong et al., 1997; Olbrecht, 2000; Van Praagh, 2000).

Most competitive swimming events are equal to or below 200 m, typically taking 2 min or less to accomplish at maximal efforts (Amaro et al., 2017; Di Prampero et al., 2011; Peyrebrune et al., 2014), indicating that the competitive effort exerted has an expressive anaerobic component (Figueiredo et al., 2013b; Gastin, 2001; Ribeiro et al., 2015a) and practical application to training should aim to enhance short event swimming performance (Olbrecht, 2000; Salo & Riewald, 2008). Therefore, evaluating the anaerobic power of swimmers is crucial, both for training control and a better understanding of competitive performance (Fernandes et al., 2008a; Kilding et al., 2010; Olbrecht, 2000).

Despite young swimmers being engaged in systematic and demanding training (Fernandes et al., 2008b; Lätt et al., 2009), insufficient scientific evidence regarding anaerobic efforts (Pinos et al., 2021; Ribeiro et al., 2017a; Zamparo et al., 2020) make the training planning process less accurate. This lack of understanding is probably associated with ethical and methodological challenges

in conducting invasive methods to assess anaerobic function (Marinho et al., 2011). However, by employing direct, ecological, and user-friendly methodologies (Zamparo et al., 2020) specific to swimming, it might be possible to obtain more information to enhance young swimmers' performance.

Acknowledging the challenges above and aiming to contribute to their resolution, this thesis focuses on the indirect assessment of the anaerobic potential of young swimmers. Following the current General Introduction, **Chapter 2** will revisit the literature to systematize knowledge about the different methodologies to measure anaerobic performance. It was a complex task because anaerobic testing methodologies present challenges from unclear results and limited research (Demarie et al., 2019; Morouço et al., 2012). Consequently, the results obtained are presumably not beneficial for coaches in developing the anaerobic performance of their swimmers.

The direct methods commonly used to assess variables related to anaerobic performance capacity include muscle biopsy (Bangsbo, 1998; Houston et al., 1983; Jacobs et al., 1983) and nuclear magnetic resonance (Degroot et al., 1993; Hancock et al., 2005; Miller et al., 1988; Petersen et al., 1999). However, while considered reference standards, these methods are expensive and invasive and provide limited information, such as an inability to quantify the total potential of the anaerobic system. In addition, they are not specific to swimming and do not allow for evaluation under natural swimming conditions (Barbosa et al., 2010b; Fernandes et al., 2022; Marinho et al., 2009a; Strzala et al., 2021; Zacca et al., 2016). Moreover, the specific swimming test should address the challenges inherent to the aquatic environment. (Csajági et al., 2015; Marinho et al., 2009b; Morais et al., 2014; Morgado et al., 2018). By so, a promising indirect test, not yet validated, was extracted from the literature.

Following the review chapter, the primary aim of the first experimental study was to assess the robustness of a chosen procedure to evaluate swimmers' anaerobic potential, aiming to improve training monitoring and assessing changes in anaerobic performance. The main objective of this chapter was to explore the feasibility of utilizing the anaerobic fatigue threshold concept [previously proposed by Soares et al. (2014) as a method of training control by demonstrating the robustness of the methodology (**Chapter 3**).

The methodology outlined in **Chapter 3** was tested with several age-group swimmers (Soares et al., 2014). The impact of training on the anaerobic potential of young swimmers was evaluated using a cable speedometer, which recorded velocity variations during sprint swimming (Lima et al., 2006; Soares et al., 2006; Soares et al., 2017; Soares et al., 2014). The cable speedometer offers a wide range of data, including instantaneous velocities during sprint swims, which are crucial for designing anaerobic training programs (Bartolomeu et al., 2018; Lima et al., 2006; Soares et al., 2014; Vilas-Boas et al., 2011). Moreover, the cable speedometer is user-friendly, providing immediate feedback to coaches and swimmers, making it a valuable tool in training (Lima et al., 2006; Soares et al., 2014; Vilas-Boas et al., 2011).

After establishing the method's reliability, it becomes crucial to apply it to measure changes in anaerobic performance induced by swimming training. Periodization is a highlight in sports training theory (Clemente-Suárez et al., 2018; Ferreira et al., 2021; Hellard et al., 2017; Zacca et al., 2020a). In swimming, as in other sports, a well-structured annual plan is essential for enhancing swimmers' performance across all age groups (Costa et al., 2011; Smith, 2003). Typically, the season planning is divided into periods known as macrocycles, which consist of preparatory phases (general and specific phases), competitive and transition periods (Clemente-Suárez et al., 2017; Rodeo & Riewald, 2015; Zacca et al., 2020b). **Chapter 4** of this thesis evaluates changes in young swimmers' anaerobic performance during the first macrocycle of the competitive swimming season, that aimed a general preparation to establish swimmers' physiological foundations.

Swimming training microcycles vary in their application of specific principles governing the distribution of training loads (Toubekis et al., 2013), mainly when they precede a competitive event. Before essential competitions, it becomes critical to assess the swimmer's condition and ascertain whether changes in swimming training indices align with the coach's expectations regarding performance. That's why the last study focused on evaluating changes during a more specific preparation period for a significant competition.

In the most crucial competitive events of the season, maximizing swimming performance is closely linked to changes in training load in the preceding days, a phase commonly referred to as the taper period (Clemente-Suárez et al., 2017; Mujika & Padilla, 2003; Pyne et al., 2009). During this specific cycle of the competitive period, swimmers are expected to be primed for peak performance (Mujika et al., 2004), achieved through a progressive and non-linear reduction in training load over a variable time interval (Mujika, 2009). The taper period aims to reduce the physiological and psychological stress accumulated during the preceding weeks of daily training (Mujika et al., 1996; Pyne, 2011). Therefore, optimizing sports performance (Hooper et al., 1998) has become relevant to the outcome of the competition (Mujika & Padilla, 2003). The training volume should be significantly reduced without compromising or diminishing training-induced adaptations (Le Meur et al., 2012) while ensuring that training intensity remains unaffected or benefits from maintenance (Bosquet et al., 2007; Mujika et al., 2002).

The last study aimed to investigate whether a one-week taper (preceding a major competition) positively influences a swimmer's anaerobic performance (**Chapter 5**). The limited literature focusing on the taper period, particularly in young swimmers, provides few insights into the effects of changes in anaerobic potential on performance. This lack of knowledge may be partly due to the sensitivity and critical nature of the taper period in a swimmer's preparation. Sometimes, the taper period does not yield the expected results due to various psychosocial and physical factors (Grivas, 2018). Furthermore, coaches may hesitate to involve their swimmers in experimental studies close to the main event, fearing potential negative impacts on performance. While the taper period should be tailored to individual swimmers' needs, applying the same training program uniformly across a team may yield inconsistent results (Sweetenham & Atkinson, 2003).

After presenting the experimental studies, a comprehensive and general discussion follows (**Chapter 6**), highlighting the evidence gathered from our review and experimental investigations. These findings are contextualized within the existing literature, particularly regarding the methodology for assessing anaerobic performance and the impact of training on the anaerobic potential of young swimmers. **Chapter 7** encapsulates the conclusions drawn from the

research, while **Chapter 8** offers suggestions for future studies. Finally, a list of references supporting the development of this thesis is provided.

Assessment of anaerobic performance in swimming

Measuring velocity in the aquatic environment efficiently and reliably is a significant challenge for researchers and is essential for determining performance levels. Swimming performance, specifically swimming velocity, is strongly influenced by both energetical and biomechanical factors (Barbosa et al., 2019; Carvalho et al., 2023; Fernandes et al., 2010; Vilas-Boas et al., 2015), essential components of the complex performance variables group (Fernandes et al., 2013a). The variables previously mentioned are among the most studied in elite (Figueiredo et al., 2014; Ribeiro et al., 2015a), young (Barbosa et al., 2019; Morais et al., 2017; Silva et al., 2019) and master swimmers (Neiva et al., 2021), with more experienced swimmers tending to maximize energetic and biomechanical variables to achieve or sustain high velocities. In the case of young swimmers, the literature reinforces the concerns above (Figueiredo et al., 2016; Morais et al., 2021; Silva et al., 2022).

To improve performance, coaches are responsible for adapting the training process according to swimmers' specific requirements (Smith et al., 2002). The conscious adaptation of swimmers training should be preceded by regular training monitoring, grounded in a biophysical approach (Almeida-Coelho et al., 2016; Carvalho et al., 2020), which constitutes an essential process of enormous importance and indisputable significance (Fernandes et al., 2012; Morais et al., 2014; Pyne et al., 2006; Zacca et al., 2020). Over the past two decades, there has been remarkable progress in patents related to measurement methodologies in swimming. Still, the challenges associated with conducting instrumental measurements of human locomotion in an aquatic environment persist, heightening the complexity of developing specific swimming tests (Csajági et al., 2015; Morgado et al., 2018).

Evaluating the physiological demands of each swimmer during competitive events is crucial for designing effective training programs and consequently enhancing performance (Figueiredo et al., 2013; Ribeiro et al., 2015b). Even if well-designed training plans should be applied early (Costa et al., 2011; Smith,

2003), assessing physiological variables raises ethical concerns; sometimes, these are difficult to overcome. Studies focused on measuring energy supply in swimming have predominantly concentrated on oxygen consumption over long distances (Ribeiro et al., 2015b), with the overwhelming majority of studies related to aquatic performance and locomotion based on analyzing energy expenditure in submaximal efforts that do not require assessing anaerobic pathways (Zamparo et al., 2020).

Aerobic energy output is probably the most accessible and most reliable measurement, given the close relationship between the aerobic production of adenosine triphosphate in the whole body and oxygen consumption (Barbosa et al., 2019; Figueiredo et al., 2011; Sousa et al., 2015). Conversely, anaerobic pathways are not so straightforward to measure (Campos et al., 2017a; Figueiredo et al., 2011). It yields less reliable results and limited information (Pinos et al., 2021; Ribeiro et al., 2017; Rodríguez, 2011). The anaerobic capacity is the maximum amount of adenosine triphosphate that can be resynthesized by the anaerobic metabolic pathways (Noordhof et al., 2010). Determining anaerobic capacity relies on various and often questionable assumptions (Zamparo et al., 2020), with complexity arising from the fact that adenosine triphosphate is produced at an intracellular level, requiring complex and invasive assessment methods (Gastin, 2001).

Nonetheless, its importance should not be underestimated since most official competitive swimming events (up to 200 m) involve a high energy supply from the anaerobic system (Amaro et al., 2017; Capelli et al., 1998; Di Prampero et al., 2011; Peyrebrune et al., 2014). Considering the previously synthesized arguments, determining anaerobic capacity and power is highly complex (Gastin, 2001; Olbrecht & Mader, 2006; Zamparo et al., 2020). Moreover, the results can differ throughout the day, with a higher predisposition of participants in the afternoon due to body and muscle temperature (Ravindrakumar et al., 2022).

The accumulated oxygen deficit is the most accepted noninvasive method to estimate anaerobic contribution (Gastin, 2001; Kalva-Filho et al., 2016; Reis et al., 2010a). Experimental procedures for estimating anaerobic energy using swimmers' accumulated oxygen deficit face constraints that may limit their applicability (Fernandes et al., 2013b). These include the time required to obtain

the results due to the various tests to be performed, the material used that reduces and influences the swimming skill and the velocity (Campos et al., 2017b), and the material (e.g., snorkel) that usually is not designed for young swimmers (Barbosa et al., 2019). To reduce the negative impact of using a snorkel, extrapolating the rapid oxygen consumption phase immediately after an intense effort proves a helpful alternative for measuring the anaerobic contribution (Monteiro et al., 2020). In all-out efforts, the determination error increases with the swimming distance (Reis et al., 2010b).

The direct approaches employed to assess anaerobic performance capacity, such as magnetic resonance (Degroot et al., 1993; Hancock et al., 2005; Miller et al., 1988; Petersen et al., 1999) and needle muscle biopsy (Bangsbo, 1998; Houston et al., 1983; Jacobs et al., 1983) have proven to be reliable and accurate procedures. These methods allow for the direct measurement of concentrations of the anaerobic pathways' main compounds, although expensive and invasive. In addition, they may be limited in the scope of the information offered, often failing to quantify the complete potential of the anaerobic system (Bangsbo, 1998). The breakthroughs that may be made in whole-body magnetic resonance provide significant developments in this field. Still, the abovementioned methodologies could be more practical, so non-invasive methods are suggested (Zamparo et al., 2020).

Despite the efforts to develop specific swimming tests, land-based measures remain the most employed strategies for determining anaerobic power and capacity in swimmers. The gold standard test for assessing the anaerobic potential is the Wingate anaerobic test (Bar-Or, 1987; Nagle Zera et al., 2021; Tasmektepligil et al., 2012), but it has several limitations and is not applicable in the aquatic environment (Smolka & Ochmann, 2013; Soares et al., 2006; Soares et al., 2014). Among other limitations, the Wingate anaerobic test induces excessive neuromuscular fatigue, imposes restrictions on following physical assessments, and disrupts regular high-quality training for at least 48 hours (Morán-Navarro et al., 2017). These considerations reinforce the incessant search for sport-specific instruments that produce more comprehensive and exhaustive results (Müller et al., 2000). Undoubtedly, to better explain swimming performance and to obtain reliable results, assessments should be carried out

using pool-based tests (Marinho et al., 2009b; Strzala et al., 2021; Zacca et al., 2016).

To employ more specific evaluation methodologies, some researchers have utilized the swim bench protocol (Dalamitros et al., 2014), which, although regarded as a reliable method for simulating actions used in swimming (like the arm-cracking), is unlike the swimming pattern (Aspenes & Karlsen, 2012; Smith et al., 2002; Soares et al., 2014) and non-ecological for the swimmers. The upper limb movements remain confined to a closed chain, primarily in the sagittal plane, poorly replicating the upper limbs' propulsive and recovery phase movements in swimming.

The tethered swimming test is widely employed in swimming research to obtain biomechanical and physiological responses (Costill, 1986; Morouço et al., 2014; Morouço et al., 2012; Nagle Zera et al., 2021; Papoti et al., 2013) and is considered easy and inexpensive to operate (Toubekis et al., 2010). The all-out 30 s tethered swimming test (Morouço et al., 2011) is an excellent adaptation to the land-based measures and may assess the anaerobic profile of adult and young swimmers (Morouço et al., 2012; Ogonowska et al., 2009; Soares et al., 2010).

Tethered swimming mobilizes similar muscle groups to those used in the four conventional swimming techniques (Morouço et al., 2011) and aims to assess not only the force production but also its kinematics and kinetic asymmetries (Carvalho et al., 2019; Toubekis et al., 2010). Furthermore, several authors highlight the association between force production and sprint swimming performance (Loturco et al., 2016; Morouço et al., 2015; Ruiz-Navarro et al., 2020). Despite exhibiting relevant muscular and physiological responses, tethered swimming is not entirely similar to free swimming (Samson et al., 2019). It might provide different outcomes, making it more challenging to evaluate anaerobic capacity.

Some authors claim that the construction of a specific anaerobic test for swimming cannot be based exclusively on the measurement of race time (Demarie et al., 2019; Smolka & Ochmann, 2013; Soares et al., 2014), emphasizing the need to propose a profile of instantaneous swimming velocities.

Therefore, the test should diagnose anaerobic potential through varying velocity profiles and provide information similar to the Wingate anaerobic test (Smolka & Ochmann, 2013; Soares et al., 2014). Swimming velocity is also influenced by the swimmers' technique and skills (Barbosa et al., 2010; Zamparo et al., 2020), which cannot be expressed in non-specific tests. Thus, assessing swimmers' anaerobic potential depends on a test applied in the aquatic environment, able to closely simulate the efforts performed in a 50 m event.

The velocity profiles used to determine anaerobic potential can be acquired using high-frequency and high-resolution video cameras, with the results of the video analyses exhibiting smooth variations in velocity and acceleration (Demarie et al., 2019; Soares et al., 2014). Although only a few upper limb cycles can be analyzed, limiting the study of each swimmer's anaerobic profile might discourage those less familiar with the process from benefiting from this methodology. Recently, the automatic underwater system for optical motion capture (e.g., Oqus 3 and 4 series Qualisys AB, Gothenburg, Sweden) has been used to reduce the amount of time processing the data collected (Chainok et al., 2022; Chainok et al., 2021; Magalhaes et al., 2013; Olstad et al., 2012; Ukai & Rekimoto, 2013). Some swimming-related studies have been conducted using this technology, such as the evaluation of starts and turns (Chainok et al., 2023; de Jesus et al., 2019) or assessing the coordination in young swimmers (Silva et al., 2019; Silva et al., 2022). Although, for anaerobic potential evaluation effects, the system assembly is too complex.

Despite its relevant contributions, the cameras-based swimming system faces challenges that are often difficult to overcome, such as the refraction of the light in the water, requiring constant illumination control (Kwon & Casebolt, 2006). In addition, this system uses bulky equipment and requires complex set-up and calibration (Dadashi et al., 2015). Suppose the field of view is limited to three or four cycles. In that case, the velocity profile analysis becomes nonexistent (Dadashi et al., 2013), making it unfeasible to assess the occurrence of a metabolic response affected by velocity variability (Vilas-Boas et al., 2010).

Researchers, coaches, and practitioners recognized the updated technology as essential to assess and improve competitive performance (Magalhaes et al., 2015). Nowadays, Wearables are an indispensable tool in sports training,

providing real-time feedback on athletic performance and training loads (Fantozzi et al., 2022; Morais et al., 2022), and swimming is no exception. Amongst others, the most common variables estimated using wearables inertial units are stroke frequency, swimming velocity (Bächlin & Tröster, 2012; Le Sage et al., 2010; Simbaña-Escobar et al., 2020; Zhang et al., 2017) and energy cost (Dadashi et al., 2014; Demarie et al., 2019; Lee et al., 2018).

Some researchers have noted that employing these devices offered insights into swimming performance analysis, particularly the instantaneous and average velocity produced as indicators of anaerobic capacity in elite swimmers (Demarie et al., 2019). To obtain accurate results when assessing swimmers' performance using portable inertial units, the swimmer's displacement should not be restricted and should not affect the actions of the upper and lower limbs (Magalhaes et al., 2015). However, minimizing these constraints may only sometimes be feasible, with the primary concern for researchers being the data reliability collected by the wearables inertial units (Dadashi et al., 2015).

The variations in the swimming velocity and the swimming technique can modify swimmers' metabolic and physiological responses (Jalab et al., 2011). The literature reports data based on the mean swimming velocity of maximum trials, specifically during short distances (Gourgoulis et al., 2019; Silva et al., 2019; Strzala et al., 2019; Wądrzyk et al., 2022), and the mean velocity is affected by the high peak velocities and elevated resistance forces (Ribeiro et al., 2015a). According to some authors, the data obtained by mean velocity in swimming assessments seems insufficient to describe swimmers' performance (Fernandes et al., 2022; Smolka & Ochmann, 2013; Soares et al., 2014).

The swimming-specific tests are usually modeled on tests previously employed in land-based versions. The Swimming Anaerobic Sprint Test (Wądrzyk et al., 2022) appears to be a valuable example of this approach, adapted from the Running Anaerobic Sprint Test (Milioni et al., 2017; Zagatto et al., 2009). This test consists of a 6 x 25 m front crawl with the maximum effort required to analyze changes in velocity, stroke length, stroke frequency, and stroke index (Wądrzyk et al., 2022) to assess the anaerobic capacity in swimming. Despite the low cost and the strong correlation of velocity, stroke length, and stroke index with short

distance (100 m front crawl), this test cannot determine the instantaneous velocities during the trial time. The primary limitations lie in the difficulty of comparing the fatigue index between individuals and its restriction in detecting individual changes produced by training.

The time required to cover a distance as fast as possible is considered the best performance measure in competitive swimming. Nevertheless, several swimmers may achieve the same race time while developing completely different velocity curve profiles, and these velocity change profiles may be related to a shift in energy regiments (Soares et al., 2006; Soares et al., 2014). With this in mind, Smolka & Ochmann (2013) designed a swimming test of anaerobic efficiency based on velocity patterns analyses (Smolka & Ochmann, 2013). Findings reported that maximum and minimum velocity are decisive factors in the 100 m front crawl ($r = -0.90$, $r = -0.92$, respectively). These results are related to anaerobic metabolism and play a significant role in swimming performance at distances of 50 and 100 m (Neiva et al., 2011; Vitor & Böhme, 2010).

The Smolka & Ochmann (2013) test to assess anaerobic efficiency was conducted in a 25 m indoor swimming pool, affecting the results negatively due to the multiple turns each swimmer had to complete (Smolka & Ochmann, 2013). Therefore, it became more challenging to analyze velocity progression and a time-consuming process of manual video digitizing (Demarie et al., 2019; Soares et al., 2014). Furthermore, this test is longer than the Wingate anaerobic test and failed to fulfill the requirements for assessing anaerobic potential (Soares et al., 2014). Among the weaknesses of the test mentioned previously, the instantaneous velocity profile of a swimmer can provide researchers and coaches with more detailed and valuable information to identify bilateral strength discrepancies, as well as intra-cyclic velocity variations to minimize the risk of injury and enhance performance through strength and conditioning and swimming training (Demarie et al., 2019; Smolka & Ochmann, 2013; Soares et al., 2014).

Diagnosing physiological readiness levels enables identifying factors that limit swimmers' performance (Smith et al., 2002). In an all-out exercise, the variations in swimming technique and the decrease in swimming velocity over time may be associated with the fatigue that occurs when the swimmer power decreases,

providing information that appears significant to the change in energy pathways (ATP-PCr cycle to lactic acid transition), i.e., the swimmers anaerobic potential (Smolka & Ochmann, 2013; Soares et al., 2014). Inspired by the Wingate anaerobic test, (Soares et al., 2014) assessed swimmers' anaerobic potential by determining fatigue thresholds related to all-out front crawl efforts, reporting promising results. Those authors noted that it is possible to identify one to two fatigue thresholds from the intracycle velocity-variation patterns obtained using a speedometer.

Anaerobic fatigue thresholds were translated into abrupt changes in the frequency domain of velocity for time series and were conceptually associated with changes in available bioenergetic power. It is unclear when the ATP-PCr domain ceases and the glycolysis domain initiates. The literature suggests different limits (Brooks et al., 2000; Gastin, 2001; Powers et al., 2007), although it is accepted that the 8-12 s limit for changes in the energy regimen occurs when the bioenergetics approach is employed for training (Gastin, 2001). For very short and intense metabolic exercise up to 10 s, the contribution of anaerobic energy from PCr and anaerobic glycolysis is equivalent (Hargreaves & Spriet, 2020). However, after 10 s is probably associated with changes in the pathways from alactic to glycolytic dominance (Soares et al., 2014).

The fatigue threshold could result from training, with a delayed or a soon onset (Soares et al., 2014). This could explain the improvements in anaerobic performance, specifically in anaerobic potential (Soares et al., 2014). Despite its apparent usefulness in evaluating anaerobic potential for training control purposes, just using a cable speedometer (Soares et al., 2017; Soares et al., 2014), the processing method requires thorough clarification, but not of the cable speedometer system, that is used to provide automatic and precise assessments of the instantaneous swimming velocity in competitive swimmers (Barbosa et al., 2021; Craig et al., 2006; Craig et al., 1985; Davey & James, 2007; Lima et al., 2006; Soares et al., 2006; Soares et al., 2014) and even in competitive lifesaving (Abralles et al., 2010; Soares et al., 2017).

The cable speedometer system is a mechanical technique to collect velocity-time data (Soares et al., 2014). It comprises a tachometer and a fishing reel, measuring the velocity through a fine nylon line tied to the swimmer's waist (Craig

et al., 1985; Lima et al., 2006). The tool estimates the total power output in swimming (Barbosa et al., 2015; Ria et al., 1990) and efficiency variables [for instant real-time acquisition and display of velocity data, maximum, mean and minimum velocity, the velocity profile, distance per upper limb cycle, calculation of time duration and accelerations between the maximum and minimum velocity values (Soares et al., 2014; Vilas-Boas et al., 2011)]. The advantages of using this electromechanical system are (1) real-time and valuable feedback for practitioners (2) being user-friendly and (3) the easy analysis of the data extracted (Bartolomeu et al., 2018; Lima et al., 2006; Morais et al., 2016; Soares et al., 2006; Soares et al., 2017; Soares et al., 2014; Vilas-Boas et al., 2011).

Some issues are unclear in the anaerobic testing methodologies, with controversial results and fewer studies (Demarie et al., 2019; Gatin, 2001; Morouço et al., 2012). Moreover, the information provided does not seem sufficiently enlightening or helpful for coaches (Pinos et al., 2021). Authors argue that coaches require more specific information about the anaerobic potential of their swimmers to accurately design training programs (Kilding et al., 2010; Olbrecht, 2015; Salo & Riewald, 2008). On the other hand, the researchers claim that currently, there is no feasible test to assess anaerobic capacity in swimming (Holohan et al., 2023). Furthermore, most research on the indirect assessment of anaerobic performance focuses on high-level adult swimmers (Nagle Zera et al., 2021; Ruiz-Navarro et al., 2022; Soares et al., 2014), as opposed to adolescent swimmers (Mezzaroba & Machado, 2014; Szczepan et al., 2023; Zamparo et al., 2000).

Notwithstanding the difficulties, it is essential to assess the anaerobic potential of swimmers to overcome obstacles and provide reliable information to coaches and practitioners.

The continuous and precise assessment of various performance components (in this particular case, the metabolic capacities) provides essential information on training progress. There are several approaches to assessing anaerobic contribution, some about anaerobic capacity and a few on anaerobic potential. The findings of previous studies are considered dubious and have generated some controversy in the scientific community. Therefore, while one challenge is

to access a direct, non-invasive, and low-cost assessment of anaerobic pathways, another issue is the unreliability of existing indirect methods. To summarize, a test capable of answering the concerns of researchers, coaches, and practitioners is required. Determining the anaerobic potential using a speedometer test could be that test.

Are anaerobic fatigue thresholds useful to measure young swimmers' anaerobic performance?

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Abstract

Controlling, evaluating, and prescribing training is an unquestionable need. Science has instruments and protocols, but we must still bridge the gap between science and coaches, namely, finding friendly tools for measuring swim-specific anaerobic potential (Holohan et al., 2023). The current study aims to determine the usefulness of the anaerobic fatigue thresholds determination procedure in measuring young swimmers' anaerobic performance. Thirteen young swimmers of regional and national level and the same club participated voluntarily in the study, being six males (15.27 ± 1.21 years, 58.50 ± 5.01 kg and 172.83 ± 4.45 cm) and seven females (14.86 ± 1.35 years, 56.86 ± 5.84 kg and 166.00 ± 6.51 cm). Swimmers performed a 50 m front crawl sprint (all-out) connected to an electromechanical speedometer. The anaerobic fatigue thresholds (AFT) were twice determined from the velocity/time curves $[v(t)]$ of each swimmer by an experienced and a non-experienced evaluator. Swimmers also swam (all-out) the time corresponding to the personal AFT (AFTt). The blood lactate concentrations were determined after the 50 m and the AFTt swim. The relative test-retest reliability of the AFT was assessed for both evaluators. Results showed that swimming the AFT does not exponentially raise the blood lactate values. Test-retest reliability of the AFT showed no differences for both evaluators. The determination of the young swimmers' anaerobic performance through the determination of AFT appears to establish a helpful tool.

Keywords: *swimming; anaerobic potential assessment; anaerobic fatigue thresholds*

Introduction

To evaluate changes in swimming performance produced by training with eligible tools is a determinant of improving swimming training efficiency (Fernandes et al., 2013; Pyne et al., 2000). The more specific (more ecological) the assessment tools and protocols are, the greater the applicability of the results for training assessment purposes (Csajági et al., 2015; Morais et al., 2014; Morgado et al., 2018). There are some excellent tools and protocols to evaluate swimmers' aerobic power and capacity [e.g., oxygen consumption using direct oximetry (Fernandes & Vilas-Boas, 2012)], but the evaluation of the anaerobic potential (power and capacity of the anaerobic system) is far from being satisfactory (Pinos et al., 2021; Ribeiro et al., 2017a; Rodríguez, 2011). Moreover, steel is necessary to bridge the gap between science and coaches, empowering coaches with less invasive and more reliable methodologies to measure anaerobic potential.

The Wingate test (Bar-Or, 1987) is the classical gold standard for assessment of the anaerobic energy consumed during an exercise. This old indirect lab test has recognized general limitations for sports, particularly swimming. More direct measurements of the anaerobic energy consumption were used in the past. Still, procedures were highly invasive and expensive, with results being limited in the information provided [e.g., muscle biopsy (Bangsbo, 1998) and magnetic resonance (Hancock et al., 2005)]. Due to the limited uselessness of the most direct tests and the limited ecological validity of the Wingate test for swimming, researchers tried some standardized tests for assessing anaerobic potential, such as the simulated swim (Morton & Gastin, 1997), tethered swim (Rohrs et al., 1990) or treadmill swim (Wakayoshi et al., 1992).

The anaerobic contribution in maximal and submaximal efforts has been extensively studied (Figueiredo et al., 2011; Ribeiro et al., 2015), as well as anaerobic capacity through the maximal accumulated oxygen deficit (Kalva-Filho et al., 2016; Reis et al., 2010). However, this measurement methodology in swimmers has some constraints that may decrease its applicability (Campos et al., 2017). On the other hand, more literature on measuring anaerobic potential in swimmers could benefit training planning and performance optimization.

In the last decade, some authors tried to adapt the Wingate test for swimming, as Smolka and Ochmann (2013) developed an anaerobic efficiency test using a non-chronometric approach based on the 100 m freestyle event (front crawl). Each event was video-captured to produce swimming velocity patterns that were analyzed. The authors found two critical limitations in the test. First, they considered that results were negatively influenced by the lower limbs' action after the turns, changing the design of the velocity curves. Secondly, the time that the researchers and coaches took to digitize the analyzed videos manually also appeared to be restrictive in the future implementation of the same protocol. Thirdly, only a few cycles can be effectively analyzed due to limitations in the capture, restricting the assessment of velocity variations.

Other authors developed a specific anaerobic test inspired by the Wingate test to assess swimmers' anaerobic potential through the instantaneous velocity profile obtained with a speedometer (Soares et al., 2014). For the first time, the authors reported promising results on assessing anaerobic fatigue thresholds related to anaerobic efforts of 50 m all-out front crawl, determining these swimmers' thresholds over v/t curves. However, the authors did not test the reliability of the procedure. Therefore, the current study aims to assess the usefulness of the anaerobic fatigue thresholds determination procedure in measuring young swimmers' anaerobic performance.

Material and Methods

Thirteen young swimmers of regional and national level and of the same club participated voluntarily in the study, being six males (15.27 ± 1.21 years, 58.50 ± 5.01 kg and 172.83 ± 4.45 cm) and seven females (14.86 ± 1.35 years, 56.86 ± 5.84 kg and 166.00 ± 6.51 cm). Training and competitive experience were higher than four years. During the study, the swimmers performed seven training units per week, with an average duration of three hours per day (one hour in dry land and two hours in water). The training content and prescription were similar for all the swimmers. The parents signed an informed consent describing protocol and

evaluation procedures. The local ethics committee previously approved the study (CEFADE 27/2022).

Testing procedures occurred in a 50 m indoor pool with a water temperature of 28 °C. After a 1000 m standardized low-intensity warm-up (Neiva et al., 2014), each swimmer performed a 50 m front crawl sprint (all-out), connected to an electromechanical speedometer through a fine nylon line fixed on a belt placed around its waist [previously described in detail by Soares et al. (2014)]. A SONY Handycam camera (HDR-CX160E, sample frequency of 50 Hz) placed on a trolley and moving on the poolside parallel to the swimmer's movement was used to video record each sprint. A sound signal is allowed to synchronize video recording with a speedometer. This procedure allowed us to determine the v/t curve of each swimmer.

The processing of instantaneous velocity curves was performed applying a MATLAB (version 9.0) routine described elsewhere (Machado et al., 2007) and optimized for the most accessible visual graphic inspection. This process included a continuous wavelet analysis of the signal and allowed the discrimination of one or more separation time points with different spectral characteristics, called anaerobic fatigue thresholds (AFT). The AFT was determined by an experienced (G1) and a non-experienced (G2) evaluator.

The upper limbs (UL) cycle duration, stroke length (SL, quotient of mean velocity and stroke frequency), stroke frequency (SF, time taken to complete three upper limb cycles), mean velocity (Vmean), and the variation coefficient of the velocity [$CV = (sd/V_{mean}) \times 100$] were determined for each time interval defined by the AFT.

Twenty-four hours after the 50 m all-out test, seven swimmers (two females and five males) were requested to perform another all-out swim corresponding to the anaerobic fatigue threshold time (AFTt) determined by the experienced evaluator. This procedure was to test the possibility of the AFT separate physiological alactic and lactic dominant zones, using blood lactate as a reference.

The maximal blood lactate concentration $[La^-]$ ($\text{mmol}\cdot\text{l}^{-1}$) was determined using a Lactate-Pro device (Lactate Pro 2, Arkay, Inc., Kyoto, Japan), after the 50 m test and after swimmers swam the time correspondent to the personal AFT (AFTt). The blood samples were collected from the swimmers' ear lobe to a blood strip at rest and during recovery (after 1, 3, and 5 min).

To test the reliability of the AFT determination procedure, the experienced and the non-experienced evaluators determined the AFT of each swimmer in a second moment, with a week of interval (test-retest, M1 and M2). The results of the first and second evaluations of each one of the two evaluators were compared to determine the inter-observer reliability.

The normality of the data was verified with Kolmogorov-Smirnov. A log transformation (Log_{10}) was performed if the normality assumption was violated, and data were back-transformed from the log scale. The mean with one standard deviation ($M \pm SD$) was computed as descriptive statistics. A paired sample t-test was used to compare the $[La^-]$ values between 50 m and AFT and all the kinematic variables of the 1st and 2nd-time intervals defined by the AFT.

The relative test-retest reliability of AFT for both evaluators was assessed using the intraclass correlation coefficient (ICC) plus 95% confidence intervals (95CI). The ICC was classified as poor if $ICC < 0.50$, moderate if $0.50 \geq ICC < 0.75$, good if $0.75 \geq ICC < 0.90$, and excellent if $ICC > 0.90$ (Koo & Li, 2016). The absolute test-retest reliability was analyzed with the typical error (TE), coefficient of variation (CV%), and standard error of measurement (SEM) (Atkinson & Nevill, 1998). The CV% values were interpreted as poor if $CV\% > 10\%$, moderate if $5\% \geq CV\% \leq 10\%$, and good if $CV\% < 5\%$ (Duthie et al., 2003). Additionally, the ability to detect a change was rated as "good," "OK," or "marginal" when the TE was below, similar, or higher than the smallest worthwhile change (SWC), respectively. Bland–Altman plots with 95% limits of agreement (LoA) were used to display systematic differences between the test-retest moments (M1 vs M2) (Bland & Altman, 1986).

Results

Higher $[La^-]$ values (mean difference [95CI]: 3.90 [1.62 to 6.18]; t -test = 4.19, p = 0.006, d = 2.3) were found for 50 m (5.60 ± 2.10 mmol·l⁻¹) when compared to AFTt (1.70 ± 1.13 mmol·l⁻¹). The comparison of kinematic parameters between the 1st and 2nd AFT intervals is shown in Table I. Differences with a medium to large effect were found for UL cycle, SF, mean v , and dv . The SL remained similar between the 1st and the 2nd FT.

Table 1. kinematic parameters determine for the first and second time intervals (Int) determined by the anaerobic fatigue thresholds (AFT).

Variable, unit	1 st Int ($\bar{X} \pm SD$)	2 nd Int ($\bar{X} \pm SD$)	Mean difference (95CI)	t-test (p)	d
UL cycle, s	1.36 $\pm$ 0.15	1.46 $\pm$ 0.19	-0.10 (-0.16 to -0.04)	-4.17 (0.006)	0.6
SF, Hz	0.74 $\pm$ 0.09	0.70 $\pm$ 0.09	0.05 (0.02 to 0.07)	4.64 (0.004)	0.4
SL, m	2.00 $\pm$ 0.11	1.98 $\pm$ 0.09	0.02 (-0.05 to 0.09)	0.74 (0.488)	0.2
Vmean, m·s ⁻¹	1.48 $\pm$ 0.13	1.37 $\pm$ 0.12	0.11 (0.08 to 0.14)	9.89 (<0.001)	0.8
CV, %	0.14 $\pm$ 0.02	0.18 $\pm$ 0.05	-0.04 (-0.08 to 0.00)	-2.29 (0.062)	1.1

UL, upper limbs; SL, stroke length; SF, stroke frequency; Vmean, mean velocity; CV, variation coefficient of the velocity.

The test-retest reliability of the AFT is shown in Table II. No differences were found between M1 (test) and M2 (retest) for the experienced (G1) (mean difference [95CI] = 1.54 [(-0.61 to 3.68]) and non-experienced (G2) (mean difference [95CI] = -1.61 [(-3.94 to 0.71)]) evaluators. The ICC for G1 showed a “good” relative reliability. However, ICC95CI demonstrated a “moderate” to “excellent” relative reliability. A similar trend was observed for G2, but a “poor” to “excellent” relative reliability was found. TE was rated as “good” compared to the SWC, and CV% revealed a “moderate” absolute reliability of FT for both groups.

Table 2. Test-retest reliability of the AFT for the experienced (G1) and non-experienced (G2) evaluators (Eval).

Eval	M1 (M±SD)	M2 (M±SD)	p	TE	SWC	CV%	ICC	ICC _{95CI}	SEM
G1	18.08±6.54	16.54±7.23	0.144	1.00	1.38	9.87	0.86	0.60 to 0.95	2.58
G2	17.08±6.06	18.69±5.63	0.155	1.12	1.17	9.70	0.77	0.41 to 0.92	2.80

CV%, coefficient of variation in percentage; ICC, intraclass correlation coefficient; ICC95%CI, lower and upper bound of ICC; M1, moment 1 (test); M2, moment 2 (retest); SEM, standard error of measurement; SWC, smallest worthwhile change; TE, typical error.

The Bland-Altman plots are presented in Figure 1. Small bias (mean differences) were found for AFT in both groups.

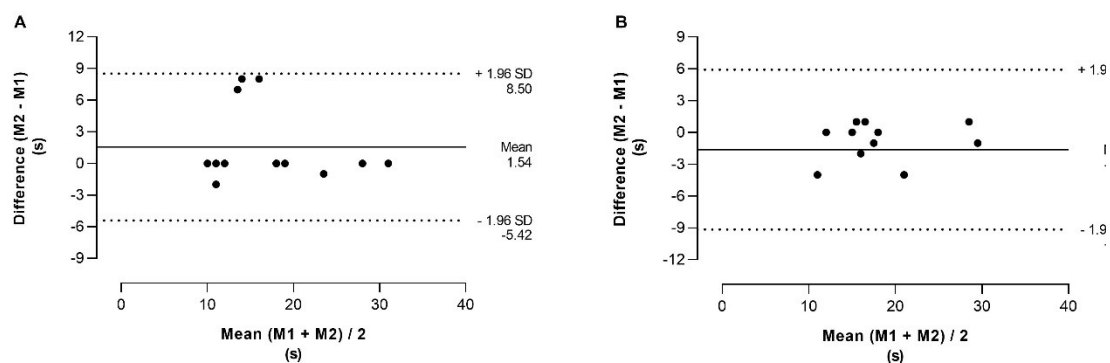


Figure 1. Bland-Altman plots of the test-retest difference, between M1 and M2 (y-axis), and mean of observations (x-axis) for AST. Dotted lines represent the upper and lower 95% LoA and solid lines represent the mean differences between the two groups (bias). Panel A and Panel B represent G1 and G2, respectively.

Regarding the inter-observer agreement, mean difference between evaluators did not differ (G1, 18.08 ± 6.54 s vs G2, 17.08 ± 6.06 s; $t = 0.404$, $p = 0.689$, $d = 0.2$) and the ICC was classified as “moderate” (ICC95CI = 0.667 [0.212 to 0.885], despite 95CI of ICC demonstrating a “poor” to “good” inter-observer agreement. The Bland-Altman analysis for AFT (Figure 2) revealed that bias was around 1 s, and most data points were within the LoA.

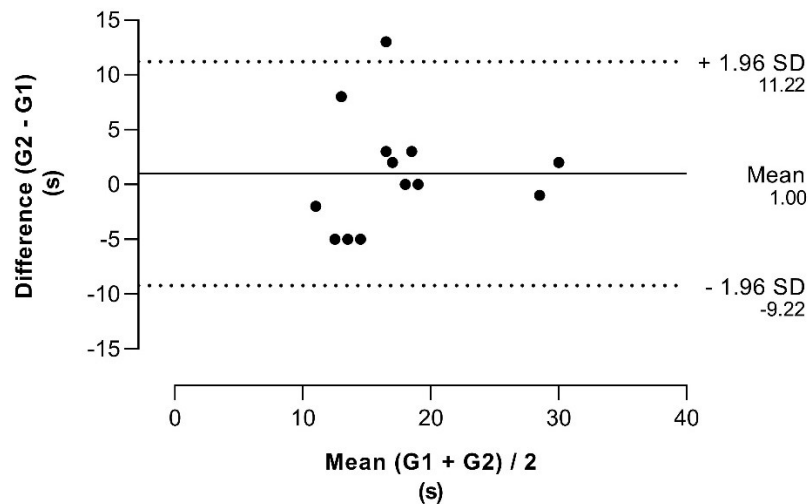


Figure 2. Bland-Altman plots between experienced (G1) and non-experienced (G2) evaluators (y axis) and mean of observations (x-axis) for AFT. Dotted lines represent the upper and lower 95% LoA and solid lines represent the mean differences between the two groups (bias).

Discussion

Determining the swimmers' anaerobic potential is fundamental for monitoring the training effects and making subsequent adjustments to the workload. This statement supports the current study's objective: to determine the usefulness of an evaluation tool for anaerobic performance assessment.

Soares et al. (2014) first suggested the procedure tested in this work. Those authors have determined an AFT over a v/t curve obtained in a short all-out effort and suggested that this threshold could mark the frontier between the alactic and lactic metabolic dominant zone. That allowed us to hypothesize that movements in the AFT position in the v(t) curve after training periods could express swimmers' anaerobic potential changes. This article tests the reliability of that procedure.

Some assumptions were based on the present research. The AFT determination procedure would be helpful to evaluate swimmers' anaerobic performance if: (1) the AFT expresses the boundary between the alactic and lactic dominant zones; (2) the threshold separates two time zones in which the swimmer's mechanical

behavior is different; (3) two evaluators with different experience in using the procedure are in agreement and (4) a test-retest shows similar results, independently of the evaluator experience.

The AFT values found in this study were similar to those obtained by other authors (Soares et al., 2006) with pubertal athletes in all-out efforts of 30 s. This is a good agreement once the threshold is determined by analyzing the content of a mechanical signal of a curve, which could seem to be affected by the young swimmers' technical instability (Soares et al., 2006).

Our results showed that the blood lactate did not rise significantly when the young swimmers swam the time corresponding to their individual AFT, allowing us to expect that it is possible that the glycolysis was not yet fully activated. This reinforces the idea of an alactic-lactic boundary expressed by the AFT.

This study also revealed that the thresholds separate time intervals where young swimmers' biomechanical behavior differs. Before the threshold, the V_{mean} and the SF are higher, and the UL cycle duration is lower. These findings are related to changes in the swimming pattern when fatigue is established in young swimmers (Figueiredo et al., 2016; Morais et al., 2017; Silva et al., 2022) and adults (Ribeiro et al., 2017b; Tella et al., 2008), as found in other studies, and reinforces the AFT as an adequate threshold.

The determination of the AFT by different evaluators with different expertise revealed no differences, meaning that this tool is easy to apply, is coach-friendly, and gives reliable results. The values show that the test to determine the AFT showed good test and retest reliability and a strong correlation with a high agreement of both evaluators. It also indicates that independent of the evaluator's expertise, the application of the method can be repeatable, thus confirming the consistency of the intended measure (Hopkins, 2000). The error associated with each evaluator was considered good, and the moderate values of the CV% reinforce the low variability in the results determined by the evaluators. The bias of around 1 s found in the Bland-Altman test, with only one case outside the range of the limit of agreement, shows low dispersion in the sample. It supports the robustness of the evaluators' analysis.

Conclusion

The fatigue thresholds determination procedure seems valuable for evaluating young swimmers' anaerobic performance once results are reliable. This may respond to the apprehensions of science in having a specific test in swimming that is non-invasive, easy to apply, and friendly for coaches and practitioners to evaluate the anaerobic potential.

Using fatigue threshold to determine changes in swimmers' anaerobic performance after a training macrocycle

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Abstract

Velocimetry is an indirect method that may be used to evaluate swimmers performance and determine anaerobic fatigue thresholds related to metabolic needs. However, how training changes the performance monitored through anaerobic fatigue thresholds is still unknown. This study aimed to assess changes in anaerobic performance and anaerobic fatigue thresholds, determined through the velocimetry method, imposed by a training macrocycle. Thirteen swimmers (six males and seven females) performed a 200 m maximum and an all-out 50 m front crawl sprint before and after a six-month macrocycle. In the 50 m, the swimmers' waists were connected to a speedometer through a cable for instantaneous velocity measurement. The anaerobic fatigue threshold was determined through wavelets analysis of frequencies using a MatLab routine. A video camera was placed in the pool deck for sagittal image recording. Rest and post-effort blood lactate concentrations were measured by dry chemistry and ear-lob puncture. A Student t-test was computed to assess pre and post-test differences ($p \leq 0.05$). Results showed a decrease of ≈ 2 s in the 50 m performance time after the macrocycle and a lactate increase of ≈ 2 mmol.l⁻¹, suggesting an improvement in the total metabolic anaerobic contribution. However, the fatigue threshold remained statistically unchanged with training (18.23 ± 6.35 vs 16.38 ± 4.98 s, $p > 0.05$). It can be concluded that anaerobic fatigue thresholds may not be good indicators of swimmers' anaerobic performance after a long training period.

Keywords: *swimming, training control, anaerobic potential, anaerobic fatigue threshold*

Introduction

A competitive swimming season is usually divided into small parts as macrocycle, mesocycle, and microcycles (Zacca et al., 2020). The training macrocycles are the longest periods of a competitive swimming season and should be programmed critically to trigger bioenergetic changes, including those relative to the anaerobic potential (ATP-CP and Glycolytic) of the swimmers (Clemente-Suárez et al., 2018; Olbrecht, 2011; Riewald & Rodeo, 2015). Within this background, the search for reliable and more friendly user methods to control the effects of the training on swimmer's anaerobic performance is needed, because magnetic nuclear resonance or muscular biopsy (direct methods) are too expensive, invasive and time-consuming (Hancock et al., 2005; Jacobs et al., 1982).

Most swimming competitive events depend on the high energy availability provided by anaerobic sources (Figueiredo et al., 2011; Kalva-Filho et al., 2015; Zamparo et al., 2011) and evaluation methods must be functional in discriminating the training effects. However, this is particularly difficult to achieve, especially when anaerobic metabolism is considered. Smolka & Ochmann (2013) used velocimetry procedures to inform swimming coaches about anaerobic performance. Still, those researchers' method implies a long analysis time and the swim analyses included turns, which somewhat disturbed the study of the time progression of speed. In contrast, Soares et al. (2014) tried to overcome the previously mentioned limitations using a different velocimetric method. Anaerobic fatigue thresholds were assessed, being traduced by abrupt changes in the frequency domain of velocity to time series and are conceptually associated with changes in available bioenergetic power. These, for very short and intense metabolic exercises, are likely to be associated with shifts from the alactic to glycolytic dominance pathways and were previously assumed as an evaluation tool of the anaerobic potential of swimmers and competitive lifesavers (Soares et al., 2017).

The anaerobic fatigue threshold could be a helpful variable for training control purposes if changes in swimmers' anaerobic performance could be effectively detected. The anaerobic fatigue threshold may express a sooner (left shift) or a

later (right shift) start of the glycolysis dominance in an all-out effort as a consequence of training. However, this phenomenon still needs to be fully understood. Therefore, this study aimed to assess changes in anaerobic performance and anaerobic fatigue thresholds, determined through the velocimetry method, imposed by a training macrocycle. It was hypothesized that improvements in anaerobic swimming performance would be associated with changes in the anaerobic fatigue thresholds.

Materials and Methods

Thirteen national level swimmers, six males (age: 15.27 ± 1.21 years, body mass: 58.50 ± 5.01 kg and statures: 172.83 ± 4.45 cm of height) and seven females (age: 14.86 ± 1.35 years, body mass: 56.86 ± 5.84 kg and statures: 166.00 ± 6.51 cm of height) performed 200 m maximum and 50 m all-out front crawl swimming efforts, immediately before and after a six months training macrocycle. The swimmers were all recruited from the same swimming team, having at least four years of training experience and did not suffer from any injury in the six months previous to data collections. Swimmers were engaged in a training plan with seven sessions per week, with an average duration of three hours (one hour in dry land and two hours in water). The parental informed consent (Helsinki Declaration), swimmers' acceptance and study ethics approval of the Faculty of Sport, University of Porto (CEFADE 27/2022) were obtained.

Subjects were evaluated in a 50 m indoor swimming pool with a water temperature of 28°C, air temperature of 28°C, and humidity of 60%. The warm-up, consisted of a 1000 m free swim at a low pace, as described previously (Taylor et al., 2013). A 200 m front crawl performance time and a 50 m all-out front crawl effort with an in-water start were assessed before and after the training macrocycle. In the 50 m, swimmers were connected to an electromechanical speedometer through a fine nylon line fixed on a belt placed around the swimmers waist, as previously described (Soares et al., 2014).

The speedometer registered the instantaneous velocity of each swimmer, and the individual velocity/time curve [$v(t)$] was drawn. The variables determined used for further analysis were chronometric (200 and 50 m swim time, in s),

velocimetric (maximum and mean velocity, in m.s^{-1}), physiological (blood lactate concentrations, in mmol.l^{-1}), and technical (stroke frequency, in Hz, and stroke length, in m). The anaerobic fatigue thresholds occurrence time was determined through wavelets analysis using a MATLAB routine (Machado et al., 2007). Fatigue thresholds were considered the time moments of effective change of the frequency content of the velocity-time curve and possibly related to a shift from ATP-PCr to glycolysis dominance in anaerobic metabolic contributions.

All efforts were video recorded at 50 Hz. The camera was in the pool deck, 25 m from the start, in the sagittal plane, and 2 m from the testing lane. The image synchronization with the velocity recordings from the speedometer was done using an auditory signal. Rest and post-effort capillary blood lactate concentrations were measured by ear puncture using a portable device (Lactate Pro 2, Arkray, Inc.).

The statistical procedures were conducted in the Statistical Package for The Social Sciences (SPSS, v.24.0, IBM, New York, USA). The basic descriptive statistics were reported as means and standard deviations, and the normality of the distributions was tested using the Shapiro-Wilk test. A Student t-test was computed to assess pre and post-test differences ($p \leq 0.05$).

Results

Table 1 shows the values of all the studied variables measured before and after the training macrocycle. The 200 and 50 m front crawl times, the mean swimming velocity, and the maximum post-effort blood lactate have improved after the training macrocycle.

Table 1. Changes of variables with the training macrocycle, comparing before and after conditions.

Variables	Before	After
200 m Swim time (s)	142 $\pm$ 8.40	136 $\pm$ 12.0*

50 m swimming time (s)	32.49 ± 3.15	30.18 ± 3.50*
Maximum 50 m velocity (m.s ⁻¹)	2.36 ± 0.19	2.37 ± 0.26
Mean 50 m velocity (m.s ⁻¹)	1.53 ± 0.16	1.61 ± 0.18*
Blood Lactate (mmol.l ⁻¹)	5.62 ± 2.13	7.90 ± 2.83*
Stroke frequency (Hz) ^{a)}	0.82 ± 0.12	0.85 ± 0.13
Stroke lenght (m) ^{a)}	1.89 ± 0.11	1.88 ± 0.11
Fatigue threshold (s)	18.23 ± 6.35	16.38 ± 4.98

*Different from before ($p \leq 0.05$); ^{a)} Stroke rate and frequency were calculated after removing the initial glide and arrival from the v(t) curve.

Discussion

This study aimed to assess changes in anaerobic performance and anaerobic fatigue thresholds, determined through the velocimetry method, imposed by a training macrocycle. It was expected that if the swimmers anaerobic performance changed with training, the anaerobic fatigue thresholds estimated based on the individual v(t) curves would graphically move to the left (sooner start of the glycolysis as a dominant energetic pathway) or to the right (later start of the glycolysis as a dominant energetic pathway).

Results showed that the swimmers anaerobic potential increased with training, particularly anaerobic power, once swimming times were reduced and maximal blood lactate concentrations increased after the 50 m exertion. Indeed, the 50 m performance improved with the training macrocycle in accordance to the expected evolution throughout the season (Clemente-Suárez et al., 2017), mainly because the post-test was done near a critical competitive event (Toubekis et al., 2013). The observed mean velocity values agree with those found in other studies using a speedometer while swimming the same distance (Soares et al., 2014). An increase of glycolytic power is also compatible with an observed tendency (not

significant) for a left shift of the anaerobic fatigue threshold, possibly traducing an earlier dominance of glycolysis after training. A mean improvement in the 200 m front crawl times was also observed, despite the high inter-individual variation. The improvement of the mean 200 m swim velocity could be associated with an also augmented anaerobic capacity once, for the swimmers age group into analysis, the anaerobic contribution for total energy expenditure in this event varies from 40 (Figueiredo et al., 2011) to 60% (Maglischo, 2003). This contribution could rise until 80% in the 50 m sprint (Rodríguez & Mader, 2011).

Lactate concentration measurements are commonly used for effectively evaluate and prescribe training (Beneke et al., 2011). The maximum lactate values observed in the present study, after the 50 m front crawl all-out swim, were taken as sufficient evidence of the substantial contribution of the anaerobic metabolism to sustain the effort. The blood lactate values increased with training season, possibly due to the type of training (Beneke et al., 2011; Smith et al., 2002).

The technical ability of a swimmer underlies the performance improvement and, therefore, the ability to generate higher velocity during a specific swimming distance. It is considered that the biomechanical variables are essential in swimming performance (Fernandes et al., 2013; Figueiredo et al., 2013; Ribeiro et al., 2017). Both stroke frequency and length did not change over the macrocycle, suggesting that those were swimmers that have reached or are near their technical limits, as seen in adult swimmers (Costa et al., 2012). However, it has also to be considered that the calculation of the stroke length and frequency over a $v(t)$ curve purged of the starting glide and arrival and some bias could be associated with the absence of change.

In general, our findings point out that, after a training macrocycle, a higher total metabolic anaerobic contribution is observed, which could not be tracked by an evident change in the time of occurrence of the anaerobic fatigue threshold, not expressing any change in the anaerobic pathways dominance induced by training over the 50 m distance. However, a deeper analysis is needed before accepting this deduction due to the large inter-individual variability observed in the mean anaerobic fatigue threshold time, meaning that the change of that parameter with

training was primarily individual. The heterogeneity of the sample, including non-clustered male and female swimmers and specialists in short and long-duration swimming events, may have influenced the results. Moreover, performing the study in a more specific training period would give better information about the effect of training on anaerobic energy production and time dominance of alactic and lactic pathways.

Although the time of occurrence of the anaerobic fatigue threshold didn't differ significantly, there was a slight tendency for a left-shifted threshold that should not be ignored once it indicates a tendency for a sooner start of the glycolysis as dominant anaerobic pathway, that is coherent with the other variables changes, being associated with a higher glycolytic power. The average fatigue thresholds of the present study occurred later than those observed in other studies, which happens around ≈ 13 s (Soares et al., 2014) and ≈ 9 s (Smolka & Ochmann, 2013). However, those were studies conducted under different conditions (using older swimmers, longer swimming distances, or short-course swimming pools).

Considering the main limitations of this work, further studies should try to use more homogeneous groups, dissect the adaptations in other specific training periods, and use short-distance specialists to clearly show the fatigue thresholds usefulness as a tool for evaluating time variations in anaerobic dominance during swimmers anaerobic performance. Nevertheless, it was made evident that following one six months macrocycle of swimming training, anaerobic power grow, and possibly anaerobic capacity also, tending to shift the anaerobic fatigue thresholds to the left-hand side, pointing for a sooner dominance of glycolytic pathway as the main energy supply system.

Chapter 5.

The anaerobic potential changes of young swimmers in response to taper

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Abstract

The current study aims to determine the effect of one-week tapering on the anaerobic potential of young swimmers based on a simple and non-invasive test. Twenty competitive young swimmers (12.83 ± 1.08 years) performed an all-out 25 m front crawl sprint coupled to an electromechanical speedometer before and after a week of tapering. The variation of the velocity along time [$v(t)$ curves] was determined for each swimmer. The push-off maximum velocity, push-off velocity decay, maximum and average gliding velocity, maximum and average swimming velocity, fatigue index, swimming velocity decay, velocity variation coefficient, total number of cycles, and total swim time were calculated. An individual anaerobic fatigue threshold was determined by applying a mathematical procedure based on wavelet analysis to the aforementioned $v(t)$ curves. The number of upper limb cycles performed was registered using video image captures. The blood lactate concentration was measured at rest and after the 25 m sprint. The swim duration time of 25 m (pre-taper: 17.91 ± 1.69 ; post-taper: 17.90 ± 2.18 s, $p = 0.976$) and the post-effort blood lactate (pre-taper: 4.92 ± 0.85 and post-taper: 4.77 ± 1.80 mmol.l⁻¹, $p = 0.780$) did not change with the taper. The other variables also did not change, except for the velocity decay (-1.19 ± 0.94 vs. -0.52 ± 0.21 m.s⁻¹, $p = 0.016$). The moment of occurrence of the anaerobic fatigue threshold was no different after the taper. The one-week taper did not significantly change young swimmers' anaerobic potential.

Keywords: *swimming, taper, anaerobic potential, velocity.*

Introduction

Swimmer performance is closely dependent on bioenergetic and biomechanical factors (Barbosa et al., 2010a; Fernandes et al., 2006; Fernandes et al., 2010; Vilas-Boas et al., 2015; Zamparo et al., 2005) and it is well accepted that other factors also contribute to improving swimming performance in young athletes (Barbosa et al., 2010b; Figueiredo et al., 2013; Figueiredo et al., 2016; Silva et al., 2019a; Silva et al., 2022). Swimming coaches have a fundamental role in the training process (Fernandes, 2012; Pyne et al., 2006; Smith et al., 2002; Zacca et al., 2020), enhancing swimmers performance by optimizing physical, technical, and psychological skills (Almeida-Coelho et al., 2016; Carvalho et al., 2020). To achieve this, they should develop a specific, controlled, and systematized training program (Zacca et al., 2019) that includes several training periods. One of those periods is known as taper and is characterized by a load change several days before a competition, allowing the optimization of the swimmer's performance (Hellard et al., 2017; Mujika & Padilla, 2003). The effects of taper over performance, namely an anaerobic potentiation, must be measured to test its efficacy.

The taper is a period of progressive and non-linear training load reduction over time, intending to reduce the physiological (fatigue) and psychological stress of daily training and optimize performance in competition (Hellard et al., 2017; Mujika et al., 1995; Mujika & Padilla, 2003). The taper content should be adapted to each swimmer's needs since variables such as recovery duration, volume, and intensity of the training tasks will determine the performance gain (Mujika et al., 2002; Sweetenham & Atkinson, 2003; Trinity et al., 2006). Studies about taper effects on the performance of athletes of different sports, such as runners, swimmers, and cyclists, point to a significant improvement in performance ($0.7 \pm 7.7\%$) with a fourteen days taper (Costill et al., 1985a; Egesoy, 2020; Houmard & Johns, 1994). Other studies report that a gradual reduction of the training volume applied seven to twenty-one days before a major competition could enhance performance by 2 to 4% (Costill et al., 1985b; Johns et al., 1992). Those reductions do not affect the training-induced adaptations (Le Meur et al., 2012). Studies also point out that the training load should not be reduced by lowering

training intensity and may benefit from its maintenance or rise (Bosquet et al., 2007; Mujika et al., 2002). Curiously, such information is missing for young swimmers.

More or less specific tests such as tethered swimming and crank ergometers (Hooper et al., 1998; Toubekis et al., 2006; Trinity et al., 2006) have been used to study the taper effects on swimmers' physiological performance. General performance tests highlight the need for a more precise evaluation of the anaerobic potential (Gastin, 2001; Ribeiro et al., 2015) using simple tests that would help coaches adjust training with efficacy, especially for young swimmers (Fernandes et al., 2008; Silva et al., 2012; Silva et al., 2013). In reality, most of the research conducted in recent years with young swimmers has focused on the study of factors that directly or indirectly determine the swimmers performance, like bioenergetics (Denadai et al., 2000; Toubekis et al., 2006), biomechanics (Figueiredo et al., 2016; Morais et al., 2012; Silva et al., 2019b) and anthropometrics (Geladas et al., 2005; Nevill et al., 2020), but the anaerobic domain keeps fragile. The little attention directed to evaluating the anaerobic potential was likely due to the difficulty of implementing indirect and less invasive assessment methodologies.

In the last 20 years, a simple 100 m maximum front crawl test was proposed to measure anaerobic power (Smolka & Ochmann, 2013; Vitor & Böhme, 2010), as well as an easier 50 m all-out front crawl test to assess the anaerobic fatigue threshold is also an indicator of anaerobic potential (Soares et al., 2014). This last test is elementary and, if used before and after the taper, would show a later occurrence of the anaerobic fatigue threshold due to the improvement of the anaerobic potential (Soares et al., 2014). Such expectations make it practical to use it as an evaluation tool during tapering. Therefore, this study intends to determine the effect of one week tapering on the anaerobic potential of young swimmers based on a simple and non-invasive test.

Materials and Methods

Twenty young competitive swimmers (12.83 ± 1.08 years, 47.95 ± 8.47 kg, and 159.1 ± 10.77 cm) participated in the study. Swimmers were evaluated in a 25 m indoor pool, with heated water at 28°C and under regulatory thermo hygrometric conditions. All the swimmers were encouraged to keep a normal/good hydration and nutrition status, without pain episodes or recent injuries. After a typical warm-up session (Neiva et al., 2012), the swimmers recovered actively for 10 to 20 min (Neiva et al., 2014) until they reached a personal readiness to perform a 25 m all-out front crawl sprint. The test was performed before and after a one-week taper. All swimmers freely volunteered for the study, and parents signed the informed consent. The local ethics committee (CEFADE 27/2022) approved all testing procedures that followed the Helsinki Declaration.

Evaluation occurred during the winter season in regular training conditions. Swimmers were tested one week before the national championship (pre-taper) and one day after its end (post-taper). Training before the evaluation was composed of 20 weeks (general and specific periods). In the pre-taper assessment week, swimmers completed 5470 ± 394.84 m per training unit, 40945 ± 3135.61 m·week⁻¹, and 7.5 ± 0.51 training units. Training volume decreased in the taper week to 3820 ± 366.49 m per training unit, 23525 ± 3476.37 m·week⁻¹, and 6.15 ± 0.59 training units.

Swimmers were connected to an electromechanical speedometer [previously described by Lima (2005)] through a fine nylon line to determine the variation of the swimming velocity with the time [$v(t)$ curve] (Soares et al., 2014). Variables defined were maximum push-off velocity, decay of the push-off velocity, maximum and average gliding velocity, maximum and average swimming velocity, fatigue index, swimming velocity decay, variation coefficient of the velocity, total upper limb cycles, and total swim time. Velocity decay was the slope of the $v(t)$ curve. The maximal and minimum velocities were used to calculate the fatigue index employing the formula $FI (\%) = [(V_{max} - V_{min}) / V_{max}] \times 100$ (Inbar et al., 1996) and the variation coefficient of the velocity was calculated using the expression $VC (\%) = (sd / V_{mean}) \times 100$.

A MATLAB routine based on the wavelets procedure [described by Machado et al. (2007)] was used to identify anaerobic fatigue thresholds over the $v(t)$ curves. Thresholds defined two-time intervals, one before (1st int) and one after (2nd int) its occurrence. The total number of upper limb cycles, stroke frequency, stroke length and stroke index were calculated for each time interval. The stroke frequency ($\text{cycles}\cdot\text{min}^{-1}$) was calculated by dividing 60 s by the mean time taken with a stopwatch to complete three upper limb cycles. Stroke length (m) was the quotient between mean velocity and stroke frequency (Craig & Pendergast, 1979), and the stroke index ($\text{m}^2\cdot\text{s}^{-1}$) was the product of stroke length by the velocity (Costill et al., 1985c).

The blood lactate concentration [La^-] was determined during rest and at the end of exercise, placing a blood drop collected by ear puncture in a blood lactate analyzer (Lactate Pro 2, Arkray, Inc.). To determine the post-exercise lactate concentration, the blood was collected at 0, 1, 3, 5 min and every second minute until the maximum value was found. All efforts were video recorded at 50 Hz using a SONY Handycam camera (HDR-CX160E) placed on a trolley and moving on the poolside parallel to the swimmers movement. A sound starting signal was used to synchronize the velocity record with the video images. Mean and standard deviations were calculated for all the variables. The sample normality was ensured using the Shapiro-Wilk test. Means were compared using a repeated measures t-test, establishing the probability value at 5%. All statistical procedures were performed in the IBM Statistical Package for The Social Sciences (SPSS) (v.24.0, IBM, New York, USA).

Results

In the current study, the variables related to the instantaneous velocity curves corresponding to the total effort time in the pre- and post-taper moments were initially analyzed. As can be seen in Table 1, only in the decay of the push-off velocity (-1.19 ± 0.94 vs. $-0.52 \pm 0.21 \text{ m}\cdot\text{s}^{-1}$; $p = 0.02$) was greater the post-taper, this being one variable that is not directly related to the anaerobic potential of the swimmers. No changes were observed in the remaining variables at both moments, pre-taper and post-taper. Other important variables studied showed minor improvements such as maximum velocity, mean velocity, velocity variation

coefficient, lactate and net lactate concentration, between pre-taper and post-taper. Also, the biomechanical variable, number of cycles, revealed a slight decrease compared to the pre-taper.

Table 1 - Mean and standard deviations of variables of instantaneous velocity curves of total effort test in pre-taper and post-taper.

Variables	Pre-taper	Post-taper
Time (s)	17.91 ± 1.69	17.90 ± 2.18
Push-off maximum velocity (m·s ⁻¹)	2.69 ± 0,28	2.67 ± 0.38
Push-off velocity decay (m·s ⁻¹)	-1.19 ± 0.94*	-0.52 ± 0.21
Gliding maximum velocity (m·s ⁻¹)	2.56 ± 0.21	2.55 ± 0.33
Gliding mean velocity (m·s ⁻¹)	1.58 ± 0.18	1.57 ± 0.17
Maximum velocity (m·s ⁻¹)	2.29 ± 0.37	2.27 ± 0.30
Mean velocity (m·s ⁻¹)	1.53 ± 0.17	1.51 ± 0.19
Fatigue index (%)	1.08 ± 10.80	4.32 ± 10.04
Swimming velocity decay (m·s ⁻¹)	-0.01 ± 0.01	-0.01 ± 0.01
Velocity variation coefficient (%)	19.03 ± 4.63	17.39 ± 2.79
Upper limb cycles per 25 m (n)	13.54 ± 3.31	12.5 ± 1.65
Lactate (mmol·l ⁻¹)	4.92 ± 0.85	4.77 ± 1.80
Net lactate (mmol·l ⁻¹)	2.72 ± 0.85	2.68 ± 0.71

* Different from Post-taper (p≤0.05).

In a second phase of data processing and using a MatLab routine, we identified the fatigue thresholds and compared the variables in the two-time intervals defined by them (Table 2). In the pre-taper there were differences between the 1st and 2nd intervals for the upper limb cycles, upper limb cycle duration, swim duration, swim distance, mean velocity and stroke frequency. In the post-taper there were differences between the 1st and 2nd intervals for the upper limb cycle

duration, mean velocity, stroke frequency and velocity variation coefficient. Finally, in a last analysis in which the fatigue thresholds were included (Table 3), we could verify that all the variables studied had a small alteration, showing the absence of differences between pre-taper and post-taper periods.

Table 2 - Mean and standard deviations of variables from the second phase of data processing presenting the comparison between the 1st and 2nd intervals separated by the defined fatigue threshold.

Variables	Pre-taper	Post-taper
Fatigue threshold (s)	9.51 ± 1.02	9.87 ± 1.63
Upper limb cycle 1 st int (n)	4.83 ± 1.33*	5.00 ± 1.59
Upper limb cycle 2 nd int (n)	6.08 ± 1.31	5.33 ± 1.45
Swim duration 1 st int (s)	5.25 ± 1.32*	5.77 ± 2.06
Swim duration 2 nd int (s)	6.96 ± 1.47	6.28 ± 1.68
Upper limb cycle duration 1 st int (s)	1.09 ± 0.07*	1.14 ± 0.1*
Upper limb cycle duration 2 nd int (s)	1.14 ± 0.1	1.18 ± 0.11
Swim distance 1 st int (m)	8.19 ± 1.75*	8.79 ± 2.8
Swim distance 2 nd int (m)	10.47 ± 1.85	9.14 ± 2.09
Maximum velocity 1 st int (m·s ⁻¹)	2.31 ± 0.24	2.21 ± 0.31
Maximum velocity 2 nd int (m·s ⁻¹)	2.26 ± 0.28	2.21 ± 0.24
Mean velocity 1 st int (m·s ⁻¹)	1.57 ± 0.16*	1.54 ± 0.2*
Mean velocity 2 nd int (m·s ⁻¹)	1.52 ± 0.18	1.49 ± 0.19
Minimum velocity 1 st int (m·s ⁻¹)	0.81 ± 0.27	0.93 ± 0.18
Minimum velocity 2 nd int (m·s ⁻¹)	0.79 ± 0.22	0.84 ± 0.23
Stroke frequency 1 st int (Hz)	0.91 ± 0.06*	0.87 ± 0.07*
Stroke frequency 2 nd int (Hz)	0.87 ± 0.07	0.85 ± 0.07
Stroke length 1 st int (m)	1.73 ± 0.18	1.75 ± 0.11
Stroke length 2 nd int (m)	1.69 ± 0.24	1.66 ± 0.28

Stroke index 1 st int ($\text{m}^2 \cdot \text{s}^{-1}$)	2.75 ± 0.52	2.73 ± 0.51
Stroke index 2 nd int ($\text{m}^2 \cdot \text{s}^{-1}$)	2.69 ± 0.56	2.64 ± 0.55
Velocity variation coefficient 1 st int (%)	0.16 ± 0.03	$0.13 \pm 0.02^*$
Velocity variation coefficient 2 nd int (%)	0.17 ± 0.04	0.17 ± 0.04

* Different from 2nd int. ($p \leq 0.05$)

Table 3 - Mean and standard deviations of the final phase of data processing with respective study variables.

Variables	Pre-taper	Post-taper
Upper limb cycles per 25 m (n)	12.91 ± 2.15	12.25 ± 1.42
Swim duration (s)	13.34 ± 2.09	13.25 ± 2.23
Cycle duration (s)	1.03 ± 0.08	1.07 ± 0.09
Swim distance (m)	20.43 ± 1.89	19.87 ± 1.50
Maximum velocity ($\text{m} \cdot \text{s}^{-1}$)	2.64 ± 0.25	2.57 ± 0.23
Mean velocity ($\text{m} \cdot \text{s}^{-1}$)	1.52 ± 0.19	1.52 ± 0.18
Minimum velocity ($\text{m} \cdot \text{s}^{-1}$)	0.67 ± 0.15	0.74 ± 0.20
Stroke frequency (Hz)	0.97 ± 0.06	0.93 ± 0.08
Stroke length (m)	1.60 ± 0.14	1.62 ± 0.1
Stroke index ($\text{m}^2 \cdot \text{s}^{-1}$)	2.49 ± 0.45	2.47 ± 0.44
Velocity variation coefficient (%)	0.20 ± 0.03	0.18 ± 0.02

Discussion

The level of performance in swimming is directly related to physiological factors, such as overcoming fatigue caused by anaerobic lactic efforts. This study explored the possibility to determine the effect of seven days taper period on the anaerobic potential of young swimmers using a specific test. This taper period was not sufficient to improve the swimming time performance and reveal any

physiological or velocity variation changes. The decay in push-off velocity was the only variable that showed differences between pre-taper and post-taper, but this difference in this isolated variable does not seem to be enough to justify any change in anaerobic potential of swimmers.

There was no difference between the swimming times before and after seven days of taper. We verified the same absence of differences in the variables related to velocity. It seems that the magnitude of changes was not sufficient to improve the performance of swimmers. Previous studies have not evaluated velocity variation before and after a taper, however, unchanged performance during a short duration 15 s test and during competition has been observed following two weeks of taper (Toubekis et al., 2013), while improved performance following a 30 s test observed following a 10 days taper (Papoti et al., 2007). It seems that the duration of taper and tests used for detecting anaerobic potential changes are confounding factors. The test used in the present study may evaluate velocity variations during free swimming as opposed to tethered swimming used in the abovementioned studies (Papoti et al., 2007; Toubekis et al., 2013). However, despite the test sensitivity to detect velocity variations and locate likely fatigue thresholds, the duration of taper may be not enough to allow anaerobic potential improvement.

The analysis of the variables related to the effort developed during the test (fatigue index and velocity decay) also did not show different values in the pre-test and post-test, results that had also been ascertained previously (Soares et al., 2014). It is important to highlight the high standard deviations associated with the fatigue index means, which reveal the existence of great variability between the sample subjects regarding the fatigue generated for the same effort and which reinforce the idea that using individual training records could help determine the ideal taper duration itself (Bosquet et al., 2007; Le Meur et al., 2012). Finally, the analysis of blood lactate concentration, one of the study variables used to analyze the impact of taper on the swimmers' anaerobic potential, revealed no differences between the two testing times, a result indicating the absence of effect of taper on this variable as well, which is not surprising in view of the maintenance of swimming time.

To evaluate the impact of taper on the anaerobic potential of young swimmers, fatigue thresholds were determined based on the velocity curves (Soares et al., 2014). In the evaluation carried out before the taper, six of the eleven variables analyzed revealed differences between the two temporal intervals (before and after the fatigue threshold) defined by the threshold, which means that the swimming pattern until the threshold has different characteristics from the swimming pattern that the swimmer performs after the occurrence of the threshold (whether the origin of the differences is physiological or technical). The instability of technical patterns differs from swimmer to swimmer, in young swimmers this seems to be more observable than that displayed in older and elite swimmers (Alberty et al., 2005).

In the post-taper evaluation, only four of the eleven analyzed variables showed differences in the two-time intervals, which indicates that the threshold calculated in the post-taper can be less robust, but with a value not different from the one found in the pre-taper. The absence of differences between the fatigue thresholds calculated in pre and post taper reinforces the conclusion that taper had no effect on the anaerobic potential of swimmers. It is likely that a longer period is required to increase anaerobic potential in young swimmers (Sperlich et al., 2010), including a specific training plan appropriate to the individual characteristics of each swimmer (Trinity et al., 2006).

The procedures for the calculation of fatigue thresholds allowed to estimate other variables (namely velocities) that, when compared, reinforce the conviction that the taper performed by the swimmers of the current study was not enough to change the swimming performance. The total swimming time was lower than the chronometric time obtained in the test and so is the velocity, because of the suppression of the influence of the push-off on the swimming velocity. Comparing this time and these velocities, corresponding to the pre-taper and post-taper, we once again observed the absence of differences, also in biomechanical variables such as the stroke frequency and the stroke length, as observed in other studies of two weeks of taper (Barbosa et al., 2020).

The velocity variation coefficient was stable before and after taper, revealing the absence of effects of taper on physiological or biomechanical variables. However,

previous study identified that the biomechanical variables play an important role in sprint performance, helping young swimmers on accomplishing a better and more efficient technique (Silva et al., 2019b; Silva et al., 2022). It should be noted that the duration of the taper was short, as the literature suggests taper periods of two weeks to reverse the fatigue caused by intense training and enable the swimmer to reach maximum performance (Bosquet et al., 2007; Hellard et al., 2017; Houmard & Johns, 1994). Although some studies examining the performance of swimmers have reported improvements after tapers lasting from seven to twenty-one days (Costill et al., 1985a; Hellard et al., 2013; Houmard & Johns, 1994; Johns et al., 1992; Reis et al., 2020; Shepley et al., 1992), in the current study, carried out on young swimmers and with a taper period of seven days proved to be insufficient.

No differences in performance were found, particularly in anaerobic potential. These results are in line with those found elsewhere (Toubekis et al., 2013), where they reported that a team of young swimmers showed no significant improvement in performance after a moderate reduction in training load with a two-week taper period. Nevertheless, half of the swimmers showed significant improvements in overall performance. Both studies demonstrated that a moderate reduction and a short duration taper period did not reflect improvements in the anaerobic potential of the athletes. Previous research indicates that power of type IIa fibers, typically anaerobic, increases 2.5-fold after taper (Trappe et al., 2001), increasing the power may also increase the swimming velocity by the direct relationship between power and velocity (Loturco et al., 2016; Morouço et al., 2015; Ruiz-Navarro et al., 2020). In the present study perhaps because the swimmers were young and not yet so strong, the influence of the taper period on power and velocity has not been evident.

The studies assessing the effect of taper on performance are still insufficient and none have yet managed to connect the change in performance with physiological changes in young swimmers. This lack of knowledge may be due to the fact that taper is a very sensitive and critical period in the swimmers preparation (Mujika, 2009; Pyne et al., 2009) and, sometimes, taper does not operate according to expectations (Grivas, 2018) due to psychosocial and physical factors. Therefore, few coaches allow their swimmers to be involved in experimental studies which

may jeopardize their performance in important competitions. Researchers and coaches should focus on a long-term approach to gain a deeper understanding of how the determinants of swimmers' performance, their interactions and their effect on performance change over time (Clemente-Suárez et al., 2017; Zacca et al., 2020). Therefore, swimmers should rest as much as necessary to overcompensate muscle strength and anaerobic potential. Given the results discussed above, that it is becoming increasingly crucial to test different taper durations for young swimmers, namely using individual training records to help determine the ideal taper duration for each swimmer (Le Meur et al., 2012). For this, more studies are needed to understand the best balance between the load and duration of the taper and its effects.

Conclusions

The main purpose of this study was to determine the effect of one-week tapering on the anaerobic potential of young swimmers based on a simple and non-invasive test. Although we have used a valid test to detect the anaerobic potential and sensitive to reveal velocity variation in swimmers, it was not possible to see changes in performance. It seems that the one-week taper duration or the overload period before taper were not adequate to induce appropriate adaptations. As previously stated, the test proved to be valid and friendly user for the coaches helping them in training planification and provide the best decisions for their swimmers. A long duration, detailed monitoring of training content is required in young swimmers helping to suggest the optimal duration of a taper.

Chapter 6. General Discussion

The advancements in swimming performance over recent years can be attributed mainly to the progress of technology and knowledge supported by research. The applied research is vital to that advancement once it aims to generate actionable content to enhance performance through refining intervention in each one of the performance domains, providing valuable support to individuals involved in practitioners' development and training. The primary objective of this thesis was to contribute to understanding swimmers' anaerobic performance and address the practical needs of professionals surrounding swimmers. Specifically, the focus was on employing indirect methods to assess the anaerobic potential of young swimmers. The thesis aimed to evaluate young swimmers' anaerobic performance through a simple velocimetric test. A novel parameter known as the anaerobic fatigue threshold was introduced.

The research commenced with (i) an extensive literature analysis to summarize and compare the methods employed in assessing swimmers' anaerobic performance. A promising method was identified from this review, and (ii) its robustness was subsequently tested. Following this, the technique was applied to evaluate changes in anaerobic performance among young swimmers resulting from (iii) long (macrocycle) and (iv) short (taper) training periods. The findings demonstrated the reliability and user-friendliness of the method.

The literature review on anaerobic performance initially revealed that while anaerobic power and capacity have been frequently discussed in older literature (Van Praagh, 2000), there still needs to be a more precise understanding regarding the domains of anaerobic power and capacity. This ambiguity makes it challenging to draw conclusive insights from research that can be directly applied to training methodologies. In addition, to achieve the goal of the thesis, which is to find a reliable and user-friendly tool, it is imperative to establish a clear definition of anaerobic potential. This concept represents the combined contribution of the alactic and lactic systems to a swimmer's performance, as accurately determining the individual contributions of these metabolic pathways poses significant challenges. Therefore, clarifying the concept of anaerobic

potential is essential for developing effective training strategies and assessment tools in swimming.

The literature review also uncovered multiple ways to evaluate swimmers' anaerobic performance, ranging from sophisticated to more straightforward approaches. However, identifying a specific test to assess swimmers' anaerobic potential proved challenging, as the most direct methods are often highly invasive and expensive, and their results may not directly apply to swimming. One of the strategies used by researchers for assessing the swimmers' anaerobic potential was the adaptation to the water of the Bar-Or (1987) Wingate Anaerobic Test (Morouço et al., 2014; Nagle Zera et al., 2021; Toubekis et al., 2010; Wells et al., 2006) which is considered the gold standard for anaerobic performance assessment.

A group of researchers devised a novel approach by adapting the Wingate Test using a cable speedometer instead of an ergometer. In this modified test, swimmers exerted maximal effort over a 50 m front crawl distance while attached to the cable speedometer (Soares et al., 2014). Through the content analysis of the $v(t)$ curve, researchers determined a critical time threshold known as the anaerobic fatigue threshold. This fatigue threshold was hypothesized to represent the transition point from alactic to lactic dominance in energy metabolism. This test was extracted from the literature review. Given that the traditional Wingate Test is conducted on land, the adaptation with the cable speedometer offered a more aquatic-specific evaluation method. Consequently, this thesis was chosen to investigate the robustness and reliability of this test and its usefulness in assessing changes in anaerobic performance following long and short training periods.

Soares et al. (2014) did not assess the robustness of the anaerobic fatigue threshold as a valid parameter to evaluate swimmers' anaerobic performance. A relation between the fatigue anaerobic threshold and the post-effort blood lactate was searched based on the logic that if the anaerobic fatigue threshold separates alactic from lactic dominance, blood lactate accumulation would not fire for all-out swimming times lower than the threshold time.

Also, a threshold should separate zones with distinct content, expecting that parameters measured before and after its occurrence would differ. Our findings revealed that blood lactate levels do not exponentially increase for swim times corresponding to the anaerobic fatigue threshold. This suggests that glycolysis might not yet be the dominant energy pathway. In addition, no disparities were observed in essential biomechanical variables between time intervals defined by the threshold, meaning we can understand it as an objective threshold.

Once the anaerobic threshold seemed practical (and not a mathematical artifact), determining the swimmers' anaerobic performance through a speedometer test was submitted to reliability tests. Results were good, revealing that the test is repeatable and gives similar results for different evaluators, even with varying experiences in using the measurement tool. So, the test was considered adequate to measure young swimmers' anaerobic potential.

The competitive swimming season is divided into training segments (Ferreira et al., 2021; Zacca et al., 2020a), the bigger ones the macrocycles, and it is expected that the training elicits physiological changes, including in the anaerobic potential of the swimmers (Clemente-Suárez et al., 2018; Olbrecht, 2011; Rodeo & Riewald, 2015; Salo & Riewald, 2008). After recognizing the usefulness of the method of determining swimmers' anaerobic potential through a speedometer test, it was applied to measure swimmers' anaerobic performance after a long training period (macrocycle duration for six months of training).

Contrary to expectations, the swimmers' anaerobic performance improvements were not statistically associated with the change in the anaerobic fatigue threshold. Although lactate and swimming performance (time, velocity, and some biomechanical variables) have improved, the threshold has revealed a tendency to decrease with the training. Due to some methodological fragilities (like a small sample), we might argue that, despite some favorable indicators, the anaerobic fatigue threshold needs to be better tested until we can say that it is a good indicator of swimmers' anaerobic performance changes occurred after long training periods.

The competitive swimming season is also divided into small training segments, as the taper typically occurs at the end of the macrocycles, preceding significant

competitive events. Taper is characterized by a reduced training load several days before a competition, allowing swimmers to optimize their performance (Hellard et al., 2017; Mujika & Padilla, 2003), improving the anaerobic potential. So, after testing the anaerobic fatigue threshold changes after a long training period, it was decided to conduct the test during a more specific and shorter period within the training macrocycle. It was expected that after such a particular phase, the results would show significant changes in anaerobic potential, which did not occur.

The absence of differences in the anaerobic fatigue thresholds after the taper period could be explained by diverse factors. First, we should consider that the swimmers' anaerobic potential change may not have happened either. Other examples with young swimmers exist where no significant improvements in anaerobic performance were observed after a two-week reduction in training load during a taper period (Toubekis et al., 2013). Accumulated fatigue must also be considered once the post-tests occur following the vital competition at the end of that macrocycle. The detrimental effects of fatigue onset are well documented (Tella et al., 2006; Tella et al., 2008).

The seven days of the taper period were insufficient to change the anaerobic potential of young swimmers effectively, and the same was observed after a six-month macrocycle. Three questions arise from those results: (I) the anaerobic fatigue thresholds are not sensitive enough to express changes, (II) the methodological limitations of the two studies did not allow us to see those changes, and (III) the changes effectively did not occur. Indeed, fatigue thresholds were insufficient to assess changes in anaerobic potential based on the results of the two studies. Still, we should not overlook some variables that provide substantial evidence supporting the existence of those changes.

The methodological limitations of the two studies lead us to reinforce the studies done to conclude about the usefulness of the anaerobic fatigue thresholds safely. The studies included small samples and young swimmers with a wide range of competitive levels, from less experienced to the national level. So, new studies with more extensive samples are welcome.

The participants also exhibited limited experience in sprint swimming, which could have influenced the accuracy of the results. In both studies, this factor is evidenced by the variability in the results, suggesting that changes in the parameters assessed with training may have been more individual than across the entire group.

Finally, the studies did not stratify the participants by gender, which is essential once physiological and performance determinants differ between boys and girls (Figueiredo et al., 2016; Morais et al., 2021). We acknowledge that the limited number of participants precluded the possibility of conducting cluster tests. The variability and the absence of significant changes in the determination of the anaerobic fatigue threshold results could also stem from the sample's heterogeneity.

The coaches need to establish realistic expectations and customized training objectives, thereby optimizing training strategies tailored to the needs of young athletes. Although the anaerobic fatigue thresholds did not express significant changes in young swimmers' anaerobic potential, this thesis showed the method's reliability. It analyzed the methodological limitations that must be overcome to decide its usefulness fully.

Chapter 7. Conclusions

The systematic, accurate, and precise process of evaluating and controlling the various variables that compose the factors affecting competitive performance, including energy factors, particularly anaerobic pathways, provides essential information on training progress. Based on findings obtained in experimental studies described in this work, it is necessary to clarify the following conclusions:

- (i) the procedure for determining anaerobic fatigue thresholds to assess the anaerobic potential of swimmers seems robust;
- (ii) the method has proven to be an easy-to-operate tool, cost-effective, and capable of extracting a wide array of variables;
- (iii) when the procedure was applied over long and short training periods, it suggested that those periods were insufficient to enhance anaerobic potential;
- (iv) more studies are needed to determine fatigue threshold efficacy so that coaches can evaluate performance and prescribe appropriate swimming training programs.

Chapter 8. Suggestions and Future Research

This thesis aimed to expand knowledge about the anaerobic performance of young swimmers. Despite the significance of the anaerobic performance, research in this area, particularly concerning young swimmers, still needs to be completed. Hence, our objective is to further:

- (i) apply the method to a homogeneous sample with a more significant number of subjects, categorized by gender, and comprising individuals specialized in swimming velocity;
- (ii) apply the method in an experimental study involves carrying out an intervention training program specially designed for the anaerobic potential development;
- (iii) include comprehensive analyses of swimmers' anaerobic potential throughout an entire competitive season, providing insights into potential fluctuations and adaptations;
- (iv) employ the method to assess the sensitivity of fatigue thresholds to changes induced by training across different seasons, facilitating a nuanced understanding of variations between seasons;
- (v) test the method over an extended taper period to evaluate the sensitivity of fatigue thresholds to training-induced adaptations, thereby informing optimal taper period strategies;
- (vi) test the reliability of the methodology by examining its efficacy with experts proficient in other swimming techniques, broadening its applicability and generalizability.

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Chapter 1

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Chapter 6

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