ANALYSIS OF PERFORMANCE DETERMINANTS IN OPEN WATER SWIMMERS AND TRIATHLETES

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Analysis of performance determinants in open water swimmers and triathletes

Análisis de los factores de rendimiento
en nadadores de aguas abiertas y triatletas

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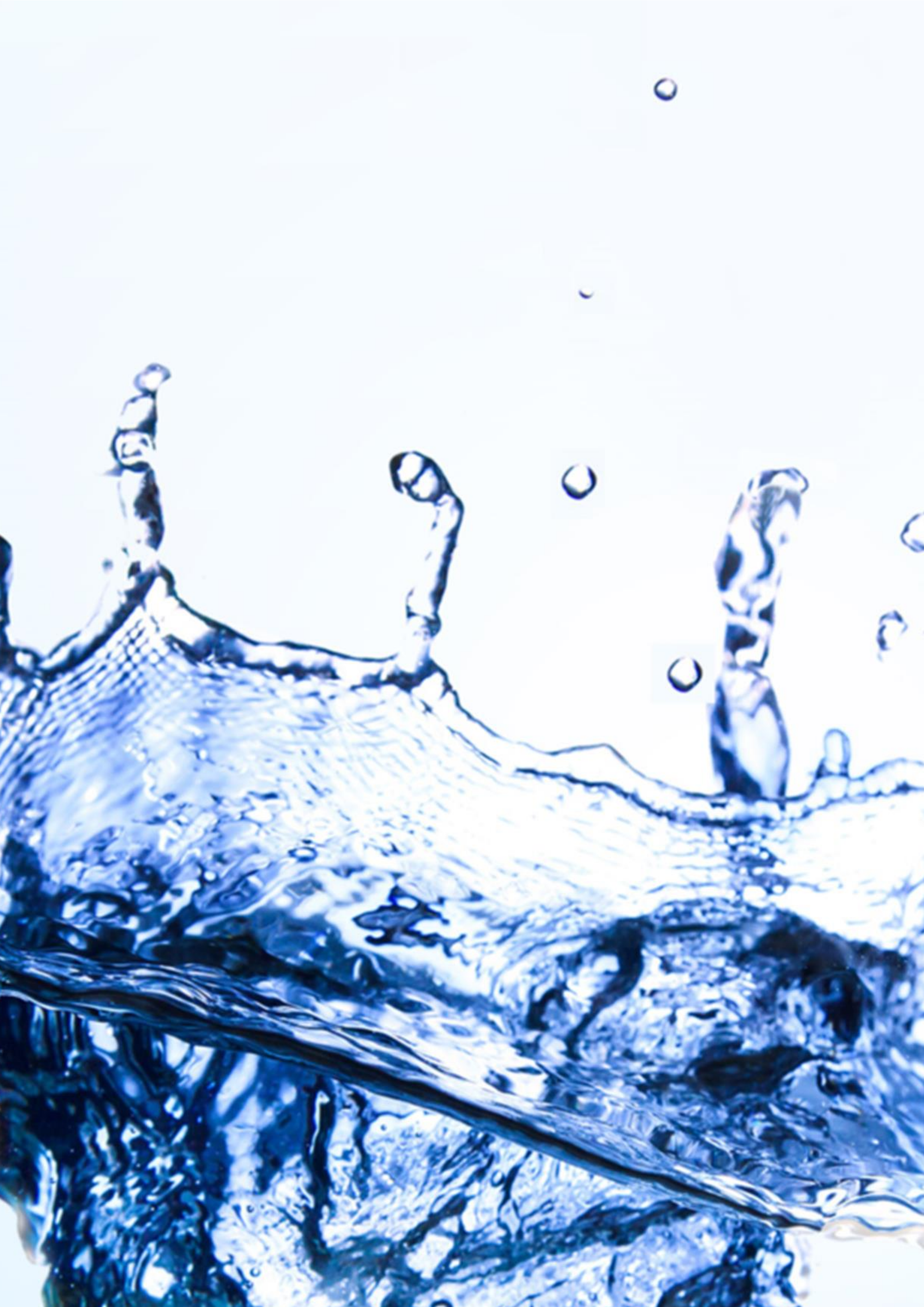
Si vuelo alto,
es por quienes me
brindaron las alas para hacerlo.

A mis padres, mis hermanos y mi familia.



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LIST OF PUBLICATIONS

Research articles published or included in the current International Doctoral Thesis:

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6. **López-Belmonte, Ó**., Baldassarre, R., Ruiz-Navarro, J. J., Bonifazi, M., Arellano, R., & Piacentini, M.F. (2024). Seasonal changes in performance, physiological and kinematic factors of maximal incremental swimming in world-class and elite open water swimmers. Under review in *International Journal of Sports Medicine*.
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LIST OF ABBREVIATIONS

AeT	Aerobic threshold
Ana_{alac}	Anaerobic alactic contribution
Ana_{lact}	Anaerobic lactic contribution
ANOVA	Analysis of variance
A_p	Amplitude of the fast oxygen uptake component
BMI	Body mass index
C	Energy cost
CSS	Clean swimming speed
CV	Coefficient of variation
d	Effect size
E	Energy expenditure
$EE\dot{V}O_2$	End-exercise oxygen uptake
FINA	International Swimming Federation
HR	Heart rate
HR_{LT}	Heart rate at lactate threshold
HR_{max}	Maximum heart rate
$HR_{max1500}$	Maximum heart rate during the 1500 m test
HR_{mean}	Mean heart rate
$HR_{mean1500}$	Mean heart rate during the 1500 m test
$HR_{meanBase}$	Mean baseline heart rate
$HR_{meanPost}$	Mean heart rate after the test
$[La^-]$	Blood lactate concentration
$[La^-]_{AeT}$	Blood lactate concentration at aerobic threshold
$[La^-]_{Base}$	Baseline blood lactate concentration
$[La^-]_{LT}$	Blood lactate concentration at lactate threshold
$[La]_{net}$	Blood lactate concentration difference between before and after exercise
$[La]_{peak}$	Peak blood lactate concentration
LT	Lactate threshold
$\eta 2$	Eta squared
n	Number of participants

OW	Open water
RER	Respiratory exchange ratio
RPE	Rate of perceived exertion
RPE_{LT}	Rate of perceived exertion at lactate threshold
SD	Standard deviation
SI	Stroke index
SL	Stroke length
SL_{LT}	Stroke length at lactate threshold
SR	Stroke rate
SR_{LT}	Stroke rate at lactate threshold
SS	Swimming speed
SS_2	Swimming speed at 2 $mmol \cdot l^{-1}$
SS_4	Swimming speed at 4 $mmol \cdot l^{-1}$
τ_p	Time constant of the fast oxygen uptake component
TD_p	Time delay of the fast oxygen uptake component
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximum oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
WBD	Water break distance
WBT	Water break time

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ABSTRACT

Open water (OW) swimming and triathlon are rapidly growing endurance sports, both characterized by the unique challenges of swimming in natural OW environments. However, research into the determinants of performance in these sports remains underexplored. Therefore, the main aim of this thesis is to deepen the understanding of the performance determinants of elite open water swimmers and triathletes.

To explore these determinants further, three studies were conducted with elite open water swimmers: i) analysis of the 3000 m swimming pacing strategy and its variability in performance; ii) 7x400 m incremental test to determine lactate threshold and examine its relationship with performance; iii) 7x400 m incremental tests to assess longitudinal changes between seasons. On the other hand, to increase knowledge of the swimming leg of triathlon, three studies were conducted with elite triathletes: i) 1500 m swimming test in pool; ii) 1500 m swimming test in OW; iii) comparison of 1500 m swimming tests between OW and pool conditions. All of these studies focused on physiological and biomechanical factors.

The results of this thesis evidenced that OW swimmers: i) adopted a parabolic pacing strategy, showing variations in turn performance and stroke parameters; ii) high swimming speeds at lactate threshold, associated with improved competitive performance; iii) there were no seasonal changes in performance or physiological factors, but there were biomechanical adaptations between tests. Regarding triathletes: i) metabolic efficiency and technical skill determined pool swimming performance; ii) OW swimming caused variations in biomechanical factors, with efficiency being the performance determinant; iii) OW conditions impaired kinematics and efficiency compared to pool swimming, but the physiological demands were similar in both environments.

In conclusion, the findings of this thesis provide a comprehensive insight into the training and competitive performance of both OW swimmers and triathletes. The holistic approach to monitoring training or assessing different swimming conditions offers relevant information for swimmers, triathletes and coaches.

RESUMEN

La natación en aguas abiertas (AA) y el triatlón son deportes de resistencia en rápido crecimiento, ambos caracterizados por los retos únicos de nadar en entornos naturales de AA. Sin embargo, la investigación sobre los factores determinantes del rendimiento en estos deportes sigue estando poco explorada. Por tanto, el objetivo principal de esta tesis es profundizar en el conocimiento de los factores de rendimiento de nadadores de AA y triatletas de élite.

Para ahondar en estos factores, se realizaron tres estudios con nadadores de AA de élite: i) análisis de la estrategia de ritmo en una prueba de natación de 3000 m y su variabilidad en el rendimiento; ii) test incremental de 7x400 m para determinar el umbral de lactato y examinar sus relaciones con el rendimiento; iii) cuatro test incrementales de 7x400 m para evaluar los cambios longitudinales entre temporadas. Por otra parte, para aumentar el conocimiento del segmento de natación del triatlón, se realizaron tres estudios con triatletas de élite: i) test de natación de 1500 m en piscina; ii) test de natación de 1500 m en AA; iii) comparación de los test de natación de 1500 m en condiciones de piscina y AA. Todos estos estudios, profundizaron en factores fisiológicos y biomecánicos.

Los resultados de esta tesis evidenciaron que los nadadores de AA: i) adoptaron una estrategia de ritmo parabólica, mostrando variaciones en el rendimiento de los virajes y parámetros de brazada; ii) altas velocidades a umbral de lactato, asociadas con un mejor rendimiento competitivo; iii) no hubo cambios estacionales en rendimiento o factores fisiológicos, pero se produjeron adaptaciones biomecánicas entre tests. Respecto a los triatletas: i) la eficiencia metabólica y la habilidad técnica determinaron el rendimiento de natación en piscina; ii) la natación de AA provocó variaciones en los factores biomecánicos, siendo la eficiencia determinante en el rendimiento; iii) las condiciones en AA perjudicaron la cinemática y la eficiencia en comparación con la natación en piscina, pero las exigencias fisiológicas fueron similares en ambos entornos.

En conclusión, los resultados de esta tesis proporcionan una visión completa del entrenamiento y el rendimiento competitivo tanto de los nadadores de AA como de los triatletas. El enfoque holístico del seguimiento del entrenamiento o la evaluación en diferentes condiciones de natación ofrece información relevante para nadadores, triatletas y entrenadores.

Chapter 1

General introduction

General introduction

From past to present

The evolution of open water swimming

Open water swimming is defined as any competition that takes place in rivers, lakes, oceans or water channels [1]. These natural environments where competitions are held, characterize these events with unique and dynamic conditions that swimmers must face [2]. The history of open water swimming began in 1810, when Lord Byron swam several times to cross the Hellespont from Europe to Asia [3]. This early achievement set the stage for another significant milestone in 1875, when Captain Matthew Webb swam for more than 21 hours to become the first person to successfully cross the English Channel [4]. However, the first competitive open-water swimming event took place in the Catalina Chanel, California, in 1927. This event consisted of a 21-mile swim from the Californian coast to Catalina Island and was the key to other open water events in subsequent years [5]. Since these milestones, open water swimming has evolved over the years with a wide variety of events and distances around the world [2].

The competitive open water swimming went through a process of regularization until it made its first appearance at the 1991 World Championships held in Perth, Australia, over a distance of 25 km. Seven years later, the 5 km open water swimming was included in the 1998 World Championships in the same Australian city. Finally, the emergence of 10 km open water event, also known as the marathon swimming, was introduced at the 2000 World Championships in Honolulu, USA [6]. From that time on, the open water swimming distances at the World Championships were 5, 10 and 25 km. However, the competitive distances have changed over the years by the World Aquatics, which is the organization responsible for regulating international swimming competitions. Currently, the World Aquatics Championships program include the 5 km, 10 km distances and the mixed 4x1500 m relays [1].

In the first three editions of the modern Olympic Games, all swimming events held in natural bodies of water before the introduction of swimming pool at the London 1908 Olympic Games. However, the inclusion of open water events came at the 2008 Beijing Olympics, where the 10 km marathon swimming has been the only distance on the Olympic program ever since [1]. During these events, swimmers complete the 10 km in around two hours [7], which requires great endurance and mental strength to overcome the challenge of open water swimming.

The evolution of triathlon

Triathlon is a multi-sport event consisting of three consecutive disciplines: swimming, cycling and running. The earliest roots of triathlon began in France in 1920, where a race called "Les trois sports" was held consisting of a 3 km run, 12 km bike and a swim across the channel Marne [8]. However, the modern triathlon as it is known today was born in 1974 in San Diego, California, with the called “Mission Bay Triathlon”. This event organized by the San Diego Track and Field Club consisted of an 8.5 km run, an 8 km bike and a 550 m swim. From this event, the popularity of triathlon grew over the years, until in 1989, when the International Triathlon Union, now World Triathlon, was founded in Avignon, France [9].

The emergence of the World Triathlon brought triathlon into an official and regulated international structure, which was also essential for the first World Championships, also held in Avignon in 1989 a few months later. More than 800 athletes from 40 countries competed in this event, covering 1.5 km swim, 40 km bike and 10 km run distances [9]. In this context, the World Triathlon categorizes events according to the distance covered in each discipline (Table 1.1) [10]. The Standard distance, also known as the Olympic distance, is considered the most important and prestigious, as it is the distance used in the World Triathlon Championship Series and the Olympic Games. The World Championships currently consist of a calendar of six to eight events in different countries over Sprint and Standard Distances, as well as Mixed Relays [10].

Table 1.1. Competition distances for each leg in triathlon events.

	Swim	**Bike**	**Run**
Mixed Relay* (km)	0.25 – 0.3	5.0 – 8.0	1.5 – 2.0
Super Sprint Distance (km)	0.25 – 0.5	6.5 – 13.0	1.7 – 3.5
Sprint Distance (km)	0.75	20.0	5.0
Standard Distance* (km)	1.5	40.0	10.0
Middle Distance (km)	1.9 – 2.9	80.0 – 90.0	20.0 – 21.0
Long Distance (km)	3.0 – 4.0	91.0 – 200.0	22.0 – 42.2

*Triathlon events included in the Olympic program.

The Standard distance was included in the Olympic program for the first time at the Sydney 2000 Olympic Games. In addition, the Tokyo 2021 Games introduced the Mixed Relay event, in which two men and two women compete over a short triathlon distance (Table 1.1). During the Standard distance, triathletes complete the race in approximately two hours [11], which makes it a great endurance challenge to complete all three disciplines consecutively.

Common grounds

The parallels between open water swimming and triathlon

Open water swimming and triathlon are among the most challenging and exhilarating endurance sports in the Olympic program, as well as being two young and rapidly growing disciplines in recent years [2,12]. Despite being two different specialties, the main common characteristic of both sports lies in the open water environment in which the competitions take place. In both open water swimming and the swimming leg of a triathlon race, the specific conditions of this environment make these sports different from other endurance sports. Swimmers and triathletes have to deal with changing environmental factors, including unpredictable water conditions, variable water and ambient temperatures or swimming with other competitors [13,14]. In addition, the approximately two-hour duration of both Olympic events introduces a significant common feature between the two disciplines, as they are influenced by similar determinants of endurance performance. Therefore, considering these similarities between the open water swimming and triathlon, the current thesis brings together a set of chapters to provide a deeper understanding of these two endurance sports, focusing on swimming and its performance determinants.

Determinants of endurance sports

Endurance is an essential attribute for optimal performance in a wide range of sports. In this regard, successful endurance performance is characterized by high levels of maximal oxygen uptake ($\dot{V}O_{2max}$), lactate threshold (LT), and work economy or efficiency [15]. The $\dot{V}O_{2max}$ is a measure of an individual's cardiorespiratory capacity at a given level of fitness and oxygen availability, limited mainly by cardiac output, muscular blood flow and the oxygen-carrying capacity of the blood [16]. In the case of the LT, it represents the highest exercise intensity that can be sustained before lactate removal exceeds lactate production, resulting in accumulations of blood lactate concentration ([La^{-}]) during exercise [17]. Hence, the interaction between $\dot{V}O_{2max}$ and LT determines how long a given rate of aerobic and anaerobic metabolism can be maintained, while efficiency determines the speed or power that can be achieved at a given amount of energy expenditure (*E*) [15,17]. In addition to the main determinants, optimal endurance performance is also influenced by other important factors, such as skeletal muscular properties [18], training-induced adaptations [19], psychological skills [20], or pacing strategies adopted during a race [21]. Consequently, analyzing performance in endurance sports is a multifaceted process influenced by a variety of factors, which requires a comprehensive approach from different areas. Understanding how these diverse factors interact and contribute to overall performance is essential for developing effective training strategies and achieving peak performance.

Determinants of swimming

Optimal swimming performance is determined by an interplay of several scientific domains, such as physiology, biomechanics or anthropometrics [22]. This complexity is further compounded by the unique characteristics of aquatic locomotion, which makes swimming particularly challenging to assess compared to land-based disciplines [23]. In this sense, swimmers must achieve the highest speeds through the aquatic environment while minimizing energy cost (*C*) [24], where physiological and biomechanical factors are the main tools used by sports scientists to determine how the swimmers maximize these factors to improve performance [25]. Consequently, this thesis explores some of these physiological and kinematic factors that contribute to optimizing swimming performance in both open water swimmers and triathletes.

Physiological factors

Swimming testing is a key element of training programs in high-level swimmers, used to objectively predict performance and to guide training prescriptions [26]. In this sense, physiological factors are assessed through specific tests to enhance training and competitive outcomes, as these factors influence directly on swimming performance [27]. Among the different measurements, the [La^{-}] is obtained at different intensities through incremental swimming testing, which is essential to detect the individual metabolic breakpoints of the swimmers [28]. In this regard, the speed-lactate curve is analyzed to identify the point at which $[La^{-}]$ begins to rise above baseline, known as aerobic threshold (AeT). As the intensity increases and lactate production exceeds its clearance, the point at which $[La^{-}]$ rises exponentially corresponds to the LT [29]. Additionally, some authors have considered the fixed $[La^{-}]$ at 4 $mmol \cdot l^{-1}$ as the LT [30], although this value not consider individual differences and may overestimate the LT in aerobically well-developed swimmers [31].

Both aerobic and anaerobic metabolic pathways are required to satisfy the energy requirements, being the sum of these contributions the *E* by the swimmer. In this sense, the *C* takes into account the differences in *E* between swimmers at a given speed [24], which depends on the swimmer's technical ability and the overall efficiency [32]. Moreover, for a deeper physiological understanding, the oxygen uptake ($\dot{V}O_2$) kinetics provide useful valuable information of the circulatory and metabolic responses during swimming [33]. From the $\dot{V}O_2$ kinetics, it is possible not only to obtain determinant factors like the $\dot{V}O_{2max}$, but also the contributions of the different metabolic pathways [34,35]. Although the aquatic environment complicates the $\dot{V}O_2$ assessment, the constant evolution of technology and new equipment allow its measurement in swimming [36,37].

On the other hand, the misguided focus on some physiological determinants of performance has resulted in a brainless model of exercise physiology [38]. For an optimal performance, swimmers make decisions about how and when to invest their energy during a race [39,40]. This distribution of work output is known as pacing or pacing strategy [21], a complex phenomenon influenced by several internal and external factors [38]. Moreover, the pacing strategies adopted by swimmers also depends on the distance covered and the swimming stroke [40]. Consequently, an effective pacing strategy can significant influence swimming performance outcomes, as variations in speed elicit different physiological responses, including an increase in *C* [41].

Kinematic factors

Competitive swimming requires to cover a given distance in the shortest possible time, thus swimming speed is the best factor to measure swimming performance [32]. In this sense, swimming speed is obtained through the product of stroke rate (SR) and stroke length (SL) [42]. These factors are considered one of the major points of interest in biomechanical research [32], as changes in swimming speed are directly influenced by combined increases or decreases in SR and SL [43]. Moreover, the product of swimming speed and SL represent the stroke index (SI), which is used as an indirect estimator of swimming efficiency due to its negative association with *C* [32,44]. On the other hand, swimming technique can be influenced by physiological factors, as the LT is not only a physiologic boundary, but also has a significant effect on kinematic and coordinative variables [45,46]. Hence, the kinematic factors related to stroke parameters, are essential to understand how swimmers achieve optimal performance, which together with the physiological factors represent an overall analysis of the performance status.

Open water swimming

Research interest in open water swimming began to gain momentum in the late 1990s, spurred on by the growing phenomenon of the sport worldwide [4]. During these years, open water swimming studies has primarily focused on non-conventional races (e.g., ultra-endurance events) [47,48], body temperature responses [49,50], anthropometric characteristics [51,52], or pacing strategies adopted during international events [53,54]. While these investigations have significantly advanced the understanding of open water swimming, there is still a need to analyze the training regimens and competitive performances of elite open water swimmers. A particular focus on the physiological factors that influence their success can provide valuable insights into optimizing training strategies and enhancing competitive outcomes for these athletes [2].

This need for a nuanced understanding is highlighted by the recent trend, as the inclusion of the 10 km marathon swimming in the 2008 Beijing Olympics led to a marked increase in participation in open water competitions, particularly among swimmers with a background in middle- and long-distance pool events [55,56]. In addition to the more recognized long-distance pool events, such as the 800 and 1500 m freestyle competitions, other long-distance pool events have emerged in the schedule of the swimming federations. In this sense, open water swimmers often include long-distance pool events in their competitive calendar as a preparation for their main goals [56,57]. Although open water swimming has unique characteristics, the specialists in this discipline have the versatility to perform at the highest level in pool swimming events as well [56].

In this evolving context, there is a notable gap in research concerning performances in intermediate distances between the long-distance pool events (i.e., 800 and 1500 m) and open water distances. While extensive studies have been conducted on the 800 and 1500 m pool events [58,59] and the 10 km marathon swimming [7,53], the dynamics of races such as the 3000 m, which bridge these two disciplines and are included as test races for some swimmers, remain underexplored. In that sense, **Chapter 3** addresses this gap by focusing on the 3000 m pool swimming event, which provides an in-depth analysis of pacing strategies and kinematics. This chapter explores how elite swimmers manage their effort over this intermediate distance and how swimming kinematics factors are affected. By examining these strategies, **Chapter 3** aims to provide valuable insights into optimizing pacing for races that fall between the traditionally studied long-distance pool events and open water distances. Understanding these pacing strategies is key not only for optimizing race outcomes but also for updating training approaches for swimmers and coaches.

Despite numerous studies on open water swimming, very few have been conducted with elite swimmers, leading to a lack of comprehensive insight into their training and competition practices [2]. In this regard, the LT assessment is key for open water swimmers, as the intensities adopted during these races are close to or at the speed of the LT [7,60]. Although these explorations were considered twenty years ago [51], the trend mentioned above among long-distance pool and open water swimming may have changed this physiological profile in elite open water swimmers. For these reasons, **Chapter 4** delves into the physiological basis of performance by focusing on LT assessment and its association with swimming performance. Moreover, due to the important of LT determination for open water swimmers, the traditional [La$^-$] at 4 mmol·l^{-1} [30] has been considered as the LT in previous research with an elite open water swimmer [61]. Hence, **Chapter 4** presents a comparison between the individually determined LT and the fixed method to evaluate their differences and practical applications for training and monitoring.

Monitoring physiological adaptations during longitudinal periods is essential for understanding performance improvements and optimizing training regimes in elite swimmers [62,63]. Similarly, tracking kinematic changes between seasons is crucial for evaluating the effectiveness in enhancing stroke parameters [64]. However, the interplay between these factors over extended periods remains underexplored in swimming [32].

In this sense, although longitudinal studies of open water swimmers have addressed aspects such as training volume, intensity distribution, physiological characteristics and heart rate variability [61,65], a comprehensive analysis of how physiological and kinematic factors interact and evolve over different seasons is still lacking. Hence, the **Chapter 5** presents a longitudinal study designed to evaluate changes in both physiological and kinematic factors in elite open water swimmers. Furthermore, this chapter aims to examine performance changes and which of these factors are associated with the best swimming performance. By integrating both physiological measurements and kinematic assessments, **Chapter 5** aims to provide a more holistic understanding of the factors that drive performance improvement and offer valuable insights into this underexplored area.

Triathlon: The swimming leg

Interest in triathlon research began in the late 1980s, driven by the sport's growing popularity around the world [66]. Since then, a large number of studies have explored the triathletes' performance from various domains, like physiology [67,68], biomechanics [69,70], anthropometrics [71,72], or psychology [73]. In addition, due to the multi-sport nature of triathlon, other research have focused on analyzing the impact of one discipline on performance in subsequent disciplines [74,75]. This body of research has contributed significantly to the ongoing development of triathlon in recent years. By deepening our understanding of how each discipline influences overall performance, these studies have driven advances in training methods, race strategies, and athlete development, ultimately shaping the progression and competitiveness of the sport.

In the Standard distance triathlon, elite triathletes spend approximately 15% of the total time swimming, 55% cycling and 30% running [45]. Although the swimming leg represents the lowest percentage of the race, it can significantly influence the subsequent cycling and running disciplines, ultimately affecting the final outcome of the triathlon [14,76]. The kick-off of the first discipline starts with a mass start, which encourages triathletes to reach the highest speed in the initial meters of the swimming leg [77]. This fast start can be essential for securing a strategic position within the leading swimming pack, thereby conserving *E* due to the drafting effect with other triathletes and increasing their chances of success [78]. For instance, the top two ranked triathletes at the 2023

World Triathlon Championships Finals forfeited their title aspirations because they failed to secure a position in the leading pack at the end of the 1500 m swimming. However, despite its critical role in the development of a triathlon race, swimming has received less research attention than the cycling and running legs [14], likely due to the challenges associated with assessment in the aquatic environment.

Therefore, the structure of this thesis is designed to provide a comprehensive understanding of the factors influencing swimming performance in elite triathletes, focusing on both pool and open water environments, as triathletes undertake the majority of their swimming training in a controlled pool environment, supplemented by regular open water sessions throughout the season. In this regard, the 1500 m covered in the swimming leg at the Olympic triathlon distance has not been explored in depth, as previous research has focused primarily on cycling performance following the swim [79,80]. Hence, **Chapter 6** initiates this exploration by presenting a cross-sectional study conducted in a controlled pool environment that examines the relationships between physiological and kinematic factors with swimming performance. This chapter lays the groundwork by identifying the key determinants of performance in elite triathletes within a standardized environment.

Building on these findings, **Chapter 7** shifts the focus to the open water environment, where the swimming leg of triathlon races takes place. In this context, the challenging conditions of open water can affect performance, which is influenced by the physiological and kinematic variations that occur as a result of natural conditions [13]. However, the performance of triathletes in a competitive swimming environment has not been investigated. While few studies have focused on controlled or simulated conditions [81], there remains a gap in understanding how triathletes perform in open water conditions where environmental factors come into play. Therefore, **Chapter 7** conducts a cross-sectional study to examine the 1500 m open water swimming and how the physiological and kinematic factors correlate with performance. This chapter aims to provide new insights into open water swimming that will update both athletes and coaches, contributing to the development of more effective training programs that take into account the physiological and kinematic adaptations required to excel in competitive open water swimming.

Finally, **Chapter 8** integrates the findings of the previous chapters by presenting a counterbalanced crossover study that directly compares the performance, kinematic and physiological variables between 1500m open water and pool swimming. This chapter not only highlights the differences and similarities between the two environments, but also deepens the understanding of how triathletes' performance is affected by the transition between these different conditions. Building on previous research which has shown that triathlon swimming performance can be predicted by an incremental pool test [82], **Chapter 8** further explores the relationship between open water and pool swimming. Through this comparative approach, this chapter seeks to uncover the nuances of performance adaptation and the practical implications for training and competition strategies.

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Chapter 2

Aims / Objetivos

Aims

The overall aim of the current International Doctoral Thesis is to gain a deeper understanding of the performance determinants of elite open water swimmers and triathletes. This general aim is addressed in six specific aims corresponding to six chapters of the thesis.

Specific aims

Specific aims I: (i) to determine the pacing strategy in the 3000 m race and (ii) to analyze the variability of performance and pacing factors (**Chapter 3**).

Specific aims II: (i) to analyze the lactate threshold in elite open water swimmers, (ii) to compare swimming speed at lactate threshold and at 4 mmol·1^{-1} and (iii) to examine the relationships between lactate threshold and swimming performance (**Chapter 4**).

Specific aims III: (i) to evaluate the seasonal changes in performance, physiological and kinematic factors in maximal incremental swimming tests in world-class OW swimmers and (ii) to examine the influence of these factors on the maximal incremental swimming performance (**Chapter 5**).

Specific aims IV: (i) to analyze the associations between physiological and biomechanical variables with swimming performance in elite triathletes and (ii) to determine whether these variables can explain performance (**Chapter 6**).

Specific aims V: (i) to analyze the 1500 m open water swimming performance in elite triathletes, (ii) to examine the associations between physiological and biomechanical variables with performance and (iii) to determine which variables can predict the open water swimming performance (**Chapter 7**).

Specific aims VI: (i) to compare performance, kinematic and physiological variables between the 1500 m open water and pool swimming conditions in elite triathletes and (ii) to examine the associations between conditions on these variables (**Chapter 8**).

Objetivos

El objetivo general de la presente Tesis Doctoral Internacional es profundizar en el conocimiento de los factores de rendimiento de los nadadores de aguas abiertas y triatletas de élite. Este objetivo general se aborda en seis objetivos específicos correspondientes a seis capítulos de la tesis.

Objetivos específicos

Objetivos específicos I: (i) determinar la estrategia de ritmo en la carrera de 3000 m y (ii) analizar la variabilidad del rendimiento y los factores de ritmo (**Capítulo 3**).

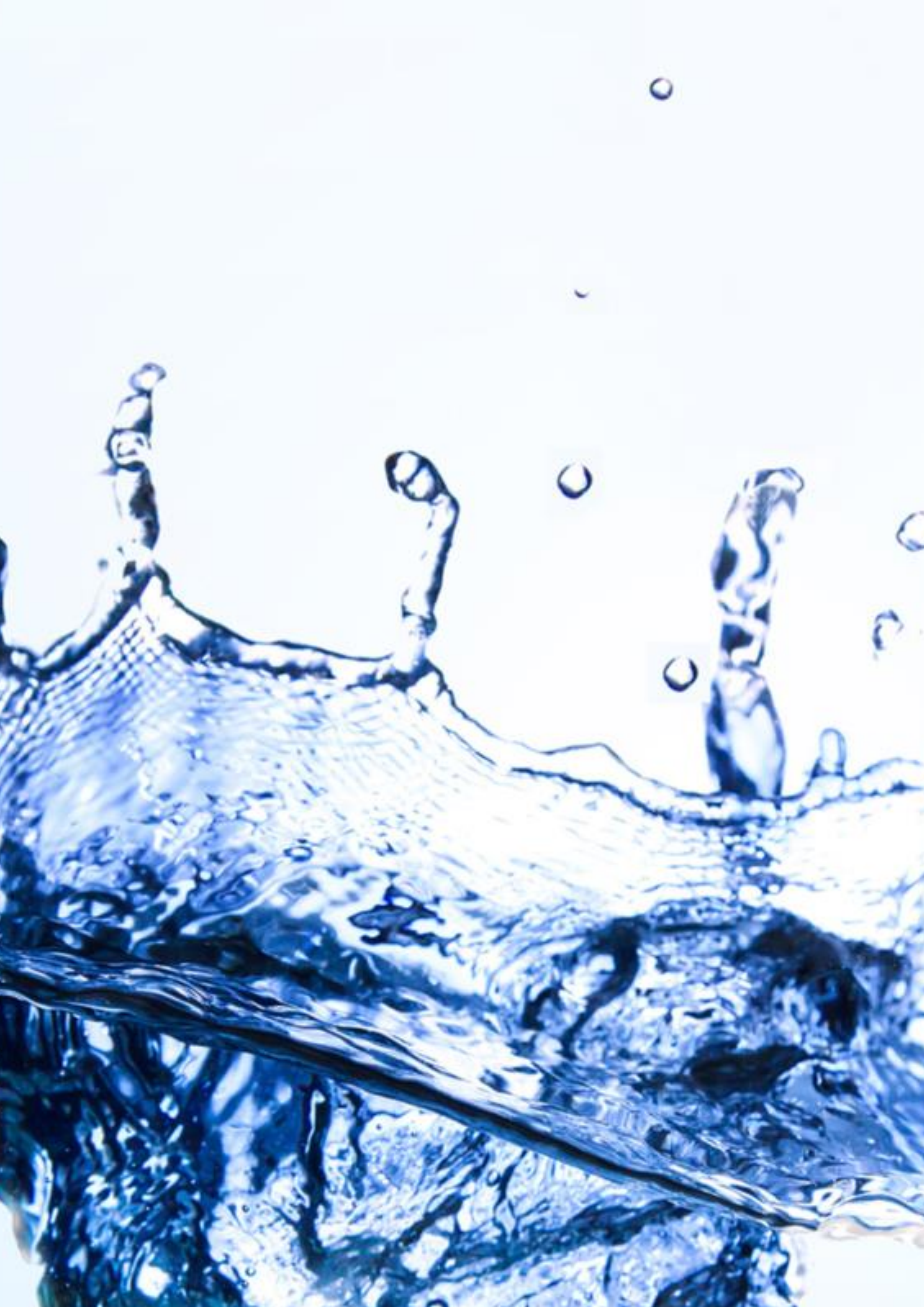
Objetivos específicos II: (i) analizar el umbral de lactato en nadadores de élite de aguas abiertas, (ii) comparar la velocidad de nado en el umbral de lactato y a 4 $mmol\text{-}1^{-1}$ y (iii) examinar las relaciones entre el umbral de lactato y el rendimiento en natación (**Capítulo 4**).

Objetivos específicos III: (i) evaluar los cambios en el rendimiento, los factores fisiológicos y cinemáticos durante las pruebas de natación incremental máxima en nadadores de élite de aguas abiertas y (ii) examinar la influencia de estos factores en el rendimiento incremental máximo de natación (**Capítulo 5**).

Objetivos específicos IV: (i) analizar las asociaciones entre variables fisiológicas y biomecánicas con el rendimiento en natación en triatletas de élite y (ii) determinar si estas variables pueden explicar el rendimiento (**Capítulo 6**).

Objetivos específicos V: (i) analizar el rendimiento en natación en aguas abiertas de 1500 m en triatletas de élite, (ii) examinar las asociaciones entre variables fisiológicas y biomecánicas con el rendimiento y (iii) determinar qué variables pueden predecir el rendimiento en natación en aguas abiertas (**Capítulo 7**).

Objetivos específicos VI: (i) comparar el rendimiento y las variables cinemáticas y fisiológicas entre las condiciones de natación de 1500 m en aguas abiertas y en piscina en triatletas de élite y (ii) examinar las asociaciones entre las condiciones sobre estas variables (**Capítulo 8**).



Chapter 3

Analysis of pacing and kinematics in 3000 m freestyle in elite level swimmers

López-Belmonte, Ó., Ruiz-Navarro, J. J., Gay, A., Cuenca-Fernández, F., Mujika, I., & Arellano, R. (2023). Analysis of pacing and kinematics in 3000 m freestyle in elite level swimmers. *Sports Biomechanics*, 1-17.

ABSTRACT

Purpose: This study aimed (i) to determine elite swimmers' pacing strategy in the 3000 m event and (ii) to analyse the associated performance variability and pacing factors. **Methods:** Forty-seven races were performed by 17 male and 13 female elite swimmers in a 25 m pool (20.7 ± 2.9 years; 807 ± 54 FINA points). Lap performance, clean swimming speed (CSS), water break time (WBT), water break distance (WBD), stroke rate (SR), stroke length (SL) and stroke index (SI) were analysed including and excluding the first (0-50 m) and last lap (2950-3000 m). **Results:** The most commonly pacing strategy adopted was parabolic. Lap performance and CSV were faster in the first half of the race compared to the second half ($p < 0.001$). WBT, WBD, SL, and SI were reduced ($p < 0.05$) in the second half compared to the first half of the 3000 m when including and excluding the first and last laps for both sexes. SR increased in the second half of the men's race when the first and last laps were excluded. **Conclusions:** All studied variables showed significant variation between the two halves of the 3000 m, the highest variation being obtained in WBT and WBD, suggesting that fatigue negatively affected swimming kinematics.

Keywords: long-distance, performance, swimming, strategy, tactics.

INTRODUCTION

Optimal sports performance involves making decisions on how to manage the energy available on the muscle system during the race [1]. In the sport sciences, the effort distribution and its impact on the final performance is known as pacing, or pacing strategy [2]. Pacing is affected by interoceptive (i.e., physiological, psychological, or biomechanical) and exteroceptive (i.e., environmental) factors [3]. Moreover, a pacing strategy is a learned behavior and it is dependent on feedback from internal receptors [4,5]. In this context, competition pacing can be developed employing different pre-planned strategies to optimize performance during the race [6].

The pacing strategies is an important element to be considered in the outcome of any competition [7]. For this reason, pacing has been studied in cyclic sports such as running [8], cycling [9], or triathlon [10]. According to these studies, the pacing strategy not only depends on the sport, but also on the specific distance and/or event [8–10]. With regard to swimming, due to the constraints of the water environment, the performance analysis constitutes sometimes a challenge compared to land locomotion sports [11], as the magnitude of the hydrodynamic resistance (i.e., active drag) experienced in the water, increases with the cube of the speed [12]. Hence, adopting an optimal pacing strategy could play an important role on swimming performance outcomes, as less speed variations within a race may lead to lower energy expenditure [13].

The pacing strategy displayed in a particular swimming event depends on both race distance and stroke [14]. A large body of research has studied the pacing strategy in different swimming distances, including sprint (50 and 100 m) [7], middle-distance (200 and 400 m) [15], long-distance (800 and 1500 m) [16], and open water swimming events (5, 10, and 25 km) [17]. Furthermore, negative (i.e. progressive velocity increase) [15], positive (i.e. velocity decrease) [7], even (i.e. evenly velocity) [13], J-shaped (i.e. conservative start with a high final velocity increase) [18], and parabolic pacing strategies (i.e. a fast start followed by an evenly paced mid-section and a fast end-spurt) [19] have been identified for different swimming events and competitors. Specifically in long-distance pool swimming events (i.e., 800 and 1500 m), the parabolic pacing strategy has mainly been observed, where the fastest laps are swum at the beginning and the end of the races, while the intermediate laps commonly show an even pace [20,21]. Hence, it is possible that the same parabolic pacing strategy would be adopted in other long-distance swimming races, where swimmers can adopt the same tactic to reduce the energy requirements and thus delay the onset of fatigue [13].

To establish the pacing strategy, apart from the split times over each lap of the event [14], other factors such as the clean swimming speed (CSS) and the turn performance have been studied in long-distance pool swimming events [22,23]. The analysis of these factors provides relevant information that could affect the lap performance, although only the aforementioned studies have analyzed the turn performance in long-distance events. Likewise, the stroke mechanics (i.e., stroke rate [SR] and stroke length [SL]) have a direct effect on the swimmers' performance [24], as SR is the main determinant of the CSS during the 1500 m freestyle race [23]. Thus, the study of all these variables together (i.e., lap performance, CSS, the turn and the stroke mechanics) allows a detailed analysis of the pacing strategy in long-distance swimming. In addition, the analysis of swimming variability provides useful information about the smallest worthwhile changes in competition performance [25,26]. Previous studies have analyzed the variability in 800 and 1500 m swimming events, where the lap performance and CSS showed a significant variation [22,23].

Recently, some swimming organizations, such as the Italian [27] or the Spanish Swimming Federations [28], have included the 3000 m race in some pool competition programs as an intermediate distance between the pool long-distance races (i.e., 800 and 1500 m) and the extreme open water events (5, 10 and 25 km). In this regard, although open water swimming has a different competitive environment, taking place in rivers, lakes or oceans [29], while swimming besides other competitors [30], the 3000 m race may be useful both for long-distance pool swimmers and open water swimmers. In fact, some swimmers participate in both pool swimming events (i.e., 800 and 1500 m) and open water races [31], demonstrating their versatile nature despite these differences in the competitive context. Moreover, it has been observed that the fastest open water swimmers have higher speed in middle- and long-distance pool events [30]. However, little attention has been allotted to this distance, so the pacing strategy used by elite swimmers in 3000 m races and how pacing is influenced by swimming mechanics and kinematic factors remain to be elucidated. It could provide different insights for long-distance swimming events both for training and competition about how performance is affected for these kinematic factors (e.g., turn performance or stroke mechanics and its variation over the race) and what could be done to improve it. Therefore, the aims of the present research were (i) to determine the pacing strategy of elite swimmers in the 3000 m race and (ii) to analyze the variability of performance and pacing factors in this event. It was hypothesized that the pacing strategy adopted by elite swimmers in the 3000 m race would be parabolic, with higher variability in the first and last lap (fastest laps).

MATERIALS AND METHODS

Participants

The study participants were 30 elite/international [32] swimmers (17 males [age: 20.4 ± 2.1 years] and 13 females [age 21.2 ± 3.9 years]), members of the Spanish, French, or Serbian national swimming teams (807 ± 54 FINA points in long-course 1500 m freestyle, performance level 2 [33]. In males, the 41.2% were pool swimmers and the 58.8% open water swimmers. In females, the 61.5% were pool swimmers and the 38.5% were open water swimmers. During training camps, the participants performed non-official 3000 m freestyle races following the competition standards in the same 25 m swimming pool at four time points: January 2018, November 2020, February and March 2021. From the total sample, 10 of the 30 swimmers (six men and four women) swam more than once. Hence, forty-seven performances of 3000 m (29 men and 18 women races) were analyzed. The study was approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022) and was conducted in compliance with the Declaration of Helsinki.

Procedures

The protocol conducted was the same in the four occasions. The participants performed their own standardized warm-up prior to the 3000 m freestyle race. The races had in-water start and the swimmers were notified 100 m before the end with the sound of a bell. For each 3000 m event, 60 laps were analyzed. In each one, lap performance was considered as the time (s) to complete 50 m. The CSS was calculated between 10-20 m, and between 35-45 m of each 50 m to avoid the effects of the push from the wall and the approach to the wall. The CSS of each 50 m was computed as the average of the two areas referred. To study the turn performance, two variables were analyzed: water break time (WBT) considered as the emersion time (s) from the contact with the wall to the head break out; and water break distance (WBD), i.e. the underwater distance (m) covered by the swimmer after the push from the wall. In the 3000 m race, a total of 119 turns were performed. However, WBT and WBD were computed as the average of the two turns performed in each lap (60 in total). To analyze the stroke parameters, SR was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by 60 to consider the number of strokes per minute [34]; SL was obtained from the ratio between the speed and SR; and stroke index (SI) was calculated as the product of swimming speed and SL [35]. Each stroke parameter was calculated by the average between the 10-20 and the 35-45 m to obtain each variable every 50 m lap. The 3000 m race was divided into two parts: the first half between 0 and 1500 m (i.e., T0-1500 m) and the second half between 1500 and 3000 m (i.e., T1500 and 3000 m). Subsequently, the two halves of the 3000 m race were analyzed and compared with each other [23]. Moreover, analyses were also performed excluding the first lap of the first half (T0-50 m) and the last lap of the second half (T2950-3000 m).

Methodology

The swimming events were recorded by an automatic system of performance analysis in swimming (ASPA) installed at the ceiling of the swimming pool. The ASPA system is composed of eight 83.33Hz 1080x1080 pixel cameras (Basler Aviator, Basler AG, Ahrensburg, Germany) located on the ceiling corridors of the swimming pool and connected through Ethernet (1GB) to a PC Work Station. The video signals are added in a frame using the video-stitching technique, thus collecting a sequence of frames in real time to analyze the swimmers' activity in every lane (eight lanes simultaneously). This system is an updated version of the procedure applied in the 2003 and 2013 Swimming World Championships [36]. Similar algorithms of image recognition used by other authors [37], allowed the event time collection and the full event processing in a very short time compared to the manual collection [38]. The authors are in the process of validating the ASPA system shortly for all kinematic variables.

Statistical analysis

Descriptive statistics (mean, standard deviation [SD] and 95% of confidence interval (CI) for the performance and pacing variables were obtained. The normality of the distribution was checked with Shapiro-Wilk test. However, when differentiating by sex, lap performance, CSS, WBT and SL showed a non-normal distribution. For analytical purposes, these variables were transformed using the Box-Cox transformation [39] and therefore parametric testing was applied. Paired samples t-test was conducted to verify differences between the first and the second half of the 3000 m races for all the variables. Effect sizes (*d*) were calculated and interpreted using [40] recommendations (small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$). Repeated measures analysis of variance (ANOVA) was used to assess the pacing variability (i.e., lap performance and CSS) and Bonferroni post-hoc test was used to check differences between each pairwise [22]. The coefficient of variation (CV) was calculated to measure the variability of all the variables analyzed, calculated from lap to lap. The mean of each half of the 3000 m race was used for analysis [23]. Due to the training and competition schedules of elite swimmers, it is highly difficult to access this kind of participants (i.e. elite level). Hence, the largest sample was obtained, being the sample size not calculated. Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS 25.0, IBM Corporation Chicago, IL, USA) and the level of statistical significance was set at $p < 0.05$.

RESULTS

Descriptive statistics of the variables analyzed are presented in Table 3.1 differentiated by sex. The variations of kinematic variables assessed are shown for male and female swimmers in Tables 3.2 and 3.3, respectively.

The average lap performance in the 3000 m races was 32.05 ± 0.92 s for males and 33.88 ± 0.95 s for females. Lap performance in the first half (T0-1500 m) was faster compared to the second half of the race (T1500-3000 m) both for males and females (Tables 3.2 and 3.3). In both sexes, the lap performance and the CSS decreased in the second half of the 3000 m race compared to the first half, for both the total of the race and also excluding the first and last laps.

Table 3.1. Descriptive statistics of the lap performance, clean swimming speed, turn variables, and stroke parameters of elite swimmers, including and excluding the first and last laps of the 3000 m race. Values are presented as mean ± SD [95% confidence interval] or median and interquartile range (IQR), according to normal or non-normal distribution, respectively.

	Men's races (n = 29)				**Women's races** (n = 18)			
	Total race		Excluding first and last lap		Total race		Excluding first and last lap	
	First half T0-1500 m	Second half T1500-3000 m	First half T50-1500 m	Second half T1500-2950 m	First half T0-1500 m	Second half T1500-3000 m	First half T50-1500 m	Second half T1500-2950 m
Lap performance (s)	31.85 ± 0.90 [31.53, 32.17]	32.26 ± 0.94 [31.93, 32.59]	31.90 ± 0.90 [31.57, 32.22]	32.31 ± 0.92 [31.99, 32.64]	33.64 ± 0.83 [33.26, 34.02]	34.13 ± 1.08 [33.62, 34.64]	33.67 ± 0.82 [33.28, 34.06]	34.13 ± 1.08 [33.65, 34.68]
CSS ($m \cdot s^{-1}$)#	1.47 [0.06]	1.44 [0.07]	1.47 [0.06]	1.44 [0.08]	1.40 [0.06]	1.38 [0.06]	1.39 [0.06]	1.38 [0.06]
WBT (s)#	2.13 [0.39]	2.02 [0.38]	2.10 [0.40]	2.01 [0.38]	2.00 [0.37]	1.89 [0.31]	1.97 [0.37]	1.89 [0.31]
WBD (m)	4.85 ± 0.42 [4.70, 5.00]	4.70 ± 0.39 [4.55, 4.84]	4.81 ± 0.41 [4.66, 4.96]	4.70 ± 0.39 [4.55, 4.84]	4.52 ± 0.44 [4.31, 4.73]	4.37 ± 0.44 [4.16, 4.58]	4.48 ± 0.44 [4.26, 4.69]	4.37 ± 0.44 [4.16, 4.58]
SR ($cycles \cdot min^{-1}$)	37.70 ± 2.75 [36.68, 38.73]	37.82 ± 2.75 [36.80, 38.83]	37.56 ± 2.73 [36.54, 38.59]	37.73 ± 2.72 [36.73, 38.75]	39.20 ± 2.05 [38.22, 40.18]	39.23 ± 1.87 [38.33, 40.13]	39.07 ± 2.01 [38.10, 40.03]	39.19 ± 1.87 [38.28, 40.08]
SL (m)#	2.31 [0.19]	2.28 [0.17]	2.32 [0.20]	2.28 [0.17]	2.12 [0.15]	2.09 [0.11]	2.12 [0.16]	2.09 [0.11]
SI ($m^2 \cdot s^{-1}$)	3.38 ± 0.28 [3.28, 3.48]	3.28 ± 0.26 [3.18, 3.37]	3.38 ± 0.28 [3.28, 3.48]	3.27 ± 0.26 [3.18, 3.37]	2.96 ± 0.20 [2.87, 3.06]	2.87 ± 0.20 [2.78, 2.97]	2.96 ± 0.20 [2.87, 3.06]	2.87 ± 0.20 [2.77, 2.96]

CSS = clean swimming speed; WBT = water break time; WBD = water break distance; SR = stroke rate; SL = stroke length; SI = stroke index. # = non-normally distributed variables.

Table 3.2. Variability of the lap performance, clean swimming speed, turn variables, and stroke parameters in male elite swimmers and comparison between the first and second half of the 3000 m race for all variables, including and excluding the first and last laps.

	Total race						Excluding first and last lap					
	Intra-swimmer variability			Comparison between first and second half			Intra-swimmer variability			Comparison between first and second half		
Variables	*p*	η2	CV	Mean Difference [95% CI]	*p*	*d*	*p*	η2	CV	Mean Difference [95% CI]	*p*	*d*
Lap performance (s)	<0.001	0.49	3.08	-0.41[-0.57, -0.26]	<0.001	0.45	<0.001	0.35	2.91	-0.42[-0.57, -0.26]	<0.001	0.45
CSS ($m \cdot s^{-1}$)	<0.001	0.42	3.66	0.02[0.01, 0.03]	<0.001	0.40	<0.001	0.24	3.43	0.02[0.01, 0.03]	<0.001	0.40
WBT (s)	<0.001	0.56	11.82	0.10[0.07, 0.11]	<0.001	0.15	<0.001	0.35	11.82	0.08[0.05, 0.10]	<0.001	0.03
WBD (m)	<0.001	0.70	9.12	0.15[0.13, 0.18]	<0.001	0.37	<0.001	0.37	8.43	0.11[0.09, 0.14]	<0.001	0.27
SR ($cycles \cdot min^{-1}$)	<0.001	0.50	7.41	-0.11[-0.30, 0.07]	0.211	0.04	<0.001	0.18	7.16	-0.17[-0.35, -0.00]	0.048	0.06
SL (m)	<0.001	0.24	6.96	0.04[0.02, 0.05]	<0.001	0.25	<0.001	0.24	6.92	0.04[0.03, 0.06]	<0.001	0.25
SI ($m^2 \cdot s^{-1}$)	<0.001	0.25	8.31	0.10[0.06, 0.14]	<0.001	0.37	<0.001	0.24	8.28	0.10[0.06, 0.14]	<0.001	0.41

CSS = clean swimming speed; WBT = water break time; WBD = water break distance; SR = stroke rate; SL = stroke length; SI = stroke index; *p* = significance value; η2 = net squared value; CV = coefficient of variation; *d* = Cohen's *d* (effect size).

Table 3.3. Variability of the lap performance, clean swimming speed, turn variables, and stroke parameters in female elite swimmers and comparison between the first and second half of the 3000 m race for all variables, including and excluding the first and last laps.

	Total race						Excluding first and last lap					
	Intra-swimmer variability			Comparison between first and second half			Intra-swimmer variability			Comparison between first and second half		
Variables	*p*	η2	CV	Mean Difference [95% CI]	*p*	*d*	*p*	η2	CV	Mean Difference [95% CI]	*p*	*d*
Lap performance (s)	<0.001	0.45	2.95	-0.49[-0.69, -0.29]	<0.001	0.51	<0.001	0.41	2.90	-0.49[-0.69, -0.30]	<0.001	0.48
CSS ($m \cdot s^{-1}$)	<0.001	0.44	3.52	0.02[0.01, 0.03]	<0.001	0.44	<0.001	0.35	3.47	0.02[0.01, 0.03]	<0.001	0.44
WBT (s)	<0.001	0.49	14.95	0.10[0.05, 0.14]	<0.001	0.33	<0.001	0.18	14.30	0.07[0.02, 0.11]	0.005	0.24
WBD (m)	<0.001	0.69	10.66	0.15[0.09, 0.22]	0.001	0.34	<0.001	0.27	9.81	0.11[0.05, 0.17]	0.002	0.25
SR ($cycles \cdot min^{-1}$)	<0.001	0.41	5.13	-0.03[-0.43, 0.36]	0.868	0.02	0.034	0.15	4.88	-0.11[-0.49, 0.26]	0.531	0.06
SL (m)	<0.001	0.27	4.94	0.03[0.02, 0.05]	0.002	0.30	<0.001	0.26	4.89	0.04[0.02, 0.06]	<0.001	0.38
SI ($m^2 \cdot s^{-1}$)	<0.001	0.31	6.93	0.10[0.06, 0.12]	<0.001	0.45	<0.001	0.33	6.89	0.10[0.06, 0.13]	<0.001	0.45

CSS = clean swimming speed; WBT = water break time; WBD = water break distance; SR = stroke rate; SL = stroke length; SI = stroke index; *p* = significance value; η2 = net squared value; CV = coefficient of variation; *d* = Cohen's *d* (effect size).

In male swimmers, there were differences in the lap performance (F = 27.34; df = 59) and CSS (F = 19.97; df = 59) (Table 3.2). The first lap was faster than the rest of the laps ($p < 0.001$) with the exception of the last one ($p > 0.05$). The last lap was also faster ($p < 0.05$) than the rest with the exception of the first three laps ($p > 0.05$) (Figure 3.1 A). In female swimmers, there were differences in the lap performance (F = 14.14; df = 59) and CSS (F = 13.24; df = 59) (Table 3.3). The last lap was faster ($p < 0.05$) than the rest of the laps of the second half of the 3000 m race (i.e., from laps 26 to 58). In both cases, a parabolic pacing profile was displayed, where the intermediate laps showed a positive trend (Figure 3.1 A and B). The CV values obtained in lap performance and CSS were higher for the total race compared to the analysis excluding the first and last laps (Tables 3.2 and 3.3).

In male turn performance, WBT and WBD were lower in the second half of the race, both including and excluding the first and last laps. In stroke mechanics, SL and SI decreased in the second half compared to the first half, for both the total of the race and excluding the first and last laps. In SR, when excluding the first and last lap an increase was observed in the second half compared to the first (Table 3.2). The CV values obtained in turn performance were higher for the total race compared to the analysis excluding the first and last laps (Tables 3.2 and 3.3).

In female turn performance, WBT and WBD decreased in the second half, both including and excluding the first and last laps. In stroke parameters, SL and SI decreased in the second half when the total race was analyzed and excluding the first and last laps. In SR, no differences were observed between the two halves of the 3000 m race when the total race was analyzed and excluding the first and last laps (Table 3.3). The CV values obtained in stroke parameters were higher for the total race compared to the analysis excluding the first and last laps (Tables 3.2 and 3.3).

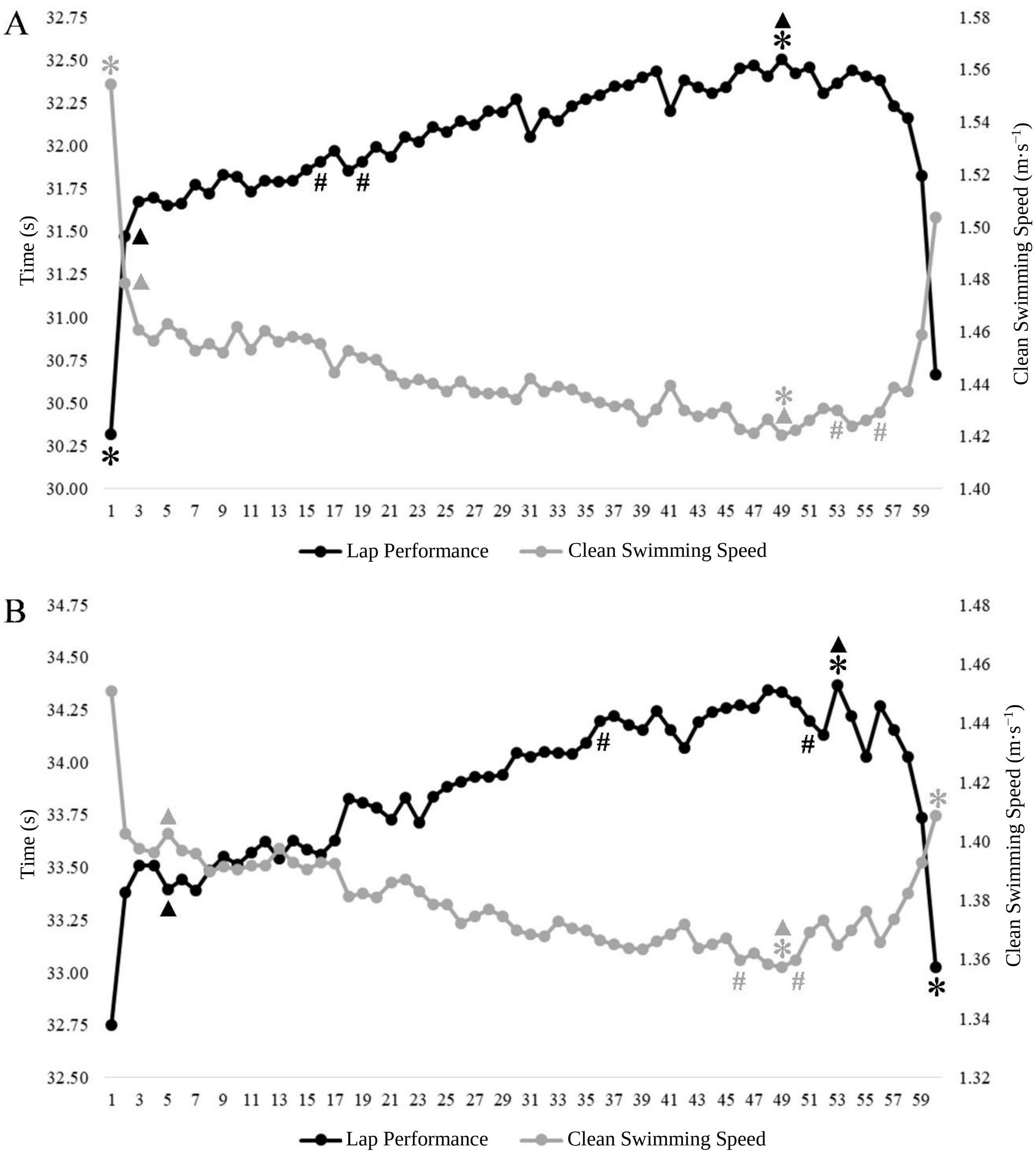


Figure 3.1. Lap performance and clean swimming speed (CSS) variability in the 3000 m race for male (A) and female (B) elite swimmers. It is represented the highest difference (p < 0.001) observed between two laps with all race analyzed (*) and the highest difference when excluding the first and last lap (▲). In addition, it is represented the lowest (#) difference (p < 0.05) observed between two laps when including and excluding the first and last lap.

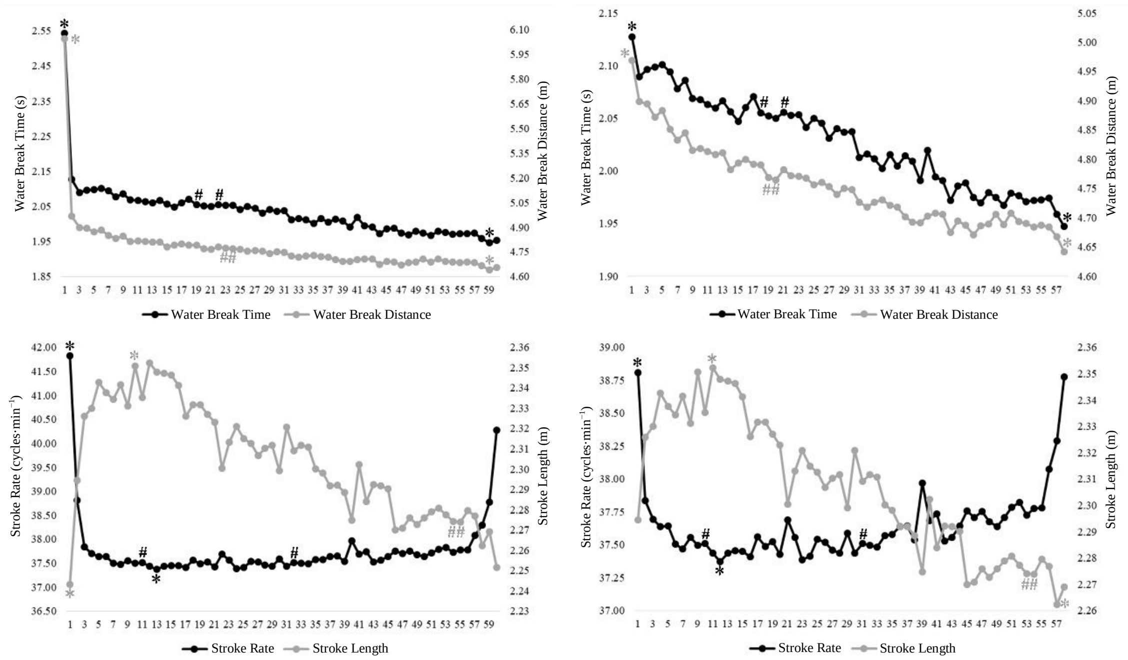


Figure 3.2. Turn performance (WBT and WBD) and stroke parameters (SR and SL) variability in the 3000 m race for male swimmers. The left panels include all laps and the right panels exclude the first and last lap. In both panels, it is represented the highest (*) difference (p < 0.001) observed between two laps. In addition, it is represented the lowest ($^{\#}$) difference (p < 0.05) observed between two laps when excluding and including the first and last lap.

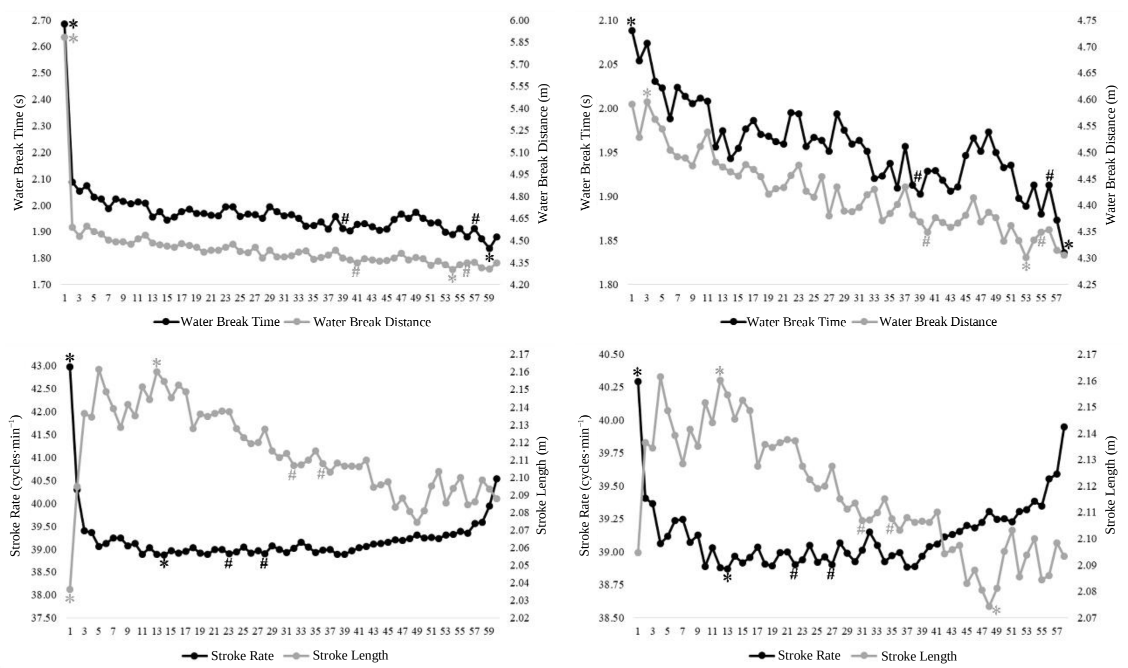


Figure 3.3. Turn performance (WBT and WBD) and stroke parameters (SR and SL) variability in the 3000 m race for male swimmers. The left panels include all laps and the right panels exclude the first and last lap. In both panels, it is represented the highest (*) difference (p < 0.001) observed between two laps. In addition, it is represented the lowest ($^{\#}$) difference (p < 0.05) observed between two laps when excluding and including the first and last lap.

DISCUSSION

The aims of the current study were to determine the pacing strategies in the 3000 m freestyle race and to analyze the variability of performance and pacing factors of elite swimmers. As it was hypothesized, the pacing profile adopted by these swimmers in the 3000 m event was parabolic. Lap performance and CSS were faster in the first half of the race (T0-1500 m) compared to the second half (T1500-3000 m). The turn performance (WBT and WBD), SL and SI declined in the second half. However, SR only increased in the second half of the men's race when the first and last lap were excluded. All the variables analyzed presented significant variation between the first and the second half of the 3000 m race, with the highest CV values observed in WBT and WBD.

To the best of the authors' knowledge, this is the first study analyzing the pacing and kinematics of 3000 m swimming in elite swimmers. The information provided on kinematic variables may constitute reference values for training or competitions of long-distance swimming events, where swimmers should reduce the kinematic variation and control their effort throughout the race. The 3000 m swimming is a useful distance both for pool and open water swimmers, although the specificity of the competitive environment should be considered. A previous study on master swimmers analyzed only the average time performed in 3000 m open water [41]. As observed in Figure 3.1, this cohort of elite swimmers adopted a parabolic strategy in the 3000 m pool event. These results are in line with previous studies conducted with long-distance swimmers, such as 800 m female elite swimmers [16,20] or 1500 m [16,21]. Moreover, the parabolic profile is also the strategy commonly adopted by middle-distance (i.e., 200 and 400 m) freestyle swimmers [14,16]. Although the parabolic profile was adopted by most of the swimmers in the present study, a negative profile was also observed in one female swimmer (Figure 3.4, Swimmer 2).

The two female swimmers observed in Figure 3.4 obtained a similar final time in the 3000 m race (32.5 min). The average lap performance was 32.49 ± 0.29 s and 32.48 ± 0.28 s for swimmer 1 and 2, respectively, with identical CSS values of 1.44 ± 0.02 $m \cdot s^{-1}$. However, the pacing strategy employed by swimmer 1 was parabolic, executing the first half of the race faster (average lap performance: 32.35 ± 0.17 s) than the second (32.63 ± 0.17 s), while the pacing strategy used by swimmer 2 was negative, performing the second half faster (32.27 ± 0.30 s) than the first half (32.68 ± 0.17 s). The differences in pacing strategy between the two swimmers could be due to the higher experience of swimmer 2 (30 years old) compared to swimmer 1 (23 years old). Indeed, athletes' experience has been highlighted as a fundamental factor in developing the ability to maintain an adequate pacing [42]. Based on greater experience and according to the specific characteristics of the event, athletes create an ideal performance strategy [6].

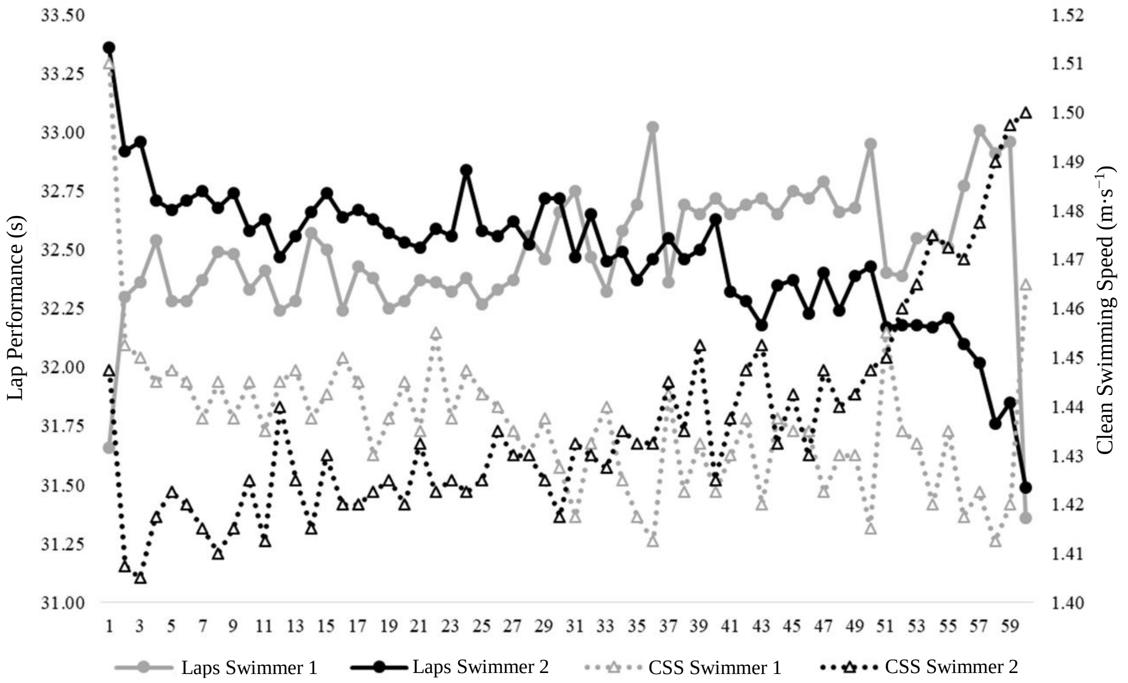


Figure 3.4. Lap performance and clean swimming speed (CSS) in the 3000 m of two similar outcomes with different pacing strategies.

In swimming, due to the hydrodynamic resistance experienced in the water, the pacing strategy may affect performance more than in other sports, as variations in speed increase the swimmer's energy expenditure [13]. Considering these factors, an appropriate pacing for a long-distance swimmer would consist on reducing the speed variations throughout the race. Despite this evidence and even though the parabolic pacing appeared to be the preferred strategy used, swimmers should try to find the pacing strategy that best fit their individual characteristics. Moreover, when analyzing pacing strategies, the competitive context should be taken into account, as long-distance swimmers may participate in both pool and open water events [31]. In contrast with pool events, faster open water swimmers adopted negative pacing, increasing intensity in the last quarter of the competition [17]. Likewise, the drafting strategies produced by swimming behind the lead pack allows for a reduction in energy cost [43]. This fact may affects the pacing strategies conducted in pool compared to open water, as during pool events the swimmers do not benefit from drafting caused by swimming behind other competitors.

The start and the emphasis to finish the race strongly impact performance in the first and last laps, affecting the overall pacing in swimming competitions [21]. Hence, to avoid major variations in pacing, some studies excluded these two laps [22,23]. In this study, the swimmers performed the 3000 m race without a dive (i.e., in-water start). However, to compare the results obtained in similar studies with long-distance swimmers, all the variables were analyzed with both the total distance of the race and also excluding the first and last laps (Table 3.1). The results of this study are in accordance with previous literature, as even after excluding the first and last laps, a significant variation was still observed in 1500 m between the first (T50-750 m) and second half of the race (T750-1450 m) in male elite swimmers [23]. Despite excluding the first and last laps, there were still significant differences (i.e., performance decline) in lap performance and CSS between the first and second half of the 3000 m race. This high variation might be probably due to the differences between the parameters measured during the multiple laps of a long-distance event [22]. Therefore, the study of other factors that affect pacing are necessary for an in-depth analysis of swimming performance, such as turn performance or stroke mechanics analyzed in this research.

The turn performance has been evaluated in long-distance swimmers in short- [44] and long-course pools [22]. The results obtained in the present study show a decline in WBT and WBD during the second half of the race, in agreement with previous studies of 1500 m races [23]. However, the average values obtained in WBT and WBD for the 3000 m swimming event performed in a short-course pool were lower than those obtained for 1500 m freestyle races performed in long-course [23]. In this regard, the difference between short- and long-course turn performance analysis should be considered, where the large number of turns in short-course cause faster race times compared to long-course, although the mean turn times are shorter in the 25 m pool [44]. The highest CV values of the pacing factors analyzed were obtained in WBT and WBD, in line with previous studies with 1500 m swimmers [23], although the variability was higher in the 3000 m race. This could be due to the longer distance, and consequently the greater number of turns, and/or to the greater number of races analyzed (i.e., 47 vs. 16 swimming performances). Considering the large contribution of turn times to total race time, fatigue would expectedly explain the reduction in turn performance [45], and this would explain the high variability observed in the present study. Another important factor to consider is that 60% of the participants of the current study were open water swimmers, which could influence the turn performance. As turns are non-existent in open water events, the high variation obtained in WBT and WBD in the 3000 m race may also be explained by the different competitive environment faced by open water swimmers. In any case, the turn performance results are consistent with other studies where elite swimmers were not capable of maintaining a similar turning pattern during a long-distance event [22].

The swimming speed is the result of the interplay between SR and SL [46]. In long-distance events, the stroke parameters directly affect swimming pacing, considering the SR the main factor responsible for the CSS in 1500 m male swimmers [23]. However, the results obtained in the 3000 m showed that male swimmers' SR increased when the first and last laps were excluded from the analyses. It might be speculated that despite obtaining higher SR values in the second half (37.73 ± 2.72 cycles·min^{-1}), the higher value obtained in the first lap (41.82 ± 3.37 cycles·min^{-1}) with respect to the last lap (40.27 ± 3.73 cycles·min^{-1}) caused a greater increase in the mean SR of the first half compared to the second. This could lead to two more similar means (when the first and last lap are included), reaching the erroneous conclusion that SR in both halves was not significantly different. However, if SR during the last lap were the same as that of the first lap, the same differences would be observed when including and excluding the first and last laps. Regarding SL and SI, a significant decrease was observed in the second half of the 3000 m, probably due to a fatigue-induced impairment in the ability to apply force in the water [47], with SL progressively declining throughout the race (Figures 3.2 and 3.3). The maintenance of SL may be an important factor for long-distance swimmers to increase the CSS during the second half of the races [22]. Moreover, the mean SL and SI values obtained in the 3000 m male races were lower than the results obtained in 800 and 1500 m also by male swimmers [22,23]. In this sense, each swimmer choose an optimal stroke interplay based on swimming distance, which seems to be quite individual [48].

As the 3000 m swimming race is an intermediate distance event between pool long-distance and open water swimming, future studies should consider the analysis of the 3000 m swimming race in long-course pool to compare the results obtained in short-course. The limitation of the current study was the different dates when the 3000 m races were conducted, which could affect the results obtained due to the different performance states of the swimmers over the season. Moreover, the anthropometric and physiological variables must be assessed to obtain more information from the swimmers and relate it to swimming kinematics. It is important to highlight the information provided by the turn performance, as few studies analyzed these variables in long-distance swimming events, although its role may be crucial for overall performance [22,23,44]. This could provide different insights and further practical information both for training and competition about how performance is affected during these events in elite swimmers.

CONCLUSION

The pacing strategy adopted by most elite swimmers in the 3000 m race was parabolic. The first half of the race was faster than the second half, where lap performance and CSS decreased. With regard to turn performance and stroke mechanics, WBT, WBD, SL, and SI were lower in the second half compared to the first half of the 3000 m. In addition, SR increased in the second half of the men’s race when the first and last lap were excluded. All variables presented significant variation between the two halves, the highest values of CV being observed in turn performance, suggesting that fatigue negatively affected swimming kinematics.

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Chapter 4

Lactate threshold and swimming performance in world-class and elite open water swimmers

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ABSTRACT

Purpose: The assessment of the lactate threshold (LT) and its relationship to open water (OW) performance is crucial. This study aimed (i) to analyze the LT in world-class OW swimmers, to (ii) compare swimming speed at LT (SS_{LT}) and swimming speed at 4 mmol·l^{-1} of blood lactate concentration ([La^{-}]) (SS_4), and (3) to examine the relationships between SS_{LT} and swimming performance. **Methods**: Twenty world-class and elite (11 males [26.4 ± 3.0 years] and 9 females [25.8 ± 3.6 years]) OW swimmers voluntarily participated. A total of 46 (29 male and 17 female tests) intermittent incremental tests (7x400 m) conducted in a 50-m pool were analyzed. Seasonal best performances on 400, 800, 1500 m and 10 km OW swimming events were obtained. **Results**: The SS_{LT} was 1.62 ± 0.02 (3.77 ± 0.96 mmol·l^{-1}) and 1.46 ± 0.04 m·s^{-1} (3.00 ± 0.67 mmol·l^{-1}) in males and females, respectively, which corresponded to 97% of the peak speed reached in the tests. There were no differences (p = 0.148) between SS_{LT} and SS_4 in males, however, SS_{LT} was lower (p = 0.019) than SS_4 in females. The SS_{LT} was negatively correlated with swimming performance, with the exception of 10 km OW and 400 m times in males and females, respectively. **Conclusions**: World-class and elite OW swimmers exhibited a great-developed aerobic capacity with LT close to their maximum speed or HR. The SS_4 could be used as an approximation to LT in males but overestimates true aerobic capacity in females. The LT is a useful tool for assessing performance, as OW swimmers with higher SS_{LT} showed better swimming performance.

Keywords: anaerobic threshold, long-distance, endurance, aerobic capacity, physiology.

INTRODUCTION

Open water (OW) swimming stands as one of the most challenging and breathtaking endurance disciplines in the swimming scene. The natural environments where OW swimming competitions are held (e.g., rivers or oceans), characterize these events with particular and changing conditions that swimmers must face [1]. Currently, the World Aquatics Championships program includes the 5 km, 10 km distances and the mixed 4x1500 m relays, being the 10 km swimming the exclusive OW event comprised in the Olympic Games [2]. Since its inclusion in the 2008 Beijing Olympics, a significant number of swimmers, particularly specialists in middle- and long-distance pool events, have also engaged in OW swimming races [3,4]. But also, OW specialist swimmers incorporate 800 m to 5 km pool events into their competition schedule as part of their preparation for major events [4–6]. Thus, OW swimmers compete in the pool because they need to swim fast as the discipline evolves, indeed, previous research has shown that the fastest OW swimmers displayed higher speeds in middle- and long-distance pool swimming events [4]. Hence, this current trend among both disciplines may potentially modify the OW swimmers' profile to date.

Swimming testing is commonly integrated into elite training programs to accurately evaluate the competitive swimmers' performance [7]. Among a wide variety of parameters, in endurance disciplines highlights the lactate threshold (LT), which is recognized to assess the swimmers' aerobic capacity [8]. The LT is determined as the breakpoint of blood lactate concentration ([La^{-}]) when arises from moderate to heavy intensities during intermittent incremental protocols [8,9]. In this regard, the LT assessment is essential in long-distance and OW swimmers, since most of these specialist training and competition are performed at this intensity [9,10]. Moreover, the fixed [La^{-}] at 4 mmol·l^{-1} is considered the method traditionally used for assessing the aerobic capacity [11]. However, some controversial results have been shown about its relationship with LT, as some authors indicate an overestimation of the swimmers' aerobic capacity [9]. Therefore, due to the relevance of the LT determination for OW swimmers, testing the differences between SS_{LT} and the swimming speed corresponding to 4 mmol·l^{-1} (SS_4) may provide valuable insights for coaches and scientists. On the other hand, an integrated physiological and biomechanical assessment of swimming performance provides a greater understanding of the performance [12], as swimming changes in swimming technique may occur at speeds above the LT [13]. Hence, the swimming speed at LT (SS_{LT}) and its respective biomechanical assessment could be crucial for OW swimmers' performance.

The LT and its relationships with endurance performance is crucial [14]. The relationships between LT and endurance performance has been demonstrated to be crucial in sports like running and cycling [14]. However, there is a paucity of data regarding relationships in swimming, particularly among elite OW swimmers, with limited information available in both training and competition [1]. Thus, the LT determination and its association with swimming performance are essential to update the OW swimmers' profile. To the best of the authors' knowledge, only one study analyzed the LT in elite OW swimmers two decades ago [15] However, this aforementioned study dates back to a time when OW swimming was not an Olympic discipline and therefore, given the rising participation in OW competitions, a different profile of OW swimmers may have emerged in recent years. Thus, the aims of this study were (i) to analyze the LT through an incremental protocol test in world-class and elite OW swimmers, (ii) to compare SS_{LT} and SS_4, and (iii) to examine the relationships between SS_{LT} and swimming performance. Due to the current evolution of OW events, it is expected that elite OW swimmers achieve higher SS_{LT} compared to previous research [15]. Moreover, taking into account the results with long-distance swimmers [9], the SS_4 would be higher than the SS_{LT}, overestimating the aerobic capacity. Finally, swimmers with higher SS_{LT} would exhibit better performance, as it is key in long-distance swimming.

METHODS

Participants

Twenty world-class and elite [16] OW swimmers (Table 4.1), members of national swimming teams and training together under the direction of the same coach, voluntarily participated in the current study. According to the classification of Ruiz-Navarro et al. [17], participants were classified between performance level 1 and 3. During the 2022 and 2023 seasons, the OW swimmers performed three 7x400 m intermittent incremental protocol tests (October 2022, February and October 2023), with an average weekly training of 54.0 ± 16.7 km during these seasons. From the total sample, fifteen swimmers (9 males and 6 females) performed the test more than once, thus a total of 46 incremental tests were analyzed (29 male and 17 female tests). The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki) and approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022).

Table 4.1. Mean ± SD of the physical characteristics of elite open water swimmers (n = 20).

	Males (n = 11)	**Females** (n = 9)
Age (years)	26.44 ± 2.96	25.78 ± 3.56
Height (cm)	185.71 ± 3.77	173.29 ± 5.31
Body mass (kg)	74.71 ± 5.82	64.43 ± 3.91
Body mass index ($kg·m^{-2}$)	21.68 ± 1.83	21.14 ± 1.31

Data collection

The protocol conducted was replicated during the three occasions. All tests took place in a 50-m long-course pool with a water temperature of ~26ºC. The swimmers performed a 1200 m standardized warm-up from low to moderate intensity prior to the swimming assessment. The 7x400 m intermittent incremental protocol consisted of seven steps, from easy to maximal effort, with 30 s rest intervals. All tests were conducted with in-water starts and at the same time of the day to avoid circadian variations [18]. Swimming speed of the first 400 m step was set at 80% of the 400 m freestyle seasonal best and was subsequently increased by 3% per step. The 400 m times performed (s) were measured through a stopwatch (FINIS 3X-300M, FINIS, Inc., USA) by an expert swimming researcher. The final times obtained were converted in swimming speed for each 400 m step ($m·s^{-1}$). The [La^-] were analyzed with a portable lactate analyzer (Lactate Pro 2.0, Arkray Inc., Tokyo, Japan) from the swimmers' right lobe during recovery periods and at the end of the test until the peak ([La^-]$_{peak}$) was reached. Rate of perceived exertion (RPE) [19] was asked to the swimmers right after each step. Stroke rate (SR) was measured every 50 m and the mean of the eight laps was considered. Stroke length (SL) was calculated from the ratio between swimming speed and SR and stroke index (SI) was computed as the product of swimming speed and SL [20].

Methodology

The LT was determined from the speed lactate curve by identifying the intersection of the lines connecting the two highest and the two lowest points of the curve [8] (Figure 4.1). From this intersection, [La^-] corresponding to individual LT ([La^-]$_{LT}$) and swimming speed at LT (SS_{LT}) were obtained. Swimming speed corresponding to [La$^-$] at 4 mmol·l^{-1} (SS_4) was interpolated [11] (Figure 4.1). Maximum heart rate (HR_{max}) was registered immediately after each 400 m step and the highest value was obtained through the Polar H10 HR sensor (Polar Electro OY, Kempele, Finland). Moreover, SR, SL, SI, HR and RPE at individual anaerobic threshold (SR_{LT}, SL_{LT}, SI_{LT}, HR_{LT} and RPE_{LT}) were determined by linear interpolation from the two closest points where $[La^-]_{LT}$ was observed.

Seasonal best performances and World Aquatics Points [2] in official 2024 long-course competitions on 400, 800 and 1500 m swimming events were retrieved from the public access website www.swimrankings.net (Table 4.3). In addition, the times performed in 10 km OW swimming events were obtained from the official websites of the European [21] and World Aquatics [2]. Due to the changing OW conditions [1], the best and worst race times were removed and the mean of two 10 km OW events per swimmer were obtained. All times were collected from international and national events held between October 2022 and October 2023.

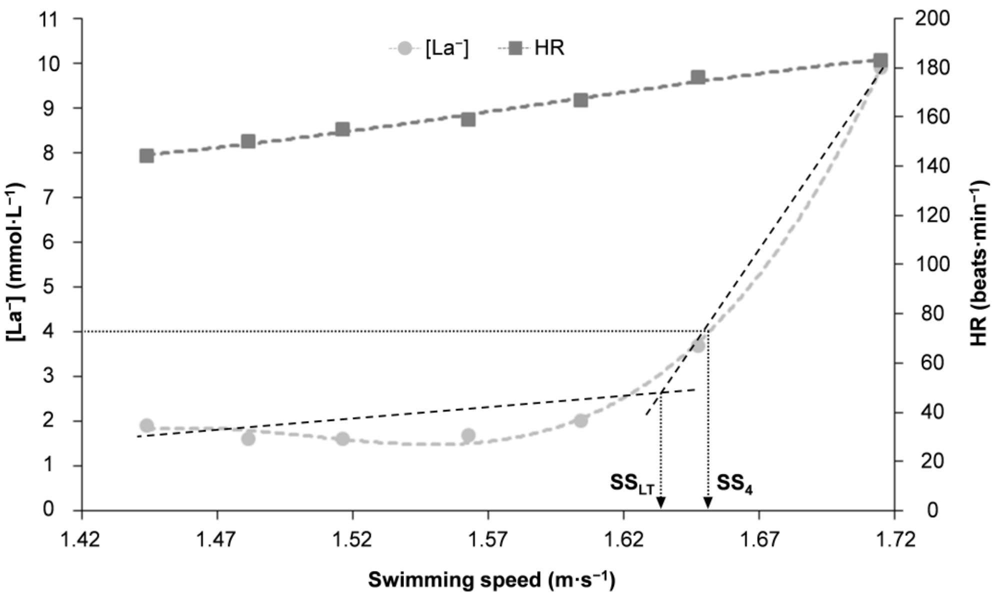

Figure 4.1. Example of blood lactate concentration ([La−]) to speed swimming curve obtained in the 7x400 m intermittent incremental protocol test of an Olympic gold medalist swimmer. The arrows indicate the lactate threshold (LT) and speed corresponding to a [La−] of 4 mmol·1−1 (SS4). Heart rate (HR) trend line is represented during the test.

Statistical analysis

Descriptive statistics (mean and standard deviation [SD]) for the swimming performance, physiological and biomechanical variables were obtained. Normal distribution of the data was checked with Shapiro-Wilk test. Paired sample t-test was conducted to verify differences between SS_{LT} and SS_4. Mean values of each swimmer were considered to calculate the differences between these variables. Pearson's correlations were used to determine the association between SS_{LT} and seasonal best performances. The threshold correlation values were defined as: ≤ 0.1 trivial; < 0.1-0.3 small; > 0.3-0.5 moderate; > 0.5-0.7 large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect [22]. All statistical analyses were conducted separately by sex. The significance level was set up at $p < 0.05$ and all the statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

The mean and standard deviation (SD) derived from the intermittent incremental protocol tests are presented in Table 4.2. Seasonal best performances obtained, swimming speed, physiological and biomechanical variables derived from the tests are shown in Table 4.3. In males, the SS_{LT} ranged from 1.58 to 1.63 $m \cdot s^{-1}$ and $[La^{-}]_{LT}$ from 2.7 to 6.0 $mmol \cdot l^{-1}$. In females, the SS_{LT} presented a range from 1.42 to 1.47 $m \cdot s^{-1}$ and $[La^{-}]_{LT}$ from 2.0 to 4.1 $mmol \cdot l^{-1}$. The SS_{LT} corresponded to 97% of the peak swimming speed achieved in the incremental protocol in both sexes. Similar HR_{LT} percentages of 96 and 97% were reached with respect to HR_{max} in males and females, respectively. No difference (p = 0.148) was observed between SS_{LT} and SS_4 in males, while a significant difference (p = 0.019) was found in females. Pearson correlation coefficients between SS_{LT} and swimming performance are shown in Table 4.4. In males, the SS_{LT} presented large to very large negative correlations with pool swimming performance. In females, the SS_{LT} presented large negative correlations with pool and OW swimming performance, with no significant association with 400 m time (Table 4.4).

Table 4.2. Mean ± SD of the performance, physiological and biomechanical variables obtained in the 7x400 m intermittent incremental protocol tests in elite open water swimmers.

		Performance		**Physiological variables**			**Biomechanical variables**		
	Step number	400 m time (s)	Swimming speed ($m \cdot s^{-1}$)	Blood lactate concentration ($mmol \cdot L^{-1}$)	Heart rate ($beats \cdot min^{-1}$)	Rate of perceived exertion	Stroke rate ($cycles \cdot min^{-1}$)	Stroke length (m)	Stroke index ($m^2 \cdot s^{-1}$)
Male's tests (n = 29)	1	286.80 ± 6.94	1.40 ± 0.03	1.52 ± 0.23	137 ± 8	0.95 ± 0.33	28.59 ± 2.74	2.79 ± 0.37	3.89 ± 0.48
	2	275.79 ± 6.87	1.45 ± 0.04	1.49 ± 0.20	149 ± 11	1.65 ± 0.52	30.78 ± 3.07	2.78 ± 0.21	4.03 ± 0.25
	3	267.55 ± 5.11	1.50 ± 0.03	1.62 ± 0.22	156 ± 9	2.47 ± 0.75	32.31 ± 2.96	2.73 ± 0.20	4.08 ± 0.25
	4	259.80 ± 4.33	1.54 ± 0.02	2.07 ± 0.41	164 ± 9	3.52 ± 0.84	34.65 ± 2.89	2.62 ± 0.20	4.03 ± 0.30
	5	252.05 ± 3.05	1.59 ± 0.02	2.91 ± 0.69	173 ± 7	4.89 ± 0.92	36.50 ± 3.11	2.56 ± 0.20	4.06 ± 0.30
	6	246.27 ± 3.00	1.63 ± 0.02	4.52 ± 1.50	179 ± 7	6.74 ± 1.05	38.26 ± 2.88	2.50 ± 0.18	4.06 ± 0.28
	7	239.41 ± 2.79	1.67 ± 0.02	8.69 ± 2.45	184 ± 5	9.47 ± 0.68	41.17 ± 3.19	2.39 ± 0.19	3.99 ± 0.32
Female's tests (n = 17)	1	308.16 ± 8.82	1.30 ± 0.04	1.64 ± 0.37	142 ± 8	0.77 ± 0.44	32.51 ± 2.24	2.35 ± 0.18	3.05 ± 0.29
	2	297.25 ± 6.23	1.35 ± 0.03	1.49 ± 0.41	150 ± 9	1.49 ± 0.64	34.57 ± 2.48	2.29 ± 0.17	3.08 ± 0.25
	3	290.11 ± 5.13	1.38 ± 0.03	1.65 ± 0.49	161 ± 6	2.48 ± 1.23	36.16 ± 2.29	2.24 ± 0.15	3.09 ± 0.23
	4	283.45 ± 3.91	1.41 ± 0.02	2.04 ± 0.64	169 ± 6	3.48 ± 1.46	37.53 ± 2.59	2.21 ± 0.15	3.12 ± 0.22
	5	276.81 ± 5.25	1.45 ± 0.03	2.63 ± 1.03	176 ± 7	4.67 ± 1.91	38.92 ± 2.63	2.18 ± 0.14	3.15 ± 0.18
	6	272.63 ± 4.79	1.47 ± 0.03	3.06 ± 0.97	180 ± 9	5.30 ± 2.15	39.95 ± 2.92	2.16 ± 0.14	3.17 ± 0.18
	7	266.58 ± 6.33	1.50 ± 0.03	6.86 ± 1.81	184 ± 11	8.54 ± 1.89	41.74 ± 3.44	2.12 ± 0.15	3.17 ± 0.19

Table 4.3. Mean ± SD of the seasonal best performances obtained, swimming speed, physiological and biomechanical variables derived from the intermittent incremental protocol tests in elite open water swimmers.

	Males (n = 11)	Females (n = 9)
Swimming performance		
400 m time (s)	232.39 ± 4.60	260.14 ± 7.40
400 m World Aquatics Points	851 ± 48	753 ± 65
800 m time (s)	477.50 ± 8.00	526.43 ± 13.20
800 m World Aquatics Points	850 ± 42	783 ± 59
1500 m time (s)	911.69 ± 18.93	1001.36 ± 24.86
1500 m World Aquatics Points	874 ± 54	779 ± 58
Best 10 km open water time (s)	6555.95 ± 105.86	7289.35 ± 112.56
Swimming speed		
SS_{LT} ($m \cdot s^{-1}$)	1.62 ± 0.02	1.46 ± 0.04
SS_{La4} ($m \cdot s^{-1}$)	1.62 ± 0.03	1.48 ± 0.03
Physiological variables		
$[La^-]_{LT}$ ($mmol \cdot l^{-1}$)	3.77 ± 0.96	3.00 ± 0.67
$[La^-]_{Peak}$ ($mmol \cdot l^{-1}$)	8.69 ± 2.45	6.86 ± 1.81
HR_{LT} ($beats \cdot min^{-1}$)	177 ± 6	178 ± 9
HR_{max} ($beats \cdot min^{-1}$)	184 ± 5	184 ± 11
RPE_{LT}	5.79 ± 0.85	5.49 ± 1.55
Biomechanical variables		
SR_{LT} ($cycles \cdot min^{-1}$)	38.05 ± 2.85	39.54 ± 3.33
SL_{LT} (m)	2.57 ± 0.18	2.20 ± 0.14
SI_{LT} ($m^2 \cdot s^{-1}$)	4.17 ± 0.30	3.23 ± 0.18

SS_{LT}: swimming speed corresponding to lactate threshold; SS_{La4}: swimming speed corresponding to $[La^-]$ of 4 $mmol \cdot 1^{-1}$; $[La^-]_{LT}$: blood lactate concentration corresponding to lactate threshold; $[La^-]_{Peak}$: peak blood lactate concentration; HR_{LT}: heart rate corresponding to anaerobic threshold; HR_{max}: maximum heart rate; RPE_{LT}: rate of perceived exertion at lactate threshold; SR_{LT}, SL_{LT} and SI_{LT}: stroke rate, length and index corresponding to anaerobic threshold.

Table 4.4. Pearson correlation coefficients between swimming speed and seasonal best performances. Black (e.g., 0.999) and grey (e.g., 0.999) font colour for male (n = 11) and female (n = 9) elite open water swimmers, respectively.

Variables	1.	2.	3.	4.	5.
1. SS_{LT} ($m \cdot s^{-1}$)		- 0.628*	- 0.825**	-0.710**	- 0.378
2. Best 400 m time (s)	- 0.570		0.726**	0.352	- 0.140
3. Best 800 m time (s)	- 0.629*	0.942**		0.785**	0.139
4. Best 1500 m time (s)	- 0.681*	0.842**	0.919**		0.280
5. Mean 10 km open water times (s)	- 0.694*	0.374	0.180	0.244	

SS_{LT}: swimming speed corresponding to lactate threshold. *$p < 0.05$; **$p < 0.01$

DISCUSSION

The current study aimed to analyze the LT in world class and elite OW swimmers, to compare SS_{LT} and SS_4, and to examine the relationships between SS_{LT} and swimming performance. The main findings of this study indicated that SS_{LT} ($[La^-]_{LT}$) were 1.62 ± 0.02 $m \cdot s^{-1}$ (3.77 ± 0.96 $mmol \cdot 1^{-1}$) and 1.46 ± 0.04 $m \cdot s^{-1}$ (3.00 ± 0.67 $mmol \cdot 1^{-1}$) in males and females, respectively, while SS_4 was 1.62 ± 0.03 and 1.48 ± 0.03 $m \cdot s^{-1}$. With regards to males, no significant differences between SS_{LT} and SS_4 were observed, however, females evidenced significantly lower SS_{LT} than SS_4. On the other hand, regarding the association between variables, the SS_{LT} was negatively correlated with swimming performance times, with the exception of 10 km OW and 400 m times in males and females, respectively.

Despite LT assessment is crucial for long-distance and OW swimmers [1,9], few studies have explored the LT or SS_{LT} in elite OW swimmers [15]. As it was expected, the SS_{LT} reported in this study (Table 4.3) were considerably higher than those reported by previous research, which indicated 1.34-1.32 $m \cdot s^{-1}$ for elite male and female OW swimmers [15]. The paradigm shift in OW events with its inclusion in the Olympic Games program and the emergence of pool swimmers [3,4] has led to a different OW swimmer profile, able to reach higher speeds at LT. In fact, the SS_{LT} represented the 97% of the peak swimming speed reached in the tests, considerably higher than the 89-94% previously reported [15]. This near-peak swimming speed reach at LT reflects the superbly developed aerobic capacity of these swimmers, which allows them to swim fast during prolonged period of times. Hence, given that successful OW swimmers must maintain swimming speeds at or above the LT [10], these values may be used as important indicators for researchers and contribute to updating the OW swimmers' profiles.

In the case of $[La^-]_{LT}$, OW swimmers exhibited similar values (Table 4.3) to those reported in elite pool swimmers (3.2-3.6 $mmol \cdot 1^{-1}$) [8], whereas long-distance swimmers exhibited lower $[La^-]_{LT}$ (1.8-2.2 $mmol \cdot 1^{-1}$) [9], away from the fixed 4 $mmol \cdot l^{-1}$ traditionally considered as the LT [11]. However, swimmers' performance level of the mentioned study was notably lower than the presented here, as the mean SS_{LT} and SS_4 were 1.07 and 1.18, respectively. In this regard, several studies have indicated that SS_4 value does not represent the individualized LT [9,23], overestimating the actual swimmers' aerobic capacity [9]. In this regard, in the current study, no differences (p = 0.148) were found between SS_{LT} and SS_4 in males, probably induced by the high variability obtained in $[La^-]_{LT}$ (SD: 0.96 $mmol \cdot 1^{-1}$; range from 2.7 to 6.0 $mmol \cdot 1^{-1}$). Hence, while some swimmers LT was below the traditional fixed 4 $mmol \cdot l^{-1}$ others were above. Indeed, due to the large individual variability of these values at LT, some authors have determined the LT training zone between 2 and 4 $mmol \cdot l^{-1}$ [24,25]. Hence, considering the lack of difference between SS_{LT} and SS_4, the SS_4 could be used as an approximation to LT in elite OW male swimmers, however, it is of paramount importance to address data variability and consider individual differences when attempting to generalize findings to the entire sample. On the other hand, elite OW female swimmers presented $[La^-]_{LT}$ notably below the 4 mmol·l^{-1} (3.0 mmol·1^{-1}), with significantly higher SS_4 than SS_{LT}, which is consistent with previous findings [9,13]. In that sense, it is important to consider the influence of sex on $[La^-]$ parameters, as females have better developed aerobic metabolism [26], larger Type I fiber proportion [27] and/or a more efficient technique due to the females' anthropometric characteristics[28] that lead them achieve a higher percentage of their personal best with lower $[La^-]$ than males [29]. Therefore, swimmers and coaches should determine the individual swimmers' LT in females, since SS_4 may denote performing considerably beyond the LT.

Regarding the $[La^-]_{Peak}$ reached by males (8.7 mmol·1^{-1}), similar values were obtained by an OW World Champion (8.5 mmol·1^{-1}) [24] and slightly higher than in elite OW swimmers (7.4 mmol·1^{-1}) after incremental protocols [15]. In females, the $[La^-]_{Peak}$ obtained was also similar (6.9 mmol·1^{-1}) than those reported in elite OW female swimmers (7.6 mmol·1^{-1}) [15]. In this context, although $[La^-]$ is a useful indicator of swimmers' individual performance [8,30], a higher swimming speed at a given $[La^-]$ does not necessarily mean a better aerobic capacity, as this may indicate both a reduced anaerobic capacity or an improved aerobic capacity [31]. Therefore, despite the $[La^-]$ assessment is essential to determine LT in OW swimmers, it is important to support these values with other physiological variables. In this sense, the HR_{LT} and HR_{max} obtained (Table 4.3) contrasted with the lower values previously reported, especially in the HR_{LT} [15,24]. However, when comparing percentage instead of absolute values, the HR_{LT} represented 93% of the HR_{max}, similar to those obtained in this study (96-97%). Therefore, these percentages at LT (SS_{LT} or HR_{LT}) with regards to maximal values underscore the remarkable development of aerobic capacity in elite OW swimmers.

As part of the intricate array of variables that determine performance [32], the swimming technique may be modified at intensities above the LT [13] as such the biomechanical assessment and its association with LT is crucial. Previous studies have reported an inverse relationship between SR and SL, leading towards increases in SR and decreases in SL to reach higher swimming speed throughout the tests [13,33], which was also observed in this study (Table 4.2). Moreover, these stoke variables at LT are considered and easy and non-invasive tool to provide useful information for training and swimmers' monitoring [34]. In this sense, the SR_{LT} reported in previous research [15] was lower in males (33.9 ± 1.4 cycles·min^{-1}) and higher in females (44.9 ± 1.6 cycles·min^{-1}) compared to those SR_{LT} values obtained in this study (Table 4.3). In the case of SL, swimmers should try to maintain SL as speed increases [34], which means that higher SL_{LT} and SI_{LT} values would be advantageous for a better performance. This fact was confirmed by the higher SL_{LT} obtained (Table 4.3) compared to the 1.7-2.2 m exhibited by well-trained swimmers [9,34]. However, when comparing stroke variables between swimmers, it is important to note that each swimmer must adopt an optimal balance between SR and SL to achieve higher speeds with lower energy cost [12]. Thus, the analysis of these variables corresponding to LT intensities may be relevant for controlling or assessing individual swimming technique, which could provide practical information in the training context.

Swimming performance and its associations with LT is scarce in elite OW swimmers [1]. In line with other endurance sports [14], the results of the correlations showed that the higher the SS_{LT}, the better the performance in pool and OW events (Table 4.4). However, this was not the case between SS_{LT} and 10 km OW times in males ($p > 0.05$). Despite OW swimmers swim close to or at LT, the effect of the currents or the speed variations during the race, as well as changes between groups [1,35], may affect to the 10 km OW times obtained in males, which could explain the lack of association between SS_{LT} and OW performance. Indeed, the OW swimming speed was 0.09 m·s^{-1} lower than SS_{LT}. On the other hand, the absence of association between SS_{LT} and 400 m performance in females ($p > 0.05$) may be explained by the higher variability between swimmers when compared to the other distances performance (Table 4.3). Moreover, despite aerobic capacity also plays an important role in 400 m swimming, the aerobic power could be more decisive in this distance [36], as the duration differs significantly between a 400 m (~ 4 min) and a 10 km OW event (~ 2 h). Therefore, despite some exceptions, the relationships between SS_{LT} and most of the seasonal best performances suggest that LT may be a useful performance indicator in elite OW swimmers.

It is important to highlight the high performance level of the OW swimmers comprised in the current study, some of them gold medalists at Olympic Games and World Championships. Moreover, the participants were under the instructions of the same swimming coach, allowing a better training control of the sample. In addition, the sex-differentiated analysis conducted in this study provides relevant information for both male and female swimmers. On the other hand, it should be noted that performance differs between pool and OW swimming conditions, which may lead different physiological and biomechanical demands in the changing natural environment [37,38]. Thus, future research should consider the analysis in an OW environment to facilitate a more comprehensive physiological examination within the competitive context.

PRACTICAL APPLICATIONS

From a practical point of view, the results obtained may provide new insights for swimmers and coaches, as LT assessment is essential to diagnosis the aerobic capacity and swimming performance. In order to succeed, swimmers should exhibit higher values at LT, obtaining SS_{LT} or HR_{LT} close to the maximums achieved in incremental tests. Considering the high performance level, these results could provide valuable benchmarks for scientists and may be applicable to other endurance sports where LT is key to performance.

CONCLUSION

Elite OW swimmers' profile exhibited a remarkable development of aerobic capacity, obtaining higher SS_{LT} compared to previous research. These findings were supported by the SS_{LT} or HR_{LT} corresponded to 96-97% of the maximum values achieved in the incremental tests, which indicates that swimmers are capable of maintaining near-maximum intensity for extended periods. The SS_4 may be used as an approximation to LT in males, although caution should be taken due to the likely variability between swimmers. On the other hand, SS_{LT} was lower than SS_4 in females, overestimating the aerobic capacity when SS_4 is used to establish the LT. Finally, the LT is a useful tool for assessing performance, as elite OW swimmers with higher SS_{LT} showed better performance in most swimming events.

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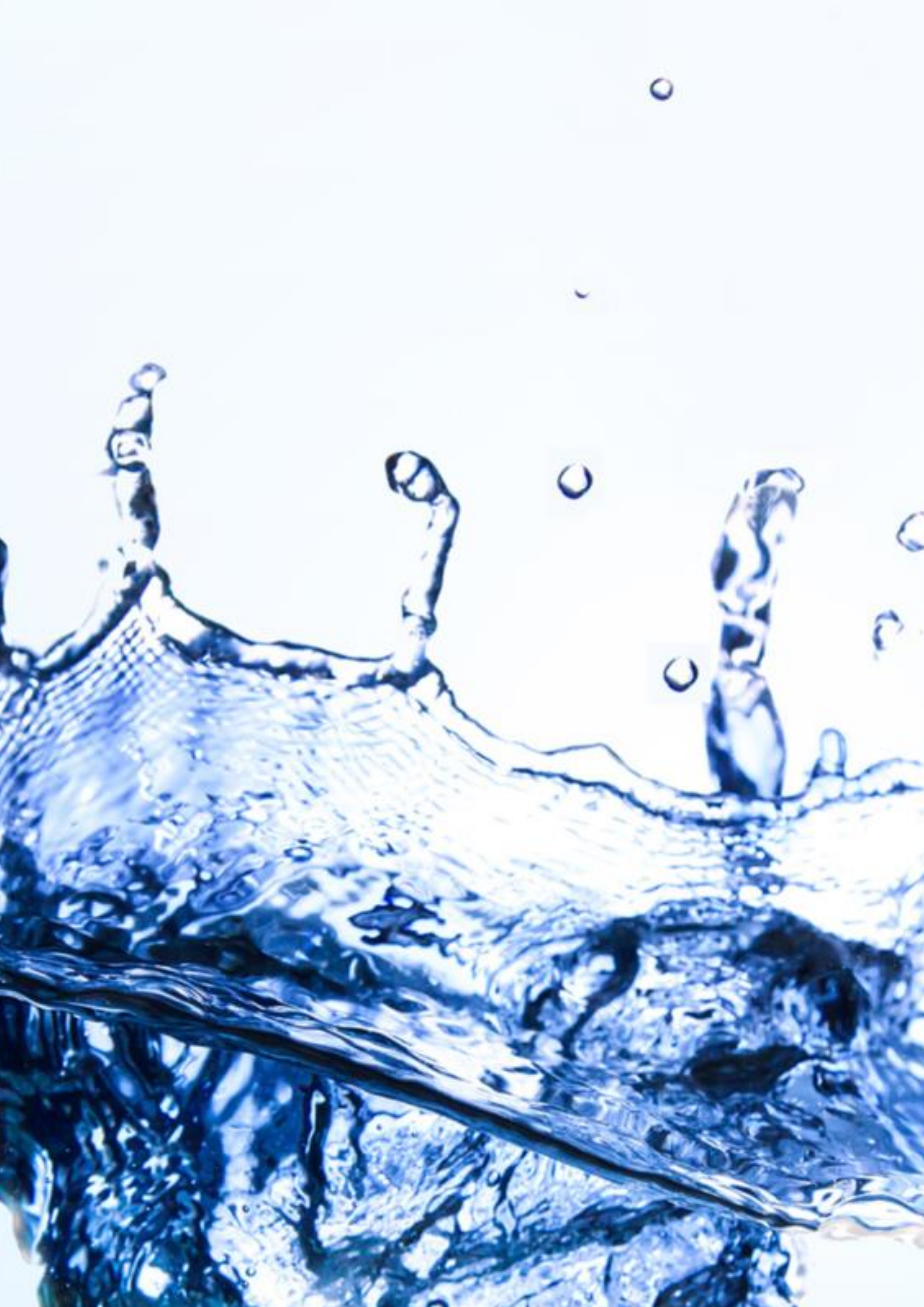

Chapter 5

Seasonal changes in performance, physiological and kinematic factors of maximal incremental swimming in elite open water swimmers

López-Belmonte, Ó., Baldassarre, R., Ruiz-Navarro, J. J., Bonifazi, M., Arellano, R., & Piacentini, M.F. (2024). Seasonal changes in performance, physiological and kinematic factors of maximal incremental swimming in world-class and elite open water swimmers. Under review in *International Journal of Sports Medicine*.

ABSTRACT

Purpose: This study aimed (i) to evaluate the seasonal changes in performance, physiological and kinematic factors in maximal incremental swimming tests in world-class open water (OW) swimmers and (ii) to examine the influence of physiological and kinematic factors on the maximal swimming performance. **Methods:** Eighteen world-class and elite (12 males [25.4 ± 3.3 years] and 6 females [26.4 ± 3.9 years]) OW swimmers voluntarily participated. A total of 57 (40 male and 17 female) intermittent incremental tests (7x400 m) in a 50m pool were analyzed at four different moments (October 2022, February and October 2023 and March 2024). Heart rate, blood lactate concentration ($[La^{-}]$), aerobic (AeT) and lactate thresholds (LT), swimming speed (SS), stroke rate (SR), length (SL) and index (SI) were assessed. **Results:** The OW swimmers showed no changes in performance or physiological factors between tests. In males, the SL and SI changed in both AeT and LT, whereas no kinematic changes were observed in females. The maximum SS was positively associated with speed at AeT and LT in both sexes, while only males showed association between $[La^{-}]$ at LT. SL and SI at AeT and LT in males and SR at AeT and LT were positively associated with maximum SS. **Conclusions:** Despite the performance and physiological invariance between seasons, changes in stroke technique underscore the relevance of quantifying kinematic factors when assessing swimmers.

Keywords: endurance, long-distance, lactate threshold, efficiency, aerobic capacity.

INTRODUCTION

Improvements in endurance performance depend on the athletes' physiological profile, which is shaped by several factors such as maximum oxygen uptake, lactate threshold (LT) or metabolic efficiency [1]. During a competitive season, regular physiological testing is essential to monitor these factors and assess athletes' performance, using incremental exercise tests to identify metabolic inflection points [2]. In swimming, testing is a key component of elite training programs, as maximal incremental swimming helps to assess competitive performance outcomes and determine swimmers' physiological profiles by identifying their individual LT [3]. Given the importance of testing, many studies have focused on monitoring physiological adaptations over longitudinal periods in elite swimmers [4–6]. Indeed, modeling data obtained from incremental tests for longitudinal comparisons is an interesting area within sport sciences [2], which has been applied to swimming to examine seasonal changes [5]. Thus, the assessment of physiological adaptations in swimmers is crucial to compare the performance status at different times of the season.

Open water (OW) swimming is an endurance discipline held in natural environments (e.g., ocean or river) over distances from 5 to 25 km, or 1.5 km in the case of mixed relays [7]. Due to the inclusion of the 10 km race in the Beijing Olympics, OW swimming has experienced a notable increase in popularity in recent years, with a significant number of pool swimmers also taking part in OW events [8,9]. During these races, the LT plays an important role, as successful OW swimmers adopt intensities close to or above the LT [10,11], often set at a fixed value of 4 mmol·l^{-1} of blood lactate concentration ([La^{-}]) [12,13]. Consequently, the assessment of the LT and its changes over the seasons may be essential to monitor the performance status of OW swimmers. In this regard, previous studies analyzed the metabolic breakpoints derived from incremental swimming tests in elite OW swimmers [14,15]. However, the current paradigm of pool swimmers competing in OW races, coupled with the removal of the longest event (i.e., 25 km) from the 2023 World Championships, may have altered the metabolic profile of these swimmers. Furthermore, the assessment of elite OW swimmers warrants further research due to the lack of data derived from both training and competition performance [10].

Swimming testing goes beyond physiological measurements as it also provides useful information on kinematic factors at increasing speeds [5]. In this sense, an optimal combination of stroke rate (SR) and stroke length (SL) is essential to achieve higher swimming speeds while minimizing the energy cost [16]. In fact, kinematic and physiological factors are interrelated, for instance, a higher stroke index (SI) is associated with lower energy cost for swimmers [16]. Hence, SI is considered a valid indicator of swimming efficiency [17], which is essential for long-distance events. On the other hand, these kinematic factors are influenced by the LT intensities during incremental tests, suggesting that LT is not only a physiological transition but also a kinematic boundary, characterized by increases in SR and decreases in SL [6,18]. Thus, the interaction between physiological and kinematic factors may be essential to understand how swimmers achieve maximum incremental swimming performance, as metabolic breakpoints may lead to kinematic changes through different tests over the seasons [19].

Longitudinal studies of world-class OW swimmers have focused on training volume or intensity distribution, physiological characteristics and heart rate variability [13,20]. However, to the best of the authors’ knowledge, no recent studies have assessed the performance, physiological and kinematic variations over different seasons in a sample of world-class OW swimmers. Therefore, the aims of the current study were (i) to evaluate the seasonal changes in performance, physiological and kinematic factors in maximal incremental swimming tests in world-class OW swimmers and (ii) to examine the influence of physiological and kinematic factors on the maximal incremental swimming performance. It was hypothesized that performance, physiological and kinematic factors would change over the seasons. In addition, swimmers with higher threshold speeds and more technical efficiency (i.e., higher SI values) would perform better in the incremental tests.

METHODS

Participants

Eighteen world-class and elite [21] OW swimmers (Table 5.1) voluntarily participated in the current study. All participants were classified between performance level 1 and 3 [22] and belong to the same training group under the direction of the same coach. The OW swimmers performed four 7x400 m intermittent incremental protocol tests [Tests 1

(October 2022), 2 (February), 3 (October 2023) and 4 (March 2024)]. During the 2022, 2023 and 2024 seasons, the average weekly training was 54.5 ± 17.2 km (Figure 5.1). From the total sample, four males and one female performed the test three times, and two males and three females performed the test twice, thus a total of 57 incremental tests were analyzed (40 male and 17 female tests). The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki) and was approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022).

Table 5.1. Mean ± SD of the physical characteristics of world-class and elite open water swimmers (n = 18).

	Males (n = 12)	**Females** (n = 6)
Age (years)	25.43 ± 3.28	26.40 ± 3.89
Height (cm)	184.11 ± 4.62	172.55 ± 5.43
Body mass (kg)	75.00 ± 5.10	63.33 ± 3.71
Body mass index ($kg \cdot m^{-2}$)	22.17 ± 1.89	21.52 ± 1.63
Best 1500 m freestyle time (s)	917.10 ± 21.84	1008.70 ± 26.30
World Aquatics Points	859 ± 61	762 ± 61

Procedures

The same protocol was conducted in all the testing sessions. The evaluations were carried out in a 50-m long-course pool with a water temperature of ~26ºC. Before the swimming assessment, a standardized 1200 m warm-up from low to moderate intensity was performed. All tests were conducted with in-water starts and at the same time of the day to avoid circadian variations [23]. The 7x400 m intermittent incremental protocol consisted of seven steps, from easy to maximal effort, with 30-s rest in between. Swimming speed (SS) of the first 400 m step was set at 80% of the 400 m freestyle seasonal best and subsequently increased by 3% per step. The 400 m times performed (s) were measured using a stopwatch (FINIS 3X-300M, FINIS, Inc., USA) by an expert swimming researcher. The [La^-] were analyzed with a portable lactate analyzer (Lactate Pro 2.0, Arkray Inc., Tokyo, Japan) from the swimmers' right lobe during recovery periods and at the end of the test until the peak ($[La^-]_{peak}$) was reached. Maximum heart rate (HR_{max}) was registered immediately after each 400 m step and the highest value was obtained through the Polar H10 HR sensor (Polar Electro OY, Kempele, Finland). The final times obtained were converted in SS for each 400 m step ($m \cdot s^{-1}$). The maximum SS was considered as the speed obtained in the last step of the protocol. The SR was measured every 50 m and the mean of the eight laps was used. The SL was calculated from the ratio between SS and SR and SI was computed as the product of SS and SL [17]

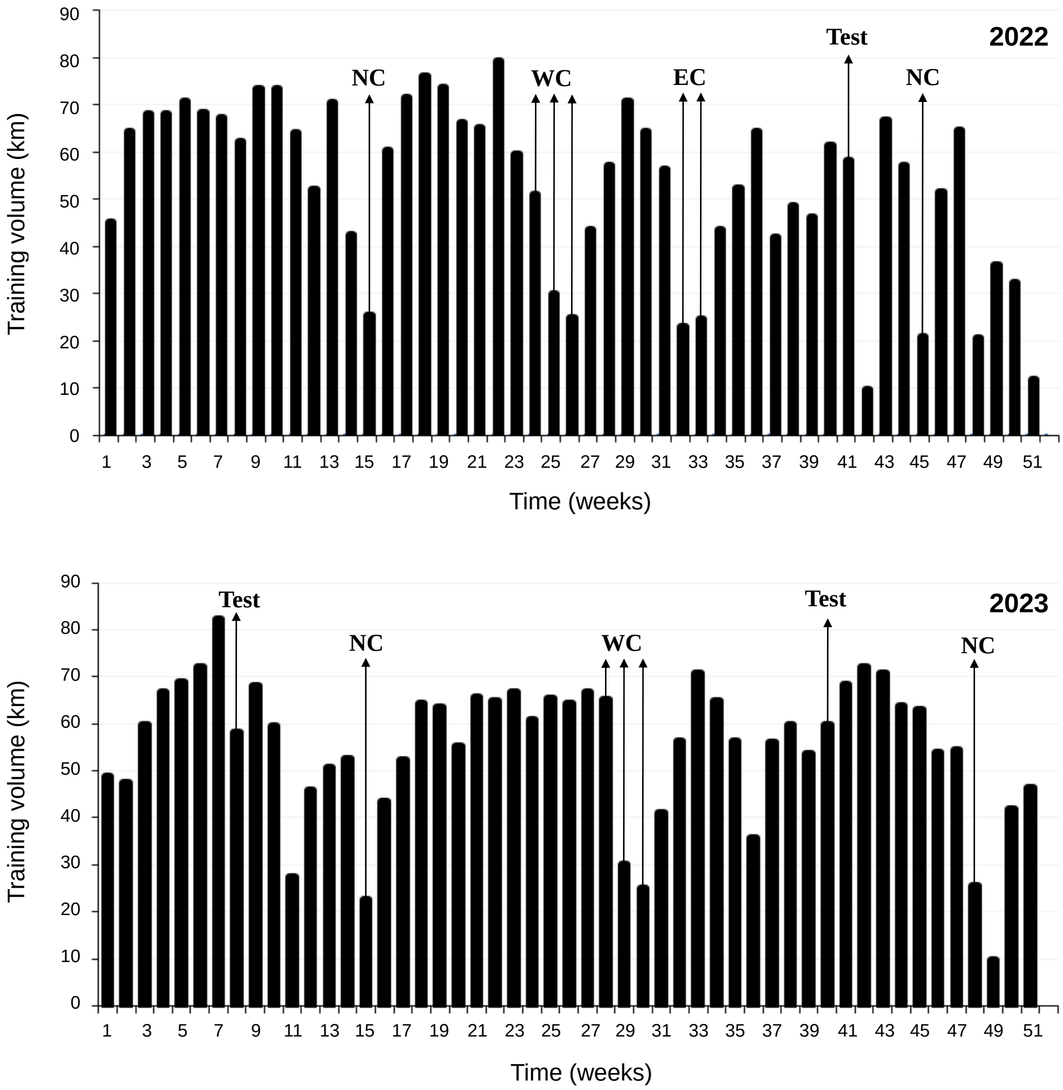

Figure 5.1. Weekly training volume distribution (km) performed by world-class and elite OW swimmers in the 2022 and 2023 seasons. Test = 7x400 m intermittent incremental protocol performed during seasons; NC, EC and WC = National, European and World Championships.

Methodology

The aerobic threshold (AeT) was determined from the speed lactate curve and considered as the highest workload at which there was no significant rise in $[La^-]$ above baseline [24]. From this intersection, $[La^-]$ and SS corresponding to individual AeT were obtained ($[La^-]_{AeT}$ and SS_{AeT}, respectively) were obtained. Two independent researchers identified

AeT following the aforementioned criteria. The intraclass correlation coefficient was computed to verify the agreement between researchers, obtaining almost perfect correlation (0.931-0.999). The LT was determined from the speed lactate curve by identifying the intersection of the lines connecting the two highest and lowest points of the curve [4]. From this intersection, $[La^-]$ corresponding to individual LT ($[La^-]_{LT}$) and SS at LT (SS_{LT}) were obtained. The SS corresponding to the theoretical and fixed thresholds were obtained by interpolating for $[La^-]$ at 2 (SS_2) and 4 $mmol \cdot l^{-1}$ (SS_4) [12]. Moreover, SR, SL, SI and heart rate (HR) at AeT and LT were determined by linear interpolation from the two closest points where $[La^-]_{AeT}$ and $[La^-]_{LT}$ were observed.

Statistical analysis

Normal distribution of the data was checked with Shapiro-Wilk test. Homoscedasticity and multicollinearity were checked by visual inspection and using the variance inflation factor, respectively. Linear mixed model analysis was used to compare performance (SS), physiological ($[La^-]$ and HR) and kinematic (SR, SL and SI) factors at both AeT and LT between test measurements. The same analysis was applied to performance (maximum SS) and physiological ($[La^-]_{peak}$ and HR_{max}) factors during the last 400 m step of the protocol. The different tests measurements (i.e., Tests 1, 2, 3 and 4) were served as fixed factors. Subject was included as a random factor to account for variability and missing values in the different tests. Bonferroni's corrections was used to correct post hoc tests for pairwise comparison. Pearson's correlations were used to examine physiological and kinematic factors on the maximum SS achieved in the best individual performance. The threshold correlation values were defined as: ≤ 0.1 trivial; < 0.1-0.3 small; > 0.3-0.5 moderate; > 0.5-0.7 large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect [25]. All statistical analyses were conducted separately by sex [26]. The significance level was set up at $p < 0.05$ and all the statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

Descriptive statistics (mean and standard deviation [SD]) for the swimming performance, physiological and kinematic factors are presented in Table 5.2.

Table 5.2. Mean ± SD of performance, physiological and kinematic variables derived from the 7x400 m intermittent incremental protocol tests in world-class and elite open water swimmers.

	Male's tests (n = 40)				**Female's tests** (n = 17)			
Variables	**Test 1** (n = 9)	**Test 2** (n = 10)	**Test 3** (n = 12)	**Test 4** (n = 9)	**Test 1** (n = 4)	**Test 2** (n = 5)	**Test 3** (n = 5)	**Test 4** (n = 3)
Last 400 m step time (s)	238.04 ± 3.9	239.22 ± 4.8	241.57 ± 4.1	243.01 ± 6.8	268.63 ± 7.4	264.37 ± 8.1	268.24 ± 4.8	262.67 ± 3.8
Maximum SS ($m \cdot s^{-1}$)	1.68 ± 0.03	1.68 ± 0.03	1.66 ± 0.03	1.65 ± 0.05	1.49 ± 0.04	1.51 ± 0.05	1.49 ± 0.03	1.52 ± 0.02
SS at AeT ($m \cdot s^{-1}$)	1.54 ± 0.03	1.54 ± 0.04	1.52 ± 0.03	1.53 ± 0.05	1.38 ± 0.01	1.43 ± 0.02	1.39 ± 0.04	1.41 ± 0.02
SS at LT ($m \cdot s^{-1}$)	1.62 ± 0.03	1.62 ± 0.03	1.60 ± 0.03	1.59 ± 0.05	1.45 ± 0.04	1.47 ± 0.04	1.45 ± 0.03	1.46 ± 0.01
SS at 2 mmol·L^{-1} ($m \cdot s^{-1}$)	1.56 ± 0.03	1.57 ± 0.04	1.56 ± 0.02	1.57 ± 0.04	1.43 ± 0.03	1.46 ± 0.04	1.43 ± 0.02	1.45 ± 0.02
SS at 4 mmol·L^{-1} ($m \cdot s^{-1}$)	1.64 ± 0.02	1.63 ± 0.03	1.61 ± 0.02	1.62 ± 0.04	1.47 ± 0.04	1.50 ± 0.04	1.49 ± 0.05	1.50 ± 0.02
[La$^-$] at AeT ($mmol \cdot L^{-1}$)	1.78 ± 0.36	1.73 ± 0.52	1.69 ± 0.36	1.44 ± 0.41	1.50 ± 0.41	1.25 ± 0.25	1.45 ± 0.37	1.33 ± 0.29
[La$^-$] at LT ($mmol \cdot L^{-1}$)	3.56 ± 0.73	3.45 ± 1.04	3.38 ± 0.71	2.89 ± 0.82	3.00 ± 0.82	2.50 ± 0.50	2.90 ± 0.74	2.67 ± 0.58
$[La^-]_{peak}$ ($mmol \cdot L^{-1}$)	6.91 ± 1.71	7.70 ± 2.31	8.43 ± 2.26	6.70 ± 2.19	5.98 ± 1.92	5.80 ± 1.87	6.80 ± 2.75	5.90 ± 1.56
HR at AeT ($beats \cdot min^{-1}$)	162 ± 7	162 ± 11	160 ± 14	160 ± 14	166 ± 13	169 ± 11	162 ± 8	161 ± 11
HR at LT ($beats \cdot min^{-1}$)	177 ± 4	177 ± 8	174 ± 7	174 ± 7	179 ± 12	178 ± 9	175 ± 11	174 ± 7
HR_{max} ($beats \cdot min^{-1}$)	185 ± 5	185 ± 7	183 ± 5	184 ± 7	185 ± 12	184 ± 11	182 ± 13	187 ± 9
SR at AeT ($cycles \cdot min^{-1}$)	33.78 ± 3.38	34.86 ± 3.05	33.33 ± 2.86	34.17 ± 2.03	36.20 ± 3.09	36.53 ± 4.10	35.98 ± 3.81	38.80 ± 2.52
SR at LT ($cycles \cdot min^{-1}$)	37.68 ± 3.60	38.67 ± 2.91	37.02 ± 2.58	37.71 ± 2.23	40.08 ± 3.38	38.23 ± 4.90	39.10 ± 3.29	41.53 ± 1.32
SL at AeT (m)	2.86 ± 0.29	2.56 ± 0.22	2.64 ± 0.21	2.58 ± 0.18	2.39 ± 0.20	2.26 ± 0.22	2.23 ± 0.20	2.10 ± 0.13
SL at LT (m)	2.71 ± 0.21	2.42 ± 0.21	2.49 ± 0.18	2.43 ± 0.21	2.26 ± 0.15	2.23 ± 0.23	2.14 ± 0.15	2.03 ± 0.08
SI at AeT ($m^2 \cdot s^{-1}$)	4.39 ± 0.44	3.92 ± 0.36	4.00 ± 0.31	3.95 ± 0.37	3.29 ± 0.26	3.23 ± 0.27	3.09 ± 0.27	2.95 ± 0.17
SI at LT ($m^2 \cdot s^{-1}$)	4.38 ± 0.28	3.92 ± 0.37	3.98 ± 0.33	3.86 ± 0.45	3.27 ± 0.16	3.27 ± 0.25	3.10 ± 0.20	2.97 ± 0.15

SS: swimming speed; AeT and LT: aerobic and lactate thresholds; [La$^-$]: blood lactate concentration; $[La^-]_{peak}$: peak blood lactate concentration: HR: heart rate; HR_{max}: maximum heart rate; SR, SL and SI: stroke rate, length and index.

In males, the linear mixed model revealed a main test measurement effect on SL at AeT (R^2_C = 0.222; p = 0.027) and at LT (R^2_C = 0.244; p = 0.017). In addition, the SI showed effects at AeT (R^2_C = 0.215; p = 0.032) and at LT (R^2_C = 0.241; p = 0.018). Post hoc comparisons with Bonferroni indicated differences in SL at AeT between Tests 1 and 2 (p = 0.036); and SL at LT between Tests 1, 2 and 4 ($p < 0.05$). Moreover, the SI at AeT showed changes between Tests 1 and 2 (p = 0.04); and SI at LT between Tests 1 and 4 (p = 0.028). No changes were observed in the remaining factors analyzed. In the case of females, no significant effect was obtained for any of the variables measured, which indicates that no changes in performance, physiological or kinematic variables were observed between tests. Pearson correlation coefficients between maximum SS and physiological and kinematic factors are shown in Tables 5.3 and 5.4, respectively. In males, maximum SS was positively associated with individual and fixed thresholds and $[La^-]_{LT}$ (Table 5.3). Both SL and SI at AeT and LT were positively correlated with maximum SS (Table 5.4). In females, positive associations were observed between maximum SS and thresholds, except for fixed SS_4 (p = 0.166) (Table 5.3). The SR at AeT (p = 0.037) and LT (p = 0.039) were positively associated with maximum SS (Table 5.4).

Table 5.3. Pearson correlation coefficients between maximum swimming speed and physiological factors. Black (e.g., 0.999) and grey (e.g., 0.999) font colour for male (n = 12) and female (n = 6) world-class and elite open water swimmers, respectively.

Variables	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Maximum SS		0.632*	0.937**	0.502*	0.810**	0.464	0.588*	0.232	0.299	0.367	0.395
2. SS at AeT	0.758*		0.687**	0.727**	0.383	0.282	0.478	0.677*	0.710*	0.488	0.456
3. SS at LT	0.971**	0.875*		0.575*	0.777*	0.488	0.567*	0.296	0.412	0.514*	0.467
4. SS at 2 $mmol \cdot L^{-1}$	0.892**	0.770*	0.919**		0.634*	- 0.194	- 0.048	0.212	0.336	0.147	0.257
5. SS at 4 $mmol \cdot L^{-1}$	0.484	0.526	0.548	0.676		0.046	0.100	-0.259	0.002	0.230	0.391
6. $[La^-]$ at AeT	0.264	0.080	0.204	- 0.168	- 0.316		0.730**	0.527*	0.220	0.292	0.129
7. $[La^-]$ at LT	0.151	0.189	0.136	- 0.262	- 0.417	0.923**		0.650*	0.539*	0.521*	0.329
8. $[La^-]_{peak}$	0.313	0.208	0.268	- 0.122	- 0.346	0.976**	0.972**		0.611*	0.267	0.059
9. HR at AeT	- 0.046	0.486	0.071	- 0.124	- 0.205	0.129	0.493	0.317		0.799**	0.686**
10. HR at LT	0.031	0.281	0.055	- 0.229	- 0.595	0.482	0.755*	0.644	0.833*		0.902**
11. HR_{max}	0.134	0.275	0.137	- 0.129	- 0.650	0.492	0.716	0.647	0.712	0.971**	

SS: swimming speed; AeT and LT: aerobic and lactate thresholds; $[La^-]$: blood lactate concentration; $[La^-]_{peak}$: peak blood lactate concentration: HR: heart rate; HR_{max}: maximum heart rate; SR, SL and SI: stroke rate, length and index. **p* < 0.05; ***p* < 0.01

Table 5.4. Pearson correlation coefficients between maximum swimming speed and kinematic factors. Black (e.g., 0.999) and grey (e.g., 0.999) font colour for male (n = 12) and female (n = 6) world-class and elite open water swimmers, respectively.

Variables	1.	2.	3.	4.	5.	6.	7.
1. Maximum SS		- 0.011	0.146	0.520*	0.502*	0.631*	0.675*
2. SR at AeT	0.769*		0.819**	- 0.770**	- 0.648*	- 0.655*	- 0.523*
3. SR at LT	0.763*	0.952**		- 0.539*	- 0.623*	- 0.522	- 0.456
4. SL at AeT	- 0.657	- 0.951**	- 0.971*		0.919**	0.954**	0.911**
5. SL at LT	- 0.639	- 0.893**	- 0.979**	0.971**		0.906*	0.971**
6. SI at AeT	- 0.423	- 0.790*	- 0.872*	0.940**	0.939**		0.936**
7. SI at LT	- 0.445	- 0.803*	- 0.906**	0.938**	0.971**	0.982**	

SS: swimming speed; AeT and LT: aerobic and lactate thresholds; $[La^-]$: blood lactate concentration; $[La^-]_{Peak}$: peak blood lactate concentration: HR: heart rate; HR_{max}: maximum heart rate; SR, SL and SI: stroke rate, length and index. *$p < 0.05$; **$p < 0.01$

DISCUSSION

This study aimed to evaluate the changes in performance, physiological and kinematic factors in incremental tests in world-class and elite OW swimmers and to examine the influence of these factors on the maximum speed. Contrary to the initial hypothesis, the OW swimmers did not show changes in performance or physiological factors between test measurements, although kinematic variations were observed in males. In addition, male swimmers with greater $[La^-]_{LT}$ obtained a higher maximum SS. Both SL and SI were positively associated with maximum SS in males, whereas the SR was related with maximum SS in females.

The identification of trends within a season and the progression over different years provide reference values for national and international swimmers [5]. The absence of seasonal changes in performance and physiological factors observed in this study suggests a steadying in world-class and elite OW swimmers. This plateauing effect in performance or physiological measures is common in high-level swimmers over the course of a long competitive career [5], which may also be attributed to the experienced swimmers in this study (Table 5.1). In fact, the age and high-level of the swimmers suggest that they may have reached their physiological peak performance, typically around 24 and 22 years for males and females, respectively [27]. Moreover, the similar period of the seasons in which the swimmers were assessed may have contributed to the low variability obtained, as the timing of the test during a season affects performance and physiological factors in swimmers [28]. In addition to the aforementioned discusses, the small sample size of female OW swimmers may have precluded us from obtaining significant changes in all factors, which should be addressed in future studies.

On the other hand, despite the lack of changes in the physiological factors measured, male swimmers evidenced kinematic variations induced by the training. The kinematic changes observed in SL and SI at both AeT and LT suggest that male OW swimmers make technical adjustments to achieve similar performance, aligning with previous findings [6]. Although these stroke parameters are influenced by energy contributions [29,30], the kinematic variations did not result in significant physiological changes between the different tests, likely due to the different SR and SL combinations that elite swimmers can adopt during the incremental tests [6]. Furthermore, given the important role of stroke parameters in swimming efficiency [16], it is possible that other key physiological factors that were not measured, such as energy cost or oxygen uptake, may have altered between seasons.

The OW swimmers with the maximum SS also exhibited the greatest SS_{AeT} and SS_{LT} (Table 5.3), reflecting the specific characteristics of the incremental test used to determine thresholds. Moreover, the fixed thresholds corresponding to SS_2 and SS_4 [12] were also associated with maximum SS, except for SS_4 in females (Table 5.3). In this regard, the fixed LT method is not a reliable indicator of female OW swimming performance, as it overestimates aerobic capacity [31]. In addition, the positive association between maximum SS and $[La^-]_{LT}$ (Table 5.3) indicates that the best performing male OW swimmers are able to generate higher $[La^-]$ at LT intensities. This fact may highlight the importance of anaerobic pathways in today's OW races, where swimmers swim close to or at LT and the international events are decided in the final meters [11,32]. Indeed, successful OW swimmers are also the fastest in middle- and long-distance pool events [9]. Therefore, the ability to reach high speeds and greater $[La^-]$ assimilation at LT intensities may be key for OW male swimmers. On the contrary, the lower $[La^-]_{LT}$ values observed in females, probably due to hormonal or genetic factors and the resulting lower anaerobic metabolism implication [33], may explain the lack of association between maximum SS and $[La^-]_{LT}$.

Regarding kinematic and performance associations, male OW swimmers with higher SL and SI values at AeT and LT were the fastest in the incremental tests (Table 5.4). In this sense, the SL is a critical factor in swimming performance and one of the best predictors of SS [6,34]. Thus, although swimmers need to find an optimal balance between SR and SL [16], focusing on maximizing SL seems to be more relevant for achieving better performance in males. In addition, due to the close relation between SL and SI, swimmers with higher SI were also the fastest, indicating a better swimming efficiency [16,17]. On the contrary, female OW swimmers showed positive correlation between SR in both AeT and LT and the maximum SS in the tests (Table 5.4). In this regard, elite swimmers attempt to compensate the reduction of SL by increasing SR during swimming [35,36], which may indicate that the ability to increase SR to maintain or increase speed is more critical than SL in females. However, it is important to consider not only the individual characteristics [16] but also the specific demands on swimmers, as, for instance, the OW swimming conditions may influence technique and lead to changes in stroke parameters [37].

From a practical standpoint, the findings of this study underscore the importance of quantifying not only performance or physiological, but also kinematic factors when assessing swimmers, as these variables may fluctuate across different seasons and may impact performance. Monitoring these factors provided valuable insights not only into the current performance status, but also on how swimmers achieve the best performance in different incremental swimming tests. Some limitations of this study include the absence of additional factors that could influence performance over different seasons, such as anthropometric characteristics and oxygen uptake assessment. Moreover, future studies should focus on examining physiological or kinematic factors in OW or long-distance swimmers of different performance levels, as the available information is still limited and could lead to different outcomes.

CONCLUSION

World-class and elite OW swimmers showed no changes in performance and physiological factors in the incremental protocol tests conducted in different seasons. In the case of males, the SL and SI changed over the seasons, whereas no kinematic variation was observed in females. The higher $[La^-]_{LT}$ obtained by the fastest male swimmers highlights the relevance of $[La^-]$ assimilation at LT intensities. While males tended to rely on higher SL and SI values, females increased their SR to achieve the best performance in the incremental swimming tests.

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Chapter 6

Determinants of 1500 m front-crawl swimming performance in triathletes: Influence of physiological and biomechanical variables

López-Belmonte, Ó., Ruiz-Navarro, J. J., Gay, A., Cuenca-Fernández, F., Cejuela, R., & Arellano, R. (2023). Determinants of 1500-m Front-Crawl Swimming Performance in Triathletes: Influence of Physiological and Biomechanical Variables. *International Journal of Sports Physiology and Performance*, *18*(11), 1328-1335.

ABSTRACT

Purpose: The aims of this study were (i) to analyse the associations between physiological and biomechanical variables with the FINA-points (i.e., swimming performance) obtained in 1500 m front-crawl swimming and (ii) to determine whether these variables can be used to explain the FINA-points in triathletes. **Methods**: Fourteen world class, international and national triathletes (10 males: 23.24 ± 3.70 years; and 4 females: 23.36 ± 3.76 years) performed a 1500 m front-crawl swimming test in a short-course pool. Heart rate (HR), oxygen uptake ($\dot{V}O_2$) and blood lactate concentrations were obtained before and after the test. HR was also measured during the effort. Peak oxygen uptake value ($\dot{V}O_{2peak}$) was estimated by extrapolation. Clean swimming speed, turn performance, stroke-rate (SR), stroke-length (SL) and stroke-index (SI) were obtained by video analysis. **Results**: Average 1500 m performance times were 1088 ± 45 s and 1194 ± 31 s for males and females, respectively. The HR after the effort, $\dot{V}O_{2peak}$, aerobic contributions, energy expenditure, energy cost and turn performance presented moderate negative associations with swimming performance (r~0.5). In contrast, respiratory exchange ratio, anaerobic alactic contribution, clean swimming speed, SL and SI were positively related, being clean swimming speed and SI very large associated (r~0.7). A multiple stepwise regression model determined that 71% of variance in FINA-points was explained by SI and energy expenditure, being predictors in 1500 m front-crawl swimming. **Conclusions**: Swimming performance in triathletes was determined by the energy demands and biomechanical variables. Thus, coaches should develop specific technique skills to improve triathletes' swimming efficiency.

Keywords: triathlon, oxygen uptake, biomechanics, energetic, elite level.

INTRODUCTION

Triathlon is a multi-sport event involving three consecutive disciplines: swimming, cycling and running. The World Triathlon classifies the events depending on the distance covered in each discipline: Sprint (swim 0.75 km, cycle 20 km and run 5 km), Standard (swim 1.5 km, cycle 40 km and run 10 km) or long distance (swim 3 to 4 km, cycle 91 to 200 km and run 22 to 42.2 km), among others [1]. The Standard, also known as Olympic distance, is considered the most important and acknowledged event, as it is the distance performed in the World Triathlon Series and the Olympic Games [2].

The energy obtained for a triathlon event stems mainly from the aerobic metabolism [3]. Maximal aerobic power is one of the determinants in endurance sports, which can be measured through the evaluation of cardiorespiratory responses to obtain the maximal oxygen uptake [4,5]. Moreover, during a Standard distance, triathletes perform high intensity phases, which requires well-developed anaerobic capacity, allowing triathletes to support sudden changes of pace or high power outputs requirements [6]. Thus, all the energy systems work together to satisfy the energy requirements during a triathlon race [7]. To quantify these energy requirements, the energy expenditure (*E*) is used, which is calculated as the sum of aerobic and anaerobic energy contributions [8]. Moreover, as the energy produced during a triathlon varies depending on the event, the energy cost (*C*) is calculated as ratio of the energy expended per distance covered [8,9]. Hence, understanding the underlying performance mechanisms in any of the triathlon disciplines requires an analysis of these variables, which are essential to determine the physiological capabilities of the athletes.

The swimming initial discipline in a Standard distance triathlon begins with a mass-start. This leads triathletes to reach high swimming speeds at the start of the race [10], achieving a strategic position in the first pack and, consequently, reducing *E* due to the drafting effect [11]. Moreover, despite that the swim leg has showed low association with the final position, most studies highlighted the importance of positioning in the first swimming pack [12,13], as the *E* used during the 1500 m swimming may highly affect the subsequent cycling and running performance [2,14]. However, despite its importance in the development of a triathlon race, swimming has been less studied compared to cycling and running legs [15], probably because of the complexity of assessing in the aquatic environment.

In swimming, biomechanical analysis is crucial to determine relationships between performance and physiological variables [16]. The assessment of the clean swimming speed determined by the product of the stroke rate (SR) and the stroke length (SL), represent some variables of the kinematics analysis in a swimming race [17]. Indeed, some authors suggest the SL as an assessment technical variable in triathletes [18], since the most efficient swimmers present higher SL and lower SR than less skilled swimmers [18,19]. These variables are associated with the swimmers' technical skills, considering the stroke index (SI) as an indirect estimation of swimming efficiency, since high SI values were strongly associated with low *E* [20]. Hence, less skilled triathletes would require higher *E* and *C* to achieve the same performances for a given distance swimming [21]. Previous studies analysed some biomechanical variables in 1500 m swimming in triathletes [14,22]; however, the relationship of these variables with the physiological demands was not explored in triathletes' swimming.

The swim leg of Standard distance triathlon requires further research in the scientific literature [15]. For instance, to understand the level of triathletes in the swimming leg, a categorisation according to the 1500 m front crawl time endured, using the FINA points system recognised by the World Aquatics [23] would be useful for triathletes and coaches. In addition, further physiological and biomechanical analyses are needed to gain a deeper understanding of the determinants of swimming performance in triathletes. Therefore, the aims of the current study were (i) to analyse the associations between physiological and biomechanical variables with the FINA points obtained in a 1500 m front crawl swimming test and (ii) to determine whether these variables can be used to predict the FINA points (i.e., swimming performance) in triathletes. It was hypothesised that triathletes with better performance in the 1500 m front crawl swimming would require lower *E* and *C*, thus exhibiting higher swimming efficiency (i.e., higher SL and slower SR values).

METHODS

Participants

Fourteen world class, international and national [24] triathletes voluntarily participated in the current study (Table 6.1). Among the participants, there were a junior and an under-23 World Championship medallist. Triathletes trained in the same squad under the supervision of the same certified coach. The protocol was fully explained to the participants before providing written consent to participate. The study was approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022) and was conducted in accordance with the Declaration of Helsinki.

Table 6.1. Mean ± SD of the triathletes' physical characteristics.

Variable	**Males** (n = 10)	**Females** (n = 4)	**Total sample** (n = 14)
Age (years)	23.24 ± 3.70	23.63 ± 4.47	23.36 ± 3.76
Body height (cm)	177.50 ± 6.62	169.75 ± 10.56	175.29 ± 8.32
Body mass (kg)	66.73 ± 7.48	58.30 ± 8.72	64.32 ± 8.48
Body mass index (kg/m^2)	21.12 ± 1.08	20.13 ± 1.05	20.84 ± 1.13
Sum of 6 skinfolds (mm)	32.20 ± 2.60	55.20 ± 7.80	38.82 ± 7.42

Design

A cross-sectional study was performed during a summer training camp. The average and maximum total (i.e., swim, bike and run together) weekly training of all participants were 15.8 ± 2.7 and 26.8 ± 3.2 h, respectively. Recovery times during sessions and strength training were not included as training time. The training load of the fourteen triathletes was calculated using ECOs (objective load equivalents) model [25], obtaining 1354 ± 184 and 2046 ± 293 ECOs weekly average and maximum, respectively. Participants were randomly divided to perform the test on two different days in the morning. The 1500 m test were conducted individually with in-water start, preceded by a 1000 m standardized warm-up [16]. Triathletes used their competition tri-suit and completed the swimming test at race pace, starting with a higher speed in the initial metres [12]. During the test, the participants were notified at the 500, 1000 and 1400 m with a whistle blow. No other feedback or encouragement was provided. Participants were asked to refrain from intense exercise at least 24 hours before the testing day. Swimming test was performed in a 25 m indoor pool with 27.9ºC, 29.4ºC and 53.3% water and air temperatures and humidity, respectively.

Methodology

Previous to the warm-up, anthropometric variables were assessed following standardised measurement techniques adopted by the International Society for the Advancement of Kinanthropometry (ISAK) [26]. All measurements were taken by the same ISAK Level

3 researcher. Anthropometric variables were measured for each participant: body height, body mass and thickness of six skinfolds (triceps, subscapular, suprailiac, supraspinal, abdominal and thigh) were measured using a caliper calibrated to the nearest 0.2 mm (Holtain Ltd, Crymych, UK). Body height and body mass of participants were measured using a stadiometer/scale (Seca 799, Hamburg, Germany). Body mass index (BMI) was calculated as body mass (kg)/height (m)^2. After the standardized warm-up, triathletes rested 15 min before performing the 1500 m front crawl swimming test. Oxygen uptake ($\dot{V}O_2$) was continuously measured 5 min before (baseline) and after 1500 m swimming test in sitting position, during recovery period (i.e., off-kinetics) [16]. Respiratory gas exchange was measured breath by breath using a portable gas analyser (Cosmed K5, Rome, Italy). Prior to the tests, air, flowmeter, reference gas, scrubber and time delay calibrations were performed following manufacturers' recommendations. The off-kinetics response was modelled with VO_2FITTING [27], a free and open-source software, (https://shiny.cespu.pt/vo2_news/) web application based on the R language (www.r-project.org, R Core Team 2015), with support of the "Shiny"package [28]. Raw data were used in all the cases. Bootstrapping with 1000 samples was used to estimate $\dot{V}O_2$ kinetics parameters [27]. Breath-by-breath data obtained during 5 min of recovery were adjusted as a function of time using mono exponential model using the following equation (1) [27]:

$$\dot{V}O_2(t) = EE\dot{V}O_2 - H\left(t - TD_p\right) A_P\left(1 - e^{-(t-\mathrm{TD}_p)/\tau_p}\right) \qquad (1)$$

where $\dot{V}O_2$(t) represents the relative $\dot{V}O_2$ at the time *t*, EE$\dot{V}O_2$ is the $\dot{V}O_2$ at the end of exercise (i.e., 1500 m swimming test), *H* represents the Heaviside step function [29], and A_p, TD_p and τ_p are the amplitude, time delay and time constant of the $\dot{V}O_2$ fast component [27]. The peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) was estimated by backward extrapolation at zero recovery time using linear regressions applied to the first 20 s of recovery [30]. Heart rate (HR) was recorded using a Polar H10 sensor chest strap device (Polar Electro Oy, Kempele, Finland) during the test and during the 5 min before and after the effort in sitting position. HR recordings were exported from the Polar Flow website to an Excel spreadsheet. Then, mean baseline HR ($HR_{meanBase}$), mean HR during the test ($HR_{mean1500}$), maximum HR during the test ($HR_{max1500}$) and mean HR after the test ($HR_{meanPost}$) were obtained. Blood lactate concentrations [La^-] was collected with a portable lactate analyser (Lactate Pro 2.0, Arkray Inc., Japan) from the swimmers' right lobe 1 min prior to the test and after the effort, at minute 1 and every 2 min until the peak was reached. Rate of perceived exertion (RPE) was asked to the swimmers immediately after the test [31]. The *E* was estimated as the sum of aerobic (Aer), anaerobic lactic (Ana_{lac}) and anaerobic alactic (Ana_{alac}) energy contributions. The Ana_{alac} was estimated from the maximal phosphocreatine splitting in the contrasting muscle [30]. Ana_{alac} was expressed in kJ assuming an energy equivalent of 0.468 kJ mM and a phosphate/oxygen ratio of 6.25 [32]. The Ana_{lac} energy was calculated using the following equation (2):

$$Ana_{lac} = [La^{-}]_{net} \cdot \beta \cdot M \qquad (2)$$

where $[La^{-}]_{net}$ is the difference between the $[La^{-}]$ before and after the exercise ($[La^{-}]_{peak}$), β is the constant for O_2 equivalent of $[La^{-}]_{net}$ (2.7 $ml \cdot kg^{-1} \cdot mM^{-1}$) [33], and M is the body mass of the swimmers. Both energy systems were then expressed in kilojoules assuming an energy equivalent of 20.9 $kJ \cdot L^{-1}$ [34]. The *C* was obtained as the ratio between *E* and the distance covered (i.e., 1500 m) [8].

The swimming tests were recorded with a Sony FDR-AX53 (Sony Electronics Inc) at 50 Hz sampling rate. Videos were analysed by one expert evaluator on an in-house customized software for race analysis in competitive swimming. For each 1500 m test, 15 laps were analysed, considered as the time (min:s) to complete 100 m. Swimming performance was considered using the short-course FINA points to standardise the performance times (min:s) obtained in the 1500 m test for male and female triathletes [35]. The clean swimming speed was calculated between 5-20, 30-45, 55-70 and 80-95 m of each lap (i.e., 100 m). The clean swimming speed of each lap was computed as the average speed ($m \cdot s^{-1}$) of the four areas mentioned. Moreover, the SR was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by sixty to consider the number of strokes per minute. The SL was obtained from the ratio between the clean swimming speed and SR. The stroke index (SI) was calculated as the product of swimming speed and SL [20]. Each stroke variable was computed by the average between the 5-20, 30-45, 55-70 and 80-95 m of each lap. The turn performance was considered as the sum time between the in-5m (i.e., previous 5 m before wall contact) and the out-5m (i.e., initial 5 m after wall contact) and it was computed as the average time (s) of the four turn performed in each lap.

Statistical Analysis

The normality of the distribution was checked with Shapiro-Wilk test. Pearson's Correlation Coefficient was computed to analyse the associations between FINA points (i.e., swimming performance) physiological and biomechanical variables. Stepwise multivariate regression analysis was applied including those variables that were correlated with FINA points to determine the strongest predictors. Regression analysis was performed including and excluding the clean swimming speed due to its high positive correlation with swimming performance. The threshold correlation values were defined as: ≤ 0.1, trivial; < 0.1-0.3, small; > 0.3-0.5, moderate; > 0.5-0.7, large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect [36]. The significance level was set up at $p < 0.05$ and all the statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

Descriptive statistics (mean ± SD) and the results of the correlations between swimming performance (i.e., FINA points), and physiological and biomechanical variables are presented in Table 6.2. Four biomechanical (clean swimming speed, turn performance, SL and SI) and eight physiological variables ($HR_{meanPost,}$ $\dot{V}O_{2peak}$, respiratory exchange ratio (RER), Aer (in kJ and percentage), *E*, Ana_{alac} and *C*) were correlated with FINA points (i.e., swimming performance).

Table 6.2. Mean ± SD of performance, anthropometrics, physiological and biomechanical variables in male and female triathletes. Correlations between FINA points (i.e., swimming performance) and the variables analysed are presented for all triathletes.

Variable	**Males** (n = 10)	**Females** (n = 4)	**Total sample** (n = 14)	
	Mean ± SD	Mean ± SD	Mean ± SD	r
Performance variables				
$T100_{mean}$ (min:s)	1:12 ± 0:03	1:19 ± 0:02	1:14 ± 0:04	- (-)
T1500 (min:s)	18:08 ± 0:45	19:54 ± 0:31	18:38 ± 1:01	- (-)
FINA points	474 ± 50	455 ± 36	469 ± 46	- (-)
Physiological variables				
$HR_{meanBase}$ (beats·min^{-1})	75 ± 11	78 ± 13	76 ± 11	0.12, small
$HR_{mean1500}$ (beats·min^{-1})	167 ± 9	170 ± 5	168 ± 8	−0.39, moderate
$HR_{max1500}$ (beats·min^{-1})	177 ± 10	179 ± 6	177 ± 9	−0.32, moderate
$HR_{meanPost}$ (beats·min^{-1})	110 ± 12	123 ± 8	113 ± 12	−0.51*, large
$[La^-]_{Base}$ (mmol·L^{-1})	2.21 ± 0.31	1.85 ± 0.30	2.10 ± 0.34	−0.01, trivial
$[La^-]_{peak}$ (mmol·L^{-1})	8.38 ± 1.85	6.23 ± 2.22	7.76 ± 2.13	−0.10, small
$[La^-]_{net}$ (mmol·L^{-1})	6.17 ± 1.86	4.38 ± 2.04	5.66 ± 2.01	−0.11, small
$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	60.16 ± 8.47	51.64 ± 13.95	57.72 ± 10.51	−0.50*, large
RER	1.14 ± 0.17	0.95 ± 0.04	1.09 ± 0.17	0.61**, large
A_p (ml·kg^{-1}·min^{-1})	47.84 ± 7.49	39.22 ± 13.88	45.37 ± 9.99	−0.42, moderate
TD_p (s)	5.07 ± 5.98	4.48 ± 6.26	4.90 ± 5.82	0.01, trivial
τ_p (s)	36.12 ± 5.86	46.46 ± 13.16	39.07 ± 9.34	−0.24, small
Ana_{alac} (kJ)	27.73 ± 3.11	24.23 ± 3.62	26.73 ± 3.52	0.14, small
Ana_{lact} (kJ)	23.52 ± 9.14	13.74 ± 5.18	20.73 ± 9.22	−0.08, trivial
Aer (kJ)	1407.8 ± 356.0	1121.4 ± 357.8	1326.0 ± 367.7	−0.47*, moderate
E (kJ)	1459.1 ± 363.9	1159.4 ± 356.8	1373.4 ± 375.2	−0.46*, moderate
Ana_{alac} (%)	1.97 ± 0.34	2.28 ± 0.94	2.05 ± 0.55	0.53*, large
Ana_{lact} (%)	1.63 ± 0.44	1.31 ± 0.65	1.54 ± 0.50	0.30, moderate
Aer (%)	96.41 ± 0.65	96.42 ± 1.45	96.41 ± 0.88	−0.51*, large
C (kJ·m^{-1})	0.97 ± 0.24	0.77 ± 0.24	0.92 ± 0.25	−0.47*, moderate
RPE	9.60 ± 0.70	8.50 ± 1.29	9.29 ± 0.99	−0.25, small
Biomechanical variables				
CSS (m·s^{-1})	1.31 ± 0.05	1.20 ± 0.03	1.28 ± 0.07	0.78**, very large
SR (cycles·min^{-1})	39.74 ± 3.20	39.01 ± 1.89	39.53 ± 2.83	−0.13, small
SL (m)	1.99 ± 0.19	1.85 ± 0.09	1.95 ± 0.18	0.59*, large
SI (m^2·s^{-1})	2.61 ± 0.32	2.20 ± 0.14	2.50 ± 0.34	0.72**, very large
Turn performance (s)	6.67 ± 0.22	7.35 ± 0.23	6.87 ± 0.38	−0.67**, very large

$T100_{mean}$ = mean 100 m performance time; T1500 = time performed in the 1500 m test; $HR_{meanBase}$ = mean baseline heart rate; $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{Base}$ = baseline blood lactate concentration; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{Base}$ and $[La^-]_{peak}$; $\dot{V}O_{2peak}$ = peak oxygen uptake value; RER = respiratory exchange ratio after the test; A_p, TD_p and τ_p = amplitude, time delay and tau of the fast oxygen uptake; Ana_{alac}, Ana_{lact}, and Aer = anaerobic alactic, anaerobic lactic and aerobic contributions; E = energy expenditure; C = energy cost; RPE = rating of perceived exertion; SR, SL and SI = stroke rate, length and index. *p < 0.05. **p < 0.01.

When including clean swimming speed in the stepwise multiple regression, the 81% of the variance of swimming performance was explained by clean swimming speed and $\dot{V}O_{2peak}$ ($R^2 = 0.806$, adjusted $R^2 = 0.770$). However, when excluding clean swimming speed in the analysis, SI and E were the predictor variables for swimming performance, which were the selected model. This model indicated that 71% of the variance in FINA points (i.e., swimming performance) ($R^2 = 0.714$, adjusted $R^2 = 0.662$) was explained by these two variables. The raw and standardised regression coefficients and partial correlations of the predictors are shown in Table 6.3. An example of physiological variables obtained from the under-23 World Champion triathlete is displayed in Figure 6.1.

Table 6.3. Predictive model to explain the strongest predictors of swimming performance in triathletes (n = 14).

Variable	Raw beta	Std. error	Std. beta	t	p value	Partial correlation
Including clean swimming speed in the stepwise multiple regression analysis						
Constant	-45.01	119.43		-0.38	0.713	
Clean swimming speed ($m \cdot s^{-1}$)	490.53	87.62	0.75	5.60	<0.001	0.860
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	-1.95	0.58	-0.45	-3.35	0.006	-0.711
Excluding clean swimming speed in the stepwise multiple regression analysis						
Constant	303.33	62.42		4.86	<0.001	
SI ($m^2 \cdot s^{-1}$)	96.21	21.99	0.71	4.38	0.001	0.797
E (kJ)	-0.05	0.20	-0.44	-2.75	0.019	-0.638

$\dot{V}O_{2peak}$ = peak oxygen uptake value; SI = stroke index; E = energy expenditure.

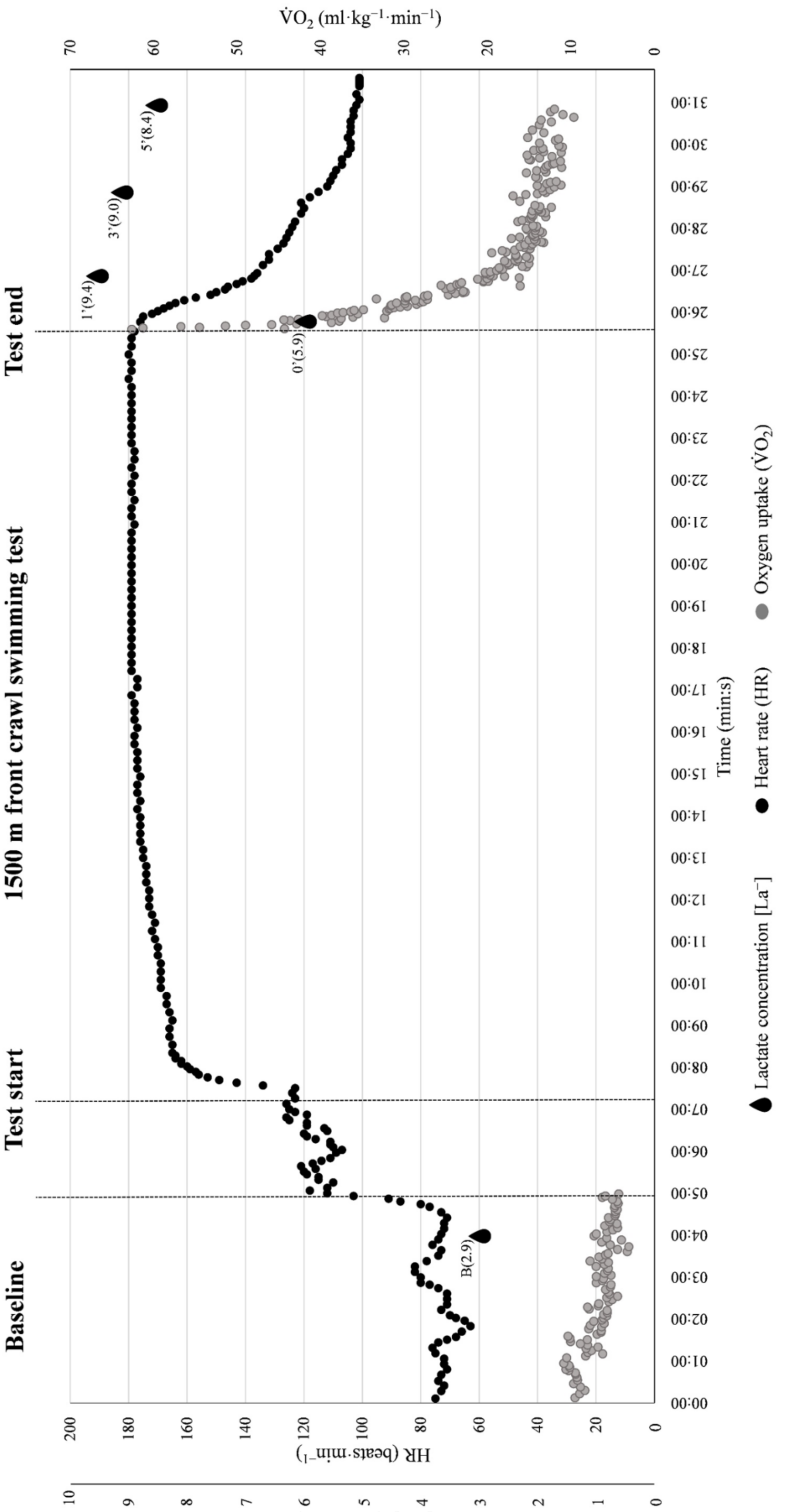

Figure 6.1. Physiological variables obtained during the protocol from the under-23 World Champion triathlete with 1500 m swimming performance time of 18 min 27 s. Blood lactate concentration is expressed as min of data collection (value obtained). [La⁻] = Blood lactate concentration; HR = heart rate; $\dot{V}O_2$ = oxygen uptake.

DISCUSSION

The aims of this study were to analyse the associations between physiological and biomechanical variables with the FINA points obtained in 1500 m front crawl swimming and to determine whether these variables can be used to explain the swimming performance in triathletes. As hypothesised, triathletes who performed better in 1500 m swimming were more efficient, exhibiting lower *E* and *C* and higher SI values. On the contrary, there was no relationship between SR and FINA points (i.e., swimming performance). Other physiological variables, such as $HR_{meanPost}$, $\dot{V}O_{2peak}$, Aer, *E*, and *C*, together with some biomechanical variables such as turn performance, presented negative associations with swimming performance. Furthermore, RER, Ana_{alac}, clean swimming speed, SL and SI were positively associated with FINA points.

The physiological demands during a Standard distance triathlon differ from other endurance disciplines [21], however, most studies have focused on the physiological responses of triathletes in cycling and running [3]. In the current study, the $\dot{V}O_{2peak}$ was negatively associated with swimming performance. Since the maximal aerobic power is obtained with efforts of ~4 min (e.g. 400 m front crawl swimming test) [5], the $\dot{V}O_{2peak}$ obtained after 1500 m front crawl swimming test could not reflect the maximum values. However, previous studies reported 53.0 ± 6.7 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ of maximal oxygen uptake after an incremental swimming test [37], in contrast to 60.2 ± 8.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ of $\dot{V}O_{2peak}$ obtained after the 1500 m swimming test analysed in male triathletes, which could be explained by the different acute physiological responses combined with the sports speciality (i.e., swim, bike or run) of each triathlete, thereby influencing the $\dot{V}O_2$ values [38]. Besides, according to the correlations, the higher the FINA points on 1500 m front crawl, the lower $HR_{meanPost}$. It may suggests that triathletes with better performance, recovered earlier from the effort, reducing HR during the 5 min after the test, which could be extremely important for the subsequent cycle leg. Nevertheless, the lack of relationships found between A_p, TD_p and τ_p with swimming performance are not in line with the values obtained in HR, which could support that the lower the A_p and τp, the better the performance and, therefore, the better the recovery (i.e., lower HR and $HR_{meanPost}$).

The capacity to maximize efficiency and conserve energy for subsequent legs is crucial for triathlon success [10]. The *E* and *C* presented negative associations with swimming performance (Table 6.2), hence, the fastest triathletes required less energy to complete the 1500 m swimming, which is in accordance with the negative relationship found for $\dot{V}O_{2peak}$. In this context, the energy demands induced harmful effects on energy expenditure during subsequent disciplines [2,14], which may also explain the energy-saving metabolism developed by top triathletes. Moreover, the Aer was predominant in the 1500 m swimming, being the most efficient triathletes those that required the lowest energy demand. However, there were also positive associations between Ana_{alac} and swimming performance (Table 6.2), which reflects the intense threshold nature of the Standard distance triathlon. Therefore, although Aer is essential for any triathlon distance, Ana_{alac} may also play an important role to deal with some specific competitive moments [6]. In this sense, the sprinting skills of the best triathletes could explain the positive associations between Ana_{alac} and swimming performance.

An in depth biomechanical analysis of triathletes in 1500 m swimming has previously not been studied. Some authors assessed the Standard swim distance, however, the main target was to examine performance in subsequent cycling [14,22]. In the current study, clean swimming speed was positive associated with swimming performance, probably because the clean swimming phase (i.e., between 5-20 and 30-45 of each 50 m lap) represents the 60% of the total distance (i.e., 900 m) analysed in the 1500 m. Male triathletes presented an average clean swimming speed of 1.31 $m \cdot s^{-1}$, slightly higher than the 1.28$m \cdot s^{-1}$ obtained in a previous study [22]. In addition, the average clean swimming speed for female triathletes has not been previously reported in a 1500 m front crawl swimming pool test, thus the results obtained provide useful information for triathletes and coaches. Instead, clean swimming speed was evaluated during the swimming leg in a World Cup, being 1.39-1.27 and 1.21-1.14 $m \cdot s^{-1}$ for males and females, respectively [12]. However, the specific aspects of open water swimming (e.g., mass starts or passing buoys) and swimming pool (e.g., turn or push off) must be considered when comparing the events.

Regarding stroke variables, SL and SI showed positive associations with performance, while SR was not related. In line with previous studies [18,19], triathletes with lower SL have worse swimming efficiency than those with higher SL. This was also supported by the higher *E* and *C* values obtained in the current study. Moreover, some authors have categorised SL as a marker to assess technical improvements in triathletes

[19], thus this variable should be considered both for training and competition. Likewise, the large correlation between SI and swimming performance could be explained by the fact that this stroke variable is obtained by the product of swimming speed and SL. In contrast to SL and SI, as SR seems to be highly individual [37], each triathlete chose a SR according to his or her characteristics, which could explain the absence of correlation with performance. Hence, triathletes should seek an optimal balance between SR and SL, focusing on the SL that allows them to optimize swimming performance from energetics. Regarding turn performance, it was negative related with swimming performance; hence, the fastest triathletes (i.e., triathletes with highest FINA points) in 1500 m swimming were also the fastest in the turns. It could be explained by the influence of the approach speed in-5m and the short underwater distances covered, which evokes greater involvement of the clean swimming phase. Although there are no previous studies and turn performance may be considered less relevant in triathletes compared to swimmers, its analysis was included to have a global kinematic analysis of the 1500 m front crawl in the swimming pool.

Standard distance triathlon has been studied to determine predictive models of overall performance, extracting data from competitions [39] and laboratory testing [40], which showed the importance of completing the swim leg close to the leader [39]. Two predictive models were examined in this study to determine the most influence variables for swimming performance in triathletes. Due to the high contribution of the clean swimming phase to the performance and the high correlation of clean swimming speed ($r = 0.779$; $p < 0.001$) with FINA points (i.e., swimming performance), the second analysis, excluding clean swimming speed, was conducted (Table 6.3). In this second model, SI and E determined the 1500 m front crawl swimming performance, which emphasise the importance of efficiency and technical skills in triathletes. Thus, the predictive model obtained confirms the results of previous studies [18], highlighting the importance of stroke variables as an assessment tools for technical improvement in triathletes. Therefore, these two distinctive variables for efficiency and technique (i.e., E and SI) could make the difference between international and national level triathletes.

One limitation of the current study was the small sample of participants, as it did not allow for sex-differentiated analysis. Nevertheless, it is important to highlight the physiological and biomechanical analysis developed in the least studied leg of triathlon (i.e., swimming), providing benchmarks from female triathletes. Although the swimming pool is the usual environment to train, future studies should consider performing swimming test in an ecological context, as triathletes complete the swim leg in open water, such as oceans or lakes.

PRACTICAL APPLICATIONS

The results obtained in this study showed the relevance of technical swimming skills and their influence on energetic demands. Hence, coaches and triathletes should include specific swimming technical skills in their training program, which would enable them not only to perform better in the water but to save more energy for the subsequent parts of the race. In addition, due to the importance of the biomechanical variables (e.g. SR, SL and SI), to optimize performance, they should be assessed with specific test (e.g., video analysis). This would allow to observe the technical progression of the triathletes and, consequently, to control their development in swimming efficiency.

CONCLUSION

Swimming performance in triathletes was determined by the energy demands and the technical skills. *E* and SI were identified as the potential variables to predict 1500 m front crawl swimming performance.

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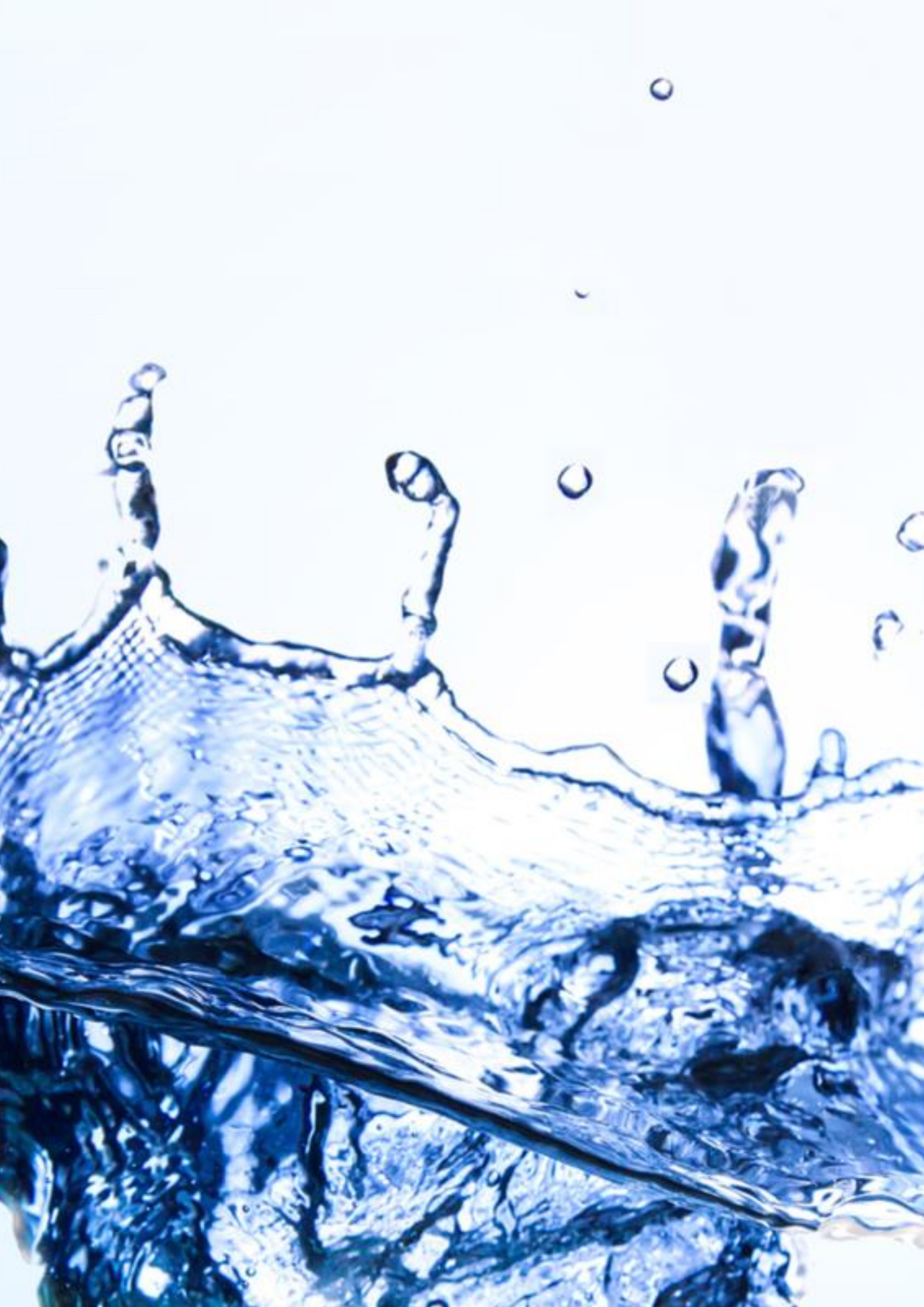

Chapter 7

Open water swimming in elite triathletes: Physiological and biomechanical determinants

López-Belmonte, Ó., Gay, A., Ruiz-Navarro, J. J., Cuenca-Fernández, F., Cejuela, R., & Arellano, R. (2024). Open Water Swimming in Elite Triathletes: Physiological and Biomechanical Determinants. *International Journal of Sports Medicine*, *45*(8), 598-607.

ABSTRACT

Purpose: This study aimed (i) to analyse the 1500 m open water swimming performance, (ii) to examine the associations between physiological and biomechanical variables with swimming performance and (iii) to determine which variables can predict swimming performance in triathletes. **Methods:** Fourteen elite triathletes (23.4 ± 3.8 years) performed a 1500 m in open water swimming conditions. Swimming performance was considered as World Aquatics Points obtained in the 1500 m open water swimming test. Heart rate, end-exercise oxygen uptake ($EE\dot{V}O_2$) and blood lactate concentrations were assessed. **Results:** The initial 250 m of the 1500 m swimming test presented the highest values of biomechanical variables [i.e., swimming speed, stroke rate (SR), length (SL), index (SI)] in males. A decrease in SL was observed in the last 250 m in both sexes. Positive association were found between $EE\dot{V}O_2$ (r = 0.513; p = 0.030), swimming speed (r = 0.873; $p < 0.001$) and SI (r = 0.704; p = 0.002) with swimming performance. In contrast, time constant of the oxygen uptake (r = -0.500; p = 0.034) and buoy turn times (r = -0.525; p = 0.027) were negatively associated with performance. SI was the main predictor (R^2 = 0.495) of open water swimming performance in triathletes. **Conclusions:** In conclusion, triathletes and coaches must conduct open water training sessions to maximize SI (i.e., swimming efficiency).

Keywords: triathlon, performance, kinematics, energetic, endurance.

INTRODUCTION

Swimming kicks off the first leg of a triathlon race, in which athletes must complete the cycling and running subsequent legs consecutively. Since the Sydney 2000 Olympic Games, the Standard distance has been included in the Olympic program, consisting of a 1.5 km swim, 40 km bike and 10 km run [1]. Despite the relatively close inclusion as an Olympic sport, the research focused on triathlon began in the late 1980s [2]. During these years, the scientific literature has focused on analysing different aspects of triathlon, such as pacing strategies [3], physiological [4] or biomechanical parameters [5]. However, the cycling and running legs have received greater attention from the scientific community compared to the swimming leg [6], possibly due to the complexity of assessing performance in the aquatic environment [7].

Although early research did not report associations between the swimming leg with the final triathlon outcome [8], recent studies have highlighted the importance of this leg to increase the chances of success by achieving a strategic position [9,10]. Indeed, this strategic position results in energy expenditure savings due to the drafting effects during swimming [11], which eventually, may affect to the subsequent cycling and running performance [9,12]. In addition to energy expenditure, the main physiological variables that determine triathlon performance are the maximum oxygen uptake ($\dot{V}O_{2max}$), lactate threshold and mechanical efficiency, which have been extendedly studied in the cycling and running legs compared to the swimming leg [13]. Recently, the physiological responses of triathletes in a 1500 m pool swimming test has been analysed, showing that those with better performance presented the lowest energy expenditure and peak oxygen uptake ($\dot{V}O_{2peak}$) values. Hence, this study suggested that the faster triathletes are more efficient than less skilled in a 1500 m swimming pool test [7]. Nevertheless, the swimming leg still requires further research, especially in natural open water environments where the international triathlon events are held.

Biomechanical swimming parameters are related to the swimmers' technical ability, especially the role attached by the stroke variables [14,15]. Indeed, previous studies suggested the stroke length (SL) as a biomechanical variable to assess the skill enhancement in triathletes [16,17], where the most skilled usually present higher SL and lower stroke rate (SR) values than less skilled triathletes [16,17]. Moreover, the stroke index (SI) is considered an indirect estimation of the swimming efficiency, due to its negative association with energy expenditure [18]. Therefore, a better swimming efficiency, related to higher SL [16] and SI values [7], may significantly influence triathletes' swimming performance. Indeed, these results have been previously observed; however, the aforementioned work was conducted under steady swimming pool conditions [7]. Consequently, considering the biomechanical fluctuations inherent in open water and their impact on swimmers' physiological responses [19] it is crucial to investigate the associations between biomechanical variables (e.g., stroke variables) and physiological responses in competitive triathlon environments. This exploration would contribute to a deeper understanding of swimming performance, particularly considering its potential implications for subsequent cycling and running disciplines.

Swimming is the only triathlon discipline that is mostly trained in a non-competitive environment (i.e., swimming pool), in which performance may be influenced by the turns, push off or gliding [7]. However, the swimming leg of a Standard distance triathlon takes place in natural open water environments, such as oceans, rivers or lakes, where changing conditions are challenging [20]. Hence, swimming performance may be affected by the open water characteristics, as observed in long distance swimmers in previous research [19]. In this regard, the information provided in real competitive places may be useful for triathletes and coaches, since it would allow them to know the biomechanical and physiological demands in open water swimming. In this way, coaches may organize their open water training with greater knowledge about triathletes' performance and its demands. However, no research has studied yet triathletes' swimming performance in natural competitive scenarios. Therefore, the aims of the current study were (i) to analyse the 1500 m open water swimming performance, (ii) to examine the associations between physiological and biomechanical variables with swimming performance and (iii) to determine which variables can predict the 1500 m open water swimming performance in triathletes. Based on previous research, it was hypothesised that swimming performance would be influenced by the open water conditions. Due to its negative association with energy expenditure, the fastest triathletes in the 1500 m open water swimming would display a better swimming efficiency, exhibiting higher SI values. Moreover, the SI could predict the open water swimming performance.

METHODS

Participants

Fourteen elite triathletes (10 males and 4 females) volunteered to participate in the current study (Table 7.1). Among the participants, 1 World Class, 9 Elite/International Level and 4 Highly Trained/National Level were included [21]. Triathletes trained in the same squad under the supervision of the same certified coach. The protocol was explained to the participants before providing written consent to participate, being approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022) and conducted in accordance with the Declaration of Helsinki.

Design

The cross-sectional study took place during a summer training camp. The average weekly training time (i.e., three disciplines) was 15.8 ± 2.7 h, while the maximum was 26.8 ± 3.2 h. The recovery times during the sessions and the resistance training were not included as training time. The training load was calculated for all participants using objective load equivalents (ECOs) model [22], obtaining 1354 ± 184 and 2046 ± 293 ECOs weekly average and maximum, respectively. The ECOs model quantifies the training load in triathlon, considering the time in each intensity zone (i.e., from 1 to 10), multiplied by an intensity factor (i.e., from 1 to 300) and by an exercise factor or mode of locomotion (e.g. swimming or running). Triathletes were measured on a single testing session randomly divided to perform the test on two different days under similar conditions. The 1500 m open water swimming test were conducted individually with in-water start, preceded by a 1000 m open water standardized warm-up [23]. Participants used their competition tri-suit (i.e., no wetsuit) and completed the open water swimming test at race pace [3]. During the test, no feedback or encouragement was provided. Participants were asked to refrain from intense exercise at least 24 hours before the testing day. The swimming tests were conducted in a lake with 26.8-27.5ºC water temperature, 29.4-31.2ºC air temperature, 12-16% humidity and 10-14 km/h northwest wind during both days. The wind direction was favourable to the triathletes during odd laps and opposite during even laps (Figure 7.1).

Methodology

Anthropometric variables were measured for each participant in the same conditions. Body height and body mass were measured using a stadiometer/scale (Seca 799, Hamburg, Germany). Body mass index (BMI) was calculated as body mass (kg)/height $(m)^2$. After the standardized warm-up, triathletes rested 15 min before performing the 1500 m open water swimming test. Oxygen uptake ($\dot{V}O_2$) was continuously measured during 5 min before (baseline) and after the test in sitting position. During recovery period (i.e., off-kinetics), mask fitting was right after completing the last stroke of the test [23]. Respiratory gas exchange was measured breath by breath using a portable gas analyser (Cosmed K5, Rome, Italy). Prior to the tests, air, flowmeter, reference gas, scrubber and time delay calibrations were performed following manufacturers' recommendations. The off-kinetics response was modelled with VO_2FITTING, a free and open-source software [24] based on the R language (www.r-project.org, R Core Team 2015) with support of the "Shiny package" [25]. Raw data were used in all the cases. Bootstrapping with 1000 samples was used to estimate $\dot{V}O_2$ kinetics parameters. Besides, breath-by-breath data obtained during 5 min of recovery were adjusted as a function of time using mono exponential model using the following equation (1) [24]:

$$\dot{V}O_2(t) = EE\dot{V}O_2 - H\left(t - TD_p\right) A_P\left(1 - e^{-(t-\mathrm{TD}_p)/\tau_p}\right) \qquad (1)$$

where $\dot{V}O_2$(t) represents the relative $\dot{V}O_2$ at the time *t*, $EE\dot{V}O_2$ is the $\dot{V}O_2$ at the end of exercise (i.e., 1500 m swimming test), *H* represents the Heaviside step function [26], and A_p, TD_p and τ_p are the amplitude, time delay and time constant of the $\dot{V}O_2$ fast component [24]. The $EE\dot{V}O_2$ was estimated by backward extrapolation at zero recovery time using linear regressions applied to the first 20 s of recovery [27].

Heart rate (HR) was recorded using a Polar H10 sensor chest strap device (Polar Electro Oy, Kempele, Finland) during the test. Moreover, HR was recorded during the 5 min preceding and following the effort in a seated position. HR recordings were exported from the Polar Flow website to an Excel spreadsheet. Then, mean baseline HR ($HR_{meanBase}$), mean HR during the test ($HR_{mean1500}$), maximum HR during the test ($HR_{max1500}$) and mean HR after the test ($HR_{meanPost}$) were obtained. Blood lactate concentrations $[La^-]$ were collected with a portable lactate analyser (Lactate Pro 2.0, Arkray Inc., Japan) from the swimmers' right lobe 1 min prior to the test and right after the effort, at minute 1 and every 2 min until the peak was reached [7]. Moreover, rate of perceived exertion (RPE) was asked to the swimmers right after the test (0-10 scale) [28]. The Ana_{alac} was estimated from the maximal phosphocreatine splitting in the contracting muscle [29]. It was expressed in kJ assuming an energy equivalent of 0.468 kJ mM and a phosphate/oxygen ratio of 6.25 [30]. The Ana_{lact} was calculated using the following equation (2):

$$\mathrm{Ana_{lact}} = [La^{-}]_{net} \cdot \beta \cdot M \qquad (2)$$

where $[La^{-}]_{net}$ is the difference between the $[La^{-}]$ after and before the exercise ($[La^{-}]_{peak}$), β is the constant for O_2 equivalent of $[La^{-}]_{net}$ (2.7 $ml \cdot kg^{-1} \cdot mM^{-1}$) [31], and M is the body mass of the swimmers. Both energy systems were then expressed in kJ assuming an energy equivalent of 20.9 $kJ \cdot L^{-1}$ [32]. The methods used (i.e., off-kinetics and backward extrapolation) have been previously validated in the scientific literature, specifically in the swimming area [27,33]. However, considering the calculation of the aerobic component as the time integral of the net $\mathrm{EE}\dot{\mathrm{V}}\mathrm{O}_2$ vs. time relationship [30], the swimming speed fluctuations in the 1500 m open water tests may lead to an overestimations of these values [27]. Hence, the aerobic contribution and the variables related to it were discarded from the analysis.

The open water swimming tests were recorded with a Sony FDR-AX53 (Sony Electronics Inc) at 50 Hz sampling rate. Videos were analysed on an in-house customized software for race analysis in competitive swimming by one expert evaluator (i.e., specialist in race analysis, member of a national performance analysis team) [7]. For the 1500 m open water circuit measurement, a 250 m length rope was placed with small floats every five metres and two big buoys at each end. The participants completed the 1500 m swimming test with three 500 m rounds (i.e., rope round trip) with five 180º turns, leaving the buoys always on the left side. For an in-depth biomechanical analysis, each 500 m round were divided in two laps of 250 m, obtaining a total of six laps of 250 m for its assessment (Figure 7.1). The buoy turn times (s) were calculated from the moment the swimmers' head was next to the buoy and finished the same way in the opposite direction, after the 180º turn. The intraclass correlation coefficient was computed to verify the agreement between repeated measures for each test, obtaining an almost perfect correlation (intraclass correlation coefficients: 0.902 - 0.999). Swimming performance was considered using the World Aquatics Points [34] to standardise the performance times (min:s) obtained in the 1500 m test for male and female triathletes [35], which allows to establish correlations regardless of sex. The swimming speed ($m \cdot s^{-1}$) was measured as the time to cover the distance between the two competition buoys (i.e., 250 m) excluding the buoy turn times. Moreover, the SR was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by sixty to consider the number of cycles per minute. The SR was measured two times every 50 m of each lap (i.e., ten times per 250 m) to obtain the SR in each 250 m lap. The SL was obtained from the ratio between the swimming speed and SR. The SI was calculated as the product of swimming speed and SL [18].

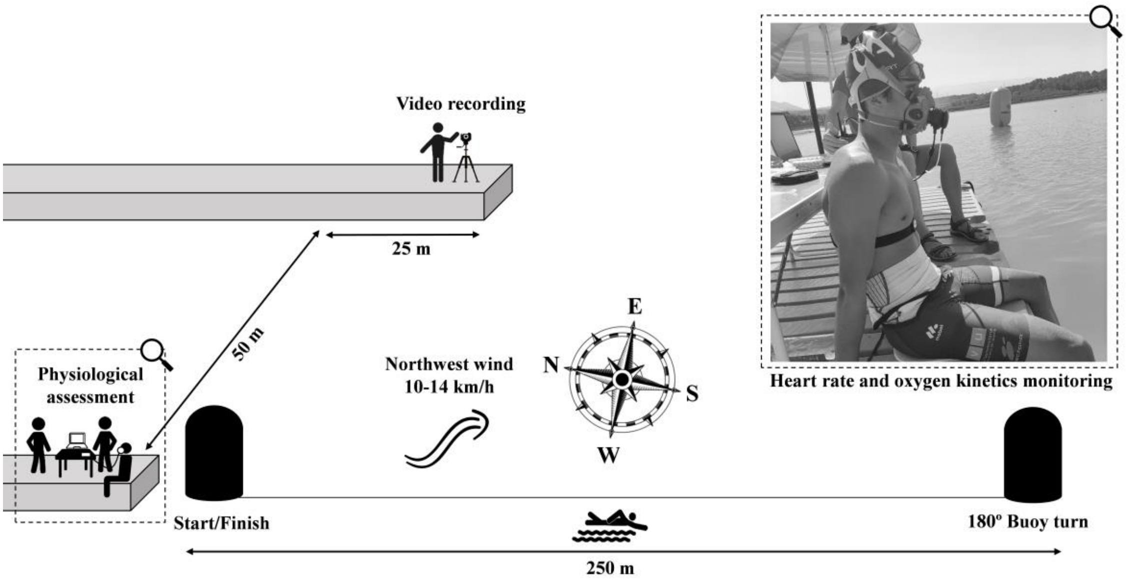

Figure 7.1. Visual representation of the open water swimming circuit and the assessment of physiological variables

Statistical Analysis

The normality of the distribution was checked with Shapiro-Wilk test. Mean and standard deviation (SD) for descriptive analysis were obtained for all variables. Repeated measures analysis of variance (ANOVA) differentiating by sex, was used to assess the change in performance and biomechanical variables every lap during the 1500 m open water swimming test and Bonferroni post-hoc was used to check differences between each 250 m lap and the respective mean value of the variable during the test (i.e. 1500 m). For the ANOVA effect size index, the eta squared (η^2) was computed and interpreted as: $0 < \eta^2$

< 0.04 without effect; 0.04 < η^2 < 0.25 minimum; 0.25 < η^2 < 0.64 moderate; η^2 > 0.64 strong [36]. Pearson's Correlation Coefficient was computed to analyse the associations between World Aquatics Points (i.e., swimming performance) with the physiological and biomechanical variables. Due to the small sample size, the correlation and regression analysis were performed without differentiating by sex. For that reason, World Aquatics Points were used to standardize the swimming performance and to perform the correlation analyses with both sexes. Stepwise multivariate regression analysis was applied including only the variables that showed significant association with swimming performance to determine the strongest predictors in open water swimming. Regression analyses were performed including and excluding the swimming speed due to its direct and high positive correlation with swimming performance [7]. Moreover, the possibility of collinearity and multicollinearity in the multiple regression models was examined using the variance inflation factor (VIF). The threshold correlation values were defined as: ≤ 0.1, trivial; < 0.1-0.3, small; > 0.3-0.5, moderate; > 0.5-0.7, large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect [37]. To verify the correlation and regression analyses, a network analysis was conducted [38]. Following the procedures in previous swimming research [39], measures of centrality (i.e., betweenness, closeness and strength centrality) were calculated to identify the role of each variable correlation, transforming the values into a z-score [39]. The network analysis was conducted in the RStudio software (RStudio Inc., Boston, MA) and the "*qgpraph*" package was used to develop the figure [38]. The significance level was set up at p < 0.05 and the rest of the statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

Descriptive statistics are presented in Table 7.1. Changes and differences between 250 m laps and mean values of the biomechanical variables for each sex are shown in Figure 7.2. In male triathletes, the highest values in all biomechanical variables were obtained in the first 250 m (Figure 7.2, left panels). There were reductions in swimming speed (η^2 = 0.75; p < 0.001), SI (η^2 = 0.66; p < 0.001) and SL (η^2 = 0.47; p < 0.001). Instead, higher SR (η^2 = 0.54; p < 0.001) was observed in the first 250 m (Figure 7.2, left panels). On the other hand, females only showed a decrease in SL (η^2 = 0.82; p < 0.001) in the last 250 m (Figure 7.2, right panels).

Table 7.1. Mean ± SD of physical characteristics, performance, physiological and biomechanical variables of elite triathletes.

	Males (n = 10)	**Females** (n = 4)	**Total sample** (n = 14)
Variable	Mean ± SD	Mean ± SD	Mean ± SD
Physical characteristics			
Age (years)	23.24 ± 3.70	23.63 ± 4.47	23.36 ± 3.76
Body height (cm)	177.50 ± 6.62	169.75 ± 10.56	175.29 ± 8.32
Body mass (kg)	66.73 ± 7.48	58.30 ± 8.72	64.32 ± 8.48
Body mass index ($kg \cdot m^{-2}$)	21.12 ± 1.08	20.13 ± 1.05	20.84 ± 1.13
Performance variables			
T0-500 (min:s)	6:36 ± 0:15	7:10 ± 0:11	6:46 ± 0:21
T500-1000 (min:s)	6:50 ± 0:18	7:24 ± 0:12	6:59 ± 0:22
T1000-1500 (min:s)	6:50 ± 0:21	7:28 ± 0:15	7:01 ± 0:26
T1500 (min:s)	20:17 ± 0:53	22:01 ± 0:37	20:46 ± 1:08
World Aquatics Points	369 ± 49	339 ± 29	360 ± 45
Physiological variables			
$HR_{meanBase}$ ($beats \cdot min^{-1}$)	76 ± 19	83 ± 10	78 ± 17
$HR_{mean1500}$ ($beats \cdot min^{-1}$)	166 ± 11	167 ± 4	166 ± 10
$HR_{max1500}$ ($beats \cdot min^{-1}$)	174 ± 12	175 ± 2	175 ± 10
$HR_{meanPost}$ ($beats \cdot min^{-1}$)	113 ± 11	119 ± 2	115 ± 10
$[La^-]_{Base}$ ($mmol \cdot L^{-1}$)	2.37 ± 0.41	2.05 ± 0.31	2.29 ± 0.40
$[La^-]_{peak}$ ($mmol \cdot L^{-1}$)	7.49 ± 1.58	7.43 ± 2.56	7.47 ± 1.80
$[La^-]_{net}$ ($mmol \cdot L^{-1}$)	5.12 ± 1.54	5.38 ± 2.47	5.19 ± 1.75
$EE\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	56.98 ± 7.47	48.65 ± 5.56	54.60 ± 7.81
RER	1.05 ± 0.13	0.92 ± 0.04	1.01 ± 0.13
A_p ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.63 ± 7.89	40.05 ± 4.33	44.75 ± 7.55
TD_p (s)	5.56 ± 8.38	8.31 ± 9.31	6.35 ± 8.38
τ_p (s)	41.02 ± 6.88	48.68 ± 13.83	43.20 ± 9.48
Ana_{alac} (kJ)	27.73 ± 3.11	24.23 ± 3.62	26.73 ± 3.52
Ana_{lact} (kJ)	19.42 ± 6.64	17.22 ± 7.53	18.79 ± 6.69
RPE	9.80 ± 0.42	9.00 ± 0.82	9.57 ± 0.65
Biomechanical variables			
Swimming speed ($m \cdot s^{-1}$)	1.24 ± 0.05	1.14 ± 0.03	1.21 ± 0.06
SR ($cycles \cdot min^{-1}$)	40.72 ± 3.03	39.71 ± 1.61	40.43 ± 2.68
SL (m)	1.83 ± 0.15	1.73 ± 0.08	1.80 ± 0.14
SI ($m^2 \cdot s^{-1}$)	2.27 ± 0.23	1.98 ± 0.12	2.19 ± 0.24
Buoy Turn Times (s)	4.54 ± 0.24	5.02 ± 0.66	4.68 ± 0.44

T0-500 = performance time of the first and second laps; T500-1000 = performance time of the third and fourth laps; T1000-1500 = performance time of the fifth and sixth laps; T1500 = time performed in the 1500 m test; $HR_{meanBase}$ = mean baseline heart rate; $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{Base}$ = baseline blood lactate concentration; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{peak}$ and $[La^-]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake value; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact}= anaerobic alactic and anaerobic lactic contributions; RPE = rating of perceived exertion; SR, SL and SI = stroke rate, length and index.

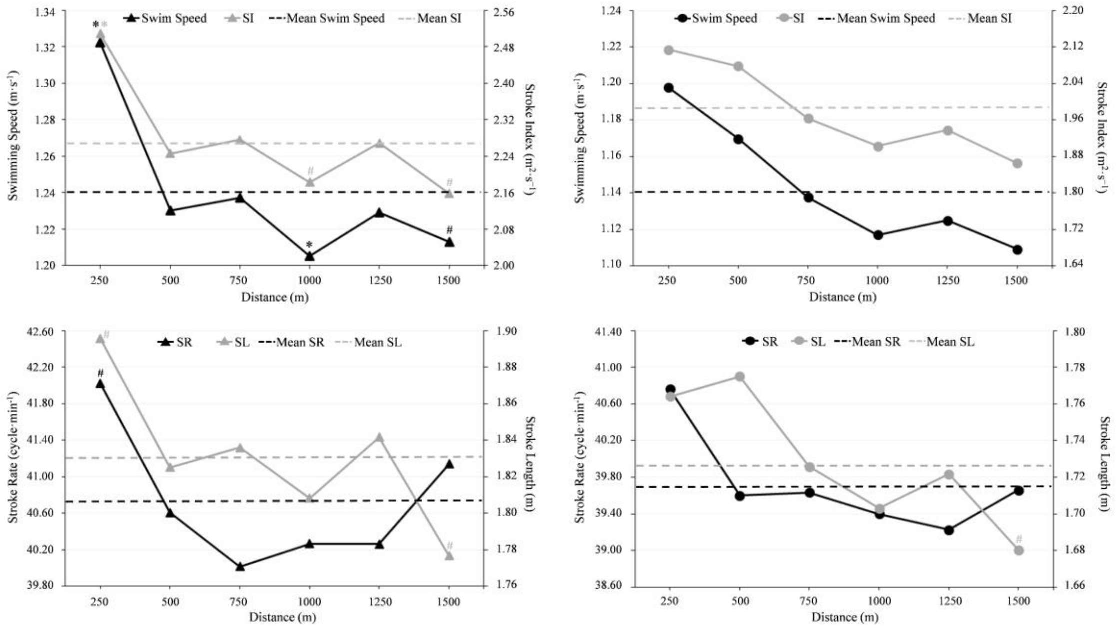

Figure 7.2. Biomechanical changes for male (n = 10; left panels) and female triathletes (n = 4; right panels) during the 1500 m open water swimming test. Significant differences between 250 m laps and the respective mean value of each variable are represented (# $p < 0.05$; * $p < 0.001$).

Pearson's correlations showed positive associations between World Aquatics Points (i.e., swimming performance) and $EE\dot{V}O_2$ (moderate, r = 0.513; $p = 0.030$), while τ_p presented negative associations (moderate, r = -0.500; $p = 0.034$). Regarding biomechanical variables, swimming speed (very large, r = 0.873; $p < 0.001$) and SI (large, r = 0.704; $p = 0.002$) were positive associated with swimming performance, while buoy turn time presented negative relationships (moderate, r = -0.525; $p = 0.027$).

The stepwise multiple regression showed that the 76% of the variance of swimming performance was explained by swimming speed ($R^2 = 0.762$, adjusted $R^2 = 0.742$). The VIF calculated for all regression was always below 2.5, indicating a lack of collinearity. However, when excluding swimming speed in the analysis, SI emerged as the main predictor for swimming performance, explaining 50% of the variance in swimming performance ($R^2 = 0.495$, adjusted $R^2 = 0.453$). This second model was selected, due to the high correlation between swimming performance and swimming speed observed in the first model. The raw and standardised regression coefficients and partial correlations of the predictors are presented in Table 7.2.

Table 7.2. Summary of model selected based on stepwise multiple regression analysis for the 1500 m open water swimming performance of elite triathletes (n = 14).

Variable	Raw beta	Std. error	Std. beta	*t*	*p* value	Partial correlation
Stepwise multiple regression analysis including swimming speed						
Constant	-392.79	121.65		-3.23	0.007	
Swimming speed ($m \cdot s^{-1}$)	621.52	100.29	0.87	6.20	<0.001	0.873
Stepwise multiple regression analysis excluding swimming speed						
Constant	76.75	83.10		0.92	0.037	
Stroke index ($m^2 \cdot s^{-1}$)	129.53	37.77	0.70	3.43	0.005	0.704

The network of associations between World Aquatics Points (i.e., swimming performance) and physiological and biomechanical variables are shown in Figure 7.3. The representation displayed the positive associations between swimming performance with swimming speed and SI. Certainly, SI exhibited a central position in the network, obtaining the highest z-score in the centrality measures (Table 7.3).

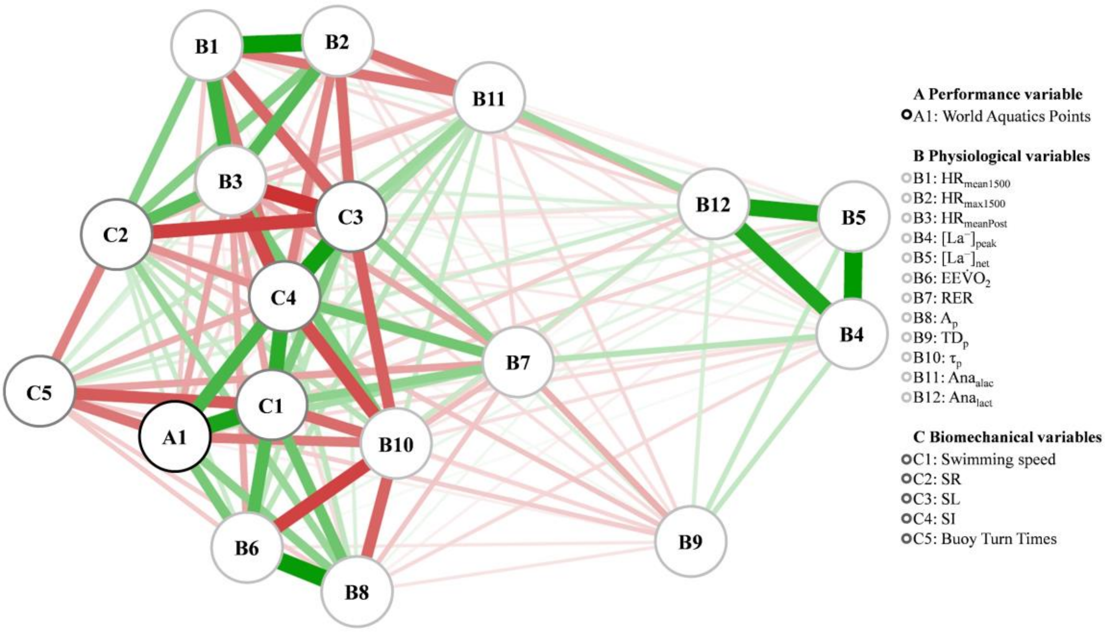

Figure 7.3. Network analysis of correlations between swimming performance, physiological and biomechanical variables in elite triathletes (n = 14). The positive and negative relationships are represented in green and red, respectively. The thickness and intensity of the colours indicate the magnitude of the associations. $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{peak}$ and $[La^-]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact} = anaerobic alactic and anaerobic lactic contributions; SR, SL and SI = stroke rate, length and index.

Table 7.3. Z-score obtained for the betweenness, closeness and strength centrality measures between performance, physiological and biomechanical variables.

	Centrality measures		
	Betweenness	**Closeness**	**Strength**
Performance variable			
World Aquatics Points	-0.61	-1.82	1.24
Physiological variables			
$HR_{mean1500}$	-0.42	-0.38	-0.01
$HR_{max1500}$	-0.61	-0.36	0.06
$HR_{meanPost}$	-0.94	-0.67	1.22
$[La^-]_{peak}$	0.59	0.26	-0.59
$[La^-]_{net}$	0.16	-0.24	-0.45
$EE\dot{V}O_2$	0.87	0.82	0.62
RER	0.10	0.78	-0.74
A_p	-0.55	-0.04	0.20
TD_p	-0.36	-0.37	-0.22
τ_p	-0.68	-0.71	0.93
Ana_{alac}	-0.48	-0.84	0.05
Ana_{lact}	0.87	-0.03	-0.64
Biomechanical variables			
Swimming Speed	-0.74	-1.68	1.19
SR	-0.76	-0.54	-0.31
SL	-1.01	0.89	1.26
SI	1.21	1.84	1.60
Buoy Turn Times	-0.03	0.59	-0.80

$HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{peak}$ and $[La^-]_{Base}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; Ana_{alac} and Ana_{lact} = anaerobic alactic and anaerobic lactic contributions; SR, SL and SI = stroke rate, length and index.

DISCUSSION

The aims of the present study were to analyse the 1500 m open water swimming performance, to examine the relations between physiological and biomechanical variables with swimming performance and to determine which variables can predict the performance. The main findings of this study corroborated the hypothesis that swimming performance was affected by the open water conditions. Moreover, triathletes with better swimming performance were more efficient, exhibiting higher SI values than less skilled triathletes. In addition, when excluding swimming speed, the SI was the main predictor of 1500 m open swimming performance for elite triathletes.

The initial meters of the swimming leg in a triathlon race are the fastest to achieve a strategical position [3]. Regarding males, this was observed in the results obtained, since triathletes were asked to complete the test following the same strategy performed in real events (Figure 7.2, left panel). Moreover, the highest values of the stroke variables (i.e., SR, SL and SI) were obtained in these initial meters of the open water swimming test. On the other hand, the swimming speed decreased in the fourth and the last 250 m laps (Figure 7.2, left panel), together with a SL and SI declined. These changes may be explained by the open water environment, affecting swimming speed and stroke variables and how swimmers modify their technique depending of the tides or currents [20]. In fact, as Figure 7.2 shows, both swimming speed and SI did not follow a linear trend, probably induced by the influence of the currents. In females, no differences were found in swimming speed, SR and SI between each lap and their respective mean values, finding only a significant decrease in SL in the last 250 m (Figure 7.2, right panel). This could be explained due to fatigue and loss of efficiency in the last part of the test [19], but also by the currents against the triathletes' swimming direction, as explained above. In line with previous studies with long-distance swimmers [15,40], the SL impairment was compensate by an increase in SR to maintain the swimming speed. However, in the case of female triathletes, SR was not significantly different from the mean throughout the race. Yet, it is worth noting that the lack of significant biomechanical changes in females might be explained by low sample size. Thus, future research should try to delve more deeply into the swimming behaviour of female triathletes, who are often underrepresented in triathlon literature. Upon these results, triathletes should find a balance between a fast start that allows them to get a strategic position and to conserve an efficient biomechanics to maintain swimming speed in open water conditions, being essential for the subsequent cycling and running legs.

The analysis of physiological variables in swimming is always a challenge, increasing even more its complexity in an open water environment [19]. In contrast to the negative associations between $\dot{V}O_{2peak}$ and energy expenditure with 1500 m swimming performance shown in previous research [7], the positive correlations between $EE\dot{V}O_2$ and performance obtained in the current study seems to indicate some differences between pool and open water swimming tests. In that sense, differences between $\dot{V}O_{2peak}$ in the pool and $EE\dot{V}O_2$ after the open water test may arise from variations in swimming speed and biomechanical adaptations to the natural environment. Moreover, these higher $EE\dot{V}O_2$ values may be due to the high demands of open water swimming [20] and the differences with swimming pool races (i.e., turns, push off or gliding) [7]. Thus, the continuous arm action in open water compared to the effect of acyclic phases in the pool, may explain these physiological differences. In addition to the aforementioned association, the negative relationship between τ_p and performance may indicate a higher level of aerobic fitness, since endurance performance times (e.g., in cycling or running) has been significantly correlated with τ_p [41]. Moreover, shorter τ_p has been associated with both increased time to exhaustion and fatigue tolerance [42]. Therefore, the shorter τ_p obtained by the best performing triathletes may highlight a better coordination between the cardiorespiratory and muscular systems in the fastest triathletes [41], responding faster to energy demands than triathletes with lower swimming performance.

Regarding biomechanical variables, swimming speed and SI presented positive associations with swimming performance, matching previous results in a 1500 m front-crawl swimming pool test with triathletes [7]. The high correlation between the swimming speed and performance is evident, as speed is an essential factor in open water swimming [43]. Moreover, considering the SI as an indirect estimation for the swimming efficiency [18], the positive association between SI and performance could explain the more efficient technique of the fastest triathletes. Hence, triathletes must focus on maximizing the SI, in which the SL maintenance also plays an essential role [16], as SI is the product of swimming speed and SL [18]. On the other hand, the negative correlations between the buoy turn times and swimming performance showed that the fastest triathletes also obtained the shortest time to complete the buoy turn. Although it has not been previously studied, the turn analysis was included to obtain an accurate swimming speed of each lap and, also, to discern if these buoy turns affect the overall swimming performance. However, the lack of real competition circumstances must be acknowledged, as during the races triathletes face the buoy turns with other opponents and speed variations from positioning against other triathletes may influence the open water swimming performance.

Performance analysis and predictive model in Standard distance triathlon reported the relevance of finishing the swimming leg close to the leader [44]. Hence, increasing the knowledge and how to achieve enhancements in the swimming discipline is crucial for triathletes' success. The model obtained in the current study determined the SI as the main predictor variable for the open water swimming performance. This finding partially aligns with the conclusion of previous study, determining SI and energy expenditure as the predictors in 1500 m swimming pool performance [7]. In this case, the results were not corroborated by the energy expenditure as the calculation of the aerobic component could be overestimated when using off-kinetics method at unstable swimming speeds [27], thus the total energy expenditure was not considered. However, the indirect estimation of swimming efficiency through the SI may be essential [18], since the ability to manage energy is decisive for triathlon success [3]. On the other hand, considering the World Aquatics Points as the swimming performance variable, and the SI calculation (i.e., product of swimming speed and SL) [18], it is important to highlight the close relationships between World Aquatic Points, swimming speed and SI, also revealed by the network analysis (Figure 7.3, Table 7.3). The relationship between these variables might have influenced the correlation and regression analyses results. Nevertheless, the VIF results in our models indicated the non-existence of collinearity or multicollinearity between the predictors. Thus, considering the results obtained in the current study and partially agreeing with previous research in swimmers [45], triathletes must optimize their efficiency through the stroke variables (i.e., technical skills), trying to maximize the SI values.

To the best of the authors' knowledge, there is no previous study that investigated the open water swimming in triathletes, hence the results obtained may have great relevance for coaches and athletes. One of the limitations of the current study was the small sample size, especially of females. Nevertheless, it is important to highlight the high level of the participants and the controlled condition (i.e., same squad and coach). Moreover, the 180º turns performed during the 1500 m open water swimming are unusual in a triathlon competition; yet, this procedure was followed to increase the accuracy of the biomechanical variables. On the other hand, the competitive situations approach should be considered (e.g., swimming alone vs. swimming with opponents or swimming before the cycling and running legs), as these circumstances may differ from the results obtained in the current study. Future research should analyse open water swimming performance with on-kinetics method, considering the aerobic contribution and total energy expenditure. Moreover, large samples with participants of different performance levels should be considered. Based on the current results, triathletes and coaches should include specific open water training sessions, as it is the competitive environment and may affect swimming biomechanics. In addition, technical skills must be promoted and quantified in training in order to optimize the swimming efficiency for increasing the successful coping in the following cycling and running legs.

CONCLUSION

The analysis of the 1500 m open water swimming performance showed the highest values of biomechanical variables (i.e., swimming speed, SR, SL and SI) in the initial meters in males, while a decrease in SL was observed in the last meters in both sexes. The fastest triathletes in 1500 m open water swimming obtained the highest $EE\dot{V}O_2$ and the lowest τ_p values, exhibiting better efficiency through higher SI values. Indeed, the SI was the main predictor for the 1500 m open water swimming performance in triathletes.

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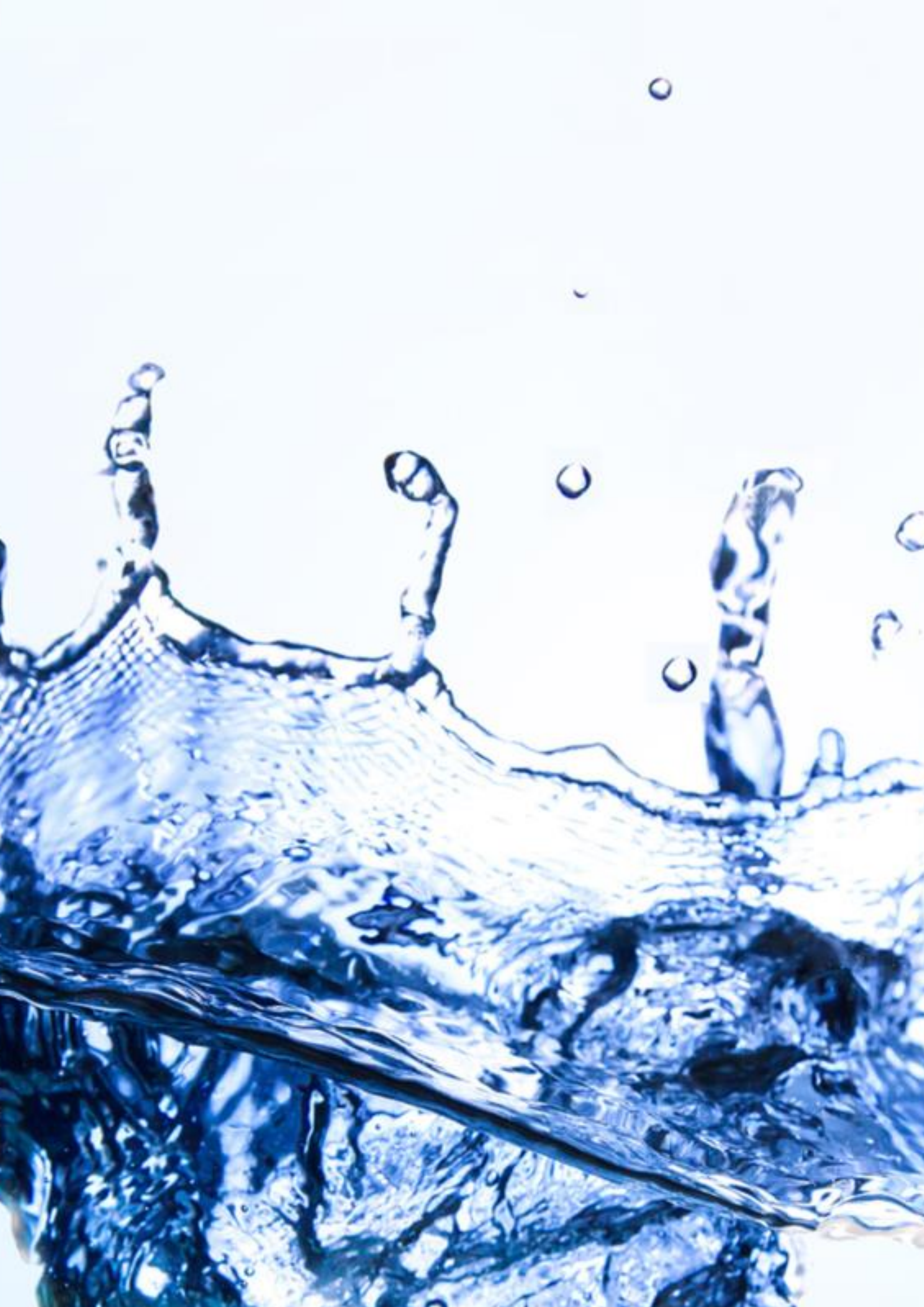

Chapter 8

Swimming performance in elite triathletes: Comparison between open water and pool conditions

López-Belmonte, Ó., Ruiz-Navarro, J. J., Gay, A., Cuenca-Fernández, F., Arellano, R., & Cejuela, R. (2024). Swimming Performance in Elite Triathletes: Comparison Between Open Water and Pool Conditions. *Scandinavian Journal of Medicine & Science in Sports*, *34*(8), e14702.

ABSTRACT

Purpose: This study aimed (i) to compare performance, kinematic and physiological variables between open water and pool swimming conditions in elite triathletes and (ii) to examine the associations between conditions on these variables. **Methods:** Fourteen elite triathletes (10 males and 4 females [23.4 ± 3.8 years]) performed two 1500 m swimming tests in open water and in a 25-m pool. Swimming speed, stroke rate (SR), length (SL) and index (SI), heart rate (HR), blood lactate concentrations $[La^-]$ and end-exercise oxygen uptake ($EE\dot{V}O_2$) were assessed in both conditions. **Results:** Lower SL and SI and higher SR were obtained in open water compared to pool swimming ($p < 0.05$). Moreover, kinematic variables changed as a function of distance in both conditions ($p < 0.05$). No differences were found in the main physiological variables (HR, $[La^-]$ and $EE\dot{V}O_2$) between conditions. Respiratory exchange ratio presented lower values in open water compared to pool conditions ($p < 0.05$), while time constant was higher in open water ($p = 0.032$). The fastest triathletes in open water obtained the best performance in the pool ($r = 0.958$; $p < 0.001$). All kinematic variables, HR and peak $[La^-]$ presented positive associations between conditions ($r > 0.6$; $p < 0.05$). **Conclusions:** Despite physiological invariance, triathletes and coaches should monitor specific open water training to adapt their swimming technique to the competitive environment.

Keywords: triathlon, swimmers, physiology, biomechanics, energetics, endurance.

INTRODUCTION

Swimming makes the plunge of triathlon races, where athletes are challenged to subsequently complete cycling and running legs. The established order may potentially impact the performance of the subsequent legs, thus triathletes should manage their effort during a triathlon competition [1]. In fact, the lower energy cost resulting from strategic positioning during the 1500 m swimming may significantly affect the subsequent cycling and running performance [2,3]. Hence, a good position in the first pack or finish the swimming leg close to the leader, is essential for triathlon success [4,5]. However, despite its relevance, the swimming leg has been less studied than the cycling and running ones [6], probably as a consequence of the complexity of assessing in the aquatic environment [7].

The swimming leg in triathlon competitions takes place in open water conditions, like oceans or lakes, where the environmental circumstances (i.e., waves, tides or currents) are challenging [8]. However, triathletes' training programs are developed in swimming pool [9], likely to mitigate the constraints of open water environment and for better performance monitoring by coaches. In this regard, the differences between open water and pool swimming performance have not been examined in triathletes [9] and underexplored in swimmers [10,11]. Certainly, some research focused on the associations between open water a pool swimming performance, indicating that the fastest open water swimmers also obtained the highest swimming speed in pool events [10]. A similar trend was showed in triathletes, where an incremental pool swimming test may serve as a predictor of the swimming leg in a triathlon race (i.e., open water conditions) [12]. However, the open water results were taken from official competitions, which may yield different outcomes when compared to a controlled pool test. Hence, the analysis of open water and pool swimming tests under controlled conditions (i.e., laboratory settings) could provide valuable insights into the differences and associations of performance in both environments.

To understand performance and how athletes deal with the first triathlon leg is essential to asses swimming kinematics [7]. For instance, the interaction between performance and stroke variables represent a major point of interest in swimming research, as this interaction allow researchers to identify optimal swimming techniques tailored to individual swimmers, maximizing their speed and efficiency [13]. In that sense, the stroke index (SI) is considered the main predictor in both open water [9] and pool swimming performance in elite triathletes [7], since this parameter essentially reflects how efficiently a swimmer converts their strokes into forward propulsion. On the other hand, the dynamic nature of open water conditions induces kinematic fluctuations and thus affect swimmers' physiological responses differently [8,11]. In this regard, swimmers' energy expenditure is influenced by the adjustments to face these open water conditions, which may affect oxygen uptake ($\dot{V}O_2$), heart rate (HR) or blood lactate concentrations ($[La^-]$) [11]. Consequently, the analysis of physiological variables linked to kinematic changes during open water and pool swimming may be of interest to understand the different demands in competitive and usual training environments.

Considering the relevance of swimming as the initial leg in a triathlon race and its impact on overall performance, a deeper knowledge about this discipline may lead to more specific training plans. However, to the best of the authors' knowledge, no study has compared triathletes' swimming performance in both environments. Therefore, the aims of the current study were (i) to compare performance, kinematic and physiological variables between the 1500 m open water and pool swimming conditions and (ii) to examine the associations between conditions on these variables. It was hypothesized that open water conditions would deteriorate performance and kinematics compared to pool conditions, leading to greater physiological demands. Moreover, the fastest triathletes in open water swimming would also perform the best times in pool swimming.

METHODS

Participants

Fourteen world class, international and national [14] triathletes (10 males [23.2 ± 3.7 years, 177.5 ± 6.6 cm of body height and 66.7 ± 7.5 kg of body mass] and 4 females [23.6 ± 4.5 years, 169.8 ± 10.6 cm of body height and 58.3 ± 8.7 kg of body mass]) participated voluntarily in the current study. Two World Championship and World Cup medallists were included among the participants. Triathletes trained in the same team under the supervision of the same certified coach. The protocol was fully explained to the athletes before providing written consent to participate. The study was approved by the ethics committee of the University of Granada (project code: 2658/CEIH/2022) and was conducted in accordance with the Declaration of Helsinki.

Design

A counterbalanced crossover study was performed along four days during a training camp. Participants were randomly assigned to two groups, performing a 1500 m open water and pool swimming tests in two different days with 48 h of recovery in-between. The sequence order of the swimming conditions was randomly assigned for each group (Figure 8.1). Both tests were conducted at the same time of the day to avoid circadian variations [15]. The average and maximum total weekly training time (i.e., across all three disciplines) were 15.8 ± 2.7 and 26.8 ± 3.2 h, respectively. This time refers only to actual working time and did not take intra-set rest periods into account nor included the resistance training sessions. The training load was calculated for all participants using objective load equivalents (ECOs) model [16], obtaining 1354 ± 184 and 2046 ± 293 ECOs weekly average and maximum, respectively.

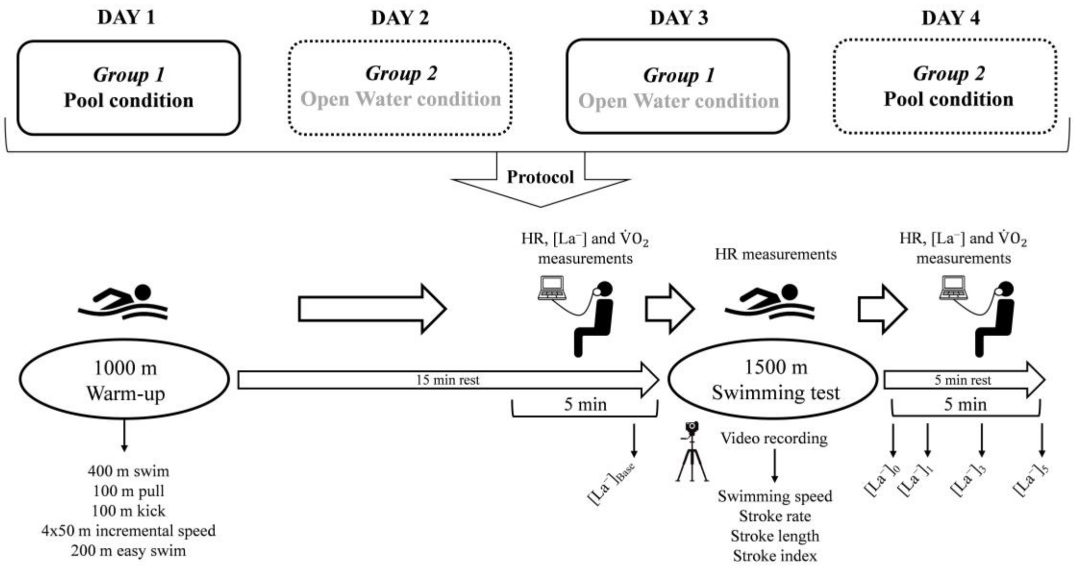

Figure 8.1. Overview of the experimental study design. HR: heart rate; $[La^-]$: blood lactate concentration; $[La^-]_{Base}$: baseline blood lactate concentration; $[La^-]_0$, $[La^-]_1$, $[La^-]_3$, $[La^-]_5$: blood lactate concentration at one, three and five min after the effort; $\dot{V}O_2$: oxygen uptake.

Open water and pool swimming conditions

The 1500 m swimming tests were conducted individually with in-water start, preceded by a 1000 m standardized warm-up [17]. Participants used their competition tri-suit (i.e., no wetsuit) and completed the open water and pool swimming tests at race pace, starting with a higher speed in the initial metres [18]. The open water swimming tests were conducted in a lake with 26.8-27.5ºC and 29.4-31.2ºC water and air temperatures, respectively; 12-16% relative humidity and 10-14 km/h northwest wind. For the 1500 m open water circuit measurement, a 250 m length rope was placed with small floats every five metres and two big buoys at each end. The participants completed the 1500 m swimming test with three 500 m rounds (i.e., rope round trip). A total of five 180º turns were performed, leaving the buoys always on the left side. For a better kinematic analysis, each 500 m round were splitted in two laps of 250 m, analysing a total of six laps of 250 m. The pool swimming tests were performed in a 25 m indoor pool with 27.9ºC, 29.4ºC and 53.3% water and air temperatures and relative humidity, respectively. During the pool tests, the participants were notified at the 500, 1000 and 1400 m with a whistle blow. No feedback or encouragement was provided in any of the conditions. During the testing period, triathletes were required to refrain from high-intensity activities.

Performance and kinematic measurements

The swimming tests were recorded with a Sony FDR-AX53 (Sony Electronics Inc) at 50 Hz sampling rate. In open water conditions, the camera was positioned on a side dock, 50 m to the side and 25 m ahead of the triathletes' starting position. In pool conditions, it was placed in the stands of the pool, at a water height of 7 m, and at a distance of 20 m from the swimmer. In both cases, the camera recorded with an optical zoom by following the triathlete, capturing a 7 m area with the triathlete centered in the image. Videos were analysed on an in-house customized software for race analysis in competitive swimming by one expert evaluator [7]. The times (s) performed in the 1500 m swimming tests were obtained by video analysis. In addition, World Aquatics Points were used as a performance variable to standardize the times performed between male and female triathletes [7].

In open water conditions, the swimming speed ($m \cdot s^{-1}$) was measured as the time to cover the distance between the two competition buoys (i.e., 250 m), obtained from the moment the swimmers' head was next to the buoy and finished when the same position was reached at the next buoy (i.e., excluding buoy turn times). Moreover, the stroke rate (SR) was obtained by considering three upper limb cycles divided by the time elapsed during this action and multiplied by sixty to consider the number of cycles per minute. The SR was measured two times every 50 m of each lap (i.e., ten times per 250 m) to obtain the mean SR in each 250 m lap. The stroke length (SL) was obtained from the ratio between the swimming speed and SR. The SI was calculated as the product of swimming speed and SL [19].

On the other hand, in pool conditions, the swimming speed ($m \cdot s^{-1}$) was calculated between 5-20 and 30-45 m marks every 50 m to avoid the push-off influence on the wall (i.e., excluding turn times). To standardize the comparison, swimming speed was computed for every 250 m lap as the average speed of ten measurements as done in open water conditions. Finally, the same open water procedures were carried out to obtain the SR, SL and SI [19]. In this case, each stroke variable (i.e. SR, SL and SI) was computed by the average between the 5-20 and 30-45 every 50 m.

Physiological measurements

Respiratory gas exchange was measured breath by breath using a portable gas analyser (Cosmed K5, Rome, Italy) during the 5 min before (baseline) and after the test in sitting position (i.e., off-kinetics) [20]. During recovery period, mask fitting was right after completing the last stroke of the test [20]. Prior to the tests, air, flowmeter, reference gas, scrubber and time delay calibrations were performed following manufacturers' recommendations. The off-kinetics response was modelled with VO_2FITTING, a free and open-source software [21] based on the R language (www.r-project.org, R Core Team 2015) with support of the "Shiny package" [22]. Raw data were used in all the cases. Bootstrapping with 1000 samples was used to estimate $\dot{V}O_2$ kinetics parameters. Besides, breath-by-breath data obtained during the 5 min of recovery were adjusted as a function of time using mono exponential model by the following equation (1) [21]:

$$\dot{V}O_2(t) = EE\dot{V}O_2 - H\left(t - TD_p\right) A_P\left(1 - e^{-(t-\mathrm{TD}_p)/\tau_p}\right) \qquad (1)$$

where $\dot{V}O_2(t)$ represents the relative $\dot{V}O_2$ at the time *t*, $EE\dot{V}O_2$ is the $\dot{V}O_2$ at the end of exercise (i.e., 1500 m swimming test), *H* represents the Heaviside step function [23], and

A_p, TD_p and τ_p are the amplitude, time delay and time constant of the $\dot{V}O_2$ fast component [21]. The $EE\dot{V}O_2$ was estimated by backward extrapolation at zero recovery time using linear regressions applied to the first 20 s of recovery. Respiratory exchange ratio (RER) was obtained from the average of the first 20 s after the effort [24].

The HR was recorded using a Polar H10 sensor chest strap device (Polar Electro Oy, Kempele, Finland) during the test and during the 5 min before and after the effort in sitting position. HR recordings were exported from the Polar Flow website to an Excel spreadsheet. Then, mean baseline HR ($HR_{meanBase}$), mean HR during the test ($HR_{mean1500}$), maximum HR during the test ($HR_{max1500}$) and mean HR after the test ($HR_{meanPost}$) were obtained. In addition, the mean HR obtained every 250 m lap (i.e., HR_{250}, HR_{500}, HR_{750}, HR_{1000}, HR_{1250} and HR_{1500}) in each triathlete was analysed. Moreover, $[La^-]$ were collected using a portable lactate analyser (Lactate Pro 2.0, Arkray Inc., Japan) from the swimmers' right lobe 1 min prior to the test ($[La^-]_{Base}$), right after the effort ($[La^-]_0$), at min 1 ($[La^-]_1$), and every 2 min (i.e., at min 3 $[La^-]_3$ and 5 $[La^-]_5$) until the peak ($[La^-]_{peak}$) was reached. The $[La^-]_{net}$ was the difference between the $[La^-]_{Base}$ and $[La^-]_{peak}$. Moreover, Finally, rate of perceived exertion (RPE) was asked to the swimmers right after the test (0-10 scale) [25].

Statistical Analyses

The normal distribution of the data was confirmed by the Shapiro-Wilk test. Paired sample t test was used to compare differences between open water and pool swimming conditions for the mean value of each variable. Effect sizes (*d*) of the obtained differences were calculated and categorized as follow: small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$ [26]. A two-way repeated measures ANOVA (condition x distance) was used to assess the effect of the 250 m laps on kinematic variables and HR during the test. The same analysis was replicated to examine the effect of the measurement time and $[La^-]$ (condition x measurement time) after the swimming tests. Bonferroni post-hoc test was used to compare between each pairwise and effect size was expressed as eta squared (η^2). Pearson's correlations were conducted in performance, kinematic and the main physiological variables (i.e., $HR_{mean1500}$, $HR_{max1500}$, $[La^-]_{peak}$ and $EE\dot{V}O_2$) to test the association between open water and pool swimming performance. The threshold correlation values were defined as: ≤ 0.1 trivial; < 0.1-0.3 small; > 0.3-0.5 moderate; >

0.5-0.7 large; > 0.7-0.9 very large; and > 0.9-1.0 almost perfect [27]. The significance level was set up at $p < 0.05$ and all the statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 28.0, IBM Corporation Chicago, IL, USA).

RESULTS

Mean, standard deviation (SD) and comparisons between the open water and pool swimming conditions are presented in Table 8.1. Swimming performance declined in open water compared to pool conditions (Table 8.1). Lower swimming speed, SL and SI were obtained in open water compared to pool, whereas a higher SR was reached in open water. Regarding physiological variables, no differences were found in HR, $[La^-]$ and $EE\dot{V}O_2$ between conditions. Instead, lower RER and higher τ_p were obtained in open water compared to pool swimming (Table 8.1). The two-way repeated measures ANOVA revealed a condition (i.e., open water and pool) main effect in swimming speed ($p < 0.001$; $\eta^2 = 0.939$), SR ($p = 0.005$; $\eta^2 = 0.474$), SL ($p < 0.001$; $\eta^2 = 0.843$) and SI ($p < 0.001$; $\eta^2 = 0.878$) (Figure 8.2). However, no differences were found in HR ($p = 0.818$; $\eta^2 = 0.006$; Figure 8.3) and $[La^-]$ ($p = 0.350$; $\eta^2 = 0.088$; Figure 8.4). There was a distance (i.e., 250 m laps)/measurement time (i.e., ($[La^-]_{Base,\ 1,\ 3}$ and $_5$) main effect in swimming speed ($p < 0.001$; $\eta^2 = 0.918$), SR ($p = 0.021$; $\eta^2 = 0.727$), SL ($p < 0.001$; $\eta^2 = 0.915$) and SI ($p < 0.001$; $\eta^2 = 0.964$) (Figure 8.2), HR ($p < 0.001$; $\eta^2 = 0.962$; Figure 8.3) and $[La^-]$ ($p < 0.001$; $\eta^2 = 0.910$; Figure 8.4). There was an interaction between condition and distance in swimming speed ($p = 0.002$; $\eta^2 = 0.835$). No other significant interaction between condition and distance/time was observed ($p > 0.05$). The associations between open water and pool swimming of performance and kinematic, and physiological variables are presented in Figures 8.5 and 8.6, respectively.

Table 8.1. Mean ± SD values for open water and pool swimming conditions in elite triathletes (n = 14), 95% confident interval (95%CI) and *p*-values (paired sample t test) with effect size (*d*) for performance, kinematic and physiological variables.

	Open Water	**Pool**		
Variables	Mean ± SD	Mean ± SD	Difference [95%CI]	*p*-value (*d*)
Performance variables				
$Time_{1500}$ (s)	1246.95 ± 68.26	1118.29 ± 61.54	128.66 [117.18, 140.13]	<0.001* (1.98)
World Aquatics Points	360 ± 45	469 ± 46	-109 [-120, -98]	<0.001* (2.10)
Kinematic variables				
Swimming speed ($m \cdot s^{-1}$)	1.21 ± 0.06	1.28 ± 0.07	-0.07 [-0.07, -0.06]	<0.001* (1.07)
SR ($cycles \cdot min^{-1}$)	40.43 ± 2.68	39.52 ± 2.83	0.91 [0.32, 1.47]	0.002* (0.33)
SL (m)	1.80 ± 0.14	1.95 ± 0.18	-0.15 [-0.18, -0.11]	<0.001* (0.93)
SI ($m^2 \cdot s^{-1}$)	2.19 ± 0.24	2.50 ± 0.33	-0.31 [-0.38, -0.24]	<0.001* (1.07)
Physiological variables				
$HR_{meanBase}$ ($beats \cdot min^{-1}$)	78 ± 17	76 ± 11	2 [-6, 12]	0.246 (0.21)
$HR_{mean1500}$ ($beats \cdot min^{-1}$)	166 ± 10	168 ± 8	-2 [-2, 2]	0.470 (0.00)
$HR_{max1500}$ ($beats \cdot min^{-1}$)	175 ± 10	177 ± 9	-2 [-4, 1]	0.066 (0.21)
$HR_{meanPost}$ ($beats \cdot min^{-1}$)	115 ± 10	113 ± 12	2 [-2, 8]	0.129 (0.27)
$[La^-]_{peak}$ ($mmol \cdot L^{-1}$)	7.47 ± 1.80	7.76 ± 2.13	-0.29 [-1.33, 0.74]	0.275 (0.15)
$[La^-]_{net}$ ($mmol \cdot L^{-1}$)	5.20 ± 1.75	5.66 ± 2.01	-0.46 [-1.54, 0.61]	0.184 (0.24)
$EE\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	54.60 ± 7.81	57.72 ± 10.51	-3.12 [-10.07, 3.83]	0.175 (0.16)
RER	1.01 ± 0.12	1.08 ± 0.16	-0.07 [-0.12, -0.02]	0.005* (0.24)
A_p ($ml \cdot kg^{-1} \cdot min^{-1}$)	44.74 ± 7.5	45.37 ± 9.99	-0.63 [-7.03, 5.78]	0.418 (0.07)
TD_p (s)	6.35 ± 8.39	4.90 ± 5.81	1.45 [-3.72, 6.61]	0.278 (0.20)
τ_p (s)	43.20 ± 9.48	39.07 ± 9.34	4.13 [-0.29, 8.55]	0.032* (0.44)
RPE	9.57 ± 0.64	9.29 ± 0.99	0.28 [-0.19, 0.76]	0.109 (0.34)

$Time_{1500}$ = time performed in the 1500 m test; SR, SL and SI = stroke rate, length and index; $HR_{meanBase}$ = mean baseline heart rate; $HR_{mean1500}$ = mean heart rate during the test; $HR_{max1500}$ = maximum heart rate during the test; $HR_{meanPost}$ = mean heart rate after the test; $[La^-]_{peak}$ = peak blood lactate concentration; $[La^-]_{net}$ = lactate concentration difference between the $[La^-]_{Base}$ and $[La^-]_{peak}$; $EE\dot{V}O_2$ = end-exercise oxygen uptake; RER = respiratory exchange ratio; A_p, TD_p and τ_p = amplitude, time delay and time constant of the oxygen uptake fast component; RPE = rate of perceived exertion. $*p < 0.05$.

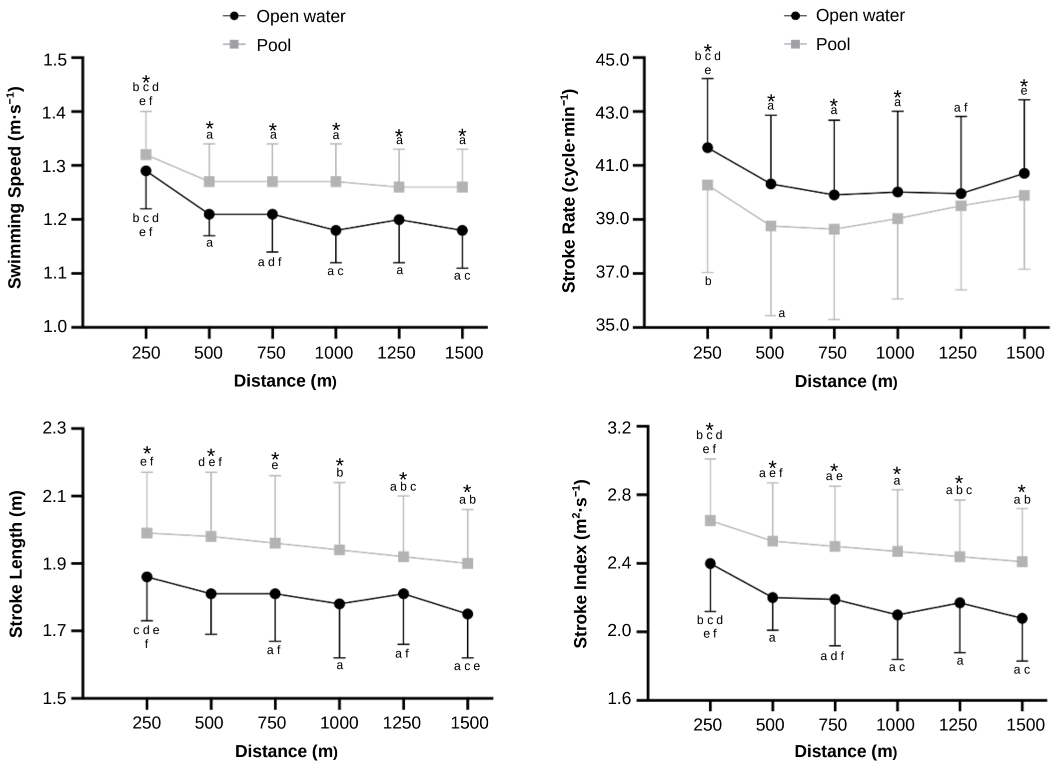

Figure 8.2. Mean and SD of kinematic variables analysed every 250 m lap during the 1500 m swimming tests in elite triathletes (n = 14).*Differences (p < 0.05) between open water and pool conditions in each 250 m lap. Different letters represent the differences (p < 0.05) between 250 m laps in each condition according Bonferroni post hoc test: a, b, c, d, e and f show the difference with the first, second, third, fourth, fifth and sixth 250 m lap, respectively.

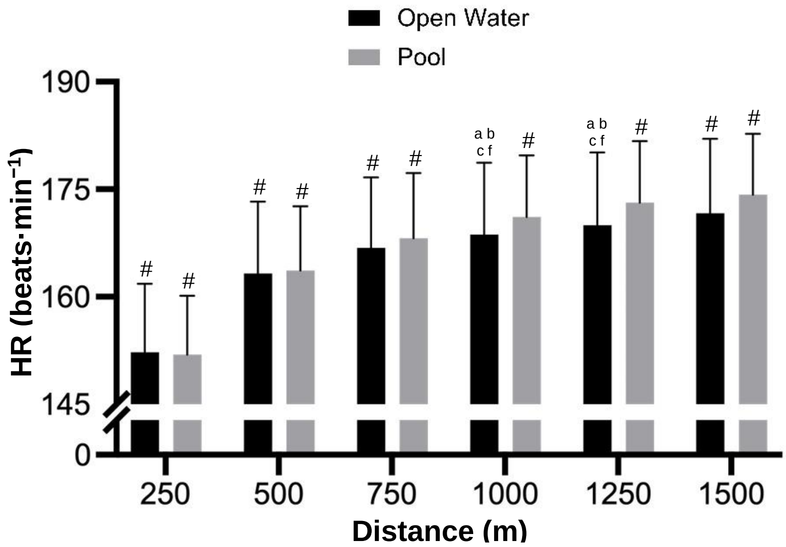

Figure 8.3. Comparison in mean heart rate (HR) for each 250 m lap between open water and pool swimming conditions in elite triathletes (n = 14). Different letters represent the differences ($p < 0.05$) between 250 m laps in each condition according Bonferroni post hoc test: a, b, c, and f show the difference with the first, second, third and sixth 250 m lap, respectively. # Difference ($p < 0.05$) with all 250 m laps in each condition.

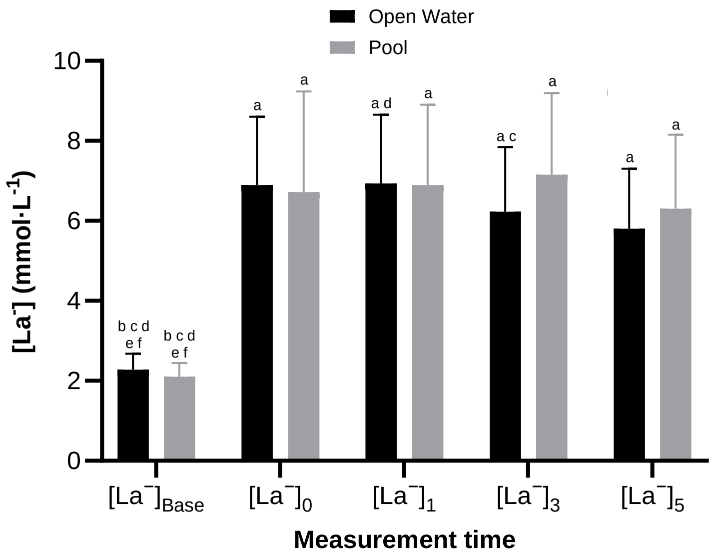

Figure 8.4. Comparison in blood lactate concentrations $[La^-]$ between open water and pool swimming conditions in elite triathletes (n = 14). $[La^-]_{Base}$: baseline blood lactate concentration; $[La^-]_0$, $[La^-]_1$, $[La^-]_3$, $[La^-]_5$: blood lactate concentration immediately after the effort, and at one, three and five min after. Different letters represent the differences ($p < 0.05$) between measurement times in each condition according Bonferroni post hoc test: a, b, c, d, e and f show the difference with the $[La^-]_{Base}$, $[La^-]_0$, $[La^-]_1$, $[La^-]_3$ and $[La^-]_5$, respectively.

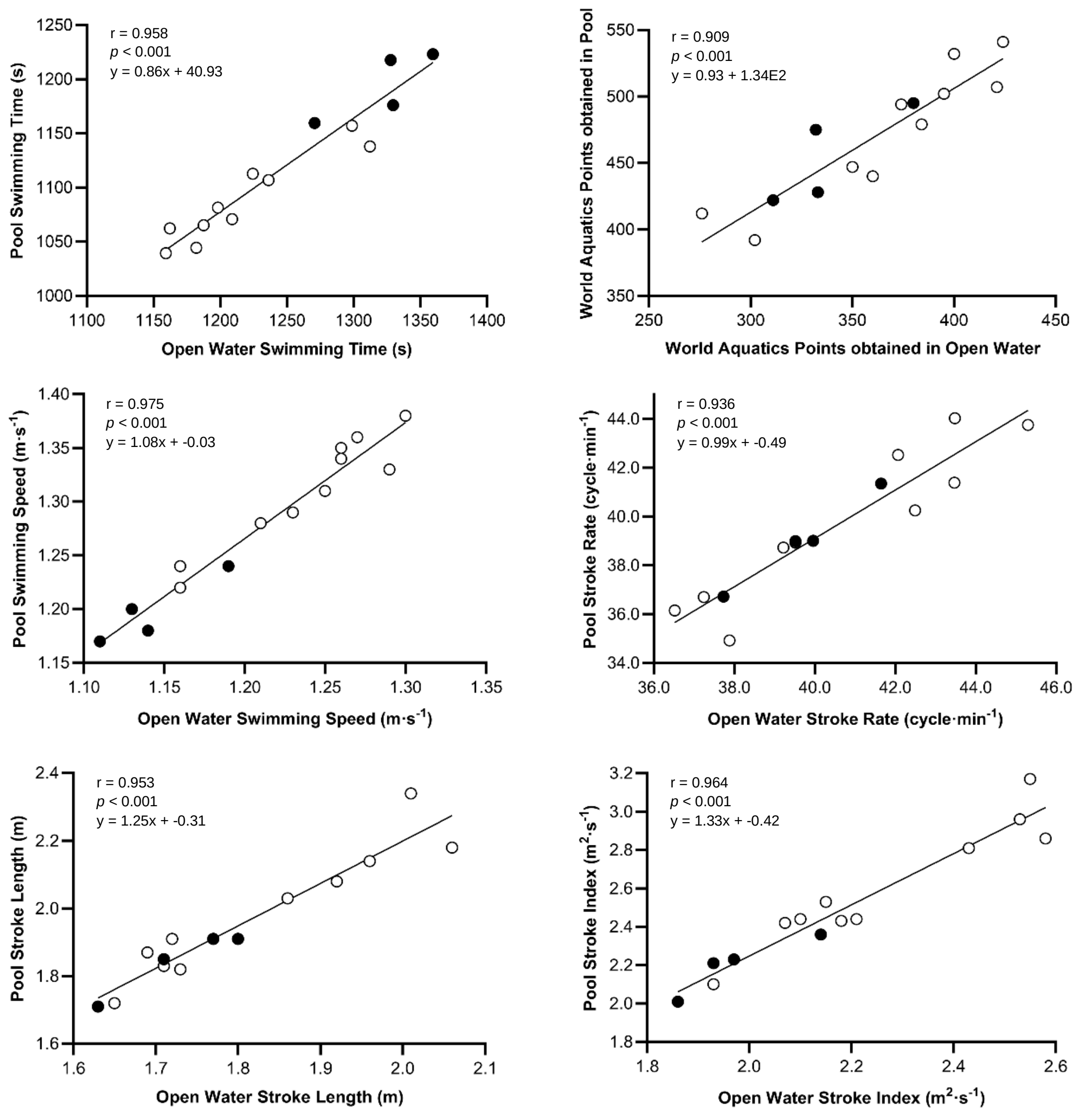

Figure 8.5. Correlations between open water and pool swimming performance and kinematic variables in elite triathletes. White (○) and black (●) dots represent males (n = 10) and females (n = 4), respectively.

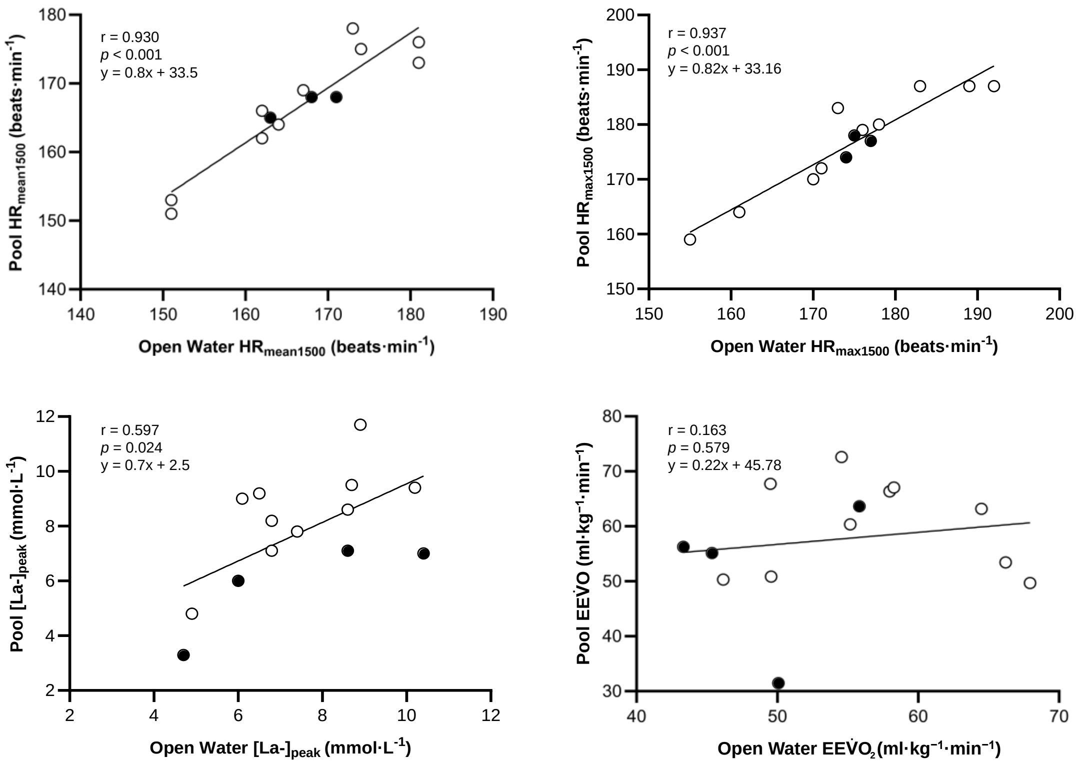

Figure 8.6. Correlations between open water and pool swimming physiological variables in elite triathletes. White (○) and black (●) dots represent males (n = 10) and females (n = 4), respectively. $HR_{mean1500}$: mean heart rate during the test; $HR_{max1500}$: maximum heart rate during the test; $[La^{-}]_{peak}$: peak blood lactate concentration; $EE\dot{V}O_2$: end-exercise oxygen uptake.

DISCUSSION

The aims of the current study were to compare performance, kinematic and physiological variables between the 1500 m open water and pool swimming conditions and to examine the associations between conditions on these variables. As it was hypothesized, swimming performance and kinematics were negatively affected by the open water condition. On the other hand, contrary to the initial hypothesis, the physiological demands were similar in both conditions, where HR, $[La^{-}]$ and $EE\dot{V}O_2$ did not differ between open water and pool swimming. The fastest triathletes in open water obtained the best performance in the swimming pool. All kinematic variables, $HR_{mean1500}$, $HR_{max1500}$ and $[La^{-}]_{peak}$ presented positive associations between open water and pool swimming.

The external conditions inherent to open water swimming have an overall impact on swimmers' performance [8], which contributed to the higher times and lower swimming speeds (Table 8.1, Figure 8.2) obtained in the 1500 m open water compared to those achieved in the pool. Moreover, the actual distance covered in open water [28] or swimming continuously without turns and push-offs performed in pool conditions [7] may explain the higher time and lower speed obtained in the 1500 m open water swimming. On the other hand, despite environmental differences, previous studies showed positive relationships between open water an pool swimming performance in both swimmers and triathletes [10]. This is consistent with the positive associations found in the current study, indicating that the fastest triathletes in open water also achieved the best performance in pool swimming conditions (Figure 8.5). Therefore, in terms of performance or swimming speed, triathletes may improve in both open water and pool conditions, as these are highly positively associated despite their different environments.

Triathletes increased SR at the expense of SL in open water compared to pool conditions to maintain swimming speed, as observed in the mean values (Table 8.1) and between 250 m laps during the tests (Figure 8.2). However, the SR changes could not compensate for the decrease in SL, leading to a lower speed in open water (Table 8.1, Figure 8.2). In that sense, although swimmers could either increase SR or SL for maintaining speed [29] the open water conditions (e.g., coping with currents or looking at the buoys for orientation) influence swimming kinematics [8]. Regarding changes as a function of distance in open water, the SR was higher in the first and last 250 m laps compared to the intermediate ones, as a consequence of a fast start [18] and the compensation for a loss of SL in the last meters [29]. In fact, the SL decrease was observed throughout the tests in each condition, probably evoked by the fatigue induced throughout the test [30]. Moreover, the odd laps in open water were influenced by a current in favor of the course, where the triathletes increased their SL [8]. Besides, as a consequence of the reductions in swimming speed and SL, SI also declined in open water compared to pool (Table 8.1) and decreased throughout the tests in each condition (Figure 8.2). In this regard, given the negative association between SI and energy expenditure [19], SI impairments may imply a loss of efficiency. Hence, the decline in SI observed during the open water indicates that triathletes are less efficient in the natural environment. On the other hand, the positive associations observed between the two conditions across all kinematic variables (Figure 8.5) suggest that all triathletes adjusted their swimming technique similarly to adapt to fluctuating open water conditions. This adjustment entailed an increase in SR and a decrease in SL compared to pool swimming, thus specific open water swimming technique must be considered by triathletes and coaches.

Physiological responses vary depending on the swimming environment [11]. However, the main physiological variables analysed in the current study (HR, $[La^-]$ and $EE\dot{V}O_2$) did not show differences between open water and pool conditions (Table 8.1, Figure 8.3 and 8.4). In addition, the similar behaviour between conditions in both HR (Figure 8.3) and $[La^-]$ (Figure 8.4) during and after the tests emphasises the substantial invariance of physiological variables. In that sense, as triathletes were asked to complete the tests at race pace [18], similar physiological responses were obtained, which was supported by the similar RPE values (Table 8.1). Contrary to previous findings where swimmers' HR and $\dot{V}O_2$ were affected by the open water fluctuations [11], it seems that elite triathletes are able to sustain the same submaximal effort despite the different swimming conditions and kinematics in both environments. In this regard, it is important to note the athletes' performance level and experience of training and competition in open water condition, as this may trigger similar responses to those obtained in the pool. On the other hand, the few physiological differences between both swimming conditions were reflected by the higher RER obtained in the pool compared to open water conditions (Table 8.1). These differences indicate a predominant use of carbohydrates in pool compared to the lower RER obtained in open water, suggesting a higher contribution of lipids in the natural environment [31]. In this regard, the longer duration of the open water test may explain the lower RER values and different energy demands (i.e., increased lipid oxidation) obtained compared to pool swimming. In addition, the lower τ_p observed in swimming pool conditions (Table 8.1) may indicate a faster physiological response compared to open water [32], probably due to the more stable pool conditions, which allowed an earlier cardiovascular and muscular systems adaptation to the effort.

Besides, the positive associations found in $HR_{mean1500}$, $HR_{max1500}$ and $[La^-]_{peak}$ between open water and pool swimming demonstrated similar physiological responses in the two environments (Figure 8.6). Instead, no significant relationships were found among open water and pool conditions in $EE\dot{V}O_2$. In that sense, the interaction and contribution of the energy systems depends on the duration, intensity and mode of exercise [33]. Hence, the longest durations (i.e., times performed) and pace changes (i.e., swimming speed variations) (Figure 8.2) in open water compared to pool swimming may modify the energy contributions and, as a consequence, alterations in the $\dot{V}O_2$ kinetics. In addition, although the mode of locomotion is the same, open water environment and its swimming kinematic differences, may also cause these alterations in $EE\dot{V}O_2$ [11]. Therefore, knowing the differences in competitive and usual training environments, coaches and triathletes might this into account for planning specific training sessions to simulate the experience of open water swimming.

In general terms, coinciding with previous studies in swimmers [8] and triathletes [7], the results obtained seem to indicate that a technical enhancement (i.e., kinematic variables) has more effects on swimming performance than the improvement in physiological variables in elite triathletes. The current study presents some interesting and novel results for triathletes and coaches, however, it was limited by the small sample size. Further studies should consider larger sample sizes with different performance levels and dividing the results by sex. On the other hand, it is important to highlight the high level and the control over the sample, since triathletes belong to the same team. Another limitation is the real distance covered in open water by each triathlete, which was not measured and might affect the results obtained. Nevertheless, the characteristics of the open water course in a straight line facilitated the triathletes' orientation in the current study.

PERSPECTIVES

The analysis of physiological variables linked to kinematics in competitive and usual training contexts is essential in sports. Given the crucial role of swimming as the first leg in a triathlon competition and its influence on performance, a deeper knowledge about this discipline may lead to more specific training plans. The main findings showed that swimming kinematics is affected by the open water conditions. Based on these results, triathletes must perform specific training sessions to adapt their technique to the changing open water conditions. Moreover, during the process of kinematic adaptation physiological responses should be monitored to gain knowledge about its demands or enhancements. In this way, triathletes would be able to maximize the swimming efficiency in the competitive environment. Finally, the development of pacing strategies based on the quantification of kinematic variables (e.g. SR) could be a useful and easy tool to apply in a training context.

CONCLUSION

The open water conditions had an impact on performance leading to lower swimming speed and changes in kinematic variables. However, these influences were similar for all swimmers, as the fastest in open water were also the fastest in pool swimming and kinematic variables displayed positive associations between conditions. With regards to physiological variables, the substantial invariance between open water and pool conditions showed similar demands in both environments.

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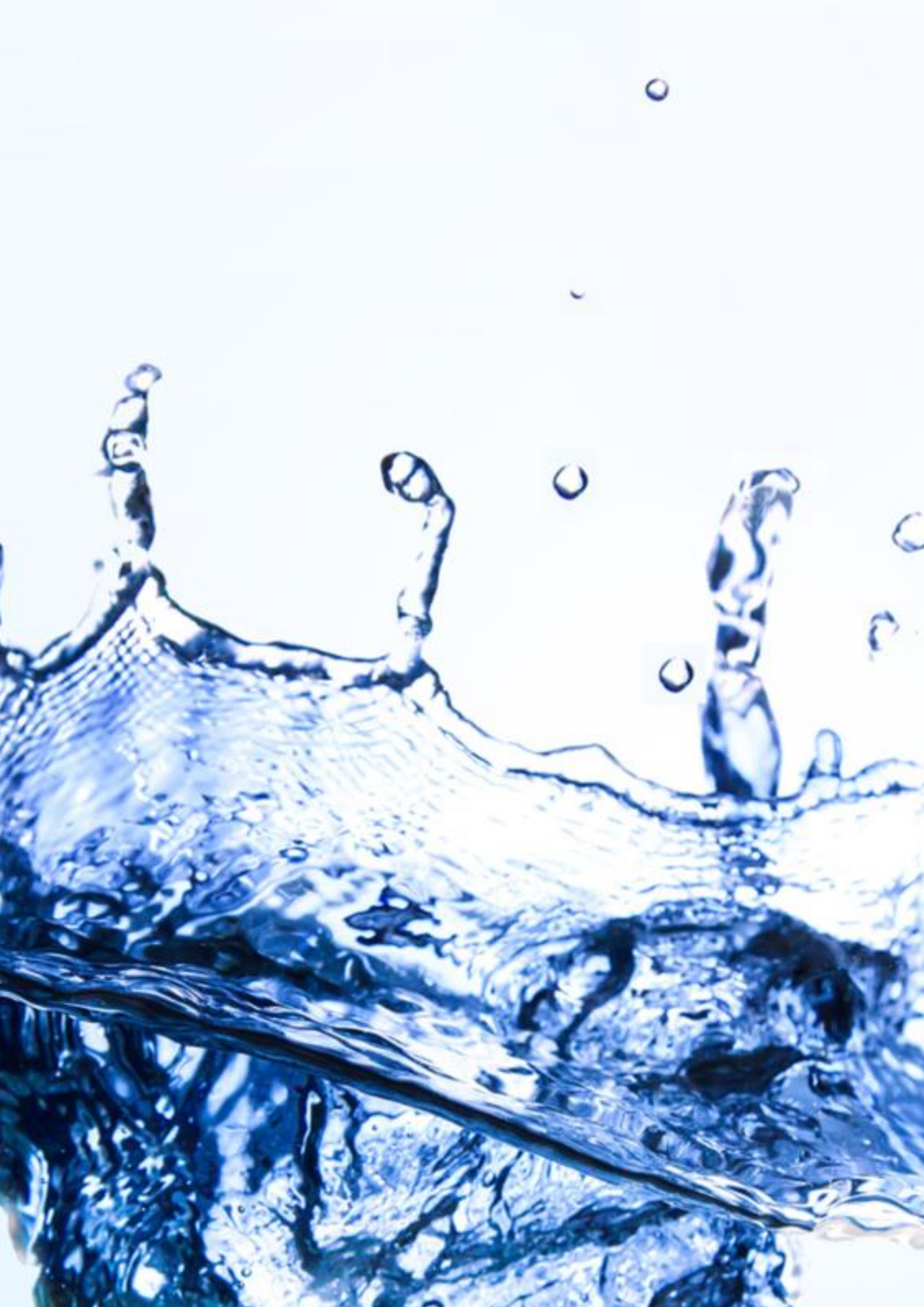

Chapter 9

General discussion

General discussion

The current doctoral thesis contributes to a better understanding of the determinant factors in both open water swimmers and triathletes. In six studies, physiological and kinematic factors influencing swimming performance in both endurance sports were investigated. Firstly, **Chapter 3** examined the pacing strategies adopted by elite swimmers during a 3000 m swimming race, together with an analysis of performance and pacing variability. Subsequently, **Chapter 4** assessed the LT in elite open water swimmers, conducted a comparative analysis of individual and fixed LT methods, and explored the relationship between LT and swimming performance. Finally, **Chapter 5** evaluated seasonal changes in performance, focusing on physiological and kinematic factors during maximal incremental swimming tests.

Shifting the focus to elite triathletes, **Chapter 6** analyzed the relationships between physiological and biomechanical factors and pool swimming performance, determining the key factors in elite triathletes. Thereafter, **Chapter 7** analyzed the open water swimming performance, investigating the physiological and biomechanical demands and their associations with performance, and identifying key predictors of performance. Finally, **Chapter 8** compared performance, kinematic, and physiological factors between open water and pool swimming conditions, examining how these environments influenced performance. This structured approach provided a detailed understanding of the complex factors that drive elite performance in open water swimming and triathlon, making a significant contribution to the field of swimming.

Open water swimming

As discussed in **Chapter 1**, the transition of long-distance pool swimmers into open water events has introduced a new paradigm that has led to significant changes in open water swimming [1,2]. In addition to the 800 and 1500 m swimming freestyle, the open water swimmers include longer pool distances as test races [3], although research on these events remains limited. In this regard, the findings from **Chapter 3** revealed that elite open water swimmers predominantly adopted a parabolic pacing strategy during the 3000 m swimming race. This strategy, characterized by a faster pace in the early stages of the race, followed by a deceleration and a fast end-spurt, aligns with previous research in long-distance pool events [4–6]. However, it is important to consider individual characteristics, as the swimmer's experience plays a crucial role in developing optimal performance strategies [7]. On the other hand, the in-depth kinematic analysis in **Chapter 3** pointed out the great variability of the swimmers throughout the test, especially in the turn and stroke parameters. The highest variability and progressive decline in turn performance (i.e., WBT and WBD) were consistent with previous observations in long-distance events [8,9], attributed to the large number of turns and the effects of fatigue [10]. Moreover, the reduction in clean swimming speed and SL, offset by the increase in SR, led to a decrease in SI, indicating a loss of swimming efficiency during the race [11]. Therefore, an effective pacing strategy coupled with stability in performance and kinematics can result in a better outcome.

In addition to pacing and kinematic factors, the physiological profile of elite open water swimmers was examined in **Chapter 4**. Although LT intensities are decisive in open water swimming events [12], there is limited in-depth analysis of this aspect in elite swimmers [13,14]. Swimming speeds at LT were higher than those reported in previous studies [13], indicating an updated profile of the open water swimmers capable of maintaining near-maximum intensities for prolonged periods. In addition, the comparison between individual LT and the fixed [La^-] at 4 $mmol{\cdot}l^{-1}$ [15] in **Chapter 4** showed different results between sexes. While swimming speed at LT were not different from the speed at 4 $mmol{\cdot}l^{-1}$ in males, it was notably lower than 4 $mmol{\cdot}l^{-1}$ in females. Contrary to previous findings [16,17], the fixed method is a potential but imperfect proxy for LT in males, due to the high variability and individual kinetics of [La^-] [16]. However, the use of 4 $mmol{\cdot}l^{-1}$ as a fixed measure in females leads to an overestimation of aerobic capacity due to hormonal or genetic differences [18] or a more efficient swimming technique [19] resulting in lower [La^-] values. While the relationship between LT and performance is well-established in running or cycling, the evidence in other endurance sports, such as swimming, remains unclear [20]. Consequently, **Chapter 4** showed a positive association between swimming speed at LT and most of the seasonal best performances, suggesting that the LT is a valuable performance indicator in elite open water swimmers, consistent with findings from similar studies in marathon runners [21,22].

Physiological and kinematic changes over the seasons can be induced by training loads or specific technical training to improve swimming performance [23,24]. Thus, monitoring swimmers' adaptations is key for optimizing performance [25], although there is little information on open water swimmers [14]. In **Chapter 5**, the four incremental tests conducted in three different seasons showed no changes in performance or physiological factors. In this sense, the common plateau effect in elite and experienced swimmers during long competitive careers [23], in addition to the similar time periods of the tests [26], could be the reasons for this steadying in open water swimmers. On the contrary, the kinematic variations observed in SL and SI at both AeT and LT suggest technical adaptations to achieve similar performance, as reported in previous studies [27]. In this sense, given the significant role of stroke parameters in swimming efficiency [28,29], other key physiological variables that were not measured, such as *C* and $\dot{V}O_2$, may have changed between seasons. Although there were no kinematic changes in females, probably due to the small sample size, individual characteristics and sex-specific adaptations [24] in kinematics between seasons are also relevant aspects to consider when monitoring.

To better understand the physiological and kinematic factors in elite open water swimmers, **Chapter 5** also displayed the relationships between these factors and the maximum speed achieved in the tests. Due to the specificity of the incremental test, swimmers with the highest speed at both AeT and LT achieved the best performance. Moreover, the higher [La^-] at LT intensities observed in the fastest male swimmers highlighted the importance of anaerobic pathways in open water races. In addition to swimming close to or at LT [12], the end-spurt adopted in the final meters is often decisive to success in international events [30]. Therefore, although it is a long-distance event, swimmers also need a well-developed anaerobic capacity to be successful in open water. In the case of females, the lower [La^-], possibly influenced by differences in anthropometrics and metabolism [18], explained the lack of associations with performance. In terms of kinematics, **Chapter 5** showed that higher SL and SI at AeT and LT were linked to faster speeds in males, echoing previous findings that highlight SL as a key predictor of swimming speed [31] and SI as an indicator of greater efficiency in the water [28]. On the contrary, the fastest female swimmers presented higher SR at AeT and LT, which indicated that the ability to increase SR to maintain or increase speed is more critical than SL.

Triathlon: The swimming leg

Swimming performance in triathletes has been less extensively addressed in the literature compared to the cycling and running legs [32], as highlighted in **Chapter 1**. In this context, **Chapter 6** and **Chapter 7** revealed the importance of swimming efficiency, both in the 1500m controlled pool and in the changing open water swimming, respectively. In **Chapter 6**, triathletes with lower *E*, *C* and higher SI achieved the best performance in the pool swimming test. In addition, the negative relationships between performance and $\dot{V}O_{2peak}$ and the mean HR after the test reinforced the lower physiological demands and better recovery of the fastest triathletes, which is essential for the following disciplines [33,34]. On the other hand, similar to the findings for open water swimmers (**Chapter 5**), anaerobic pathways played an important role in the swimming test. Although the aerobic pathway predominates, anaerobic metabolism is also key, as triathletes face frequent high-intensity bursts, as well as pacing positive strategies, which are often characteristics of medal-winning performance [35]. As discussed in **Chapter 6** and in agreement with previous authors [36,37], using SL as a tool to assess swimming technique and focusing on maximizing it is crucial to optimizing performance. Moreover, the findings regarding SI and *E* as determinants of swimming performance underscored the essential role of technical skill and efficiency in elite triathletes.

Open water swimming in elite triathletes displayed performance changes induced by the dynamic and variable conditions of the open water environment, as observed in **Chapter 7**. Contrary to the findings in pool swimming, triathletes with higher end-exercise $\dot{V}O_2$ achieved better performance in the 1500 m open water swimming, probably due to the greater demands and variations of this environment [38]. In addition, the fastest triathletes presented an earlier response to exercise demands, as evidenced by a shorter τp than those with poorer swimming performance [39]. Regarding biomechanical factors, the positive pacing typically adopted in the swimming leg [40] resulted in the highest values for the speed and stroke parameters in the initial meters. Furthermore, the lack of a linear trend in these factors during the test showed how male triathletes modified their technique as a result of the current effects [14]. However, due to the small sample size of female triathletes, a change in SL was only found in the final meters, offset by an increase in SR, as previous reported in long-distance swimming [8]. On the other hand, in line with **Chapter 6** and again emphasizing the importance of efficiency, the SI was the main predictor of open water swimming performance.

Finally, the comparison between pool and open water swimming conditions in **Chapter 8** exposed some differences between the usual training and competition environments of triathletes. Although physiological responses depends on the swimming conditions [38], the main factors measured in **Chapter 8** remained consistent between open water and pool swimming, resulting in similar behaviors in HR and [La$^-$], and end-exercise $\dot{V}O_2$ values. In this sense, the submaximal intensities at race pace adopted in both conditions [40], together with the high-level and experience of the triathletes in both training and competition in open water, led to similar physiological responses. On the other hand, the fluctuating open water conditions, including swimming against currents or orienting by sighting buoys [14], contributed to longer times and reduced swimming speeds compared to stable pool conditions. In addition, all triathletes changed their swimming technique similarly, with a decrease in SL and an increase in SR in open water compared to pool, which also led to lower SI values in the natural environment. Despite the different conditions, the fastest triathletes in open water were also the fastest in the pool conditions, consistent with similar research in elite triathletes [41].

General limitations

Several strengths and limitations have been acknowledged in the different chapters of this doctoral thesis. Nevertheless, there are wider limitations that should be highlighted:

- The small sample sizes in some of the studies included in this thesis, particularly with an under-representation of female participants. However, the high level of performance and the participants belonging to the same training group helped to maintain controlled conditions.
- The absence of key physiological factors in open water swimmers, such as *C* or $\dot{V}O_2$ in open water swimmers. The addition of this information would provide a more comprehensive understanding of their metabolic requirements and responses during swimming.
- The thesis lacks assessments of anthropometric, strength and conditioning measures, as well as their relationships with swimming performance, which limits insight into other factors influencing performance.

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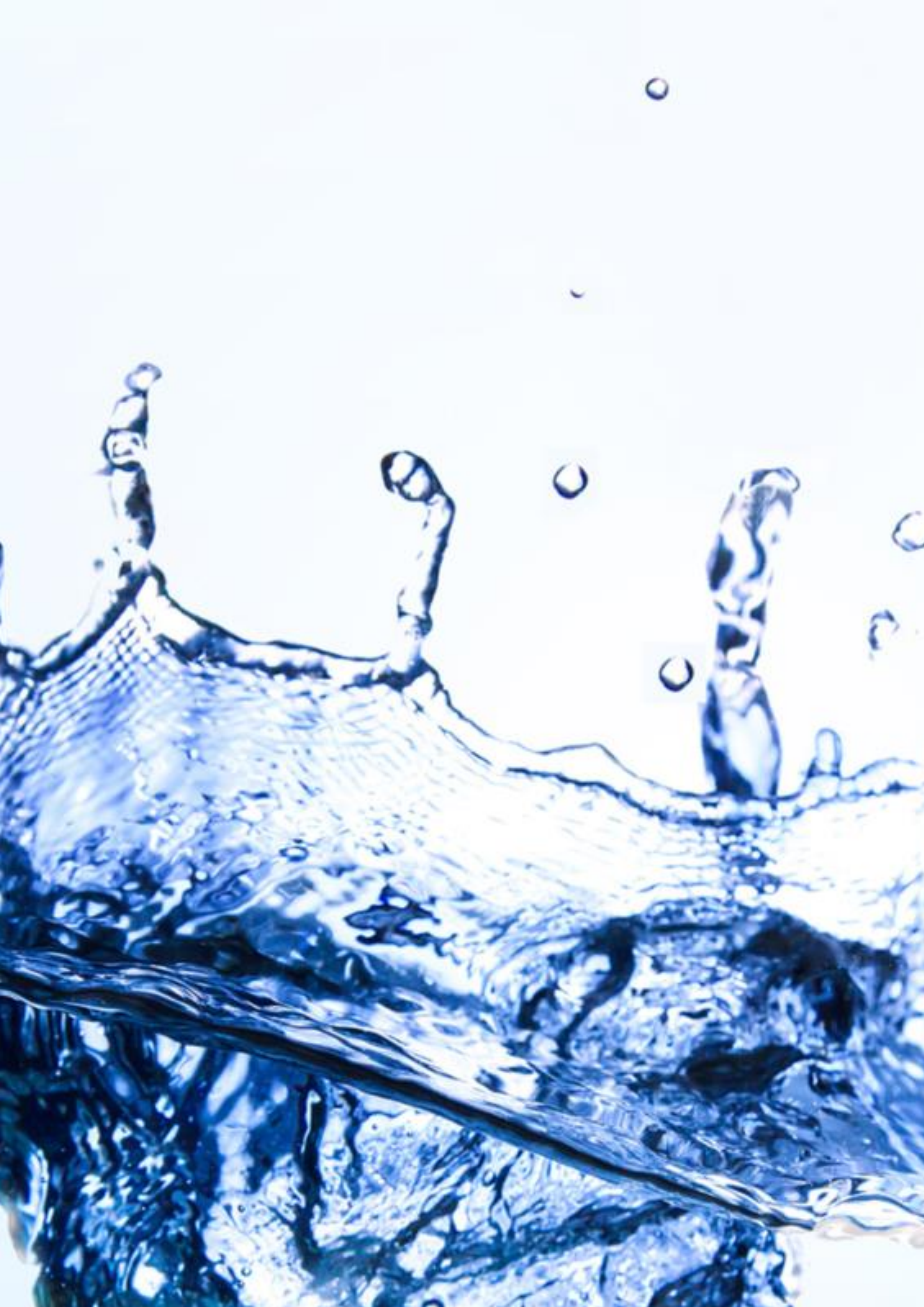


Chapter 10

Conclusions / Conclusiones

Conclusions

The current doctoral thesis contributes to a better understanding of the performance determinants in both OW swimmers and triathletes. These findings provide valuable information for training and monitoring procedures to improve swimming performance in both endurance sports.

- The pacing strategy adopted by most elite swimmers in the 3000 m race followed a parabolic pattern, with significant variability in both turning performance and stroke parameters.
- Elite OW swimmers showed high swimming speeds at LT, close to the maximum values obtained in the incremental tests. These swimmers are therefore able to maintain speeds close to the maximum for long periods of time.
- In male swimmers, the speed at 4 mmol$\cdot$1^{-1} of [La^{-}] may serve as a practical approximation of the LT. However, caution should be exercised due to potential individual variability. In female swimmers, the speed at individual LT was notably below to the speed at 4 mmol$\cdot$1^{-1}, overestimating true aerobic capacity.
- Elite OW swimmers with a higher speed at LT demonstrated better performance in most competitive swimming events, emphasizing the importance of LT in training and assessment in endurance sports.
- Elite OW swimmers showed no changes in performance or physiological factors during the incremental protocol tests across different seasons. However, the changes observed in SL and SI between measurement tests indicated some technical adaptations in males.
- The higher [La^{-}] at LT intensities observed in the fastest male swimmers highlighted the importance of anaerobic pathways in open water races, where swimming close to or at LT intensities and sprinting in the final meters are often decisive.
- Male swimmers achieved their maximum speed by relying on greater SL and SI, whereas the fastest female swimmers achieved higher SR, showing clear sex-induced kinematic differences.

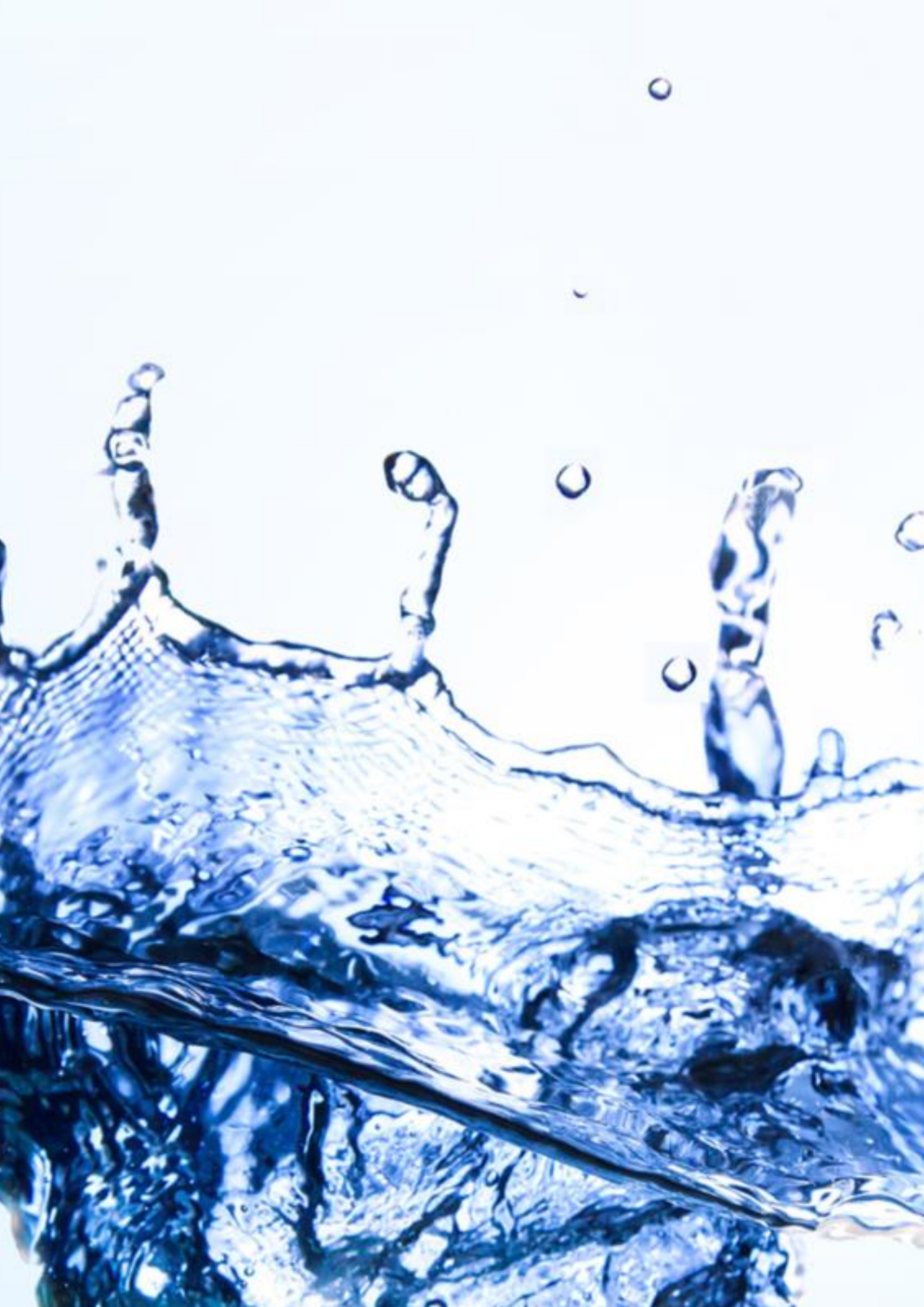
- Swimming performance in elite triathletes was influenced by metabolic efficiency and technical skill, with *E* and SI being key factors in the 1500 m pool swimming.
- Triathletes and coaches should design specific open water sessions to improve efficiency in the competitive environment, as SI was also determinant in this open water swimming.
- Open water conditions impaired kinematics and efficiency compared to pool swimming. However, the physiological demands were similar in open water and pool conditions.
- The fastest elite triathletes in open water were also the fastest in the pool. In this sense, their swimming technique adapted similarly to the different swimming conditions.

Conclusiones

La presente tesis doctoral contribuye a una mejor comprensión de los factores de rendimiento tanto en nadadores de aguas abiertas como en triatletas. Estos hallazgos aportan información valiosa para los procedimientos de entrenamiento y monitorización destinados a mejorar el rendimiento en natación en ambos deportes de resistencia.

- La estrategia de ritmo adoptada por la mayoría de los nadadores de élite en la prueba de 3.000 m siguió un patrón parabólico, con una variabilidad significativa tanto en el rendimiento de los virajes como en los parámetros de brazada.
- Los nadadores de élite de aguas abiertas mostraron altas velocidades de nado en el umbral de lactato, cercanas a los valores máximos obtenidos en las pruebas incrementales. Por tanto, son capaces de mantener velocidades cercanas a la máxima durante largos periodos de tiempo.
- En hombres, la velocidad a 4 $mmol \cdot 1^{-1}$ de $[La^{-}]$ puede servir como aproximación práctica del umbral de lactato. Sin embargo, debe tenerse precaución debido a la posible variabilidad individual. En mujeres, la velocidad a umbral de lactato individual fue notablemente inferior a la velocidad a 4 $mmol \cdot 1^{-1}$, sobrestimando la capacidad aeróbica real.
- Los nadadores de élite en aguas abiertas con una mayor velocidad a umbral de lactato demostraron un mejor rendimiento en la mayoría de las competiciones de natación, lo que subraya la importancia del umbral de lactato en el entrenamiento y la evaluación en los deportes de resistencia.
- Los nadadores de élite de aguas abiertas no mostraron cambios en el rendimiento ni en los factores fisiológicos durante los test incrementales entre las diferentes mediciones. Sin embargo, los cambios observados en SL y SI entre temporadas indicaron algunas adaptaciones técnicas en los hombres.
- La mayor $[La^{-}]$ a intensidades de umbral de lactato observada en hombres más rápidos puso de relieve la importancia de las vías anaeróbicas en las competiciones de aguas abiertas, donde nadar cerca o a intensidades de umbral de lactato y esprintar en los metros finales suelen ser decisivos.

- Los hombres alcanzaron su velocidad máxima apoyándose en una mayor SL y SI, mientras que las nadadoras más rápidas lograron una mayor SR, lo que muestra claras diferencias cinemáticas inducidas por el sexo.
- El rendimiento en natación de los triatletas de élite se vio influido por la eficiencia metabólica y la habilidad técnica, siendo *E* y SI factores clave en los 1500 m de natación en piscina.
- Los triatletas y los entrenadores deben diseñar sesiones específicas en aguas abiertas para mejorar la eficiencia en el entorno competitivo, ya que el SI también fue determinante en la natación de aguas abiertas.
- Las condiciones en aguas abiertas perjudicaron la cinemática y la eficiencia en comparación con la natación en piscina. Sin embargo, las exigencias fisiológicas fueron similares en aguas abiertas y en piscina.
- Los triatletas de élite más rápidos en aguas abiertas también lo fueron en la piscina. Asimismo, su técnica de nado se adaptó de forma similar a las diferentes condiciones de nado.



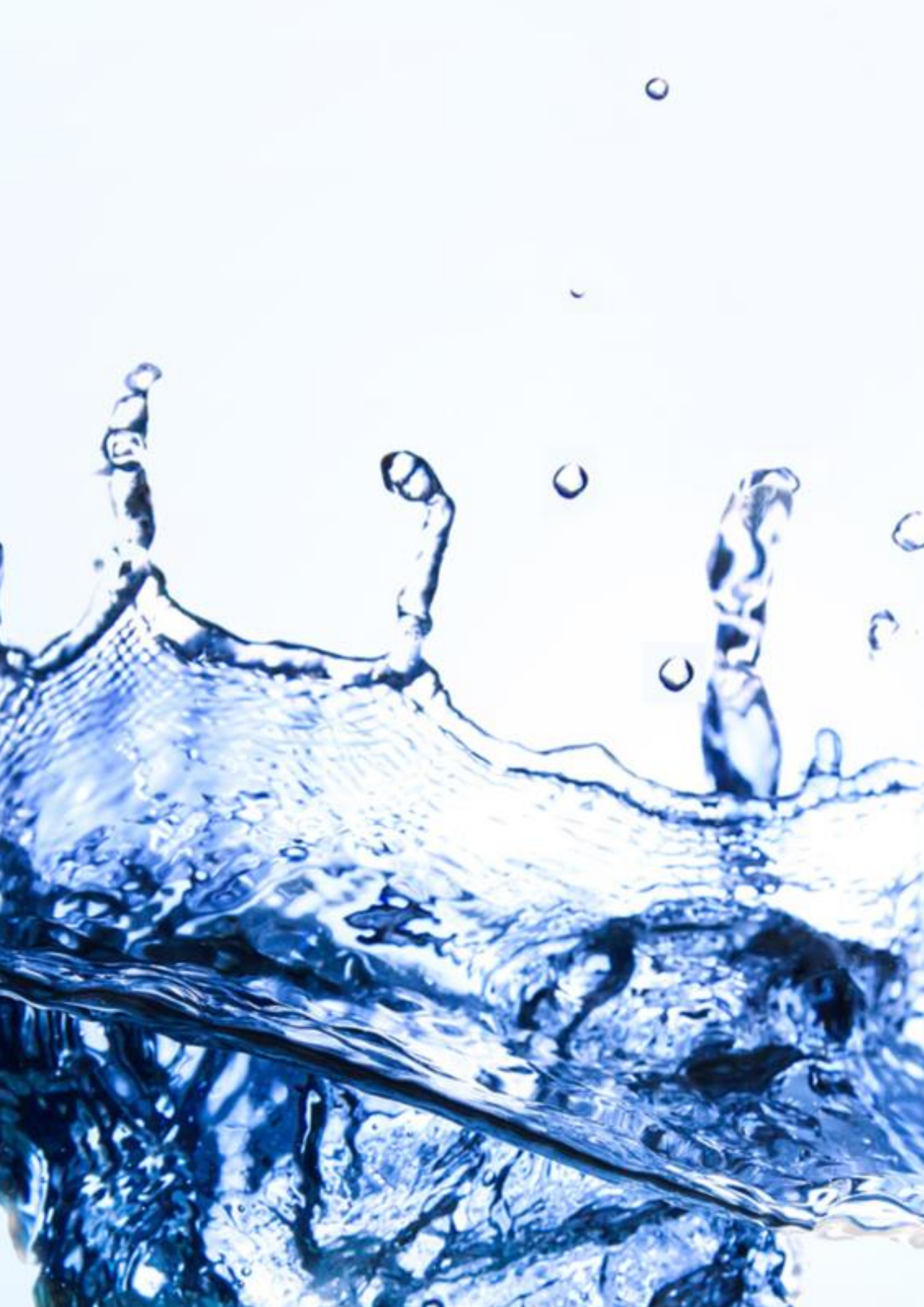
Chapter 11

Suggestions for future research

Suggestions for future research

The current thesis opens up new avenues for practical research into the swimming performance of open water swimmers and triathletes. Although some aspects have been clarified, many questions remain unanswered. Suggestions for future research to fill these gaps are outlined:

- To examine the relationships between the different pacing strategies adopted by long-distance swimmers and their physiological responses.
- To identify the most effective pacing strategy based on individual swimmer characteristics to optimize performance.
- To monitor other key physiological factors and their possible long-term changes in open water swimmers and triathletes.
- To compare the physiological and biomechanical factors between open water swimmers and triathletes in both training and competition environments.
- To study the performance determinants of swimmers and triathletes in real competitive situations, as other factors may influence performance.
- To increase the sample size of female swimmers and triathletes for a more comprehensive analysis.
- To implement a specific training program aimed at maximizing swimming efficiency in triathletes and to investigate the physiological and biomechanical effects following the intervention.
- To analyze and compare physiological and biomechanical factors in other performance levels of swimmers and triathletes.



Annexes

I. SHORT CURRICULUM VITAE

PERSONAL DATA

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EDUCATION

2013-2019	Double Bachelor's Degree in Physical Activity and Sports Science and Primary Education with a specialization in Physical Education. Faculty of Education and Sport Sciences, University of Granada, Melilla, Spain.
2019-2021	Double Master's Degree in Research in Physical Activity and Sport and Teacher Training, Faculty of Sport Sciences, University of Granada, Granada, Spain.
2020-2024	PhD Student in Biomedicine. Aquatics Lab, Department of Physical Education and Sports, Faculty of Sport Sciences, University of Granada, Granada, Spain.

GRANTS

2016-2017	Erasmus + Program Grant at the Jagiellonian University, Krakow, Poland, supported by the University of Granada.
2018-2019	Research Initiation Fellowship supported by the University of Granada.
2020-2024	FPU Research Fellowship. University Teacher Training supported by the Ministry of Science, Innovation and Universities, Government of Spain.

2023 **(April - July)** International Research Mobility Grant at the University of Rome 'Foro Italico', Rome, Italy, supported by the Ministry of Science, Innovation and Universities, Government of Spain.

PUBLICATIONS

- **López-Belmonte, Ó**., Ruiz-Navarro, J. J., Gay, A., Cuenca-Fernández, F., Mujika, I., & Arellano, R. Analysis of pacing and kinematics in 3000 m freestyle in elite level swimmers. Sports Biomech 2023; 1–17. IF JCR: 2.0; Q2, Sport Sciences.
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TEACHING EXPERIENCE

2020-2021 Sports Specialization: Cycling (3 ECTS Credits). Degree in Physical Activity and Sport Sciences. University of Granada, Spain.
Sports Improvement: Cycling (3 ECTS Credits). Degree in Physical Activity and Sport Sciences. University of Granada, Spain.

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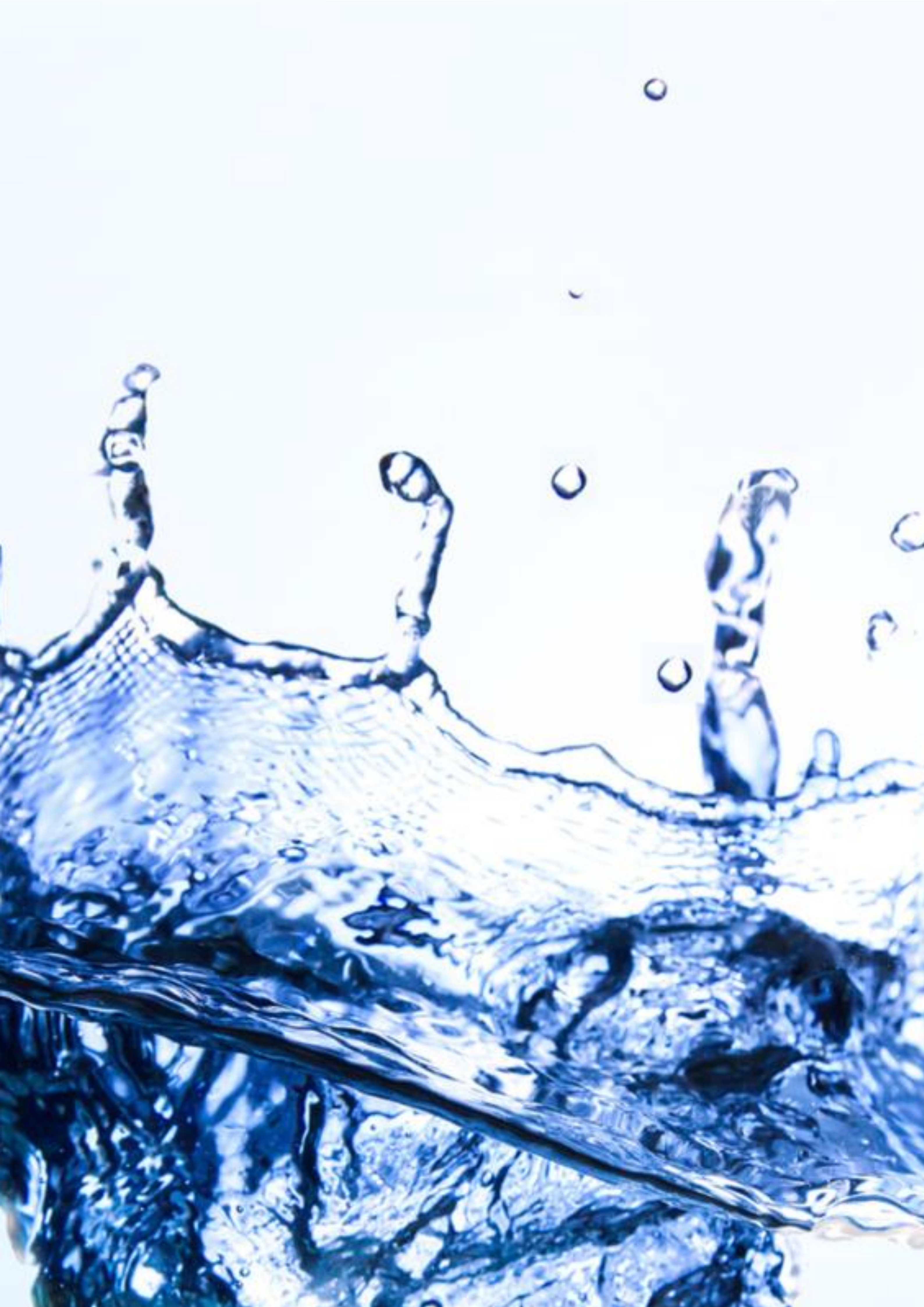
	Recreational and Leisure activities (2.4 ECTS Credits). Degree in Physical Activity and Sport Sciences. University of Granada, Spain.
2023-2024	Academic Tutor for Practicum students (0.6 ECTS Credits). Degree in Physical Activity and Sport Sciences. University of Granada, Spain.

RESEARCH PROJECTS

2020-2024	Member of the Research Group Aquatics Lab – CTS-527: 'Sports and Physical Activity in the Aquatic Environment'. Department of Physical Activity and Sports, Faculty of Sport Sciences, University of Granada, Granada, Spain.
2022-2023	Project Research Staff of the Swimming Performance Evaluation from the Spanish Swimming Federation (RFEN).
2022-2024	Project Research Staff of PID2022-142147NB.I00 "SWIM III: Effects of the application of different specific warm-ups [PAPE: Post-activation Performance Enhancement] on muscular, physiological and technical response in competitive swimmers.

OTHER MERITS

- Extraordinary Award for best 2019 academic performance in Double Bachelor's Degree in Physical Activity and Sports Science and Primary Education.
- Award for the best Final Degree Project in 2019.
- Six participations in International Congress.
- Author of more than ten Scientific Transfer Reports in the area of swimming.



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Acknowledgements | Agradecimientos

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Open water swimming earned its place in the Olympic program at the 2008 Beijing Games with the inclusion of the 10 km marathon swimming, a race that requires both exceptional endurance and mental strength. Similarly, triathlon made its Olympic debut at the 2000 Sydney Games and quickly became one of the most demanding endurance sports. Despite being distinct sports, open water swimming and triathlon share key similarities, particularly by the open water environment in which these events are held. The unpredictable nature of open water presents unique challenges to both swimmers and triathletes. These factors require athletes to constantly adapt and push themselves to their physical and mental limits. In recent years, both disciplines have gained significant momentum, making them central to modern endurance sports. The overall aim of this International Doctoral Thesis is to provide a deeper understanding of the performance determinants of elite open water swimmers and triathletes. This work presents a holistic approach to monitoring training and assessing the unique challenges of these sports, contributing essential knowledge for optimizing performance in both open water swimming and triathlon.

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