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Determinant factors of sprint swimmers' performance: influence of biomechanical and physiological variables

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Factores determinantes del rendimiento en nadadores velocistas: influencia de variables biomecánicas y fisiológicas

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Si puedo ver más lejos de lo que imaginé
es porque estoy a hombros de gigantes

A Carmen María de Jimena y
Juan Antonio de Algeciras,
mis padres, mis gigantes

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LIST OF ABBREVIATIONS

AnAL	Anaerobic alactic contribution
AnCV	Anaerobic critical velocity
ANOVA	Analysis of variance
AnL	Anaerobic lactic contribution
A*p*	Amplitude of the fast $\dot{V}O_2$ component
A_{sc}	Amplitude of the slow $\dot{V}O_2$ component
ATP	Adenosine triphosphate
β	Constant for O_2 equivalent of the blood lactate concentration difference between before and after exercise
BMI	Body mass index
CI	Confidence interval
CMJ	Countermovement jump
CMJ_H	Countermovement jump height
CO_2	Carbon dioxide
CSS	Clean swimming speed
CV	Critical velocity
d	Effect size
dF	Intra-cyclic force variation
dv	Intra-cyclic velocity variation
$\dot{E}$	Metabolic power
E_{tot}	Total energy expenditure
E_{ana}	Anaerobic energy expenditure
$\dot{E}_{ana}$	Anaerobic metabolic power
F	Force
Favg	Average force measured in tethered swimming
FINA	International Swimming Federation
Fmax	Maximum force measured in tethered swimming
HR	Heart rate
HR_{base}	Heart rate before exercise
HR_{net}	Heart rate difference between before and after exercise
Hz	Hertz

I	Impulse
Iavg	Average impulse measured in tethered swimming
ICC	Intra-class correlation coefficient
IPAQ	International Physical Activity Questionnaire
Imax	Maximum impulse measured in tethered swimming
κ	Cohen's Kappa coefficient
kg	Kilogram
km	Kilometer
L	Liter
$[La^-]$	Blood lactate concentration
$[La^-]_{max}$	Maximal blood lactate concentration
$[La^-]_{net}$	Blood lactate concentration difference between before and after exercise
m	Meter
M	Body mass
mM	Millimoles
Max U	Maximum underwater swimming velocity
Mean U	Mean underwater swimming velocity
METs	Metabolic equivalent of task
min	Minute
Min U	Minimum underwater swimming velocity
ml	Milliliter
n	Number of participants
η_p^2	Partial eta squared
O_2	Oxygen
PCr	Phosphocreatine
pH	Potential of hydrogen
PHV	Peak height velocity
P_i	Inorganic phosphate
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analyses
PUf_{avg}	Pull-up's average propulsive force
PUp_{avg}	Pull-up's average propulsive power

PUv_{avg}	Pull-up's average propulsive velocity
r	Correlation coefficient
r^2	Coefficient of determination
RMSE	Root-mean-square error
ROM	Range of motion
RPE	Borg rating of perceived exertion scale
s	Second
SD	Standard deviation
SI	Stroke index
SL	Stroke length
SR	Stroke rate
TD_p	Time delay of the fast $\dot{V}O_2$ component
TD_{sc}	Time delay of the slow $\dot{V}O_2$ component
τ_p	Time constant of the fast $\dot{V}O_2$ component
τ_{sc}	Time constant of the slow $\dot{V}O_2$ component
T.U.	Training units
µL	Microliter
UUS	Undulatory underwater swimming
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2peak}$	Peak oxygen uptake
WD	In-water + dry-land training group
WO	In-water training group

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Chapter 7

ABSTRACT

Competitive swimming pool events can be split-up in the start, the clean swimming, the turn(s), and the finish phases for in-depth analysis. The contribution of each one of these components is crucial in sprint swimming, since a fraction of a percent difference in performance determines whether a swimmer wins or loses a race. Therefore, the main purpose of this thesis was to increase the understanding of the biomechanical and physiological variables that influence sprint swimming performance.

First, in order to investigate the relationship between tethered forces in a flume and sprint swimming performance, 16 male swimmers performed four 30 s tethered swimming tests in a flume at 0, 0.926, 1.124, and 1.389 $m \cdot s^{-1}$ water flow speeds and 25, 50, and 100 m front crawl trials. Subsequently, to provide a comprehensive approach between two anaerobic tests, muscle strength, and swimming performance, 14 males and 9 females performed an anaerobic critical velocity test, two 30 s tethered swimming tests in a flume at 0, and 1.124 $m \cdot s^{-1}$ water flow speeds, five pull-ups and countermovement jumps, and 50 m front crawl. Then, physiological and biomechanical variables were evaluated in 13 males and 8 females before and after a five-weeks off-season period to quantify the effects of detraining on 50 m front crawl. Furthermore, a systematic review was developed to provide an overview of the determinants of undulatory underwater swimming (UUS). Lastly, eight male and six female swimmers performed three countermovement jumps and three maximal UUS trials before and after a five-weeks training period. Swimmers were divided into two different UUS training groups (in-water only *vs.* in-water combined with conical exercises on land) to analyze the impact of skill-specific training and strength training on UUS performance.

The results of the present doctoral thesis showed that tethered swimming variables were correlated with sprint swimming performance. These correlations were stronger as the water flow speed increased. The anaerobic critical velocity was positively correlated with tethered swimming in both conditions and both tests were associated with dry-land-based variables and 50 m swimming performance. The five-weeks training cessation evoked a 50 m performance impairment in both sexes. After the five-weeks, it was observed lower stroke rate and clean swimming speed, higher heart rate, anaerobic metabolic power deterioration (only in males), lower in-water force at zero speed (only in males), and upper and lower body strength impairments in males and females, respectively. The systematic search included a total of 15 articles, which provided a substantial body of research on kicking frequency, vertical toe and body wave velocity, angular velocity of the joints, distance per kick, joint amplitudes and mobility, and body position in UUS performance. The five-weeks training protocol evoked UUS improvements in the combined group (in-water and dry-land exercises), whereas no changes were elicited in the in-water only training group.

Collectively, the results of this doctoral thesis suggest that the propulsive force depends on the swimmer's muscular strength production and the swimmers' ability to effectively apply that force in the water, both of which should be taken into consideration when training and monitoring. Tethered swimming and the anaerobic critical velocity might be used as interchangeable tools for evaluating anaerobic performance. Coaches should find alternatives to minimize the detraining effects prompted during the off-season. Moreover, this doctoral thesis suggests that caudal momentum transfer as well as vertical toe velocity should be maximized to improve UUS performance, taking into account individual characteristics. Furthermore, specific lower limbs strength exercises in conjunction with in-water training should be performed to improve UUS performance.

RESUMEN

Las pruebas de natación de competición en piscina se dividen en las siguientes fases, salida, nado, viraje(s) y llegada para un análisis en profundidad. La contribución de cada uno de estas fases es crucial en las pruebas de velocidad de natación, ya que una pequeña diferencia en el rendimiento determina si un nadador gana o pierde una prueba. Por lo tanto, el objetivo principal de esta tesis es aumentar la comprensión de las variables biomecánicas y fisiológicas que influyen en el rendimiento de las pruebas de velocidad en natación.

En primer lugar, para investigar la relación entre las fuerzas de nado atado en una piscina contracorriente y el rendimiento en las pruebas de velocidad, 16 nadadores realizaron 4 pruebas de 30 s de nado atado en una piscina contracorriente a velocidades de flujo de agua de 0, 0’926, 1’124 y 1’389 $m \cdot s^{-1}$ y 25, 50 y 100 m crol. Posteriormente, para proporcionar un enfoque global entre dos pruebas anaeróbicas, la fuerza muscular y el rendimiento en 50 m, 14 nadadores y 9 nadadoras realizaron un test de velocidad crítica anaeróbica, 2 pruebas de 30 s de nado atado en piscina contracorriente a velocidades de flujo de agua de 0 y 1’124 $m \cdot s^{-1}$, cinco dominadas, cinco saltos con contramovimiento y un 50 m crol. A continuación, se evaluaron variables fisiológicas y biomecánicas en 13 nadadores y 8 nadadoras, antes y después de un periodo de cinco semanas de transición entre temporadas, para cuantificar los efectos del desentrenamiento en 50 m crol. Además, se realizó una revisión sistemática con el fin de proporcionar una visión general de los factores determinantes del nado ondulatorio subacuático (NOS). Finalmente, nadadores y 6 nadadoras fueron evaluados realizando tres saltos con contramovimiento y tres pruebas máximas de NOS, antes y después de un periodo de entrenamiento de cinco semanas. Los nadadores fueron divididos en dos grupos de entrenamiento diferentes (solo agua *vs.* agua combinado con ejercicios en tierra usando poleas cónicas) para analizar el impacto tanto del entrenamiento de las habilidades específicas como el entrenamiento de fuerza en el rendimiento del NOS.

Los resultados de la presente tesis mostraron que las variables de nado atado estaban correlacionadas con el rendimiento en pruebas de velocidad. Estas correlaciones eran más fuerte a medida que aumentaba la velocidad del flujo de agua. La velocidad crítica anaeróbica se correlacionó positivamente con el nado atado en las dos condiciones

y ambas evaluaciones se asociaron con las variables de fuerza fuera del agua y con el rendimiento de 50 m crol. La interrupción del entrenamiento durante cinco semanas provocó un deterioro del rendimiento de 50 m crol en ambos sexos. Después de las cinco semanas se observó una menor frecuencia de brazada y velocidad de nado, una mayor frecuencia cardíaca, un deterioro de la potencia metabólica anaeróbica (sólo en los chicos), una reducción de la fuerza en nado atado a velocidad cero (sólo en los chicos), y una disminución de la fuerza de los miembros superiores en chicos y de los miembros inferiores en chicas. La revisión sistemática incluyó un total de 15 artículos, que proporcionaron un conjunto sustancial de investigaciones sobre la frecuencia de patada, la velocidad vertical de la punta del pie y de la onda corporal, la velocidad angular de las articulaciones, la distancia por patada, las amplitudes y el rango de movimiento de las articulaciones, y la posición del cuerpo en el rendimiento del NOS. El protocolo de entrenamiento de cinco semanas mostró mejoras en el grupo combinado (agua y fuerza), mientras que el grupo de entrenamiento en el agua no obtuvo cambios en el rendimiento del NOS.

En conjunto, los resultados de esta tesis doctoral sugieren que la fuerza propulsiva depende de la producción de fuerza muscular del nadador y de la capacidad de los nadadores para aplicar eficazmente esa fuerza en el agua, aspectos que deben tenerse en cuenta en el entrenamiento y la monitorización. El nado atado y la velocidad crítica anaeróbica podrían utilizarse como herramientas intercambiables para evaluar el rendimiento anaeróbico. Los entrenadores deberían encontrar alternativas para minimizar los efectos del desentrenamiento durante el periodo de transición entre temporadas. Asimismo, esta tesis doctoral sugiere que la transferencia del impulso caudal, así como la velocidad vertical de la punta del pie deben maximizarse para mejorar el rendimiento del NOS, siempre teniendo en cuenta las características individuales. Además, para mejorar el rendimiento del NOS deberían de incluirse ejercicios de fuerza específicos de los miembros inferiores en seco junto al entrenamiento específico en el agua.

CHAPTER 1:

General introduction

Competitive swimming: an overview

Swimming, as an Olympic sport from the beginning of the modern Olympic Games in 1896, is one of the most popular sports worldwide. In competitive swimming, performance is measured through the time spent to cover a given distance. The competitive distances have changed over the years and nowadays, the International Swimming Federation (FINA) recognizes the following ones in long course pool [1]: 50, 100, and 200 m in all four strokes (butterfly, backstroke, breaststroke, and freestyle) and this latter distance also in medley, 400 m freestyle and medley, and 800 and 1500 m freestyle. In addition to these events, the 100 m medley is also recognized in short course pool [1]. These distances are clustered in sprint (50 and 100 m), middle (200 and 400 m), and long (800 and 1500 m) distance events [2]. Furthermore, the FINA recognizes "Open water swimming" discipline, in which longer distances are developed in rivers, lakes, seas, or water channels [1].

All the aforementioned competitive swimming pool events can be split-up into several phases for in-depth analysis: the start, the clean swimming, the turn(s), and the finish [3]. The contribution of each one of these components to overall performance varies depending on the distance [4–6]. In sprint events, for instance, the four phases play a crucial role in the final outcome and therefore, deserve specific attention. Indeed, only 0.01 and 0.02 s separated the gold and silver medalist in men's and women's 50 m freestyle events in Rio 2016 Olympic Games, respectively. Hence, a minor difference in performance determines whether a swimmer wins or loses a race [7].

Start and turn phases

These two phases are defined as the segment covered from the starting signal (start) or the initiation of the turn (turn) to the emersion [8](of note, in race analysis the definition of these phases may vary according to different authors [8]). The emersion must occur before the 15 m mark since this is the maximum distance that a swimmer can travel underwater before his/her head is required to break the surface of the water (in all strokes except for breaststroke)[1]. These two phases are also known as the acyclic phases and for detailed analyses are often divided into subsections such as diving / wall push-off, underwater phase, and breakout [8]. Having well-developed acyclic phases is essential to yield high performance in major international competitions [7,9,10], especially in sprint swimming events [11]. Among the subsections, the acyclic phases clearly rely on the optimization of the underwater phase [6,12]. Hence, swimming research has widely focused on determining the factors that may explain its performance [13].

Clean swimming phase

The clean swimming phase is defined as the segment covered stroking, from the emersion to the initiation of the turn [14]. However, the emersion distance varies between swimmers and consequently, fixed distances (*e.g.*, 15 – 45 m in long course pool or 10 – 20 m in short course pool) have been used to standardize the comparisons among races or swimmers [8]. These fixed distances may underestimate the mean speed during the clean swimming phase [15] but also facilitates its calculation since clean swimming speed is measured as the quotient of the distance and the time to cover that distance [7]. Likewise, as swimming is a cyclic sport (*i.e.*, periodic movement performing synchronized actions from the limbs and the trunk), clean swimming speed can be also calculated as the product of stroke length (SL) and stroke rate (SR). Therefore, the inter-relationship of these factors is one of the major points of interest in swimming research [16].

Finish phase

The finish phase is defined as the last segment of the race, which covers the final 5 meters [7] (although 7.5 or 10 m have also been used [8]). During this phase swimmers approach the wall stroking as in the clean swimming phase, however, the strokes are altered (*e.g.*, changing the SR) compared to the clean swimming phase [17]. Unfortunately, due to the small contribution to the total race time, the finish is the least investigated phase of all [8]. Nevertheless, the determinants of the finish phase are considered similar to the clean swimming phase.

Determinant factors in sprint free swimming

One of the first attempts to explain the swimming techniques and training procedures based on empirical data was the textbook "The science of swimming" by James E. ('Doc') Counsilman [18]. From that moment on, a solid and large scientific community emerged to investigate competitive swimming [13]. As a result of all the previous work, it might be concluded that success in swimming performance depends on biomechanical, physiological, psychological, and anthropometrical factors to a greater or lesser extent depending on the event [13]. Among the variety of factors, muscular force production while stroking [19] and aerobic / anaerobic energy production [20] have been highlighted as determinants of sprint swimming performance.

Muscular force production while stroking

The direct measurement of the components affecting performance is complicate to obtain due to the aquatic environment. This leads, in most cases, to land-based measurements, which, although valuable in determining training adaptations, do not meet the criterion of specificity and neglect the swimming technique [21]. This is crucial because, unlike on land, where humans uses the ground surface as a stable support to apply force and move due to the grounds' reaction force, in the aquatic environment humans need to create the stable support in the water, using its density and viscosity. The swimmers' displacement is therefore generated using hydrodynamic reaction forces to overcome water resistance [22] and neglecting the specificity of the environment might lead to inaccurate conclusions when assessing swimmers' propulsive forces [23].

Swimming research has also used experimental techniques to assess the propulsive force in the water, such as the measurement of active drag or the velocity perturbation method [24,25]. These measurements are based on the fact that at constant speed active drag and propulsive force are equal in magnitude and opposite in direction. Hence, these methods estimate mean propulsive force by computing active drag rather than measuring the force directly [26]. On the other hand, one of the most common approaches to the direct measurement of force in the water is tethered swimming [27]. Tethered swimming involves fixing the swimmer to a force transducer through a non-elastic cable attached to swimmers' hip [28–30]. The force transducer may be fixed on the pool wall aligned with the swimming direction and minimizing interferences with swimmers' normal technique [30]. However, it presents the disadvantage of the feet touching the cable producing alterations to assessed force values [27]. Likewise, it could also be fixed higher than the water surface (*e.g.*, starting block) which may overcome the aforementioned inconvenience. Nonetheless, this placement creates an angle between the cable and the water surface that should be rectified to evaluate the horizontal component of the force exerted [31].

During tethered swimming, similar muscular activity [32] and physiological responses to free swimming are produced [33]. Hence, the assessment of force via tethered swimming has been proposed as a valid and reliable methodology [27,29,34,35] that also enables the assessment of anaerobic performance [36–39], showing high correlations with anaerobic land-based tests [27,39]. However, tethered swimming may induce changes to stroke patterns [40], especially in the first half of the aquatic path where the hand velocity and acceleration differ with respect to free swimming [41]. These changes to the stroke pattern are likely due to the stationary water and the absence of swimmers' displacement. It was then suggested that the inclusion of a swimming flume could overcome these differences and therefore tethered swimming would be performed more similar to free swimming [42]. Thus, in this doctoral thesis, one cross-sectional study analyzing the relationship between tethered swimming in a flume and sprint free swimming performance was conducted (**Chapter 3**).

The tiny differences in competitive swimming lead swimming coaches to continuously search for the slightest improvement in performance. In this endeavor, swimmers perform several sessions per week of resistance training to enhance muscle strength [43]. Indeed, the enhancement of the lower limbs strength prompted by resistance training seems worthwhile to elicit improvements in swimming start and turn performance [44,45]. However, regarding swimming performance, some inconsistencies have been found, whereas some studies reported that resistance training had positive effects, others studies found that gains in strength were not transferred into better swimming performance [46]. The reason for this lack of improvement could be explained by the non-swimming specific nature of the resistance exercises and the non-transferee to the propulsive force produced during swimming [47].

A positive transfer of resistance training happens when training focuses on improving the muscle activation pattern required in the execution of the sports skills [48]. Hence, the training adaptations are determined by the muscle group trained, the range of motion, or the speed of movement among others factors [47]. For instance, the performance in some exercises such as bench press and lat pull-down, which involve the same muscles used during swimming, presented positive correlation with tethered swimming [49,50]. However, among the resistance exercises explored, information related to the pull-up is scarce, despite being widely used by swimming strength and conditioning coaches during resistance training [43,51]. Therefore, in this doctoral thesis, one cross-sectional study analyzing the relationship between tethered swimming, strength-based variables, sprint swimming performance and its kinematics was developed (**Chapter 4**).

Aerobic / anaerobic energy production

Three distinct but closely integrated metabolic processes work together to satisfy the energy requirements of muscles. The aerobic (oxidative) energy system refers to the combustion, in the presence of oxygen, of carbohydrates, fats, and, to a lesser extent, proteins. This is an efficient system for the production of energy, with the largest energy-producing capacity of the three energy pathways. However, the aerobic system is slow to turn on, as it involves three different processes (glycolysis [carbohydrates] or beta-oxidation [fats], the Krebs cycle, and the electron transport chain) that slow down energy production [52]. Thus, as this system requires a longer time to provide energy, the aerobic energy contribution increases as the exercise time increases. Consequently, sprint swimming events have lower aerobic energy contribution than middle and long distance events [53]. Indeed, the aerobic energy system provides ~30 and ~45% of the total energy contribution in 50 and 100 m, respectively [36,53–55]. The remaining energy is obtained via anaerobic metabolism.

The anaerobic metabolism is separated into two discrete systems: the ATP-PCr and the glycolytic system. The ATP-PCr system, also known as anaerobic alactic, is the simplest of the three energy systems. This system does not release the energy of phosphocreatine (PCr) breakdown directly for cellular work, instead, it regenerates the ATP in the cells to maintain a relatively constant supply. Since the small amount of ATP in the muscle cells is used to obtain energy, the ATP-PCr system degrades the PCr and donates the inorganic phosphate (Pi) obtained to ADP generating more ATP. As the simplest energy system, the ATP-PCr is the first system to provide energy, sustaining muscles' energy between 3 and 15 s [56]. Thus, its energy contribution decreases as exercise time increases. Consequently, in sprint swimming events the ATP-PCr has a higher contribution than in middle and long distance events [53].

The glycolytic system or also known as anaerobic lactic system, is the second method of ATP production. This system obtains energy through the degradation of glucose (process known as glycolysis) to pyruvate, which in absence of oxygen is converted to lactate [56]. The amount of ATP produced via the glycolytic system is not large, but it supplies energy when the oxygen is limited, approximately during the first 2 min of intense exercise. Therefore, the glycolytic system has high contribution in sprint events and 200 m, but its contribution decreases from the latter distance on [53,57].

Anaerobic assessment

Physiological testing requires the accurate assessment of swimming-specific underlying factors [58]. Two of the most reliable indicators of swimmers metabolic profile are the oxygen uptake ($\dot{V}O_2$) kinetics and the metabolic contributions [55,59]. The $\dot{V}O_2$ kinetics to the onset of exercise provides a valuable evaluation of swimmers' body to adapt to different metabolic demands, providing useful information of the circulatory and metabolic responses to exercise [60]. From the $\dot{V}O_2$ kinetics assessment, it is possible to obtain the contribution of the three aforementioned energy systems. However, due to the aquatic environment, its assessment is complicated [61]. Yet, nowadays, thanks to the evolution of technology and the development of automated portable devices, the $\dot{V}O_2$ kinetics and energy contributions can be assessed in the water.

The $\dot{V}O_2$ is directly measured using a telemetric portable gas analyzer, which is connected to a specific respiratory snorkel (AquaTrainer®) and valve system [55]. This snorkel allows to continuously measure (breath by breath) during the whole swimming effort (on-kinetics) without increasing active drag in front crawl [62]. However, the snorkel affects the execution of the turns, increasing the time and restricting the underwater phase [62]. Hence, to measure in a more ecological way, reliable swimming recovery-based methods are also applied (off-kinetics) to estimate $\dot{V}O_2$ kinetics-related variables [63,64]. Indeed, from the fast component of the $\dot{V}O_2$ off-kinetics, the anaerobic alactic energy contribution is obtained [64,65]. On the other hand, the anaerobic lactic energy contribution is calculated as the product of blood lactate concentration ($[La^-]$) raise, the constant for oxygen (O_2) equivalent (2.7 $ml \cdot kg^{-1} \cdot mM^{-1}$ [66]), and the swimmers' body mass [67](further explained in **Chapter 5**).

Although highly valuable, the above-mentioned assessment only allows to measuring one swimmer at a time, being a complex and expensive evaluation for most swimming teams [68]. Hence, alternatively, there has been a development of other assessments, easy to apply, reliable, and without extra costs for coaches to be used in their monitoring process. For instance, one of the most widely accepted and used assessments is the critical velocity (CV). The CV is defined as the maximal speed that can be sustained without exhaustion for a long period of time being used as an index of aerobic performance [69]. It is calculated from the slope of the regression line between different distances performed at maximum speed and the corresponding times [69]. The choice of distances is particularly important in CV estimation [70], as different distances could lead to different CVs [71].

Based on the concept of CV, anaerobic critical velocity (AnCV) was proposed [72]. The AnCV is calculated in the same way as CV but using different short distances trials. Thus, the AnCV is closely associated with 100 m performance [71,72] and it is employed for the assessment of swimmers' anaerobic performance [68]. Several distances such as 50, 100, and 150 m [73] or 15, 25, 37.5, and 50 m [71] have been used to calculate AnCV, exhibiting a stronger relationship with sprint swimming performance when using shorter testing distances [72]. However, scientific evidence on AnCV remains still scarce [68]. Hence, in this doctoral thesis, one cross-sectional study was conducted to analyze the relationship between tethered swimming (as previously mentioned, also used as an anaerobic indicator) and AnCV (**Chapter 4**).

Detraining

The enhancement in swimmers' performance can be mainly due to the optimization of training [74]. Tracking the factors associated with performance provides insights into swimmers' training preparation [75]. This topic has brought the attention of swimming researchers, who has monitored training throughout mesocycles, a macrocycle, or a whole season [76–79]. Nevertheless, because of illness, injuries, or more commonly, the off-season, swimmers' training regimen is interrupted. The off-season is planned to allow swimmers to rest and recover physiologically and mentally with a typical duration ranges of four to six weeks. This duration differs with the calendar of each swimming federation (national or international) and/or due to the requirements of coaches [80]. However, this stoppage evokes a partial or complete loss of training-induced anatomical, physiological, and functional adaptations known as detraining [81].

Although the off-season is planned to reduce the stresses enabling a physiological and mental recovery, it can evoke biomechanical and physiological impairments [81]. For instance, detraining causes an immediate reduction in blood and plasma volume that impairs $\dot{V}O_2$, reducing O_2 supply and utilization and therefore leading to higher maximal and submaximal heart rate (HR) for a similar effort [81]. Recently Zacca et al. [82] observed how these impairments provoked a decline in 400 m front crawl performance. Thus, it is crucial to identify the effects and to comprehend the mechanisms of any associated change in biomechanical and physiological variables that may impair swimming performance [81]. However, detraining has been mainly studied in middle and long distance events with scarce knowledge about sprint swimming performance [82–84]. Hence, in the current doctoral thesis, one longitudinal study to assess the impact of detraining in sprint swimming performance and its determinants was conducted (**Chapter 6**).

Optimization of the underwater phase

In Moscow 1980 Olympic Games swimmers began to prolong the distance traveled underwater using the undulatory underwater swimming (UUS). One of the pioneers was David Berkoff who in Seoul 1988 Olympic Games broke the 100 m backstroke World Record performing 35 and 15 m underwater after the start and turn, respectively. Nine years later Denís Pankrátov broke the 50 m butterfly World Record in short course, without performing a single butterfly stroke, only breathing at the turn and performing the rest underwater using UUS. As a consequence of that, one year later the FINA changed the rules and limited the underwater distance to 15 m in all strokes but in breaststroke [1]. Yet, despite the distance limitation, the underwater phase is one of the most important components in competitive swimming [6,12]. Especially sprint swimming performance highly rely on the optimization of the UUS [11], since the underwater phase contributes up to 30 and 60% of the race distance in short and long course events, respectively.

The UUS consists of performing body undulations while holding a streamline body position with arms outstretched and held together over the head [85]. The propulsion is produced by a “body wave”, which increases in amplitude as it travels caudally throughout the body in a “whip-like” action [86–88]. Each kick cycle comprises a complete downward (downbeat) and upward (upbeat) movement of the lower limbs delimited by the turning points of the toe landmark [89]. In a prone position, the upbeat is characterized by the combination of hip extension and knee flexion and the downbeat is executed by the combination of hip flexion and knee extension [90].

Swimmers encounter a hydrodynamic advantage when traveling underwater, which gives UUS the potential to reach higher speeds than at the surface. This hydrodynamic advantage is expressed as the reduction of total drag forces experienced by the swimmers when traveling underwater [85]. The total drag is the sum of wave (depends on the water surface deformation), profile/pressure (depends on body surface area), and friction/skin drag (depends on the friction between the skin and the water). The main advantage is due to a considerably less wave drag experienced underwater than on the surface, as at ~1 m depth wave drag is reduced considerably [91–93]. Moreover, the frontal surface and frontal shape are minimized in the fusiform streamlined shape adopted while performing UUS, which leads to lower pressure drag than when stroking [85].

In 2009 Connaboy et al. [85] reviewed the findings from both animal and human studies to provide a broad portrayal of the understanding of UUS performance. The authors provided a comprehensive evaluation of the main factors that combine to influence UUS performance. However, it was stated that further research was required to fully appreciate the complexity of UUS and examine how swimmers may further optimize their performance [85]. Indeed, over the last decade, the amount of research trying to understand the key parameters in UUS performance has grown considerably. Hence, it was necessary to provide coaches and swimming specialists with an up-to-date review of

UUS, which might aid in the optimization of UUS training and performance, especially for sprint swimmers. In this regard, within this doctoral thesis a systematic review on the biomechanical, physiological, and/or neuromuscular factors that influence UUS performance was developed (**Chapter 7**).

UUS training

The results of the systematic review (**Chapter 7**) revealed different issues to address in this doctoral thesis. Firstly, most of the studies carried out in UUS research had a cross-sectional design, with an absence of longitudinal investigations. These cross-sectional studies reported the kinematic characteristics of competitive swimmers and their association with UUS performance. In the few longitudinal studies, the effects of specific training on swimmers' performance and technique were analyzed [94–96]. However, these studies were mostly conducted on young swimmers, likely because swimmers are more prone to learn and enhance swimming skills between the ages of 7 and 12 [97]. However, throughout the adolescence, swimmers experience a dramatic improvement in their performance [98] and yet the impact of UUS-specific training on older swimmers is scarce.

Secondly, despite the identified importance of lower limbs strength in other leg-dominated swimming techniques, such as the swimming start [45], only the influence of ankle strength on UUS performance has been analyzed [99]. Indeed, it exists a wide number of studies exploring the relationship between lower limbs strength and swimming start performance [100–102] or the effects of resistance training on swimming start performance [103,104], whereas, the effect of resistance training on UUS performance remains unknown. Hence, in the current doctoral thesis, we reported the effects of a five-weeks training intervention on UUS performance in adolescent swimmers using two different training protocols (**Chapter 7**).

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CHAPTER 2:

Aims / Objetivos

Aims

The overall aim of the current Doctoral Thesis is to increase the understanding of the biomechanical and physiological variables that influence sprint swimming performance. This general aim is addressed in seven specific aims which correspond to five thesis chapters.

Specific aims

- Specific aim 1: To study the relationship between tethered swimming in a flume at different water flow speeds and sprint swimming performance (**Chapter 3**).

- Specific aim 2: To examine the associations between two swim-specific measures of anaerobic performance and dry-land strength (**Chapter 4)**.

- Specific aim 3: To study the association of two swim-specific measures of anaerobic performance and strength-based variables with sprint swimming performance and its kinematic variables. Moreover, it was aimed to analyze the possible sex-induced differences in these parameters (**Chapter 4)**.

- Specific aim 4: To assess the effect of five-weeks training cessation on sprint swimmers' performance, anthropometrics, kinematics, energetics, and strength (**Chapter 5)**.

- Specific aim 5: To identify the determinants of undulatory underwater swimming performance (**Chapter 6)**.

- Specific aim 6: To assess the effect of five-weeks specific training program on undulatory underwater swimming performance and kinematics (**Chapter 7)**.

- Specific aim 7: To evaluate the effect of dry-land strength training on undulatory underwater swimming performance and kinematics (**Chapter 7)**.

Objetivos

El objetivo general de la presente tesis es aumentar el conocimiento de las variables biomecánicas y fisiológicas que influyen en el rendimiento de las pruebas de velocidad en natación. Este objetivo general se aborda en siete objetivos específicos que corresponde a cinco capítulos de la tesis.

Objetivos específicos

- Objetivo específico 1: Estudiar la relación entre el nado atado en piscina contracorriente a diferentes velocidades de flujo y el rendimiento en pruebas de velocidad **(Capítulo 3).**

- Objetivo específico 2: Examinar la asociación entre dos medidas de rendimiento anaeróbica específicas de natación y la fuerza medida en seco **(Capítulo 4).**

- Objetivo específico 3: Estudiar la asociación de dos medidas de rendimiento anaeróbica específicas de natación y la fuerza en seco con el rendimiento de nado y sus variables cinemáticas. Además, se tuvo como objetivo analizar las diferencias entre sexos en estos parámetros **(Capítulo 4).**

- Objetivo específico 4: Examinar el efecto de cinco semanas de cese de entrenamiento en el rendimiento, antropometría, cinemática energética y fuerza de nadadores velocistas **(Capítulo 5).**

- Objetivo específico 5: Identificar los factores determinantes del rendimiento del nado ondulatorio subacuático **(Capítulo 6).**

- Objetivo específico 6: Evaluar el efecto de un programa de cinco semanas de entrenamiento específico en el rendimiento del nado ondulatorio subacuático y su cinemática **(Capítulo 7).**

- Objetivo específico 7: Evaluar el efecto del entrenamiento de fuerza en seco en el rendimiento y la cinemática del nado ondulatorio **(Capítulo 7).**

CHAPTER 3:

Relationship between tethered swimming in a flume and swimming performance

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Abstract

Purpose: This research aimed to study the relationship between tethered swimming in a flume at different speeds and swimming performance. ***Methods:*** Sixteen regional level swimmers performed 25, 50, and 100 m front crawl trials and four 30 s tethered swimming tests at zero, 0.926, 1.124, and 1.389 $m \cdot s^{-1}$ water flow speeds. Average and maximum force, average and maximum impulse, and intra-cyclic force variation (dF) were estimated for each tethered swimming trial. Swimming speed and intra-cyclic velocity variation (dv) were obtained for each free swimming trial. Stroke rate and rate of perceived exertion were registered for all trials. ***Results:*** Tethered swimming variables, both at 1.124 $m \cdot s^{-1}$ and at 1.389 $m \cdot s^{-1}$ water flow speeds, were positively associated with 25 m swimming speed ($p < 0.05$). Average force and maximum impulse in stationary swimming were associated with 25 m swimming speed ($p < 0.05$). A positive relationship between water flow speeds with dF was observed. Swimming performance was not related to dF or dv. Neither stroke rate, nor rate of perceived exertion differed between the four tethered swimming conditions and mean 50 m free swimming speed ($p > 0.05$). ***Conclusions:*** Measuring force in a swimming flume at higher water flow speeds is a better indicator of performance than stationary tethered swimming. It allows assessing the ability to effectively apply force in the water.

Keywords: tethered forces, strength, training, exercise testing, force assessment.

Introduction

Performance in competitive swimming is measured through the time spent to complete an established distance. Muscular force production while stroking [1], swimming technique [2], and aerobic / anaerobic energy production [3] are determinants in competitive swimming performance. Over short distances, the force exerted in water must be high to overcome the water resistance [4]. For that reason, the assessment of the force exerted in swimming becomes extremely important [5]. However, the aquatic environment complicates the direct measurement of force application during swimming [6]. Experimental techniques such as measurement of active drag, velocity perturbation method or assisted towing method have been used to calculate mean propulsive force. These methods calculate mean propulsive force relying on computing active drag rather than measuring the force independently [7], as the main active drag force may be considered as identical in magnitude to the mean propulsive force at a constant speed.

The direct measurement of force has been obtained through tethered swimming, which has been proposed as a valid and reliable methodology to assess swimmers' strength potential [6,8,9]. Moreover, physiological variables in tethered swimming are not significantly different to free swimming of similar duration [5]. Still, there are kinematical differences between free swimming and tethered swimming [10], especially in the first half of the aquatic path where the hand is oriented perpendicular earlier and velocity and acceleration differ [11].

Tethered swimming is a tool to measure the forces exerted in the water by assessing individual force-time curves during the exercise [12]. The most common parameters obtained are: average [13] and maximum force [1], average and maximum impulse [5]. However, there is no clear evidence suggesting which one is the most reliable parameter; demonstrating that more studies are required to better understand this topic. Considering that propulsion occurs during the whole propulsive phase of the stroke cycle [14], the relation between force and time should be considered as follows [5]:

$$I = \int_{t_1}^{t_2} F \cdot dt \quad \text{(Eq 3.1)}$$

Where I represents the impulse of force and F is the applied force from time t_1 to t_2. Thus, calculations of the impulse of force may be more accurate when analyzing the tethered forces [15], as the impulse of force depends on the magnitude, duration, and direction of the applied force. In addition, measurements combining force and speed may be more accurate and related to performance [16].

Recently, a new parameter related to tethered force has been proposed; the intra-cyclic force variation (dF)[17]. This variable appears to be effective in evaluating the swimmer's ability to effectively apply force in the water and is highly associated with performance. On the other hand, the intra-cyclic velocity variation (dv) is one of the most applied parameters by academics and practitioners to evaluate the efficiency of swimmers, even though the relationship with performance is not completely clear yet [18].

The main differences between free swimming and tethered swimming are the stationary water and the non-displacement of the swimmers. It is suggested that using a swimming flume would be a state more similar to free swimming than tethered swimming at zero speed [19]. However, to our knowledge, there is insufficient evidence of previous research studying the effects of implementing a swimming flume on tethered swimming variables and how it would affect the relationship with sprint swimming performance.

Therefore, the scarce knowledge and limitations regarding tethered swimming demonstrate the need to know whether a closer situation to free swimming could be achieved by the employment of a flume. Thus, this research aimed to study the relationships between tethered swimming in a flume at different speeds and swimming performance. It was hypothesized that higher associations would be observed when the water flow speed was closer to the free swimming speed.

Methods

Design

A cross-sectional study design was used. Swimming performance was tested in a 25 m swimming pool (25 m × 16.5 m) (water temperature = 27ºC, humidity = 65%) and tethered forces were tested in a swimming flume (Endless Pool Elite Techno Jet Swim 7.5; HP, Aston PA, USA) with predefined speed range and with flow speed being measured at 0.30 m depth using an FP101 flow probe (Global Water, Gold River, CA[20]) (water temperature = 26ºC, humidity = 52%). Swimmers were assessed on two consecutive days in the same conditions. To improve the reliability of the measurements, participants were asked to refrain from intense exercise the day prior to and on the test days. Moreover, they were asked to abstain from caffeine, alcohol, or any stimulant drink during those days. Tests execution orders were randomly assigned and performed under the same conditions. Tests were preceded by a standardized warm-up, which consisted of 1000 m of low to moderate intensity front crawl swimming (400 m swim, 100 m pull, 100 m kick, 4 × 50 m at increasing speed, 200 m easy swim)[17].

Participants

Sixteen regional male swimmers participated in the study (19.6 ± 3.3 years of age, 176.1 ± 4.5 cm in height, 70.7 ± 9.5 kg of body mass, 58.2 ± 2.2 s of long course 100 m freestyle personal best, representing 76 ± 5% of the World Record). The swimmers were required to have at least five years of experience in competitive swimming, as inclusion criteria. The protocol was fully explained to the participants before they provided written consent to participate. The study was conducted according to the Code of Ethics of the World Medical Association (Declaration of Helsinki), and the protocol was approved by the university ethics committee.

Methodology

The tethered swimming test consisted of 30 s arm stroke (without leg action) in four different conditions: at zero speed, which replicates the measurement in the pool, and at three different speeds of water flow: 0.926, 1.124, and 1.389 $m \cdot s^{-1}$. These three speeds were chosen after a pilot study, representing 50% of the maximum swimming speed, the easy swimming speed, and the maximum speed that allow registering all the forces of this group of swimmers. Higher speeds do not allow measuring any force during some parts of the path since swimmers' force would be barely enough to overcome the water flow.

All the participants were familiar with tethered swimming. Additionally, they underwent a familiarization protocol with all the procedures. A belt was attached to the hip with a 2 m steel cable. Force recordings were synchronized with three different video cameras, using a video switcher (Roland Corporation, Roland Pro A/V V-1HD, Osaka, Japan). A visual-auditory signal was used to determine the start and the end of the 30 s. Before that, the participants swam for 5 s at low intensity, in order to avoid the inertial effect, adapted from Barbosa et al. [21]. To avoid interferences in force parameters caused by breathing, a snorkel was used for tethered swimming. Feet were restrained on a rope (Figure 3.1). Placing the feet on the rope allows swimmers to rotate and keep the horizontal position as if they were kicking. Moreover, both interaction with the arms and interference with the measurements were avoided [4]. There were 15 min of active rest between each trial. After the trial, the participants were all asked for their rate of perceived effort (RPE) [22].

Forces were measured using a load cell (HBM, RSCC S-Type, Darmstadt, Germany). The load cell was aligned with the direction of the swimming, recording at 200 Hz. Data were converted (FORCE ISO flex; Remberg, Gipuzkoa, Spain), registered, and exported (National instruments, NI USB 600, Austin, USA) to a specific runtime environment developed using LabVIEW (National instruments, Austin, USA). Stroke rate (SR) was recorded and analyzed using Automatic Swimming Performance Analysis (A.S.P.A, project reference IE_57161), it allowed the collection of the performance data automatically. Technical details are provided elsewhere [23].

Figure 3.1. Swimmers' real situation during tethered swimming in the flume.

Swimming performance was measured using three distances; 25, 50, and 100 m front crawl. An in-water start was used. During the 25 m trials, a speedometer cable (lineal transducer, Heidenhain, D83301, Traunreu, Germany) was attached to the swimmers' hip by way of a belt, recording at 200 Hz. Data were recorded, converted (Signal Frame MF020, Sportmetrics, Spain), and exported to a specific software (Signalframe an v.2.00). Total time and SR were recorded using A.S.P.A.

Speed-time and force-time curves were smoothed using a fourth-order Butterworth low-pass digital filter, with a cut-off frequency of 10 Hz. From the force-time curve the following parameters were estimated for each tethered swimming trial (Figure 3.2)[5]:

- Maximum force (Fmax): highest value obtained from the individual force-time curve.
- Average force (Favg): mean of force values recorded during the 30 s.
- Maximum impulse (Imax): highest value of the impulse of force (eq. 3.1) in a single stroke.
- Average impulse (Iavg): quotient of the sum of the single-stroke impulse and the number of strokes performed during the 30 s tethered swim.

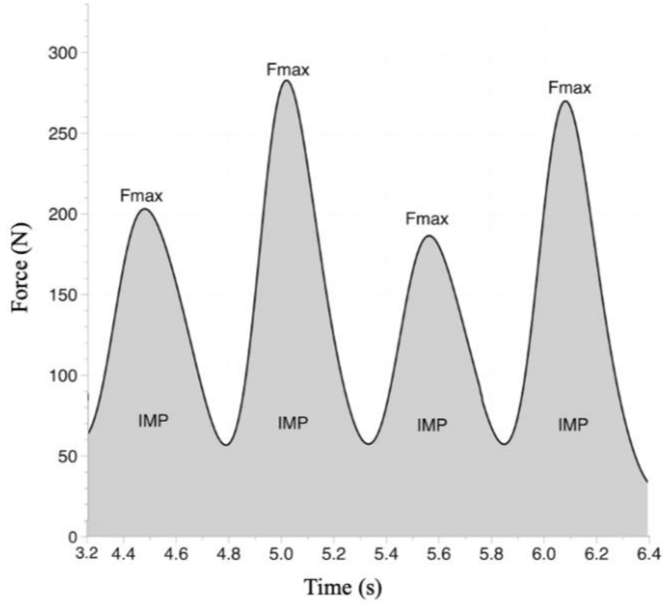

Figure 3.2. Example of force recording of two consecutive front crawl stroke cycles. The main analysis points are shown. Each curve corresponds to each arm. Fmax: maximum force; IMP: impulse.

Both speed-time and force-time curves were examined, and five successive strokes were chosen for further analysis, adapted from Morouço et al. [17]. The selected strokes occurred during mid-testing. The dv and dF were analyzed as previously described [17]:

$$dv = \frac{\sqrt{\frac{\sum_i (v_i - v)^2 \cdot AF_i}{n}}}{\frac{\sum_i v_i \cdot AF_i}{n}} \cdot 100 \qquad \text{(Eq 3.2)}$$

Where dv represents the intra-cyclic variation of the horizontal velocity of the hip, v represents the mean swimming speed, v_i represents the instantaneous swimming speed, AF_i represents the acquisition frequency, and n is the number of measured strokes. To calculate dF, the same equation was adapted using the force parameters obtained in the tethered swimming test, instead of the speed parameters.

Swimmers indicated the RPE after each trial, using the adapted Borg's scale with incremental descriptors of the perception of exertion, ranging from 1 (no exertion at all) to 10 (maximal exertion)[22].

Statistical analysis

The normality of all distributions was verified using Shapiro-Wilk test and visual inspection of histograms. For analytical purposes, the Napierian logarithm was calculated. Parametric statistical analysis was adopted. Repeated measures analysis of variance (ANOVA) was performed to determine the differences between tethered swimming variables in the four conditions. It was also performed to determine the differences between swimming speed, SR, and RPE in 25, 50, and 100 m front crawl. Bivariate Pearson's correlation coefficients (r) were determined between selected variables, and simple linear regression analyses were applied to evaluate the potential associations. Paired sample t test was used to assess differences, in SR and RPE, between 25 m and tethered swimming at zero speed. The same procedure was performed to compare SR and RPE between each free swimming distance and every tethered swimming condition. All statistical procedures were performed using SPSS 23.0 (Chicago, IL, USA) and the level of statistical significance was set at $p < 0.05$.

Results

The mean ± standard deviation (SD) values for the tethered forces, grouped into water flow and swimming performance variables respectively are presented in Tables 3.1 and 3.2. Repeated measures ANOVA analysis revealed significant differences for average force ($p < 0.001$), maximum force ($p < 0.001$), average impulse ($p < 0.001$), maximum impulse ($p < 0.001$) and dF ($p < 0.001$), between the four tethered swimming conditions. There were also differences for swimming speeds ($p < 0.001$), between the three distances analyzed. Stroke rate was not different between tethered swimming in the four conditions ($p = 0.972$) yet it was different between 25, 50 and 100 m ($p < 0.001$). Likewise, RPE was different between 25, 50 and 100 m ($p < 0.001$), but it was not different between the four conditions of tethered swimming ($p = 0.115$). Post-hoc analysis showed that tethered forces were higher at lower speeds ($p < 0.001$), except dF, which was higher as the speed increased ($p < 0.001$). Mean speed in 25 m was higher than 50 and 100 m mean speed ($p < 0.001$). Stroke rate was higher in the 25 m ($p < 0.001$) and RPE was higher in the 100 m ($p < 0.001$).

Table 3.1. Mean ± standard deviation values for the tethered swimming variables, rate of perceived exertion and stroke rate, grouped by water flow speed.

	Water flow speed: 0 m·s^{-1}	**Water flow speed: 0.926 m·s^{-1}**	**Water flow speed: 1.124 m·s^{-1}**	**Water flow speed: 1.389 m·s^{-1}**
Favg (N)	93.20 ± 16.92	60.14 ± 18.23	43.89 ± 15.32	35.49 ± 15.23
Fmax (N)	214.58 ± 48.66	156.55 ± 37.00	125.14 ± 38.86	110.11 ± 36.18
Iavg (N·s)	50.16 ± 10.92	31.97 ± 8.76	23.56 ± 8.23	18.80 ± 7.89
Imax (N·s)	78.75 ± 13.70	58.83 ± 13.65	47.28 ± 11.21	39.74 ± 10.44
dF (%)	39.72 ± 8.15	47.58 ± 10.64	50.07 ± 13.65	53.56 ± 11.72
RPE	8.25 ± 1.06	8.13 ± 0.95	8.56 ± 0.72	8.56 ± 0.96
SR (Hz)	0.92 ± 0.10	0.92 ± 0.08	0.92 ± 0.08	0.92 ± 0.10

Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse; dF: intra-cyclic force variation; RPE: rate of perceived exertion; SR: stroke rate.

Table 3.2. Mean ± standard deviation values for swimming performance variables and rate of perceived exertion.

	25 m	**50 m**	**100 m**
SS (m·s^{-1})	1.84 ± 0.05	1.80 ± 0.06	1.66 ± 0.06
RPE	7.38 ± 0.80	8.69 ± 0.60	9.44 ± 0.62
SR (Hz)	1.01 ± 0.13	0.92 ± 0.9	0.81 ± 0.05
dv (%)	8.08 ± 1.82*		

SS: swimming speed; RPE: rate of perceived exertion; SR: stroke rate; dv: intra-cyclic velocity variation. * Speedometer additional data.

Table 3.3 shows Pearson´s correlations of tethered swimming variables at different water flow speeds and free swimming performance. Simple linear regression analysis showed positive associations of 25 m speed with all tethered force variables at 1.329 m·s^{-1} water flow speed (Figure 3.3). Maximum force was positively associated with the 50 m speed ($r = 0.520$; $p = 0.390$). Average force, maximum force, and maximum impulse at 1.124 m·s^{-1} water flow speed were positively associated with 25 m speed ($r = 0.565$, $r = 0.523$ and $r = 0.627$; $p = 0.023$, $p = 0.038$ and $p = 0.009$ respectively). There were associations between dF, at zero and 1.389 m·s^{-1} water flow speeds, and dv ($r = 0.507$ and $r = 0.436$; $p = 0.022$ and $p = 0.045$ respectively). However, there was no association between dF and dv with swimming performance.

Table 3.3. Pearson´s correlation of tethered swimming variables at different water flow speeds with swimming performance.

	Water flow speed: 0 m·s^{-1}					**Water flow speed: 0.926 m·s^{-1}**					**Water flow speed: 1.124 m·s^{-1}**					**Water flow speed: 1.389 m·s^{-1}**					
	Favg	Fmax	Iavg	Imax	dF	Favg	Fmax	Iavg	Imax	dF	Favg	Fmax	Iavg	Imax	dF	Favg	Fmax	Iavg	Imax	dF	dv
S25m	0.435*	0.271	0.196	0.455*	-0.299	0.436*	0.414	0.439*	0.445*	-0.204	0.565*	0.523*	0.483*	0.627**	-0.292	0.603**	0.673**	0.546*	0.523*	-0.033	0.101
S50m	0.268	0.138	0.083	0.380	-0.290	0.222	0.244	0.229	0.291	-0.133	0.415	0.418	0.359	0.472*	-0.319	0.476*	0.520*	0.465*	0.424	-0.213	-0.112
S100m	0.351	0.187	0.172	0.442*	-0.216	0.263	0.228	0.302	0.298	-0.248	0.358	0.357	0.322	0.494*	-0.376	0.396	0.435*	0.415	0.405	-0.238	-0.028

Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse; dF: intra-cyclic force variation; dv: intra-cyclic velocity variation; S25m: swimming speed in 25 m front crawl; S50m: swimming speed in 50 m front crawl; S100m: swimming speed in 100 m front crawl. * $p < 0.05$. **$p < 0.01$.

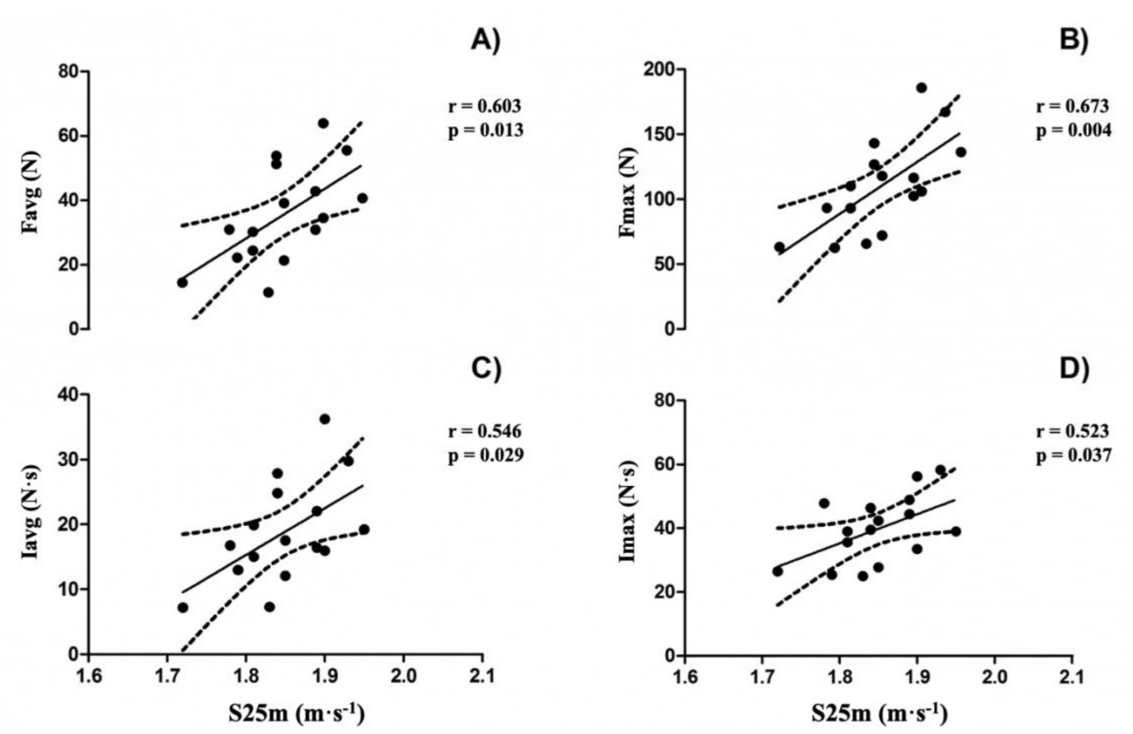

Figure 3.3. Linear regressions between tethered force variables at 1.389 m·s^{-1} water flow speed and 25 m speed ($p < 0.05$). Individual values and 95% confidence lines are represented. A) Favg: Average force; B) Fmax: maximum force; C) Iavg: average impulse; D) Imax: maximum impulse; S25m: speed in 25 m.

Results showed differences in SR and RPE between tethered swimming in the four conditions and 25 and 100 m ($p < 0.05$), yet no differences were observed between SR and RPE in 50 m and tethered swimming in the four conditions.

Discussion

The main finding of this study was that tethered swimming variables measured at different water flow speeds were positively associated with 25 and 50 m swimming speeds. Our results confirm the established hypothesis; the association is higher when the water flow speed approaches the free swimming speed.

With free swimming speed increasing the force production declines; diminishing the capability to apply force [1]. At zero speed this is unnoticeable as there is no displacement while including the water flow simulates the displacement in the water [19]. Surprisingly, swimmers with lower level of force at zero speed were able to develop higher values at high water flow speeds than their stronger teammates, being also the faster swimmers [19]. Thus, including the water flow in tethered swimming seems to evaluate the ability of the swimmers to effectively apply force in the water while tethered swimming at zero speed seems to mostly measure the strength potential of the swimmer. This fact explains why the relationship between tethered swimming and swimming performance becomes stronger when the water flow increases. This is of crucial importance, as performance depends on the ability to effectively apply force in the water, rather than on the relative force of the swimmers [4].

Relationships between pulling force at zero speed and eight different water flow speeds with 100 m swimming speed have been reported [19]. The latter authors compared elite swimmers using 100 m competitive mean swimming speed in front crawl. This might explain why our results did not show an association between tethered swimming variables and 100 m. The first point to consider is that we used swimming speed measured in short course, where turning might affect the outcome [24]. Secondly, 100 m is a distance with different aerobic and anaerobic contributions compared to 25 or 50 m [25]. Thus, swimmers' aerobic and anaerobic capacity plays an important role. Thirdly, the heterogeneity in the sample level might have affected this relationship. Besides, the magnitude of the main forces identified in this study was considerably lower than the previously presented [19]. However, there is an important difference in test time (30 s *vs.* 5 s). This fact added to the restriction of the legs might explain the considerable difference in the force values obtained.

The magnitude of force produced in tethered swimming has been compared to other experimental techniques. For instance, the mean propulsive force obtained using the assisted towing method is not closely related to tethered swimming variables at zero speed [7]. However, tethered swimming at zero speed measures the strength potential of the swimmers [6,8,9], not the ability to effectively apply force in the water. Therefore, since tethered swimming in a flume is a more similar situation to the assisted towing method situation than at zero speed, the association between these two different methods might increase. Hence, future research is required to explore this association.

Comparing our results at zero speed with previous studies it is unclear which is the best tethered variable to be assessed. Average force was a reliable parameter to estimate swimming speed [26]. Nevertheless, maximum impulse showed a better association with performance (Table 3.3). This difference might be explained by the swimmers' level. Elite sprint swimmers can take advantage at each phase of the stroke, relying more on their SR to increase the very high swimming speed developed. Thus, the impulse should always be taken into consideration when analyzing top swimmers [15]. Likewise, the magnitude of Fmax, Favg, Imax, and Iavg identified at zero speed in the present study is in line with those found in previous research with the same test duration and conditions [5].

The dF was directly related to the water flow speed, increasing its magnitude as the water flow speed increased. The increase in dF as the in water flow speed increased might be explained by the restriction of the legs, which likely evoked the higher force differential of force between the propulsive and non-propulsive moments as the water flow speed increased. Therefore, the association between dF and swimming performance might have been affected by the restriction of the legs. Regarding dv, the lack of association presented in this study and the different results obtained previously [17,27] indicate that more research is required to better understand the relationship between this parameter and swimming performance.

Stroke rate and RPE were not different among the 30 s tethered swimming and 50 m free swimming. These results confirm that 30 s tethered swimming replicates the effort of 50 m free swimming [5]. Likewise, results showed SR and RPE differences between the 30 s tethered swimming and 25 and 100 m free swimming. Thus, we can assume that 30 s tethered swimming is not able to replicate the effort over those mentioned distances. Nevertheless, 15 or 60 s in tethered swimming may replicate the effort of 25 and 100 m respectively, since it is approximately the time needed to cover those distances [28].

The fact that the association between arm stroke tethered was studied with swimming front crawl free swimming and not with arm stroke free swimming was a point of discussion. However, the restriction of the legs during swimming could have influenced the outcomes, if swimmers had had to wear a pull-boy or a band on their ankle, the effect of wearing these implements on each swimmer would have been different, thus making it impossible to control its effects. This fact added to the high contribution of arms during front crawl sprint [29] were determinants to avoid restricting the legs action during free swimming.

This is the first study investigating the association between tethered swimming variables at zero, 0.926, 1.124, and 1.389 m·s^{-1} water flow speeds and 25, 50, and 100 m swimming speeds, obtaining higher association between force variables and 25 and 50 m performance at higher water flow speeds.

Practical applications

Our results will help coaches to evaluate their swimmers' ability to effectively apply force in the water. Comparing their results during the whole season might determine if performance improvements are due to enhancement in the ability to apply force in the water. Future research might study whether tethered swimming variables at high water flow speeds are affected by strength training. Thus, coaches would be able to know if strength gains are transferred to swimming performance improvements. Moreover, the fact that tethered swimming in a flume and free swimming are similar situations facilitates physiological measurements such as maximal oxygen uptake, relating it to force measurements. Future research should examine whether there are kinematic differences between tethered swimming in a flume and free swimming. This would allow more complete biomechanical analyses and comparisons of how technical changes affect the force applied by swimmers.

Conclusion

The relevance of our study is that by using a swimming flume, tethered swimming becomes a similar situation to free swimming. It allows to measure the ability of the swimmers to effectively apply force in the water, obtaining better relationship between all tethered swimming force variables and swimming performance in 25 and 50 m. The relationship is stronger as the water flow speed increases and approaches the actual free swimming speed. Measuring at zero speed position may underestimate the relationship between force variables and swimming performance since it measures the strength potential of the swimmers. Our results do not clarify the controversy of using intra-cyclic speed and force variation. Finally, it is important to mention that the similarities shown between tethered swimming and free swimming in stroke rate and rate of perceived effort highlight the use of tethered swimming in a flume as a great training and assessment tool.

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CHAPTER 4:

The relationship between tethered swimming, anaerobic critical velocity, dry-land strength, and swimming performance

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Abstract

Purpose**:** This study aimed to 1) examine the associations between two swim-specific measures of anaerobic performance and strength-based variables; 2) study the association between the aforementioned variables with swimming performance and its kinematics; 3) analyze sex-induced differences. ***Methods:*** Twenty-three regional-national swimmers performed five countermovement jumps and pull-ups, 50 m front crawl and two 30 s tethered swimming tests at 0 and 1.124 $m{\cdot}s^{-1}$ water flow speed. Moreover, 10, 15, 20, and 25 m maximal front crawl were performed to determine anaerobic critical velocity (AnCV). ***Results:*** The AnCV was positively correlated with tethered swimming variables in both conditions and based variables in both males and females ($p < 0.05$). Tethered swimming variables in both conditions were correlated with pull-ups' average propulsive force in males ($p < 0.05$). 50 m swimming performance was positively associated with AnCV, tethered swimming variables, countermovement jump (CMJ) height, and pull-ups' average propulsive force for both sexes ($p < 0.05$). Stroke rate (SR) was positively associated with AnCV in males and females ($p < 0.05$). Stroke length was correlated with tethered swimming variables in males ($p < 0.05$). Except for SR, male presented higher values than female swimmers ($p < 0.05$). ***Conclusions:*** Depending on the conditions of their training environment (equipment, time, and/or the number of lanes available) coaches might use the AnCV and tethered swimming variables as interchangeable tools for evaluating anaerobic performance. CMJ and pull-up should be used as testing tools for assessing swimming performance and as training exercises. Coaches should be aware of the sex-induced difference when comparing males and females results.

Keywords: kinematics, sprint, power, assessment, evaluation, performance analysis.

Introduction

The accuracy and reliability in the assessment of the components that influence performance are crucial in the improvement of swimmers' results [1]. Specifically, the aquatic environment complicates the direct measurement of the components that affect performance, resulting in most cases in land-based measures. Notwithstanding its reliability and efficacy in determining adaptations after training, land-based measures do not meet the criterion of specificity and neglect the swimming technique [2]. Indeed, muscular force production while stroking [3], swimming technique [4], and aerobic/anaerobic energy production [5] are determinants in competitive swimming and therefore should be assessed in the water.

As part of their training plan, swimmers perform several sessions per week of resistance training to improve the propulsive force in the water [6]. The performance enhancements prompted by strength training have been mostly studied by analyzing the associations between the changes in strength with swimming performance [7,8]. However, despite the strength gains reported in some studies, these improvements did not elicit any change in free swimming performance [9,10], possibly because of the non-swim-specific nature of the exercises [7]. Hence, to understand whether the changes in muscular strength would evoke changes in the propulsive force, tethered swimming has been widely used [11]. Certainly, some exercises such as bench press or lat pull-down have been correlated with tethered swimming variables [12–14]. However, among the exercises studied, there is no related information with the pull-up, even though it is widely used by swimming strength and conditioning coaches, and stated as one of the best predictors of swimming speed [6,15].

As for tethered swimming, this is a valid and reliable tool in swimming assessment, with muscular and physiological responses similar to free swimming that can be used to assess not only force production, but also anaerobic performance [16–19]. Indeed, the force parameters obtained in tethered swimming have been correlated with sprint swimming performance [17,20,21], and anaerobic land-based tests [18,22]. Nevertheless, most of the studies have been only conducted with male swimmers, and the sex-induced differences in tethered swimming parameters are unknown [22].

Based on the concept of critical velocity, Fernandes et al. [23] proposed the anaerobic critical velocity (AnCV). Expressed by the slope of the regression line between different short distances trials performed at maximum speed and the corresponding times, the AnCV is frequently used in the assessment of the anaerobic performance [24]. The shorter the testing distances used in AnCV evaluation, the stronger the relationship with sprint swimming performance [23]. Among the different distances used in AnCV calculation, the 10, 15, 20, and 25 m have been well correlated with the speed in 50, 100, and 200 m in the four swimming strokes [24,25]; *i.e.*, the swimming distances with the highest anaerobic contribution preponderance [26]. In any case, the AnCV test has not been yet compared with other anaerobic tests, such as tethered swimming test.

Knowing other tools that might be used interchangeably would be valuable for training monitoring due to the cost of the equipment or the time and space required to perform the tethered swimming tests. In fact, some coaches might not be able to perform tethered swimming test, being unable to monitor some determinants of swimming performance such as the muscular force production while stroking or the anaerobic energy production [3,5], during their assessment routines. Therefore, in light of the above, the purpose of the current study was three-fold 1) to examine the associations between two swim-specific measures of anaerobic performance and strength-based variables; 2) to study the association between the aforementioned variables with swimming performance and its kinematic variables; and 3) to analyze the possible sex-induced differences. It was hypothesized that the two swim-specific measures of anaerobic performance and dry-land based variables would be correlated, exhibiting high association with swimming performance. On the other hand, it was expected that male swimmers would present higher values than female swimmers in all the variables assessed.

Methods

Design

A cross-sectional study was conducted with a two-days test not separated by more than 48 h to eliminate any residual fatigue effect among the tests. Participants were familiarized with the procedures prior to testing. Moreover, to improve the reliability of the measurements, participants were asked to refrain from intense exercise, alcohol, caffeine, or any stimulant drink during the test and on previous days.

The evaluation protocol was developed in a 25 m swimming pool (25 m × 16.5 m)(water temperature 27.4ºC, air temperature = 28.9ºC, and humidity 54%). Tethered forces were tested in a swimming flume (Endless Pool Elite Techno Jet Swim 7.5; HP, Aston PA) with a predefined speed range and with flow speed being measured at 0.30 m depth using an FP101 flow probe (Global Water, Gold River, CA20)[27](water temperature 26.2ºC, air temperature = 29.1ºC, and humidity 46%).

Participants

Twenty-three regional and national swimmers, 14 males (age: 17.5 ± 2.9 years old, height: 175.5 ± 7.8 cm, body mass: 67.6 ± 9.1 kg, and FINA points in 50 m freestyle: 410 ± 81, Level 5 [28]) and nine females (age: 17.3 ± 2.4 years old, height: 166.8 ± 4.1 cm, mass: 60.8 ± 7.1 kg, and FINA points in 50 m freestyle: 515 ± 125, Level 4 [28]) volunteered to participate in the current study. Participants performed six training sessions per week under the supervision of the same coach with more than five years of regional or/and national experience. Before the beginning of the study, the protocol was fully explained to the participants and written consent to participate was requested (Parental consent for the swimmers under 18 years). The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki), and the protocol was approved by the university ethics committee (project code: 852).

Methodology

Countermovement jump assessment

Firstly, height and body mass were assessed using a stadiometer/scale (Seca 799, Hamburg, Germany). Before the strength measurements, swimmers conducted a standardized warm-up based on jogging, joint mobility, dynamic stretching, and three sub-maximal countermovement jump (CMJ)[29]. Five min after the end of the warm-up the participants were positioned in an upright stance with their feet shoulder-width apart with the arms on the hips, on the center of a force plate sampling at 1,000 Hz

(Dinascan/IBV, Biomechanics Institute of Valencia, Spain). Swimmers then performed five CMJs with 1 min of rest in between. The participants were instructed to jump maximally and were encouraged in all the jumps. If the execution was not adequately performed (*e.g.,* foot outside the plate during landing or horizontal displacement during the flight phase), an extra trial was conducted. From the five CMJs, the highest and lowest jumps were removed, and the mean height (CMJ_H) of the remaining jumps was calculated [15].

Pull-up assessment

After 10 min of rest, swimmers performed five pull-ups with 1 min of rest in between. Swimmers were required to start the pull-ups hanging from the bar with pronated grip and with their elbows fully extended. The swimmers were required to perform as quickly as possible and only if the swimmers' chin reached the bar, the pull-up was considered as correct. Performance in the ascending phase of the pull-ups was recorded through an isoinertial dynamometer (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain) attached to the subjects' hips through a harness. A researcher, inspected all pull-ups to assure that swimmers displaced vertically. If a horizontal movement was observed, an extra trial was conducted. The pull-ups which obtained the greatest and lowest mean velocity values were excluded, and the mean of the remaining was calculated [15]. Average propulsive velocity, force, and power were obtained (PUv_{avg}, PUf_{avg}, and PUp_{avg}, respectively). Three of the female swimmers were unable to perform the pull-ups. Thus, analyses were conducted with the six that were capable.

Swimming performance assessment

Swimmers then performed a 1200 m standardized warm-up (300 m [100 m usual breathing, 100 m breathing every five strokes, 100 m usual breathing], 4 × 100 m [2 × {25 m kick + 25 m increased stroke length}] on 1:50, 8 × 50 m [2 × 50 m drill; 2 × 50 m building up speed, and 4 × {25 m race pace + 25 m easy}] on 1:00, and 100 m easy [30]. After 10 min of rest, a 50 m all out trial was executed. The 50 m were recorded with a Sony FDR-AX53 at 50 Hz sampling rate (Sony electronics Inc., Tokyo, Japan) and the videos were analyzed on an in-house customized software for race analysis in competitive swimming by one expert evaluator. Stroke rate (SR) was obtained by considering three upper limb cycles and dividing it by the time taken to complete the three cycles in every 25 m lap, stroke length (SL) was obtained from the ratio between the speed and SR, and stroke index (SI) was calculated multiplying the swimming speed by the SL [27]. The Intra-class Correlation Coefficient (ICC) was computed to verify the absolute agreement between repeated measures, showing a very high agreement ranging between 0.988 and 0.999.

Tethered swimming analysis

Thirty min after completion of the 50 m all out test, 30 s tethered swimming in two different conditions were performed: at zero speed and at 1.124 water flow speed ($m \cdot s^{-1}$) in a swimming flume. This speed was chosen since it was the maximum speed that allowed registering all the forces of the whole group of swimmers. A familiarization protocol with all the procedures was conducted previously. The test began with the participants swimming for 5 s at low intensity before the 30 s, to avoid the inertial effect, adapted from Barbosa et al. [31]. The start and end of the 30 s were indicated with an auditory signal. A snorkel was used for tethered swimming to avoid interferences in force parameters caused by breathing [32]. There were 30 min of active rest between each trial. A steel cable was attached to the swimmer through a floating trapezoidal structure (which allows them to kick) and fixed to a load cell (RSCC S-Type; HBM, Darmstadt, Germany) leading to an angle of 10º with the water surface and recording at 1500 Hz. Analog data were converted (celula 1.4; Remberg, Force Isoflex, Spain), registered, and exported (NIUSB600; National Instruments, Austin, TX) to a specific software (myoRESEARCH, Noraxon, USA), allowing to visualize the recordings in real time. The force-time curves were processed, with the angle correction, as recently stated [33], using a fourth-order Butterworth low-pass digital filter, with a cut-off frequency of 4.5 Hz. From the force-time curves, the following parameters were computed [17]:

- Average force (Favg): mean of force values recorded during the 30 s.
- Maximum force (Fmax): highest value obtained from the individual force-time curve.
- Average impulse (Iavg): quotient of the sum of the single-stroke impulse and the number of strokes performed during the 30 s tethered swim.
- Maximum impulse (Imax): highest value of the impulse of force in a single stroke.

Anaerobic critical velocity evaluation

On the second day, after the completion of the standardized warm-up swimmers performed the AnCV test, which consisted of all out front crawl swimming efforts to 10, 15, 20, and 25 m, with in-water starts and 30 min of passive rest between each trial. All the trials were recorded and analyzed in the same in-house customized software for race analysis as the 50 m all out test. The AnCV was computed from the slope of the distance-time relationship [25,34]. Given that the tests were conducted in a 25 m swimming pool and to avoid the influence of the turn over the determination of the AnCV, those distances were chosen [24].

Statistical analysis

The normality of all the variables was checked using Shapiro-Wilk test. Mean and standard deviation (SD) for descriptive analysis were obtained and reported for all studied variables. Pearson product-moment correlation coefficients (r) were used to verify the relationship between the swimming performance, kinematics variables, AnCV, and tethered swimming variables. Spearman's correlation coefficients were used for the variables that were not normally distributed. The threshold values denoting small, moderate, large, very large, and extremely large correlations were defined as 0.1, 0.3, 0.5, 0.7, and 0.9, respectively [35]. Independent sample t test was used to compare all the variables measured between male and female swimmers. Non-parametric independent sample t test (Wilcoxon rank-sum test) was conducted in the non-normally distributed. As the results were identical, only parametric independent sample t test data were reported [36]. The effect sizes (d) of the obtained differences were calculated and categorized as small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$ [37]. All statistical procedures were performed using SPSS 24.0 (IBM, Chicago, IL, USA).

Results

In Table 4.1 are presented for both sexes the mean ± SD values for the swimming performance, 95% confident interval ([95%CI]), relative change, and effect sizes (d) with [95%CI] values for the swimming performance, kinematics variables, AnCV, tethered swimming variables, and the strength-based variables obtained on land. Table 4.2

reported the correlations between AnCV, tethered swimming variables, and the strength-based variables obtained on land for both male and female swimmers. Both males and females correlations between AnCV, tethered swimming variables, the strength-based variables obtained on land, and swimming performance and its kinematics are shown in Table 4.3.

Table 4.1 The mean ± standard deviation values for the swimming performance, 95% confident interval ([95%CI]), relative change (Δ%), and effect sizes (*d*) with [95%CI] values for the swimming performance, kinematics variables, anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land.

	Variable	Males	Females	[95%CI]; Δ%	Effect size (*d*) [95%CI]
	S50m ($m \cdot s^{-1}$)	1.77 ± 0.11	1.59 ± 0.11	[0.07, 0.29]; 10.16%	1.64 [0.75, 2.52]**
	SL (m)	1.87 ± 0.14	1.88 ± 0.17	[-0.15, 0.13]; -0.53%	0.07 [-0.95, 0.82]
	SR (Hz)	0.89 ± 0.07	0.78 ± 0.10	[0.02 , 0.19]; 12.35%	1.32 [0.87, 1.76]*
	SI ($m^2 \cdot s^{-1}$)	3.12 ± 0.34	2.77 ± 0.26	[0.08, 0.64]; 11.21%	1.13 [0.69, 1.57]*
	AnCV ($m \cdot s^{-1}$)	1.67 ± 0.10	1.50 ± 0.08	[0.08, 0.25]; 10,17%	1.83 [0.94, 2.72]**
Water flow speed 0 $m \cdot s^{-1}$	Favg (N)	93.96 ± 21.02	68.12 ± 9.22	[10.30 ,41.39]; 27.50%	1.48 [0.59, 2.37]**
	Fmax (N)	227.74 ± 37.53	165.29 ± 24.94	[32.86, 92.94]; 27.42%	1.89 [1.45, 2.34]***
	Iavg (N·s)	63.96 ± 12.77	49.06 ± 6.33	[5.32, 42.48]; 24.47%	1.40 [0.96, 1.85]**
	Imax (N·s)	88.37 ± 20.09	65.62 ± 9.06	[7.85, 27.65]; 25.74%	1.36 [0.47, 2.25]**
Water flow speed 1.124 $m \cdot s^{-1}$	Favg (N)	40.92 ± 11.78	18.99 ± 6.40	[14.02, 29.86]; 52.59%	2.18 [1.29, 3.07]***
	Fmax (N)	121.80 ± 34.87	56.04 ± 14.58	[43.73, 87.78]; 53.99%	2.31 [1.87, 2.76]***
	Iavg (N·s)	26.08 ± 6.62	16.23 ± 6.51	[4.00, 15.70]; 37.76%	1.50 [1.05, 1.94]**
	Imax (N·s)	50.60 ± 18.91	20.65 ± 7.84	[16.05, 43.85]; 59.18%	1.91 [1.03, 2.80]***
	CMJ_H (m)	0.33 ± 0.06	0.24 ± 0.04	[0.04, 0.14]; 27.27%	1.69 [0.80, 2.58]**
	PUv_{avg} ($m \cdot s^{-1}$)	0.69 ± 0.17	0.44 ± 0.15	[0.07, 0.43]; 36.23%	1.54 [1.10, 1.99]**
	PUf_{avg} (N)	664.66 ± 88.20	582.26 ± 75.73	[-5.83, 170.63]; 12.39%	0.99 [0.54, 1.43]
	PUp_{avg} (W)	458.77 ± 121.99	255.65 ± 81.99	[86.79, 319.47]; 44.27%	1.89 [1.45, 2.33]**

S50m: speed in 50 meters; SL: stroke length; SR: stroke rate, SI: stroke index; AnCV: anaerobic critical velocity; Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse; CMJ_H: countermovement jump height; PUv_{avg}: pull-up mean propulsive velocity; PUf_{avg}: pull-up mean propulsive force; PUp_{avg}: pull-up mean propulsive power. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$

Table 4.2. Relationship between anaerobic critical velocity, tethered swimming variables, and the strength-based variables obtained on land for both male and female swimmers.

			Water flow speed 0 m·s^{-1}				Water flow speed 1.124 m·s^{-1}			
		AnCV	Favg	Fmax	Iavg	Imax	Favg	Fmax	Iavg	Imax †
Males (n = 14)	AnCV	-	0.367	0.656**	0.384	0.091	0.602*	0.532*	0.579*	0.345
	CMJ_H	0.522*	0.003	0.164	-0.036	-0.212	0.216	0.127	0.097	0.194
	PUv_{avg}	0.712**	0.062	0.369	0.001	-0.052	0.279	0.238	0.151	0.074
	PUf_{avg}	0.479*	0.747**	0.742**	0.820***	0.832***	0.690**	0.719**	0.753**	0.714**
	PUp_{avg}	0.846***	0.404	0.658**	0.374	0.323	0.575*	0.553*	0.483*	0.258
Females (n = 9)	AnCV	-	0.592*	0.503	0.570	0.417	0.476	0.178	0.343	0.624*
	CMJ_H §	0.607*	0.214	0.385	0.633*	0.171	0.325	0.274	-0.359	0.496
	PUv_{avg}	-0.010	-0.657	-0.509	-0.422	-0.574	-0.745*	-0.409	-0.606	-0.349
	PUf_{avg}	0.790*	0.895**	0.833*	0.620	0.577	0.534	0.492	-0.153	0.548
	PUp_{avg}	0.256	-0.127	-0.22	-0.21	-0.374	-0.548	-0.232	-0.646	-0.159

AnCV: anaerobic critical velocity; CMJ_H: countermovement jump height; PUv_{avg}: pull-up mean propulsive velocity; PUf_{avg}: pull-up mean propulsive force; PUp_{avg}: pull-up mean propulsive power; Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse; † Spearman correlation used only in male swimmers; § Spearman correlation used only in female swimmers. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Table 4.3. Relationship between anaerobic critical velocity, tethered swimming variables, the strength-based variables obtained on land, and swimming performance and its kinematics.

			Water flow speed 0 m·s^{-1}				Water flow speed 1.124 m·s^{-1}							
		AnCV	Favg §	Fmax	Iavg	Imax	Favg	Fmax	Iavg	Imax †	CMJ$_H$ §	PUv$_{avg}$	PUf$_{avg}$	PUp$_{avg}$
Males (n = 14)	S50m	0.956***	0.321	0.724**	0.431	0.061	0.572*	0.622**	0.578*	0.495*	0.555*	0.706**	0.500*	0.167
	SL	0.150	0.311	0.483*	0.505*	0.399	0.322	0.524*	0.499*	0.569*	-0.122	-0.067	0.516*	0.505
	SR †	0.642**	-0.009	0.134	-0.048	-0.365	0.172	0.319	0.042	0.004	0.570*	0.658*	-0.313	0.561*
	SI	0.633*	0.370	0.705*	0.545*	0.259	0.528*	0.700**	0.651**	0.565*	0.196	0.337	0.574*	0.422
Females (n = 9)	S50m	0.915***	0.293	0.608*	0.627*	0.367	0.538	0.333	-0.396	0.726*	0.979***	0.112	0.914**	-0.391
	SL	0.289	-0.300	0.042	0.283	0.246	-0.350	0.03	0.453	-0.113	-0.265	-0.244	-0.408	0.419
	SR	0.622*	0.444	0.27	0.086	-0.005	0.532	0.133	-0.479	0.398	0.588*	0.171	0.710*	-0.158
	SI	0.403	0.150	0.488	0.751*	0.501	0.087	0.275	0.19	0.429	0.522	-0.203	0.159	0.167

S50m: speed in 50 meters; SL: stroke length; SR: stroke rate, SI: stroke index; AnCV: anaerobic critical velocity; Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse; CMJ$_H$: countermovement jump height; PUv$_{avg}$: pull-up mean propulsive velocity; PUf$_{avg}$: pull-up mean propulsive force; PUp$_{avg}$: pull-up mean propulsive power; † Spearman correlation used only in male swimmers; § spearman correlation used only in female swimmers. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Discussion

The aim of the current study was three-fold 1) to examine the associations between two swim-specific measures of anaerobic performance and strength-based variables; 2) to study the association between the aforementioned variables with swimming performance and its kinematic variables; and 3) to analyze the possible sex-induced differences. As hypothesized, the AnCV and tethered swimming were positively correlated ($p < 0.05$). Tethered swimming variables were correlated with PUf_{avg} in males in both conditions (zero speed and at 1.124 $m \cdot s^{-1}$ water flow speed in a swimming flume)($p < 0.05$). Moreover, both AnCV and tethered swimming were positively associated with swimming performance ($p < 0.05$). Finally, except for SL and PUf_{avg}, males showed higher values than females in all the variables assessed.

As it was hypothesized, AnCV and tethered swimming variables presented positive correlations between them, especially in male swimmers, since AnCV as well as tethered swimming variables have been previously stated as anaerobic performance indicators [18,23]. Both were also correlated with the based variables (*i.e.*, CMJ_H and PUf_{avg}). The higher correlation in males than in females between AnCV, tethered swimming variables, and strength-based variables might be explained by the different contributions of arms and legs to force generation between sex [38]. The fact that CMJ_H presented better correlations with AnCV and swimming performance in females than males might indicate that females' arm propulsion was heterogeneous but the difference relied on the kicking action, whose propulsive role is higher as the swimming speed decreases (*i.e.*, females presented lower speed than males and therefore higher propulsion by lower limbs must be generated in females than in males)[39].

Swimming performance was correlated with AnCV, tethered swimming, and strength-based variables. These results are in agreement with previous research [12,15,24], proving that the swimmers with higher anaerobic function are capable of developing higher amount of force in the water; thus, being the fastest. In this regard, despite previous studies investigated the isolated associations of AnCV [24,34], tethered forces [17,20,40], or land-based measures to swimming performance [15], the current investigation is one of the few studies that present a comprehensive approach to these three determinants aspects. Moreover, PUf_{avg} showed better correlation with tethered forces at zero than at 1.124 $m \cdot s^{-1}$ water flow speed. This might be explained because tethered forces at zero speed mostly indicates the swimmers' strength potential [40], whereas, as the water flow speed increases so does the perception of the ability to apply force, and therefore the association with dry-land exercises decreases.

Female swimmers also presented positive correlation between AnCV, tethered swimming, and strength-based variables. The variable with the highest correlation with performance was CMJ_H (Table 4.3). This could be explained by several reasons: 1) The propulsive role of leg kicking is higher at lower speeds [39], therefore, the female swimmers with the most powerful lower limbs could make a difference; 2) the tests were conducted in a 25 m swimming pool, where the start and turn have a big influence on the final outcome [41]. Moreover, the start and turn are highly correlated with CMJ_H [42,43]. Thus, females with superior jumping skills may be able to generate a greater impact on the final outcome. On the other hand, female swimmers presented worse correlation as the water flow speed increased. These results were contrary to males' behavior (Table 4.3) and previous work [20,40]. Despite it was previously tested that all the swimmers could produce force at the water flow speed selected, it is possible that female swimmers struggled to keep the position in the swimming flume, focusing on trying not to be carried away by the water flow rather than to give their best effort.

From a kinematic perspective, swimming speed is determined by SR and SL, and an increment or reduction of either of these two parameters has an impact on swimming speed [4]. Consequently, the positive correlation of the kinematic variables with tethered swimming variables in male swimmers, especially at 1.124 $m \cdot s^{-1}$ water flow speed, could be expected (Table 4.3). Swimmers with higher ability to apply the force would be able to increase the propulsion and therefore the distance covered per stroke (*i.e.,* SL). By contrast, SR was not correlated with tethered force variables. Despite SR is related to neuromuscular power and energy capacities [44], an increase in neuromuscular mechanisms does not essentially represent an increase in the ability to generate propulsive force by the body, but rather an increase in the movements that occur against the water, which in a sense could result in a slippery effect on the stroke cycle. Therefore, increases in SR may not be in line with increases in propulsive force [45]. Both male and female swimmers presented significant correlations among CMJ_H and SR. The same result has been previously observed, but it was not discussed [46]. Possibly the muscle coordination required during the jump had certain association with the kicking technique, which is known to affect SR [47]. Future studies are required to clarify this issue.

As a valid indicator of swimming efficiency [48], SI was positively correlated with AnCV and tethered swimming variables in male swimmers. This means that swimmers with better ability to apply force in the water would be those with higher efficiency (*i.e.*, SI). Since SI and swimming performance are associated [49] it was expected that SI and AnCV were also associated. However, female swimmers only presented significant correlation among Iavg and SI, without correlation between SI and AnCV. In this regard, it is worth mentioning that the females' correlations were similar to males, but the lower sample may have precluded obtaining similar statistically significant relationships.

Males exhibited higher values of tethered swimming variables, dry-land based variables, and swimming performance than females. The differences between sex are well known [50,51] and these results are in agreement with previous studies [38,52,53]. However, contrary to previous research, female swimmers presented similar SL and lower SR than males. This discordance with previous research could be explained by the lower SR of females obtained in the present study compared to previous work [53,54]. Since SR and SL are inversely related [55], the fact that females' SR was that low, led to a higher SL than the presented in previous studies. The different correlations observed among sex might indicate that male swimmers relied more on their upper body strength, whereas female swimmers relied more on their lower body strength. Indeed, flutter kicking contribution is higher at lower speed (*i.e.*, females had significant lower speed than males) [39] and therefore its relative contribution to propulsion is higher in female than in male swimmers [38].

Conclusion

The AnCV and tethered force parameters measured during 30 s tethered test are related, hence, depending on the conditions of the training environment (*i.e.*, equipment, time, and/or the number of lanes available) both tests could be used by coaches as interchangeable tools for evaluating anaerobic performance. Moreover, despite the non-swim-specific nature of the CMJ and pull-up, both tests showed association with tethered swimming variables and performance, which suggests the use of both exercises as testing tools for assessing swimming performance and also as training exercises. Finally, coaches should be aware of the sex-induced difference when comparing males' and females' results, since males could present a higher reliance on the upper body muscle system compared to females.

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CHAPTER 5:

Biophysical impact of five-weeks training cessation on sprint swimming performance

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Abstract

Purpose: To assess changes in swimming performance, anthropometrics, kinematics, energetics, and strength after five-weeks training cessation. ***Methods:*** 21 trained and highly-trained swimmers (13 males: 17.4 ± 3.1 years; 50 m front crawl 463 ± 77 FINA points; 8 females 16.7 ± 1.7 years; 50 m front crawl 535 ± 48 FINA points) performed a 50 m front crawl all out swim test, dry-land and pool-based strength tests, and 10, 15, 20, and 25 m front crawl all out efforts for anaerobic critical velocity assessment before and after five-weeks training cessation. Heart rate (HR) and oxygen uptake ($\dot{V}O_2$) were continuously measured before and after the 50 m swim test (off-kinetics). ***Results:*** Performance impaired 1.9% (0.54 s) for males (p = 0.007, *d* = 0.91) and 2.9% (0.89 s) for females (p = 0.033; *d* = 0.93). Neither the anthropometrical changes (males: r^2 = 0.516, *p* = 0.077; females: r^2 = 0.096, *p* = 0.930) nor the physical activities that each participant performed during off-season (males: r^2 = 0.060, *p* = 0.900; females: r^2 = 0.250, *p* = 0.734) attenuated performance impairments. Stroke rate and clean swimming speed decreased (p < 0.05) despite similar stroke length and stroke index (p > 0.05). Blood lactate concentration values remained similar (p > 0.05), but the $\dot{V}O_2$ peak decreased in females (p = 0.040, *d* = 0.85). Both sexes showed higher HR before and after the 50 m swim test after five-weeks (p < 0.05). Anaerobic metabolic power deterioration was only observed in males (p = 0.035, *d* = 0.65). Lower in-water force during tethered swimming at zero speed was observed in males (p = 0.033, *d* = 0.69). Regarding dry-land strength, upper body impairments were observed for males, while females showed lower body impairments (p < 0.05). ***Conclusions:*** Five-weeks training cessation period yielded higher HR in the 50 m front crawl, anaerobic pathways and dry-land strength impairments. Coaches should find alternatives to minimize detraining effects during the off-season.

Keywords: exercise physiology, oxygen uptake kinetics, energetics, biomechanics, detraining.

Introduction

Partial or complete loss of training-induced anatomical, physiological, and functional adaptations is termed detraining [1]. During a training season, it generally occurs as a result of illnesses or injuries [1], but swimmers typically recover for several weeks in the off-season [1,2]. Its duration, usually 4–6 weeks, may differ according to the requirements of individual coaches and/or the calendar of each national swimming federation [2]. This swimming performance impairment has been mainly studied in middle and long distance events with scarce knowledge about sprint swimming events [1,2]. Conclusive evidence concerning cause-and-effect relationships between sprint swimming determinant variables and performance during training and off-season phases is still required.

Swimming performance can be broken down into start, turn, and clean swimming phases [3]. The clean swimming phase is highly determined by the swimming technique [4,5], which during a race is assessed through clean swimming speed, stroke length (SL), and stroke rate (SR)[5,6]. Indeed, the combination of clean swimming speed and SL is known as stroke index (SI), an indirect estimation of swimming efficiency and strongly associated with lower values of energy cost of swimming [5,7]. These kinematic parameters are usually assessed to understand changes in performance during swimming events [8]. Therefore, to aid coaches in planning the next season's training, it is crucial to identify which kinematic changes might be related to performance impairment during a training cessation period.

Swimming performance is also highly determined by energetics [5,9], in which the metabolic power, *i.e.*, the energy expended per the unit of time ($\dot{E}$), is converted into mechanical power through a given metabolic efficiency [5,9]. The total energy expenditure (E_{tot}) is obtained through the sum of aerobic and anaerobic energy systems [5,9]. Although both energy pathways work in an integrated way, there is an important contribution of the aerobic energy supply during longer swimming events [10], which relies on exercise duration and intensity, as well as swimmers' training status [9]. However, in sprint swimming events (*e.g.*, 50 m front crawl) the majority of the energy is obtained via anaerobic pathways, alactic (AnAL) and lactic (AnL) energy systems (~70%)[10]. In fact, at extreme exercise intensities, not accounting for the anaerobic contribution might underestimate E_{tot} [9,11].

Moreover, short-term cardiorespiratory detraining causes an immediate reduction in blood and plasma volumes. These reductions impair the oxygen uptake ($\dot{V}O_2$)[1,2], meaning that the oxygen supply and utilization are reduced [11] and as a consequence, an increase in maximal and submaximal heart rate (HR)[1]. The detraining effects on energetics have been observed in middle distance swimming events, such as 400 m [2], but there is scarce information on sprint swimming events, particularly the 50 m front crawl. In addition, there is no information about training cessation effects on specific tools used during training to evaluate and control the anaerobic fitness, such as the anaerobic critical velocity (AnCV)[12].

Sprint swimming performance is also influenced by muscle strength and power, thus the ability to apply force in the water is a key factor for sprint swimmers [13,14]. In fact, lower and upper limbs strength are associated with starts, turns [15], and overall swimming performance [13]. Moreover, swimmers anthropometric characteristics are swimming performance determinants due to their relationship with drag and propulsion [2,6]. Thus, the aim of this study was to assess performance, anthropometrics, kinematics, energetics, and strength after five-weeks training cessation. Non-swimming specific physical activities performed during this period of swimming training cessation were quantified. We expected that five-weeks of training cessation (*i.e.*, off-season) would yield impairments in performance, anthropometrics, kinematics, energetics, and strength, partially offset by a swimmer's non-specific physical activities during the transition period.

Methods

Design

A longitudinal single cohort study was conducted in two different moments, before and after five-weeks off-season period. During this period, swimmers were advised by their coach to keep actively enrolled in any sort of physical activity they wished to, but they did not follow any specific swimming training program. The first testing (PRE) was conducted at the end of the week before the last peak-performance of the season. The second testing (POST) was performed right before the beginning of the next competitive season. Swimmers were assessed on two days to eliminate any residual fatigue effect and they were familiarized with the tests and flume prior testing to avoid the learning effect. To improve the reliability of the measurements, participants were asked to refrain from intense exercise and to abstain from alcohol, or any stimulant drink the day prior to and on the test days. Tests were conducted at the same time of the day (during PRE and POST) to avoid systematic bias due to circadian variation [16]. Swimmers were verbally encouraged during all the tests and in-water tests were preceded by a 1200 m standardized warm-up (Supplementary Material 5.1).

Swimming performance was tested in a 25 m swimming pool (25 m length × 16.5 m width with 27.3ºC, 29.4ºC and 52% of water temperature, air temperature, and humidity in the PRE, and 27.4ºC, 28.9ºC and 54% of water temperature, air temperature, and humidity in the POST). Tethered forces were assessed in a swimming flume (Endless Pool Elite Techno Jet Swim 7.5; HP, Aston PA, with 4.7 m length × 2.4 m width with 27.5ºC, 30.4ºC, and 47% of water temperature, air temperature, and humidity in the PRE, and 26.2ºC, 29.1ºC, and 46% of water temperature, air temperature, and humidity in the POST) with predefined speed range and with flow speed being measured at 0.30 m depth using an FP101 flow probe (Global Water, Gold River, CA20)[14].

Participants

Twenty-one trained and highly-trained swimmers [17], 13 males (17.4 ± 3.1 years, 50 m front crawl FINA points: 463 ± 77, Level 4 [18]) and 8 females (16.7 ± 1.7 years, 50 m front crawl FINA points: 550 ± 29, Level 4 [18]) volunteered to participate in the current study. Swimmers had over five years of competitive experience and trained six swimming and four dry-land sessions per week in the same squad and under the direction of the same coach. The protocol was fully explained to the participants and their parents (under 18) before providing written consent to participate. The study was conducted according to the code of ethics of the World Medical Association (Declaration of Helsinki), and the protocol was approved by the university ethics committee.

Methodology

Swimmers followed the training program set by their coach before the beginning of the study. Using standard methodologies swimming training load during the last macrocycle prior to PRE was computed and categorized with a five-zone system (Figure 5.1)(Supplementary Material 5.2)[19].

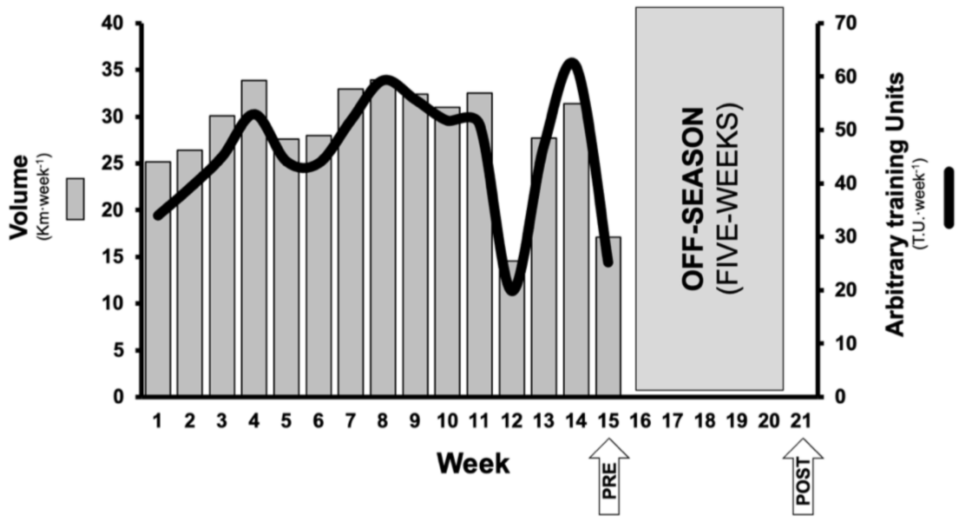

Figure 5.1. Training volume and units (T.U.) of the last monitored macrocycle prior to the off-season. PRE: assessment conducted right at the end of the macrocycle; POST: assessment conducted right before the beginning of the next season, after the training cessation period.

On day one anthropometrics measurements were performed. A stadiometer/scale (Seca 799, Hamburg, Germany) was used to measure height, body mass, and the sitting height of participants. A flexible meter was used to measure arm span. Body mass index was calculated as body mass (kg)·height $(m)^{-2}$. The data was measured by the same researcher. Moreover, biological maturation was evaluated using the age of peak height velocity (PHV)[20].

Swimmers then completed a standardized warm-up based on jogging, joint mobility, dynamic stretching, and three sub-maximal countermovement jumps (CMJ). Five min after the end of the warm-up swimmers performed five maximal CMJ on a force plate (1,000 Hz, Dinascan/IBV, Biomechanics Institute of Valencia, Spain) with 1 min of rest between repetitions. If the execution was not adequately performed an extra trial was conducted. The highest and the lowest jumps height were removed, and the mean CMJ height (CMJ_H) of the other three was calculated [21].

Subsequently, swimmers rest 10 min and performed five pull-ups with 1 min of rest in-between. Performance was recorded through an isoinertial dynamometer (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain) attached to the subjects' hips through a harness. The pull-ups were inspected by the same researcher to assure that the swimmers displaced vertically. If a horizontal movement was observed an extra trial was conducted. The pull-ups which obtained the greatest and the lowest mean velocity values were excluded, and the mean of the remaining three was calculated [21]. Average propulsive velocity, force, and power were obtained (PUv_{avg}, PUf_{avg}, and PUp_{avg}, respectively).

Then, after the in-water warm-up swimmers rest 10 min prior to performing the 50 m front crawl all out (time trial with dive start). The race was recorded with a Sony FDR-AX53 (Sony electronics Inc., Tokyo, Japan) at 50 Hz sampling rate. The videos were analyzed by one expert evaluator, on an in-house customized software for race analysis in competitive swimming. Table 5.1 shows the description of variables and respective calculation approaches. The intra-class correlation coefficient (ICC) was computed to verify the absolute agreement between repeated measures for each trial. A very high agreement was obtained (ICC: 0.979 to 0.999).

Table 5.1. Description of the variables analyzed in the 50m front crawl test.

Variable	Definition
T50 (s)	Time lag between the starting signal and the hand touches the 50 m wall.
T15 (s)	Time lag between the starting signal and the head reaches 15 m mark.
T25 (s)	Time lag between the starting signal and the feet touches the 25 m wall.
$Turn_{(20-30)}$ (s)	Time lag between the head reaches 20 and 30 m mark.
$Finish_{(45-50)}$ (s)	Time lag between the head reaches 45 m mark and the hand touches the wall.
SR_{0-25} (Hz)	Collected from 15 m mark onwards, using a frequency measuring function for each three arm strokes and divided by the time elapsed during this action.
SR_{25-50} (Hz)	Collected from 35 m mark onwards, using a frequency measuring function for each three arm strokes and divided by the time elapsed during this action.
SR_{Fin} (Hz)	Using a frequency measuring function for each the last two arm strokes and divided by the time elapsed during this action.
SL_{0-25} (m)	Collected from 15 m mark onwards, from the ratio between CSS_{0-25} and SR_{0-25}.
SL_{25-50} (m)	Collected from 35 m mark onwards, from the ratio between CSS_{25-50} and corresponding SR_{25-50}.
SL_{Fin} (m)	Collected from 45 m mark onwards, from the ratio between CSS_{Fin} and corresponding SR_{Fin}.
SI_{0-25} ($m^2 \cdot s^{-1}$)	Product of the corresponding CSS_{0-25} and SL_{0-25}.
SI_{25-50} ($m^2 \cdot s^{-1}$)	Product of the corresponding CSS_{25-50} and SL_{25-50}.
SI_{Fin} ($m^2 \cdot s^{-1}$)	Product of the corresponding CSS_{Fin} and SL_{Fin}.
CSS_{0-25} ($m \cdot s^{-1}$)	Collected as the ratio between 5 m and the time lag between the 15 and 20 m mark.
CSS_{25-50} ($m \cdot s^{-1}$)	Collected as the ratio between 5 m and the time lag between the 40 and 45 m mark.
CSS_{Fin} ($m \cdot s^{-1}$)	Collected as the ratio between 5 m and the time lag between the 45 and 50 m mark.

SR, SL, and SI: Stroke rate, length, and index; CSS: Clean swimming speed.

In an attempt to explore the effects of detraining in an ecological environment, reliable swimming recovery-based methods were applied to estimate oxygen uptake kinetics related variables, $\dot{V}O_{2peak}$ and AnAL before and after a five-weeks training cessation [2,22–24]. The $\dot{V}O_2$ was continuously measured (breath-by-breath) before (baseline) and after the 50 m test (recovery period, *i.e.*, off-kinetics). Respiratory gas exchange was measured breath-by-breath during the recovery period using a portable gas analyzer (Cosmed K4b2, Cosmed, Rome, Italy), which was calibrated with 16% O_2 and 5% CO_2 concentration gases and a 3 L syringe before each testing session. To reduce the noise in the signal, $\dot{V}O_2$ values included only those between mean $\dot{V}O_2$ ± 4 standard deviation (SD)[22]. The off-kinetics response was modeled with $\dot{V}O_2$FITTING, a free and open-source software (https://shiny.cespu.pt/vo2_news/)[25]. Raw data was used in all the cases. Bootstrapping with 1,000 samples was used to estimate $\dot{V}O_2$ kinetics parameters [25]. Breath-by-breath data obtained during 5 min of recovery were adjusted as a function of time using a bi-exponential model [22,23]:

$$\dot{V}O_2(t) = EE\dot{V}O_2 - H\left(t - TD_p\right) A_P\left(1 - e^{-(t-TD_p)/\tau_p}\right) - H\left(t - TD_{SC}\right) A_{SC}\left(1 - e^{-(t-TD_{SC})/\tau_{SC}}\right) \quad \text{(Eq 5.1)}$$

Where $EE\dot{V}O_2$ is the $\dot{V}O_2$ at the end of exercise (50 m swim test), H represents the Heaviside step function, A_p and A_{sc}, τ_p and τ_{sc}, and TD_p and TD_{sc} are the amplitudes, time constants, and time delays of the $\dot{V}O_2$(t) curve fast and slow components, respectively [25]. AnAL energy was assumed as the fast component of excess post-oxygen consumption [22], *i.e.*, the product between A_p and τ_p of the fast component was assumed as AnAL [22,25]. The AnL energy was calculated using the following equation:

$$AnL = [La^-]_{net} \cdot \beta \cdot M \quad \text{(Eq 5.2)}$$

Where $[La^-]_{net}$ is the difference between the blood lactate concentration ($[La^-]$) before and after exercise ($[La^-]_{peak}$), β is the constant for O_2 equivalent of $[La^-]_{net}$ (2.7 $ml \cdot kg^{-1} \cdot mM^{-1}$) [26] and M is the body mass of the swimmer.

Both energy systems were then expressed in kJ assuming an energy equivalent of 20.9 kJ·L^{-1} [27]. The sum of the AnAL and AnL was considered as the anaerobic energy expenditure (E_{ana}) and the anaerobic metabolic power ($\dot{E}_{ana}$) was estimated as the ratio between E_{ana} and performance (s). The $\dot{V}O_{2peak}$ was estimated by backward extrapolation at zero recovery time using linear regressions applied to the first 20 s of recovery [24]. HR was recorded using a POLAR RS800CX (Polar Electro Oy Inc., Kempele, Finland). Gas exchanges and HR were measured in sitting position for 10 min at rest prior to and after the 50 m all out trial [28]. For [La$^-$] analysis, capillary blood samples (25 µL) were collected from the same fingertip at min 5 during the resting period before the 50 m and immediately after the effort, at min 1, and every 2 min until the peak was reached, using Lactate Pro 2 analyzer (Arkray, Inc., Kyoto, Japan).

Thirty min after completion of the 50 m, swimmers performed 30 s tethered swimming in two conditions: at zero speed and at 1.124 m·s^{-1} water flow speed in a flume with 30 min of active rest between each trial. This speed was chosen after checking that this was the maximum speed that allowed registering all the forces of this group of swimmers. The start and end of the 30 s effort were determined through an auditory signal. Before that, the participants swam for 5 s at low intensity, to avoid inertial effect [14]. A snorkel was used for tethered swimming to avoid interferences in force parameters caused by breathing. A steel cable was attached to the swimmer through a floating trapezoidal structure (which allows them to kick) and fixed to a load cell (RSCC S-Type; HBM, Darmstadt, Germany) leading to an angle of 10º with the water surface, recording at 1,500 Hz. Analog data were converted (celula 1.4; Remberg, Force Isoflex, Spain), registered, and exported (NIUSB600; National Instruments, Austin, TX) to a specific software (myoRESEARCH, Noraxon, USA). The force-time curves were processed, using a fourth-order Butterworth low-pass digital filter (4.5 Hz cut-off frequency), and the average force (Favg), maximum force (Fmax), average impulse (Iavg), and maximum impulse (Imax) were computed [14].

On the second day of data collection, after the in-water warm-up swimmers performed 10, 15, 20, and 25 m all out front crawl with in-water starts and 30 min passive rest in-between. The distances were recorded and analyzed using the same methodology as for the 50 m all out. The AnCV was calculated from the slope of the distance-time relationship [12].

During the five-weeks of training cessation, swimmers were instructed to self-assess their weekly physical activity by the International Physical Activity Questionnaire (IPAQ)[2,29], which was summarized according to the registered physical activities (low, moderate, and vigorous activities). The swimmers' questionnaires results were displayed into units of metabolic equivalent of task (METs) following the IPAQ specifications [2,29]. The IPAQ is test-retest reliable with a mean correlation of ~0.80 (ranging from "fair" 0.46 to "excellent" 0.96)[29].

Statistical analysis

The normality of all distributions was verified using Shapiro–Wilk. Napierian logarithm was calculated for analytical purposes. All analyses were conducted differentially by sex. Paired sample t test was used to compare differences between PRE and POST off-season for 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 $|d| > 0.8$)[30]. To test the growth effects over performance changes, multiple regression analysis was conducted with the change in performance (*i.e.,* POST-PRE) as the dependent variable and the change score values of height, body mass, and arm span as predictors. The same procedure was conducted using the total physical activity during off-season to test the effects of non-swimming specific physical activities. Pearson's correlation was used to quantify the degree of association between deltas (Δ, *i.e.,* POST - PRE values) for each variable and the change in 50 m time. Statistical procedures were performed using SPSS 24.0 (IBM, Chicago, IL, USA) with the level of statistical significance set at 0.05.

Results

The mean volume and training load per week over the last 15 weeks immediately before the off-season were 28 ± 6 km·week^{-1} and 45 ± 12 T.U.·week^{-1}, respectively (Figure 5.1). The effects of the five-weeks off-season on swimmers' anthropometrics, kinematics, energetics, and strength are presented in Tables 5.2, 5.3, 5.4, and 5.5, respectively. The total variance in performance change was influenced by neither anthropometric changes (males: $r^2 = 0.516$, $p = 0.077$; females: $r^2 = 0.096$, $p = 0.930$) nor physical activity during off-season (males: $r^2 = 0.060$, $p = 0.900$; females: $r^2 = 0.250$, $p = 0.734$). All swimmers had reached their PHV (males maturity offset: 2.90 ± 2.86 years ago; females maturity offset: 3.41 ± 0.86 years ago).

Table 5.2. Effects of five-weeks off-season on swimmers' anthropometrics. There are displayed the PRE and POST mean ± standard deviation values with respective level of probabilities (p), mean differences, 95% confidence intervals [95%CI], relative changes (Δ%), effect sizes, and correlations between deltas and delta performance (Δ).

	Variable	PRE	POST	Difference [95%CI]; Δ%	p-value	Effect size (*d*)	ΔvsΔT50
Males (n = 13)	Height (cm)	175.8 ± 7.9	176.0 ± 7.7	0.2 [-0.1, 0.4]; 0.9%	0.117	0.46, Small	0.500
	Arm span (cm)	181.2 ± 9.9	181.6 ± 9.9	0.4 [0.1, 0.7]; 0.2%	0.007#	0.89, Large	0.247
	Body mass (kg)	66.1 ± 9.1	67.2 ± 8.9	1.1 [0.2, 1.9]; 1.6%	0.021#	0.73, Medium	-0.254
	BMI ($kg\cdot m^2$)	21.3 ± 2.3	21.6 ± 2.4	0.3 [0.01, 0.6]; 1.5%	0.030#	0.68, Medium	-0.353
	Low intensity ($MET\text{-}min\cdot wk^{-1}$)	-	1116 ± 922	-	-	-	-0.091
	Moderate intensity ($MET\text{-}min\cdot wk^{-1}$)	-	1088 ± 1526	-	-	-	0.098
	Vigorous intensity ($MET\text{-}min\cdot wk^{-1}$)	-	1426 ± 1399	-	-	-	-0.228
	Total physical activity ($MET\text{-}min\cdot wk^{-1}$)	-	3630 ± 1634	-	-	-	-0.155
Females (n = 8)	Height (cm)[a]	165.5 ± 3.3	166.0 ± 3.5	0.0 [0.0, 0.1]; 0.2%	0.012#	1.18, Large	-0.308
	Arm span (cm)[a]	169.9 ± 4.5	170.2 ± 4.3	0.0 [-0.1, 0.1]; 0.2%	0.158	0.56, Medium	-0.132
	Body mass (kg)	58.1 ± 6.2	59.1 ± 5.4	1.0 [-0.1, 2.2]; 1.8%	0.065	0.77, Medium	0.089
	BMI ($kg\cdot m^2$)	21.2 ± 2.4	21.5 ± 2.2	0.3 [-0.2, 0.7]; 1.3%	0.204	0.49, Small	0.113
	Low intensity ($MET\text{-}min\cdot wk^{-1}$)	-	817 ± 165	-	-	-	0.062
	Moderate intensity ($MET\text{-}min\cdot wk^{-1}$)	-	322 ± 233	-	-	-	-0.398
	Vigorous intensity ($MET\text{-}min\cdot wk^{-1}$)	-	213 ± 281	-	-	-	-0.038
	Total physical activity ($MET\text{-}min\cdot wk^{-1}$)	-	1352 ± 515	-	-	-	-0.182

BMI: body mass index; MET: metabolic equivalent of task; [a]Raw data is presented, but Napierian logarithm transformed data was used in the analysis. #significant difference.

Table 5.3. Effects of five-weeks off-season on swimmers' race kinematics. There are displayed the PRE and POST mean ± standard deviation values with respective level of probabilities (p), mean differences, 95% confidence intervals [95%CI], relative changes (%Δ), effect sizes, and correlations between deltas and delta performance (Δ).

	Variable	PRE	POST	Difference [95%CI]; Δ%	p-value	Effect size (*d*)	ΔvsΔT50
Males (n = 13)	T50 (s)	27.78 ± 1.71	28.32 ± 2.07	0.54 [0.18, 0.89]; 1.9%	0.007#	0.91, Large	-
	T15 (s)	7.35 ± 0.53	7.43 ± 0.71	0.08 [-0.09, 0.25]; 1.1%	0.322	0.28, Small	0.978*
	T25 (s)	13.48 ± 0.86	13.68 ± 1.10	0.20 [-0.02, 0.42]; 1.5%	0.076	0.53, Medium	0.980*
	$Turn_{(20\text{-}30)}$ (s)	5.49 ± 0.33	5.59 ± 0.32	0.10 [0.03, 0.17]; 1.9%	0.009#	0.85, Large	0.472
	$Finish_{(45\text{-}50)}$ (s)	2.91 ± 0.17	2.97 ± 0.18	0.05 [0.02, 0.08]; 1.9%	0.001#	1.21, Large	0.088
	$SR_{0\text{-}25}$ (Hz)[a]	0.94 ± 0.08	0.92 ± 0.08	-0.02 [-0.05, 0.01];-2.1%	0.164	0.41, Small	0.196
	$SR_{25\text{-}50}$ (Hz)	0.89 ± 0.09	0.87 ± 0.10	-0.02 [-0.03, -0.01];-2.2%	0.012#	0.82, Large	-0.235
	SR_{Fin} (Hz)	0.89 ± 0.01	0.87 ± 0.01	-0.02 [-0.04, -0.01];-2.4%	0.041#	0.63, Medium	-0.166
	$SL_{0\text{-}25}$ (m)[a]	1.83 ± 0.13	1.84 ± 0.12	0.01 [-0.03, 0.03]; 0.3%	0.792	0.07, Small	-0.287
	$SL_{25\text{-}50}$ (m)	1.85 ± 0.14	1.86 ± 0.15	0.01 [-0.01, 0.02]; 0.6%	0.188	0.39, Small	-0.363
	SL_{Fin} (m)	1.93 ± 0.22	1.94 ± 0.19	0.01 [-0.04, 0.05]; 0.2%	0.819	0.06, Small	0.180
	$SI_{0\text{-}25}$ ($m^2 \cdot s^{-1}$)	3.18 ± 0.29	3.13 ± 0.31	-0.04 [-0.17, 0.07];-1.5%	0.409	0.23, Small	-0.329
	$SI_{25\text{-}50}$ ($m^2 \cdot s^{-1}$)	3.05 ± 0.32	3.00 ± 0.34	-0.04 [-0.08, 0.01];-1.3%	0.084	0.52, Medium	-0.529*
	SI_{Fin} ($m^2 \cdot s^{-1}$)	3.34 ± 0.55	3.28 ± 0.48	-0.05 [-0.16, 0.04];-1.7%	0.255	0.33, Small	0.153
	$CSS_{0\text{-}25}$ ($m \cdot s^{-1}$)	1.73 ± 0.09	1.69 ± 0.10	-0.03 [-0.05, -0.01];-1.8%	0.005#	0.94, Large	-0.272
	$CSS_{25\text{-}50}$ ($m \cdot s^{-1}$)	1.64 ± 0.11	1.61 ± 0.12	-0.03 [-0.05, -0.01];-1.8%	0.014#	0.79, Medium	-0.478*
	CSS_{Fin} ($m \cdot s^{-1}$)	1.71 ± 0.10	1.68 ± 0.10	-0.03 [-0.04, -0,01];-1.9	0.010#	1.20, Large	-0.026
Females (n = 8)	T50 (s)	31.09 ± 2.53	31.99 ± 2.24	0.89 [0.09, 1.69]; 2.9%	0.033#	0.93, Large	-
	T15 (s)	8.07 ± 0.88	8.22 ± 0.54	0.15 [-0.19, 0.49]; 1.9%	0.335	0.36, Small	0.574
	T25 (s)	14.84 ± 1.31	15.16 ± 0.91	0.32 [-0.16, 0.80]; 2.2%	0.163	0.55, Medium	0.860*
	$Turn_{(20\text{-}30)}$ (s)	6.06 ± 0.43	6.21 ± 0.53	0.15 [-0.03, 0.34]; 2.6%	0.094	0.68, Medium	0.530
	$Finish_{(45\text{-}50)}$ (s)	3.36 ± 0.22	3.45 ± 0.25	0.09 [0.03, 0.14]; 2.7%	0.005#	1.40, Large	-0.292
	$SR_{0\text{-}25}$ (Hz)	0.86 ± 0.12	0.82 ± 0.12	-0.04 [-0.07, -0.01];-4.7%	0.011#	1.21, Large	-0.892*
	$SR_{25\text{-}50}$ (Hz)	0.79 ± 0.10	0.74 ± 0.10	-0.04 [-0.07, -0.02];-5.9%	0.002#	1.65, Large	-0.672*
	SR_{Fin} (Hz)	0.79 ± 0.09	0.73 ± 0.09	-0.05 [-0.09, -0.01];-6.6%	0.015#	1.13, Large	-0.638*
	$SL_{0\text{-}25}$ (m)	1.82 ± 0.21	1.84 ± 0.22	0.02 [-0.02, 0.07]; 1.2%	0.322	0.37, Small	0.157
	$SL_{25\text{-}50}$ (m)	1.83 ± 0.17	1.86 ± 0.18	0.03 [-0.04, 0.10]; 1.4%	0.437	0.29, Small	-0.863*
	SL_{Fin} (m)[a]	1.90 ± 0.18	1.98 ± 0.20	0.04 [-0.01, 0.10]; 4.6%	0.120	0.62, Medium	0.626*
	$SI_{0\text{-}25}$ ($m^2 \cdot s^{-1}$)[a]	2.85 ± 0.40	2.78 ± 0.31	-0.02 [-0.07, 0.03];-2.5%	0.333	0.37, Small	-0.442
	$SI_{25\text{-}50}$ ($m^2 \cdot s^{-1}$)	2.64 ± 0.27	2.57 ± 0.34	-0.06 [-0.32, 0.18];-2.6%	0.550	0.22, Small	-0.864*
	SI_{Fin} ($m^2 \cdot s^{-1}$)	2.83 ± 0.32	2.89 ± 0.35	0.05 [-0.15, 0.27]; 1.9%	0.554	0.21, Small	0.605
	$CSS_{0\text{-}25}$ ($m \cdot s^{-1}$)	1.56 ± 0.11	1.50 ± 0.06	-0.05 [-0.11, -0.01];-3.6%	0.042#	0.87, Large	-0.754*
	$CSS_{25\text{-}50}$ ($m \cdot s^{-1}$)	1.44 ± 0.09	1.38 ± 0.11	-0.06 [-0.14, 0.02];-4.2%	0.146	0.57, Medium	-0.841*
	CSS_{Fin} ($m \cdot s^{-1}$)[a]	1.49 ± 0.09	1.45 ± 0.09	-0.02 [-0.03, -0.01];-2.2%	0.009#	1.27, Large	0.259

T: time taken to complete the given distance; SR, SL and SI: stroke rate, length and index; CSS: clean swimming speed. [a]Raw data is presented, but Napierian logarithm transformed data was used in the analysis, *significant correlation, #significant difference.

Table 5.4. Effects of five-weeks off-season on swimmers' energetics. There are displayed the PRE and POST mean ± standard deviation values with respective level of probabilities (p), mean differences, 95% confidence intervals [95%CI], relative changes (%Δ), effect sizes, and correlations between deltas and delta performance (Δ).

	Variable	PRE	POST	Difference [95%CI]; Δ%	p-value	Effect size (*d*)	ΔvsΔT50
MalesS (n = 13)	$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	61.3 ± 15.5	55.5 ± 12.6	-5.8 [-14.3, 2.6]; -9.5%	0.162	0.41, Small	0.288
	A_p (mL·kg^{-1}·min^{-1})	42.6 ± 13.7	38.7 ± 12.4	-4.2 [-12.4, 3.8]; -10.0%	0.276	0.31, Small	0.314
	τp (s)	48.5 ± 30.0	36.5 ± 17.8	-11.9 [-27.2, 3.3]; -24.6%	0.114	0.47, Small	0.331
	$[La^-]_{base}$ (mmol·L^{-1})	4.4 ± 1.6	4.3 ± 1.6	-0.1 [-1.4, 1.1]; -2.4%	0.857	0.05, Small	0.107
	$[La^-]_{peak}$ (mmol·L^{-1})	11.5 ± 2.3	12.6 ± 2.9	1.1 [-0.9, 3.1]; 9.3%	0.262	0.32, Small	-0.182
	$[La^-]_{net}$ (mmol·L^{-1})	7.1 ± 2.8	8.3 ± 2.6	1.2 [-1.0, 3.4]; 16.6%	0.275	0.31, Small	-0.221
	HR_{base} (bpm)	102 ± 17	108 ± 15	6 [0, 12]; 6.2%	0.041#	0.63, Medium	-0.268
	HR_{50m} (bpm)	113 ± 16	126 ± 13	13 [7, 19]; 12.0%	0.001#	1.30, Large	-0.622*
	HR_{net} (bpm)	10 ± 5	18 ± 9	7 [3, 11]; 66.9%	0.003#	1.03, Large	-0.545*
	HR_{maxB} (bpm)	115 ± 18	121 ± 17	6 [-1, 12]; 5.0%	0.081	0.52, Medium	-0.331
	HR_{max50m} (bpm)	146 ± 19	168 ± 15	22 [12, 32];14.9%	<0.001#	1.33, Large	-0.192
	HR_{maxnet} (bpm)	30 ± 13	47 ± 14	16 [10, 21]; 52.1%	<0.001#	1.76, Large	0.049
	AnL (kJ)	27.05 ± 12.75	31.29 ± 10.45	4.24 [-3.73, 12.22]; 15.6%	0.269	0.32, Small	-0.240
	AnAL (kJ)[a]	46.75 ± 29.28	31.94 ± 17.32	-0.35 [-0.69, -0.01]; -31.6%	0.045#	0.62, Medium	0.451
	E_{Ana} (kJ)[a]	73.80 ± 26.62	63.24 ± 23.02	-0.15 [-0.32, 0.01]; -14.3%	0.061	0.57, Medium	0.403
	$\dot{E}_{Ana}$ (kW)[a]	2.68 ± 1.05	2.25 ± 0.88	-0.17 [-0.33,-0.01] -16.0%	0.035#	0.65, Medium	0.358
Females (n = 8)	$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})[a]	54.5 ± 14.6	45.1 ± 11.9	-0.2 [-0.3, -0.01]; -17.1%	0.047#	0.85, Large	0.227
	A_p (mL·kg^{-1}·min^{-1})	40.5 ± 12.8	34.1 ± 9.8	-6.4 [-15.7, 2.9]; -15.8%	0.148	0.57, Medium	0.403
	τp (s)	43.4 ± 9.1	41.3 ± 11.6	-2.1 [-12.5, 8.2]; -4.9%	0.639	0.17, Small	0.437
	$[La^-]_{base}$ (mmol·L^{-1})	2.6 ± 0.8	2.5 ± 0.5	-0.1 [-0.7, 0.6]; -0.9%	0.934	0.03, Small	0.099
	$[La^-]_{peak}$ (mmol·L^{-1})	10.0 ± 2.7	10.0 ± 3.1	0.00 [-1.45, 1.50]; 0.2%	0.969	0.01, Small	-0.385
	$[La^-]_{net}$ (mmol·L^{-1})	7.3 ± 2.1	7.4 ± 2.7	0.1 [-1.0, 1.2]; 0.6%	0.919	0.03, Small	-0.567
	HR_{base} (bpm)	94 ± 7	102 ± 7	8 [3,13]; 8.8%	0.008#	1.46, Large	0.808*
	HR_{50m} (bpm)	109 ± 10	122 ± 7	13 [6, 19]; 11.7%	0.003#	1.87, Large	-0.493
	HR_{net} (bpm)	15 ± 7	20 ± 8	4 [-3, 12]; 29.9%	0.224	0.51, Medium	-0.915*
	HR_{maxB} (bpm)	111 ± 7	117 ± 8	6 [-2, 14]; 5.5%	0.117	0.69, Medium	0.671*
	HR_{max50m} (bpm)[a]	147 ± 21	163 ± 13	0.11 [-0.04, 0.26]; 10.9%	0.122	0.67, Medium	-0.488
	HR_{maxnet} (bpm)	36 ± 20	46 ± 15	10 [-14, 34]; 28.0%	0.348	0.38, Small	-0.644
	AnL (kJ)	23.85 ± 6.20	24.43 ± 8.22	0.57 [-3.41, 4.56]; 2.4%	0.742	0.12, Small	-0.495
	AnAL (kJ)	34.96 ± 11.35	29.24 ± 12.74	-5.71 [-15.01, 3.58]; -16.3%	0.189	0.51, Medium	0.572
	E_{Ana} (kJ)	58.82 ± 14.30	53.68 ± 11.72	-5.14 [13.24, 2.95]; -8.7%	0.177	0.53, Medium	0.413
	$\dot{E}_{Ana}$ (kW)	1.90 ± 0.50	1.69 ± 0.41	-0.21 [-0.46, 0.04]; -11.9%	0.090	0.69, Medium	0.276

$\dot{V}O_{2peak}$: highest exercise oxygen uptake; A_p, τp: amplitude and time constant of the fast $\dot{V}O_2$ component; $[La^-]_{base}$: baseline blood lactate concentration; $[La^-]_{peak}$: peak blood lactate concentration; $[La^-]_{net}$: blood lactate concentration difference between the $[La^-]$ before and after exercise; HR_{base}: mean baseline heart rate; HR_{50m}: mean heart rate after exercise; HR_{net}: difference between the mean heart rate before and after exercise; HR_{maxB}: maximum baseline heart rate; HR_{max50m}: maximum heart rate after exercise; HR_{maxnet}: difference between the maximum heart rate before and after exercise; AnL: anaerobic lactic contribution; AnAL: anaerobic alactic contribution; E_{Ana}: anaerobic energy expenditure; $\dot{E}_{Ana}$: anaerobic metabolic power. [a]Raw data is presented, but Napierian logarithm transformed data was used in the analysis, *significant correlation, #significant difference.

Table 5.5. Effects of five-weeks off-season on swimmers' strength. There are displayed the PRE and POST mean ± standard deviation values with respective level of probabilities (p), mean differences, 95% confidence intervals [95%CI], relative changes (%Δ), effect sizes, and correlations between deltas and delta performance (Δ).

	Variable	PRE	POST	Difference [95%CI]; %Δ	p-value	Effect size (*d*)	ΔvsΔT50
Males (n = 13)	CMJ_H (cm)	0.33 ± 0.06	0.33 ± 0.06	-0.00 [-0.01, 0.08]; -0.4%	0.746	0.09, Small	0.501*
	PUv_{avg} ($m{\cdot}s^{-1}$)[a]	0.68 ± 0.18	0.64 ± 0.18	-0.06 [-0.10, -0.03]; -6.2%	0.001#	1.44, Large	0.033
	PUf_{avg} (N)	620 ± 115	625 ± 105	4.98 [-6.74, 16.71]; 0.8%	0.362	0.30, Small	-0.033
	PUP_{avg} (W)[a]	432 ± 158	408 ± 144	-0.05 [-0.08, -0.02]; -5.4%	0.004#	1.20, Large	-0.004
	$Favg_0$ (N)[a]	103 ± 20	92 ± 21	-0.11 [-0.22, -0.01]; -10.3%	0.033#	0.69, Medium	0.357
	$Fmax_0$ (N)	236 ± 42	227 ± 38	-9 [-23, 3];-4.1%	0.136	0.44, Small	-0.121
	$Iavg_0$ ($N{\cdot}s$)[a]	64 ± 14	63 ± 13	-0.87 [-6.78, 5.04]; -1.3%	0.754	0.08, Small	0.118
	$Imax_0$ ($N{\cdot}s$)[a]	89 ± 15	88 ± 20	-0.02 [-0.15, 0.09]; -1.5%	0.597	0.15, Small	-0.019
	$Favg_{1.124}$ (N)	43 ± 11	40 ± 11	-3 [-9, 2]; -7.5%	0.240	0.34, Small	0.115
	$Fmax_{1.124}$ (N)	124 ± 34	119 ± 34	-5 [-18, 7]; -4.3%	0.383	0.25, Small	0.192
	$Iavg_{1.124}$ ($N{\cdot}s$)	29 ± 9	25 ± 6	-3 [-7, 0]; -11.5%	0.094	0.50, Small	0.215
	$Imax_{1.124}$ ($N{\cdot}s$)	51 ± 15	49 ± 19	-2 [-9, 5]; -0.8%	0.564	0.16, Small	-0.053
Females (n = 8)	CMJ_H (cm)	0.25 ± 0.04	0.24 ± 0.04	-0.01 [-0.02, -0.01]; -4.9%	0.038#	0.90, Large	-0.295
	PUv_{avg} ($m{\cdot}s^{-1}$)	0.64 ± 0.21	0.59 ± 0.25	-0.05 [-0.11, 0.01]; -8.1%	0.072	0.82, Large	0.524
	PUf_{avg} (N)	609 ± 71	631 ± 71	21 [5, 38]; 3.5%	0.018#	1.22, Large	-0.297
	PUp_{avg} (W)	399 ± 147	377 ± 167	-21 [-55, 12]; -5.3%	0.172	0.58, Medium	0.559
	$Favg_0$ (N)	70 ± 8	65 ± 4	-5 [-11, 1]; -6.9%	0.087	0.70, Medium	-0.081
	$Fmax_0$ (N)[a]	164 ± 24	158 ± 16	-0.02 [-0.06, 0.01]; -3.2%	0.126	0.61, Medium	0.074
	$Iavg_0$ ($N{\cdot}s$)	47 ± 5	47 ± 5	0 [-1, 3]; 1.4%	0.516	0.24, Small	-0.547
	$Imax_0$ ($N{\cdot}s$)	69 ± 10	63 ± 7	-6 [-16, 5]; -8.1%	0.274	0.41, Small	0.447
	$Favg_{1.124}$ (N)	19 ± 5	17 ± 5	-2 [-5, 1]; -10.6%	0.176	0.53, Medium	-0.256
	$Fmax_{1.124}$ (N)	57 ± 15	53 ± 13	-4 [-17, 10]; -6.3%	0.566	0.21, Small	-0.075
	$Iavg_{1.124}$ ($N{\cdot}s$)	15 ± 10	14 ± 7	1 [-4, 2]; -7.3%	0.495	0.25, Small	-0.683*
	$Imax_{1.124}$ ($N{\cdot}s$)	24 ± 6	21 ± 5	-3 [-10, 4]; -13.0%	0.352	0.35, Small	0.223

$CMJ_{H:}$ countermovement jump height; PUv_{avg}: pull-ups' average propulsive velocity; PUf_{avg}: pull-ups' average propulsive force; PUp_{avg}: pull-ups' average propulsive power; Favg: average force; Fmax: maximum force; Iavg: average impulse; Imax: maximum impulse. [a]Raw data is presented, but Napierian logarithm transformed data was used in the analysis, *significant correlation, #significant difference.

Discussion

The main finding of this study was that 50 m swimming performance was impaired after a five-weeks training cessation in both male (1.9%, 0.54 s) and female (2.9%, 0.89 s) swimmers. Neither anthropometric changes nor physical activity during off-season significantly accounted for variance in performance decrements. The decrease in performance was mainly associated with kinematics changes, energetics and strength impairments.

After the off-season males showed a SR reduction in the latter half of the 50 m, while females' SR reduction was evidenced in the whole 50 m, suggesting biomechanical and energetic impairments[31](Table 5.4). This reduction together with the fact that SL did not increase, likely provoked the clean swimming speed decline. This behavior was also observed on T400 in young swimmers after a four-weeks of training cessation [2] and could be explained by the association between muscular power and energetic capabilities with the capacity to maintain a high SR until the end of a race [31]. Hence, the strength and energetic impairments might have provoked that swimmers were not able to reach and sustain such high SR [32,33](Tables 5.4 and 5.5). Moreover, in the current study, the SR reduction was only correlated with females' 50 m performance impairment. This difference might lie in the interaction between SR and SL, suggesting that males relied more on their SL than on their SR. Therefore, the SR reduction showed a bigger impact on females' performance. Differences in energy cost of swimming between males and females are mainly related to differences in hydrodynamic resistance, which could explain at least in part these results. Unfortunately, swimming speed was not controlled for practical purposes (which would make it difficult to compare energy cost and related variables)[32,33]. On the other hand, the performance deficiencies in both sexes were especially related to the reduction of the clean swimming speed in the second half of the 50 m. A similar association between performance and SI during the latter half of the 50 m was observed, which suggests that higher fatigue evoked a loss of swimming efficiency and therefore the reduction of clean swimming speed [7]. Although the turn ($Turn_{20\text{-}30}$) evidenced an impairment, this was not related to 50 m performance changes. By contrast, swimming start time did not decrease significantly after the training cessation period, but the changes were related to performance deterioration in males. In swimming, unlike other sports, movements cannot be fully replicated out of the water since the hydrodynamic reaction stimulus can only be experienced in the water [34]. As a result, loss of "feeling for the water" during training cessation might explain, at least in part, the kinematic changes. In addition, due to the turn influence, the impact of five-weeks training cessation on sprint swimming performance might differ between long and short courses.

Regarding cardiorespiratory responses, female swimmers evidenced lower $\dot{V}O_{2peak}$ after the training cessation period. Hence, it is possible that the same effort produced higher fatigue due to the lower blood and plasma volumes [1,2]. It is important to be aware that high aerobic power (*e.g.*, $\dot{V}O_{2peak}$), *i.e.*, elevated rate of adenosine triphosphate production by the aerobic system, is determinant even for such a short effort (PRE: 31.09 ± 2.53 s *vs*. POST: 31.99 ± 2.24 s). Thus, oxygen supply and utilization should be taken into account by coaches for maximal efforts of short duration [11], seeking for different strategies to mitigate such losses. Similar τ_p and A_p were observed for both males and females, *i.e*., not sensitive enough to a five-weeks training cessation period, perhaps as a consequence of not controlling the swimming speed [5]. The energetic determinants of swimming performance decay when the training process is interrupted evoking performance impairment [1]. Although it was observed only a significant decrease in AnAL energy contribution in males, both male and female swimmers presented the same energetics trend. Neither the E_{ana} nor the AnL decreased significantly, possibly due to the short duration of the effort and/or not controlling swimming speed [5]. Nevertheless, the $\dot{E}_{ana}$ was significantly reduced in males, and females presented similar trend (same effect size), which shows a lower anaerobic energy contribution after the five-weeks training cessation period, likely, due to the reduction or absence of high-intensity training during that period [35]. Nevertheless, none of the changes in energetics variables were correlated with the change in performance. Moreover, despite the aerobic pathways were not measured (which contribution to E_{tot} is ~27% [10]) a decline was reported in four-weeks detraining period [2], which might suggest that aerobic pathways and therefore E_{tot} could have been impaired in this study, negatively affecting performance. The data obtained provide relevant information for swimmers and coaches about the behavior of the energetic contributions during the shortest competitive event in swimming.

The [La^-] remained the same after five-weeks (Table 5.4), which does not necessarily mean that the anaerobic capacity was not reduced, since is the balance between production and removal and therefore, it is possible then that both processes were impaired (*i.e.*, similar [La^-] values)[27]. From a practical perspective, male swimmers did not evidence a change in AnCV, but presented a negative correlation between ΔAnCV and ΔT50. On the contrary, female swimmers showed a significant decrease in AnCV without correlation with performance worsening. As a non-invasive method [12], the difference between sexes might be influenced by other factors, such as the SR, which might interfere with the energy sources and with the neuromuscular power [31].

Both sexes exhibited greater mean HR before and after the 50 m (*i.e.,* HR_{base} and HR_{50m}, respectively), yet only the HR_{net} was higher in the POST in males. These increases were negatively correlated with performance impairment (Table 5.4)(*i.e.,* the less the HR_{net} increased the more the T50 increased) and might be evoked by a reduction in blood volume [1]. Hence, those that were not able to counterbalance the blood volume reduction by increasing the HR, showed worse performance. Regarding maximum HR, there was not a sex-induced difference, but the increase was only significant in males. Moreover, female swimmers showed a positive correlation between the change in performance and maximum baseline heart rate, suggesting that those swimmers for whom the warm-up was more stressful after the detraining period, were the ones who obtained greater T50 worsening.

The inconsistency of results regarding muscle strength changes after a training cessation period, previously discussed by Marques et al. [36] was also observed in our results. Female swimmers showed a significant decline in CMJ_H of 5%. However, males did not exhibit changes in CMJ_H, indeed, some swimmers reached higher heights after the off-season than before that period. The difference may lay in the activities conducted during the training cessation period. For instance, hypothetically, if swimmer A and B reached the same amount of physical activity, but swimmer A rode a bike and swimmer B played basketball, the adaptations would be different [36]. Regarding upper limbs, only males exhibited a deterioration in pull-up performance. With the exception of $Favg_0$, these muscle strength impairments were not translated into lower in-water force, probably because the ability to apply force in the water remained unaltered [14]. Yet, the fact that $Favg_0$ was reduced in males, might be more related to energy contributions than to neuromuscular impairments [4,13]. Finally, among all the pool-based strength tests, only the females change in $Iavg_{1.124}$ was negatively associated with the performance changes (*i.e.,* the higher the reduction in $Iavg_{1.124}$, the higher the T50 increments).

Contrary to our hypothesis, the amount of physical activity performed in the transition period did not attenuate the performance impairment as previously observed in 400 m front crawl [2]. Hence, although the amount of activity was quantified there is no record of the type of activity performed, which might have different effects on swimming performance. Therefore, future research should try to control not only the amount of activity but also the specific activity carried out by swimmers during the off-season. We are aware that when swimmers start a new season we do not expect them to swim a 50 m effort as fast as at the end of the previous season. However, a considerable part of the following season is lost just to return to previous performance levels. Minimizing impairments in swimming performance during the transition to the following competitive season is essential for technical continuity. Thus, identifying which changes might account for performance impairment in trained-highly trained sprint swimmers can guide coaches in planning the next season's training program [2,37].

We acknowledge some shortcomings and potential limitations in our study. For instance, although all swimmers were evaluated at a maximum relative intensity during PRE and POST, swimming speed was not controlled for practical purposes [38]. Likewise, since we tried to explore detraining effects in an ecological environment, the on-kinetics $\dot{V}O_2$ response (*i.e.*, breath-by-breath analysis during the 50 m front crawl test) was not measured. Moreover, the biophysical impact of five-weeks training cessation on sprint swimming performance might differ between long and short courses or between performance level. Hence future studies should address this issue on long course and/or with international level swimmers.

Practical applications

Our results showed the negative effects of an off-season period on sprint performance. Although swimmers need rest time to recover physiologically and mentally, such impairments could compromise the performance of the following competitive season. This is an important aspect, as otherwise, the first part of the season would consist of catching up rather than enhancing sprint swimming performance. Coaches should seek different strategies to minimize such performance deteriorations, either reducing the number of sessions per week instead of a complete break or establishing specific activities oriented to preserve sprint performance. Moreover, the sex-induced effects should be considered when planning these strategies (*e.g.*, the effect of stroke rate impairment).

Conclusion

Five-weeks training cessation impaired sprint swimming performance in 1.9% (0.54 s) and 2.9% (0.89 s) in male and female swimmers, respectively, which was mainly compromised by a reduction in SR and therefore clean swimming speed. Five-weeks training cessation impaired HR for the same distance and intensity, anaerobic pathways, and dry-land strength. These impairments had a sex-induced effect on performance.

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Supplementary material

Supplementary Material 5.1. Description of the standardized warm-up performed.

1. 300 m (100 m usual breathing, 100 m breathing every five strokes, 100 m usual breathing).
2. 4 × 100 m (2 × [25 m flutter kick + 25 m increased stroke length]) on 1:50.
3. 8 × 50 m (2 × 50 m drill; 2 × 50 m building up swimming speed; and 4 × [25 m race pace + 25 m easy]) on 1:00.
4. 100 m easy.

Supplementary Material 5.2. Description of the method use for the calculations of five-zone training system.

Swimming training load was calculated for each week and expressed in the total volume completed (km) and arbitrary training units (T.U.), which was quantified as:

$$\text{T.U.} = (km_{z1} \cdot if_{z1}) + (km_{z2} \cdot if_{z2}) + (km_{z3} \cdot if_{z3}) + (km_{z4} \cdot if_{z4}) + (km_{z5} \cdot if_{z5})$$

where *km* represents the sum of the total volume swum in kilometres in the respective zone (*z1* = zone 1, *z2* = zone 2, *z3*= zone 3, *z4* = zone 4, and *z5*= zone 5) and *if* was the respective intensity factor for each zone: $if_{z1} = 1$, $if_{z2} = 2$, $if_{z3} = 3$, $if_{z4} = 5$, and $if_{z5} = 8$.

CHAPTER 6:

The determinant factors of undulatory underwater swimming performance: A systematic review

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Abstract

Purpose: The prominence of undulatory underwater swimming (UUS) has been clearly observed during recent international events. Improvement of this phase is essential for overall performance. The aim of this systematic review was to identify the key factors that modulate UUS performance and provide coaches and sports science practitioners with valuable and practical information to optimize it. ***Methods:*** PubMed, Web of Science, Scopus, and SPORTDiscus databases were searched up to 14 October 2021. Studies involving competitive swimmers and which included UUS performance assessment were considered. Methodological quality assessment was conducted for the included articles. ***Results:*** From the 193 articles screened, 15 articles were included. There was a substantial body of research conducted on kicking frequency, vertical toe and body wave velocity, angular velocity of the joints, distance per kick, joint amplitudes and mobility, and body position in UUS performance. However, further investigation is required for muscle activation and muscle strength influence. ***Conclusions:*** The results from this review contribute to the understanding of how to optimize UUS performance, identifying the key aspects that must be addressed during training. Specifically, the caudal momentum transfer should be maximized, the upbeat duration reduced, and the frequency that best suits swimmers' characteristics should be identified individually.

Keywords: dolphin kick, swimmers, biomechanics, propulsion, sprint.

Introduction

Aside from the dive start, the highest swimming velocities are achieved during the underwater phase of butterfly, backstroke, and front crawl events and this phase of events is recognized as being one of the most influential variables on swimming performance [1]. Throughout the underwater phase, swimmers propel themselves forward by performing the undulatory underwater swimming (UUS) after a short glide. The prominence of UUS has been clearly observed during recent international events, where most of the swimmers seize the opportunity to maximize their performance in the underwater phase (limited to 15 m after each wall [2]) as an important contribution to their overall performance [3]. This fact has led to a large increase in the volume of research conducted, since the review in 2009 by Connaboy et al. [4], with the aim of understanding the key parameters in UUS performance [5–8]. For this reason, it is necessary to provide coaches and swimming specialists with an up-to-date review of UUS to optimize UUS training and therefore to improve overall swimming performance.

The UUS is a leg-dominated technique [5] that achieves propulsion by performing body undulations while in a streamlined position with the arms extended and held together over the head [9,10]. The propulsion is produced by a “body wave”, which increases in amplitude as it travels caudally throughout the body in a “whip-like” action [11–13]. When swimmers are at least 0.5 m below the water surface, the wave drag is considerably reduced [14], while the fusiform streamlined shape decreases pressure drag [4].

The UUS is a cyclic motion, which has been divided into three phases, the upbeat phase, a second upbeat phase, and the downbeat [9,15]. The second upbeat phase is initiated when the feet trajectory change from a vertical to a more horizontal displacement, due to the start of the knee flexion [9]. Nevertheless, to facilitate its grasp, most researchers have used two phases [6,8,10,16,17]: the upbeat and downbeat (also referred in the literature as up-kick and down-kick respectively). In a prone position the upbeat is characterized by the combination of hip extension and knee flexion while the downbeat is executed by the combination of hip flexion and knee extension. These phases are delimited by the turning points of the toe landmark [5]. However, due to human body anatomy [18,19] there are differences between these two phases and their contribution to total propulsion [20].

Considering the complexity of the UUS movement, the aims of this systematic review were to identify the biomechanical, physiological, and/or neuromuscular factors that have been identified in the literature as influencing UUS performance and to provide coaches and sports science practitioners with valuable and practical information that may be of interest when implementing this movement during training.

Methods

Definitions of terms related to swimming biomechanics are presented in Table 6.1. This systematic review was completed in accordance with the guidelines provided in the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) statement [21]. The review protocol was not registered.

Table 6.1. Definition of the biomechanical swimming terms used in this review.

Variable	Definition
Angle of attack	Angle of orientation of the axis of the propulsive segment with respect to the tangent of the path of the limb
Body wave velocity	Quantification of the speed of caudal momentum transfer along the body
Co-activation	Simultaneous activation between agonist and antagonist muscles
Distance per kick	Horizontal displacement of the body during one complete kick cycle
Froude efficiency	A dimensionless number, which indicates the proportion of the useful power with respect to the total power, characterized by the velocity of displacement, body length, and gravity acceleration
Heaving motion	Vertical, quasi sinusoidal motions produced at the ankle joint during undulatory underwater swimmin
Kick amplitude	Feet’s amplitude
Kick frequency	Number of kicks by unit of time
Kicking symmetry	Production of similar kinematics during the downbeat and upbeat
Pitching motion	The changes in the angle of the feet relative to the water
Pressure drag	The pressure differential between the front and the rear of the body
Strouhal number	A dimensionless number, which represents the ratio of unsteady to steady inertial forces, characterized by the kick amplitude, kick frequency, and velocity of displacement
Vortices	Rotating masses of water
Wave drag	The reaction force exerted by the waves, which are created by swimming movements near the water surface

Search strategy

A systematic literature search was performed encompassing publications from inception to 30 September 2020 on four international electronic databases: PubMed, Web of Science, Scopus, and SPORTDiscus. The complete search strategy used in PubMed was as follows: ((((Undulatory underwater swimming) OR (Underwater undulatory swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic)). To adjust to the nuances or requirements of the other databases searched, the specific search terms were modified as shown in Table S6.1. An update of the database search up to 14 October 2021 was conducted following the same steps as the ones performed during the original search, with the exception that in this case, publications were encompassed from 30 September 2020 to 14 October 2021 (Table S6.2).

Eligibility criteria

Inclusion criteria were defined as follows: 1) studies involving competitive swimmers with at least three years of competitive experience; 2) studies that measured the influence of biomechanical and/or physiological variables on UUS performance; 3) studies with outcome measures related to UUS performance.

Exclusion criteria were defined as follows: 1) studies that included participants who were non-swimmers (*i.e.*, water polo players, triathletes, scuba divers) or animals; 2) studies in which undulatory underwater swimming performance was not measured (*i.e.,* time to cover a distance or velocity); 3) reviews, case-studies, posters, conference abstracts, or presentations; 4) studies not written in English.

Study selection

Two independent researchers performed the selection process of relevant articles. First, all the studies obtained from the search of the databases were inspected, duplicate articles were removed, and titles and abstracts were independently screened. The researchers applied the eligibility criteria defined above and disagreements were discussed until consensus was reached. Then, the same procedure was conducted after full-text screening of the remaining articles for the final inclusion or exclusion decision. Finally, the reference lists of the included articles were checked for relevant articles that might not have been identified in the initial databases search.

Data extraction

The extraction process was conducted by one researcher and double-checked by another independent researcher. The items extracted were: 1) study reference; 2) main purpose; 3) number of participants per sex, age, and competitive level; 4) test performed; 5) UUS velocity and kick frequency; 6) variables measured; and 7) main findings. When there were differences between data extracted initially and the double-checking, the issue was discussed between the two researchers until consensus was reached.

Quality assessment

Due to the absence of a validated quality assessment tool appropriate for sports performance, some authors [22,23] have employed the Newcastle–Ottawa Quality Assessment Scale (NOS) [24] for cohort studies in reviews of athletes; however, the use of the adaptation for cross-sectional studies is not yet recommended, since a formal version is required [25]. Hence, Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews [26], specifically designed tool to assess quality in cross-sectional studies was used. This tool has been used lately [27] consisting of eight items with three possible answers ("yes", "no", and "not applicable"). A total score for each study provided a general indication of quality. The total score was obtained as the number of positively scored criteria divided by the total number of criteria. When the quality score was 0.75 or higher, the study was considered "high quality" and when the quality score was lower than 0.75, the study was considered as "low quality" [27]. Two independent reviewers conducted this process and disagreements, about the scores of the studies, were discussed until both researchers agreed.

Results

Article identification

In the first main search, 168 articles were identified and 66 duplicates were removed. After the screening of titles and abstracts of the remaining 109 articles, the full texts of a total of 32 articles were screened. Finally, 12 studies met the inclusion criteria and were subsequently included in this review. Some studies that met the inclusion criteria were excluded after the full-text read. For instance, the work by Hochstein and Blickhan [28] was potentially considered; however, two of the participants were triathletes and therefore the study had to be excluded from this systematic review or the work by Matsuura et al. [29] which provided valuable information about muscle synergies during UUS, however, despite performance was measured, the significance of each synergy on performance was not reported.

The updated searches in October 2021 resulted in a total of 25 new articles, of which three new studies were eligible. The study selection process is described in Figure 6.1. In total, therefore, we screened 193 records which resulted in 15 studies being included in this systematic review.

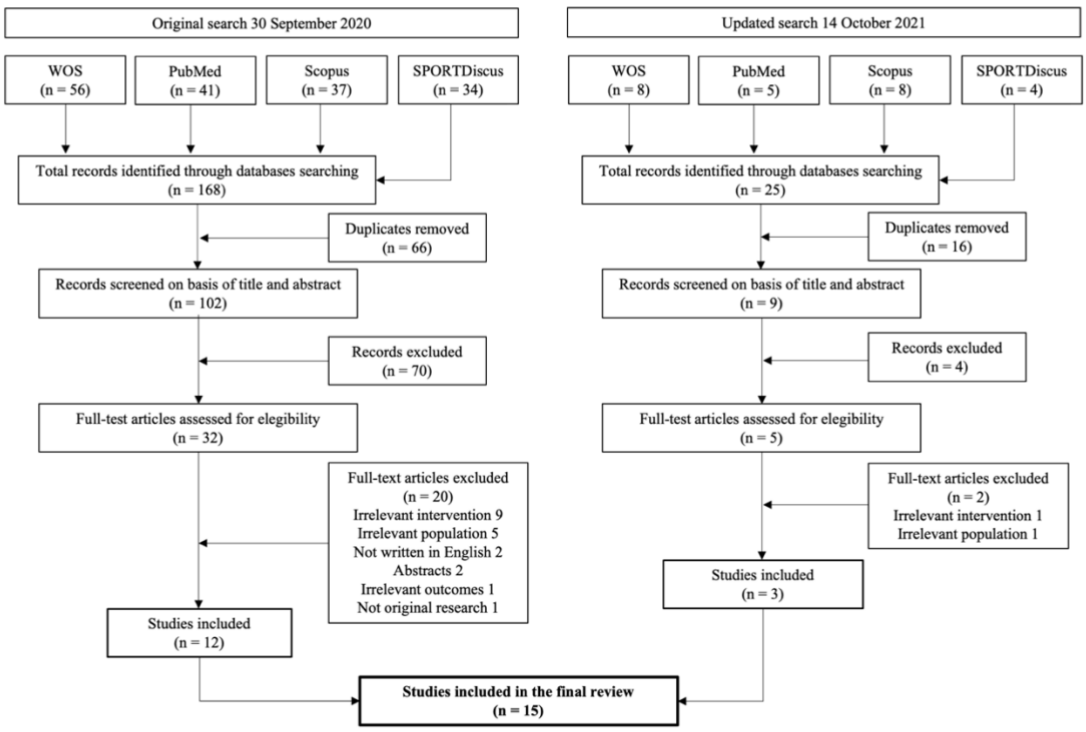

Figure 6.1. Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flowchart of the study selection process.

Description of the included articles

There were no eligible papers prior to 1999, ranging the years of publication of the 15 papers from 1999 to 2021. Nine of them were subsequent to the previous review published in 2009 [4]. The populations studied were national swimmers (n = 6), international swimmers (n = 3), and competitive swimmers (n = 6). Two of the aforementioned studies had a heterogeneous sample of swimmers with variation in performance level. Five of the studies had both male and female participants, six had all male participants, and only one had all female participants. The participants' sex in the remaining three studies was not reported. Sample size ranged from 6 to 47 participants, with 12 of the articles ≥ 10. The sample mean age ranged from 16 to 22 years, with nine of the studies having swimmers over 18 years and only six of them having swimmers under 18 years. The characteristics of the papers are presented in Table 6.2.

Table 6.2. Summary of the main purpose, participants background, methodology conducted, and main findings reported of the studies included in this review.

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m \cdot s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Alves et al. 2007 [33]	To analyze the kinematics of UUS in three body positions, prone, dorsal, and lateral	6 NS (17.0 ± 0.3) National	3 × 25 m UUS (1 prone, 1 lateral, 1 dorsal)	Prone: 1.46 ± 0.15 (2.35 ± 0.27) Lateral 1.27 ± 11 (2.08 ± 0.36) Dorsal 1.42 ± 0.21 (2.30 ± 0.33)	Prone, lateral, and dorsal: Mean velocity ($m \cdot s^{-1}$) Upbeat mean velocity ($m \cdot s^{-1}$) Downbeat mean velocity ($m \cdot s^{-1}$) Kick frequency (Hz) Strouhal number Amplitudes of toes, ankle, knee, hip, shoulder, elbow, wrist, hand, head, and center of mass (m) Peak joint angles of ankle plantar flexion and knee flexion (º) Foot resultant velocity ($m \cdot s^{-1}$) Upbeat foot resultant velocity ($m \cdot s^{-1}$) Downbeat foot resultant velocity ($m \cdot s^{-1}$) Foot resultant acceleration ($m \cdot s^{-2}$) Upbeat foot resultant acceleration ($m \cdot s^{-2}$) Downbeat foot resultant acceleration ($m \cdot s^{-2}$)	More ankle, elbow, and center of mass amplitude during lateral kicking compared to prone and dorsal kicking Prone and lateral kicking presented kinematic differences for a similar velocity
Arellano et al. 1999 [36]	To find whether the change in body position would affect UUS kinematic variables	11 M (19.9 ± 2.1) International	2 × 15 m UUS (1 prone 1 dorsal)	Prone 1.68 ± NS (2.21 ± NS) Dorsal 1.67 ± NS (2.24 ± NS)	Downbeat and upbeat duration (s) Kick frequency (Hz) Distance per kick (m) Mean velocity ($m \cdot s^{-1}$) Body oscillation (º) Downbeat and upbeat: Shoulder, hip, and knee angles (º) Trunk-horizontal angle (º)	The feet moved vertically during the knee extension and then displayed a curvilinear displacement comprising forward and upward movements Prone and dorsal kicking showed similar downbeat and upbeat duration, kick frequency, distance per kick, and mean velocity Greater shoulder and knee angles in dorsal compared to prone position Greater body oscillation in dorsal compared to prone position

(continued)

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m \cdot s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Atkinson et al. 2014 [7]	To determine how sagittal kick symmetry in UUS between the downbeat and upbeat phases is related to UUS performance	15 M (21.5 ± 3.2) Provincial – international	3 × 15 m prone UUS	1.64 ± 0.15 (2.11 ± 0.18)	Both upbeat and downbeat: Kick amplitude (m) Kick frequency (Hz) Body length (m) Distance per kick (m) Mean velocity ($m \cdot s^{-1}$) Mean velocity relative to body length (s^{-1}) Mean and maximum vertical toe velocity ($m \cdot s^{-1}$)	UUS performance correlated to sagittal kick symmetry All swimmers reached high velocities during the downbeat but only the most skillful swimmers reached high velocities during the upbeat
Connaboy et al. 2016 [6]	To identify key kinematic determinants of performance for maximal UUS velocity.	8 M 9 F (17.6 ± 1.4) National	3 × 15 m prone UUS	1.20 ± 0.13 (2.13 ± 0.23)	Maximum velocity ($m \cdot s^{-1}$) Kick frequency (Hz) Distance per kick (m) Joint ranges of movement of shoulder, hip, knee, and ankle (°) Maximum angular velocities of shoulder, hip, knee, and ankle ($° \cdot s^{-1}$) Amplitudes of wrist, shoulder, hip, knee, ankle, and 5th metatarsal phalangeal joint (m) Maximum and mean absolute angle of attack of the end effector (°)	Individual UUS technique was an important predictor of maximum velocity The maximal knee angular velocity correlated with maximal swimming velocity, which emphasizes the importance of a fast knee extension
Crespo et al. 2021 [30]	To evaluate the effects of an activation protocol based on PAPE upon UUS	10 M 7 F (16.6 ± 2.0) (15.4 ± 1.8) Competitive	2 × 10 m prone UUS (1 PAPE 1 control)	M: 1.19 ± 0.12 (2.19 ± 0.38) F: 1.17 ± 0.11 (2.60 ± 0.47)	Push-off velocity ($m \cdot s^{-1}$) Mean velocity ($m \cdot s^{-1}$) Mean peak velocity ($m \cdot s^{-1}$) Mean minimum velocity ($m \cdot s^{-1}$) Kick frequency (Hz) 10 m time (s)	The 10 m time was reduced after the activation protocol compared to the control condition

(Continued)

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m{\cdot}s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Higgs et al. 2017 [5]	To determine which kinematic variables of the upbeat and downbeat are related to prone UUS performance	7 M 3 F (21.1 ± 2.6) National	3 × 20 m prone UUS	1.73 ± 0.31 (NS)	Mean velocity ($m{\cdot}s^{-1}$) Both upbeat and downbeat: Kick duration (s) Kick amplitude (m) Peak acceleration ($m{\cdot}s^{-2}$) Peak vertical toe velocity ($m{\cdot}s^{-1}$) Body wave velocity ($m{\cdot}s^{-1}$) Knee and hip peak angular velocity ($^{o}{\cdot}s^{-1}$) Knee and hip mean angular velocity ($^{o}{\cdot}s^{-1}$)	The mean of the peak vertical toe velocities achieved in the upbeat and downbeat (72.3%) and mean body wave velocity (5.2%) explained 77.5% of the UUS performance variance The upbeat speed should be maximized
Houel et al. 2013 [35]	To determine the kinematics variables that improve performance during the underwater phase of grab starts	10 NS (21.4 ± 4.5) National	1 grab start	1.76 ± 0.17† (2.32 ± 0.22)	Center of mass mean velocity ($m{\cdot}s^{-1}$) Hip mean velocity ($m{\cdot}s^{-1}$) Trunk, thigh, leg, and foot angle of attack (º) Kick frequency (Hz) Kick amplitude (m)	Swimmers should maintain a streamlined position until reaching 6 m mark after the start to avoid hydrodynamic resistance increments Propulsion should be generated only from the legs and feet Velocity can be improved by increasing kick frequency while maintaining the kick amplitude
Ikeda et al. 2021 [31]	To identify the kinematic variables associated with UUS performance during the acceleration and deceleration phases	9 M (20.4 ± 1.67) Competitive	3–5 × 15m prone UUS	1.75 ± 0.16 (2.37 ± 0.23)	15 m time (s) Kick frequency (Hz) Time of the acceleration phase (s) Time of the deceleration phase (s) Mean velocity ($m{\cdot}s^{-1}$) Mean peak velocity ($m{\cdot}s^{-1}$) Mean minimum velocity ($m{\cdot}s^{-1}$) At maximum and minimum velocity: Shoulder, lower end of the rib, knee, and ankle relative vertical coordinate value and velocity to great trochanter Shoulder, hip, and knee joints, upper trunk, lower trunk, upper leg, and lower leg angular displacement (º) and angular velocities ($^{o}{\cdot}s^{-1}$)	Mean horizontal velocity correlated with the angular displacement of the lower trunk in the acceleration and deceleration phases Greater angular displacement of the lower trunk increased angular displacement of the shoulder, knee, and lower leg during the UUS

(Continued)

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m \cdot s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Shimojo et al. 2014 [15]	To investigate whether changes in kick frequency would change the other UUS kinematics	10 M (21.3 ± 0.9) National	UUS trials kick frequencies: (85-115%)	1.60 ± 0.12§ (2.26 ± 0.16)	Absolute values and ratio to preferred frequency: Kick frequency (Hz) Non-dimensional kick amplitude (%) Mean velocity ($m \cdot s^{-1}$) Distance per kick (m) Strouhal number Body wave velocity ($m \cdot s^{-1}$) Wave length (m) Wave length per body length Froude efficiency First and second upbeat phase (%) Downbeat phase (%)	Kicking at frequencies below the preferred frequency reduced mean velocity Similar mean velocities were obtained when kicking at frequencies above the preferred frequency When kicking at frequencies below the preferred frequency, the distance per kick and amplitude increased Distance per kick, amplitude, and Froude efficiency decreased when kicking at frequencies above the preferred frequency
Shimojo et al. 2019b [39]	To identify the importance of ankle flexibility in UUS	9 M 8 F (19.7 ± 1.1) (19.6 ± 0.8) National	2 × 20 m 80% kick frequency (1 no ankle restriction 1 ankle restriction)	1.33 ± 0.19§ (1.65 ± 0.18)	Active and passive ankle plantar flexion with and without restriction on land (º) Mean velocity ($m \cdot s^{-1}$) Kick frequency (Hz) Kick amplitude (m) Froude efficiency Body wave velocity ($m \cdot s^{-1}$) Maximal and minimal ankle angle (º) Maximal and minimal ankle angular velocity ($º \cdot s^{-1}$)	The restriction of ankle plantar flexion evoked a reduction in mean velocity When restricting the ankle plantar flexion, the ankle internal rotation was reduced

(Continued)

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m \cdot s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Wadrzykl et al. 2019 [37]	To characterize differences in the UUS technique depending on sex	23 M 18 F (16.7 ± 0.6) (16.7 ± 0.5) Competitive	3 × 7 m UUS	M: 1.35 ± 0.15 (1.85 ± 0.26) F: 1.24 ± 0.12 (1.83 ± 0.20)	Center of mass mean velocity ($m \cdot s^{-1}$) Maximal flexion and extension of the ankle (º) Range of motion of the ankles and knees (º) Kick frequency (Hz) Kick amplitude (m) Distance per kick (m) Downbeat horizontal toe displacement (m) Product of kick amplitude and kick frequency (n)	Male swimmers were faster than female swimmers Male swimmers had greater kick amplitude, distance per kick, and product of kick amplitude and kick frequency than female swimmers Female swimmers presented greater ankle range of motion than male swimmers Maximal extension of the ankles, distance per kick, and downbeat horizontal toe displacement were positively correlated with mean velocity for both sexes The correlation between the knee range of motion and center of mass mean velocity differed significantly between male and female swimmers
Wadrzyk et al. 2021 [32]	To determine whether there are any relationships between somatic build and kinematic indices of UUS	47 M (17.2 ± 1.0) Competitive	3 × 12m prone UUS Anthropometrics	1.39 ± 0.18 (1.92 ± 0.28)	Mean velocity ($m \cdot s^{-1}$) Kick frequency (Hz) Kick amplitude (m) Distance per kick (m) Product of amplitude and frequency Anthropometric measurements	Somatic build was not related to UUS technique in young male swimmers
Wang et al. 2006 [40]	To study the difference in UUS movement between elite and non-elite swimmers	20 NS (22 ± 2.0) (21 ± 1.8) Elite - non-elite	3 UUS trials	Elite 3.34 ± 0.51 (NS) Non-elite 2.10 ± 1.22 (NS)	Mean velocity ($m \cdot s^{-1}$) Mean acceleration ($m \cdot s^{-2}$) Transfer rates of the segmental peak angular velocity Upper trunk, lower trunk, thigh, shank, and foot peak angular velocity ($^{\circ} \cdot s^{-1}$) between each segment (proximal / distal)	Elite swimmers had higher shank, thigh, and lower trunk peak angular velocity than non-elite swimmers Applying the principle of the kinetic chain, better propulsion was generated as the number of segments involved increased (from upper trunk to feet)

(Continued)

Reference	Main purpose	Participants (Age, years) Level	Test	UUS velocity ($m \cdot s^{-1}$) (kick frequency, Hz)	Variables	Main findings
Willems et al. 2014 [38]	To investigate the effect of ankle flexibility and muscle strength on UUS performance	15 M 11F (16.4 ± 2.5) National - international	3 × 10 m UUS 3 × 10 m UUS ankle restriction Ankle flexibility Ankle isometric strength	1.64 ± 0.20§ (2.08 ± 0.40)	Plantar and dorsal flexors, internal and external rotators isometric strength (N) Active and passive plantar flexion and internal rotation range of motion on land (º) Free and ankle restricted: Mean velocity ($m \cdot s^{-1}$) Kick frequency (Hz) Distance per kick (m) Ankle plantar flexion, internal rotation, knee, and hip: highest point, maximal flexion point, maximal supination point, and lowest point (º)	Positive correlation between mean velocity and isometric strength (normalized by height) of the dorsal flexors and internal rotators The ankle restriction provoked a mean velocity reduction Active and passive ankle plantar flexion on land was associated with ankle plantar flexion during the downbeat The ankle restrictions evoked greater knee flexion
Yamakawa et al. 2017 [34]	To investigate the effects of increased kick frequency on the propelling efficiency and the muscular co-activation during UUS	8 F (20.9 ± 1.9) Competitive	7 × 15 m prone UUS kick frequencies: (85-115%)	1.35 ± 0.08§ (1.99 ± 0.15)	Kick frequency (Hz) Kick amplitude (m) Mean velocity ($m \cdot s^{-1}$) Froude efficiency Downbeat kick phase (%) Upbeat kick phase (%) Vertical toe velocity ($m \cdot s^{-1}$) Downbeat mean velocity ($m \cdot s^{-1}$) Downbeat maximum velocity ($m \cdot s^{-1}$) Upbeat mean velocity ($m \cdot s^{-1}$) Upbeat maximum velocity ($m \cdot s^{-1}$) Electromyography of trunk, thigh, and leg muscles	The activation pattern between agonist and antagonist changed from a reciprocal to a co-active pattern as the kick frequency increased Froude efficiency was negatively correlated to the duration of the co-active phase of the trunk muscles Mean velocity was positively correlated to the duration of the co-active phase of the trunk muscles When kicking above the preferred frequency, Froude efficiency was reduced

M: males; F: females; UUS: undulatory underwater swimming; NS: not stated; PAPE: post-activation performance enhancement.

† : Undulatory underwater swimming speed was collected after a start at different distances, only the last speed collected (*i.e.*, less influenced by the dive) is presented.

§ : Undulatory underwater swimming speed is only reported for the swimmers' preferred kick frequency or non-restricted condition.

Quality assessment

The initial agreement between both researchers had a substantial inter-rater reliability (κ= 0.64). Among the included articles, 10 of them were categorized as "high quality" and 5 as "low quality". The percentage of studies meeting each quality criteria is shown in Table S6.3.

Undulatory underwater swimming measures

Kinematic variables

The kick frequency has been the most extensively researched in the articles included, being assessed in 13 of the 15 papers included [6,15,20,30–39]. When the kick frequency increased above the preferred frequency, UUS velocity did not change [15,34] but the reduction in kick frequency led to the decrease of UUS velocity [15,34], lower peak and mean vertical toe velocity during the upbeat and body wave velocity [34]. The UUS velocity was positively correlated with peak vertical toe velocity and body wave velocity, during both the upbeat and the downbeat [5].

Elite swimmers had higher hip, knee, and ankle peak angular velocity than non-elite swimmers [40], being the UUS velocity related to peak knee and ankle angular velocity [6], mean knee and peak hip angular velocity (only during the upbeat) [5]. The distance per kick correlated with UUS velocity [37], only during the downbeat [20] and it was inversely related to changes in kick frequency [15]. The toe amplitude was not correlated with UUS velocity during UUS trials [5,6,20,37] and it was reduced when the kick frequency was increased above the preferred kick frequency [34]. The non-dimensional kick amplitude (*i.e.,* amplitude normalized to body height) was increased when the kick frequency was reduced below the preferred kick frequency [15]. When measured during the underwater phase of a grab start, the trunk, thigh, leg, and foot angle of attack correlated negatively with UUS velocity [35].

Kick phases

Nine of the studies reported the results of UUS measured as a single phase [6,15,35,37–40], six studies differentiated two phases (*i.e.,* downbeat and upbeat) and reported the results for each phase [5,20,31,33,34,36]. Note that, Ikeda et al. [31] defined the two phases as acceleration and deceleration phase, but in this manuscript, these phases will be referred to as downbeat and upbeat, respectively. The sagittal kick symmetry among downbeat and upbeat was positively correlated to UUS velocity [20]. The downbeat duration was shorter than the upbeat duration [5,20,34,36]. The UUS and mean vertical toe velocities were greater during the downbeat compared to the upbeat [20,34]. There was a very large positive correlation between the velocity during the upbeat and UUS velocity [20].

Joint mobility

In-water and on land joint range of motion have been found to be related to UUS performance [6,31,37–39]. The lower trunk range of motion was positively correlated with the UUS velocity during both the upbeat and downbeat [31]. The knee range of motion was negatively correlated with UUS velocity (10.3% velocity variation), only when “participants” was set as the fixed factor [6]. Only females’ knee range of motion was negatively correlated with UUS velocity [37]. The ankle range of motion was not correlated with UUS velocity [38,39]. When the ankle joint mobility was restricted, the UUS velocity decreased significantly [38,39].

Body position

In two out of the fifteen included papers, dorsal underwater kicking was assessed [33,36] and lateral underwater kicking was assessed in one study only [33]. The UUS velocity, phase duration, kick frequency, distance per kick, joint amplitudes, or Strouhal number were found to be similar in dorsal and prone kicking [33,36]. There were significant differences in the angle of attack of the trunk and body oscillation in dorsal kicking than in prone kicking [36]. In lateral kicking there was higher ankle, knee, hip, shoulder, elbow, wrist, and hand amplitude of motion than in either prone or dorsal kicking [36].

Muscle strength and anthropometrics

Muscle strength was assessed in only one study [38]. The dorsal flexors and internal rotators isometric strength were significantly related to UUS velocity. In young swimmers, there was no significant correlation between somatic build and UUS velocity [32].

Muscle activation

The UUS velocity was positively correlated with the co-active phase of the rectus femoris - biceps femoris muscles and the co-active phase of the tibialis anterior - gastrocnemius muscles. The muscles' activation changed when the kick frequency varied from the preferred kick frequency [34]. A high-intensity warm-up protocol elicited a post-activation performance enhancement in UUS [30].

Discussion

This systematic review aimed to identify the biomechanical, physiological, and/or neuromuscular factors that have been identified in the literature as influencing UUS performance and to provide coaches and sports science practitioners with valuable and practical information to optimize it. There was a substantial body of research conducted to address the importance of kicking frequency, vertical toe and body wave velocity, angular velocity of the joints, distance per kick, joint amplitudes and mobility, and body position in UUS performance. However, other factors such as the muscle co-activation, the influence of strength, or the anthropometric influence require further investigation.

Kinematic variables

Kick frequency is known as one of the most important factors in UUS performance. Nevertheless, while some studies have reported positive correlations with UUS velocity [33,35] others did not find significant association. The difference between these studies relied on the homogeneity of the sample. In homogeneous sample of national swimmers, there was a positive association [9,41], meanwhile in a heterogeneous sample of swimmers (*i.e.*, high inter-variation in FINA points) no correlation was found [20,31,37]. Hence, this might indicate that kick frequency plays an important role when having highly skilled swimmers, but other kinematic variables might be more important in swimmers with less advanced UUS skills.

It is worth noting that a lack of correlation (which relies on a linear relationship) doesn't necessarily mean that the kicking frequency isn't important, because it might have an optimum that is best represented as a parabolic relationship or it might be exponential in nature. In fact, increasing the kick frequency above the preferred frequency seems to be counterproductive as UUS velocity remains unchanged while the amplitude, horizontal distance per kick, and Froude efficiency were negatively affected [15,34]. Although no multi-task effect was apparent when controlling the kick frequency with a metronome [42], it was observed that the muscle co-activation increased when increasing the kicking frequency above the preferred frequency. Based on the lower muscle co-activation showed by more skilled swimmers in flutter kicking than in recreational swimmers [43], it was suggested that a training period might be required to reduce such muscular co-activation and obtain performance improvements [34].

The maximum vertical velocity of the toe was correlated with UUS velocity during the upbeat [5,20], but the results were incongruous during the downbeat [5,20]. The reason for the different outcomes might be related to the participants' level, since the participants presented in the study of [20] had a high variation in performance level. Because humans have musculo-skeletal constraints that limit the upbeat phase [44,45], it is possible that all swimmers were able to reach the same vertical velocity of the toe during the downbeat, but only the most skilled swimmers were able to reach higher vertical toe velocity during the upbeat (*i.e.*, better upbeat execution), being therefore the fastest. Nevertheless, in a homogeneous sample of national swimmers (assuming that they can perform UUS properly) those who reached higher toe velocity in both phases were able to achieve higher UUS velocity than those with lower vertical toe velocity [5].

Regardless of the correlation between vertical toe velocity and body wave velocity, there is a level of independency between them, which indicates that a higher body wave velocity does not necessarily yield higher vertical toe velocity [5]. Moreover, the UUS propulsion generated by the "whip-like" action produced during the body wave is related to the angular velocities of the hip, knee, and ankle joints [5,6,40]. Special attention should be allotted to the hip extension during training [17], as it was stated that better swimmers extend the hip before flexing the knees [9]. It should be noted that, despite the trunk undulation being important for maximizing propulsive efficiency [46], its action is not considered when measuring the hip action, and therefore the hip angular velocity might be misinterpreted [5]. Moreover, a higher mean angular velocity of the knee is related to the resistance generated by the horizontal motion of the toe during the latter phase of the upbeat [5,6], which leads to a drop in UUS velocity [37].

The body displacement in the direction of swimming is not independent of the kicking frequency as a higher frequency means less time and distance travelled during the kick cycle. Due to the human anatomical constraints swimmers spend a longer time executing the upbeat than the downbeat [5,20,34] without reaching higher velocities [17]. This might be the reason why the distance per kick was positively associated with UUS velocity only during the downbeat [20]. Therefore, the distance per kick should not be used without considering it in conjunction with the kick frequency. Swimmers can certainly vary their distance per kick by varying their kick frequency [15]; thus, a training period is required to establish the optimal combination of kicking frequency and distance travelled per kick that will enhance the velocity of the swimmer.

The kick frequency is directly related to limb segment amplitude [6]. Despite other landmarks being assessed, the end effector (*i.e.,* toe) amplitude is the variable usually measured and related to UUS performance [5,6,20,35,37]. However, the end effector amplitude was not associated with UUS velocity [5,6,20,37]. Only when the underwater phase of a grab start was studied the toe amplitude at 5.5 m from the wall was negatively correlated with performance [35]. This might be because the increase in the amplitude would increase the cross-sectional area perpendicular to the direction of motion that increases resistive drag, decelerating the body after the high velocity reached at the dive. Therefore, swimmers should avoid kicking until the kick contributes to speed rather than reducing speed [47].

The UUS efficiency does not just depend on any simple kinematic parameter but is the result of the swimmer's technique, which encompasses different aspects of body motion [44]. The amplitude of anatomical landmarks can be used to identify the UUS technique [4], which seems to be influenced by joint mobility (*e.g.,* ankle mobility restriction evokes a higher knee flexion during UUS execution) [38]. Moreover, an individual's own organismic constraints (*e.g.,* limb segment lengths) also influence the UUS technique used by swimmers [6]. For instance, tall swimmers would need to reduce their end effector amplitude to have similar kick frequencies to shorter swimmers [4].

Kick phases

Unlike cetaceans such as dolphins, the musculo-skeletal constraints that limit the upbeat phase in humans [44,45] evoke a 10% longer upbeat phase compared to the downbeat phase [9,20,34]. Hence, despite that swimmers generate propulsion during the downbeat and upbeat phases [5,8,20,48], the longer duration of the upbeat has been suggested as a recovery phase [17]. Nevertheless, Arellano et al. [9] stated that during the first phase of the upbeat (*i.e.*, when the feet displace vertically) the swimmers reached another peak velocity value and it was during the second phase of the upbeat (*i.e.*, when the foot displacement is more horizontal) that the swimmers' velocity decreased. It is therefore possible that only the second upbeat should be reduced. More studies are needed to clarify the difference between these 2 phases of the upbeat.

Faster swimmers are able to reduce the duration of the upbeat [20] with a consequent increase in swimming velocity [5]. This highlights the importance of executing the upbeat in a time similar to the downbeat [20]. In fact, the latter authors stated that, while the downbeat execution was generally suitably performed, most of the swimmers struggled to perform the upbeat successfully (*i.e.*, achieve similar velocity to the attained during the downbeat). Thus, swimmers should try to avoid using the upbeat as a recovery phase and reduce the upbeat duration to improve UUS performance [5,20]. Indeed, a recent study found that after eight weeks of training, young swimmers improved UUS performance, mainly as a consequence of the upbeat enhancement [8].

Joint mobility

Recently, Ikeda et al. [31] reported a correlation between the lower trunk range of motion and the UUS velocity. Specifically, they showed how the lower leg angular displacement was increased by increasing the lower trunk range of motion, but these increases came without increasing the knee range of motion, which was negatively correlated with UUS velocity [6,37]. Hence, the amplitude of the kick needs to be a consequence of high lower trunk range of motion rather than a high knee flexion. Moreover, a lack of ankle mobility evokes compensatory movements [49] such as higher knee flexion [38] which affected UUS velocity negatively [9]. Hence, the analysis of a single element of the UUS technique should be conducted while considering other segments [37].

Although neither the ankle range of motion measured on land nor the ankle range of motion during UUS were correlated with UUS velocity [5,37,38] an ankle mobility restriction provoked a significant reduction in UUS velocity [38,39]. This might be because the ankle mobility restriction reduced ankle plantar flexion and internal rotation [38] and its effect on heaving and pitching motions [50], which would have a direct negative effect on shedding of vortices to generate propulsion [51].

Body position

No significant differences have been reported between prone, dorsal, and lateral UUS velocity [33,36]. The main difference between prone and dorsal body positions seemed to lie in lesser upper body oscillation and knee flexion (during the downbeat) while kicking in a prone position than in a dorsal position [36]. On the other hand, the upbeat velocity, frequency, and transverse amplitude of the joints were significantly different in the lateral position compared to the prone position [33]. Yet, these differences were attributed to the lack of lateral kicking familiarization [36]. Moreover, UUS velocity was not related between conditions [36]. The authors speculated that despite being a similar movement, there is some independency between body positions.

Muscle strength and anthropometrics

Despite the importance of lower limb strength on swimming start and free swimming performance [23,52–54], only the influence of ankle strength on UUS velocity has been studied [38]. The positive association between dorsal flexion and internal rotation of the ankle with UUS performance [38] might be explained by the leg motion during the downbeat, as the ankles moved downwards with internal rotations and plantar flexion [16]. Then, the tibialis anterior muscles are activated, producing ankle dorsal flexion at the end of the downbeat and accelerating the body by the released jet flow [55]. Based on the influence of hip and knee angular velocities on UUS velocity [5,6], future studies should be designed to assess the impact of the strength of the muscles involved in hip and knee flexion and extension on UUS performance.

On the other hand, despite somatic build has been related to swimming results [56,57] no relationship has been established with UUS performance [32]. This study was only conducted with young male swimmers, and more research with different samples are needed to clarify this issue.

Muscle activation

During the UUS movement, internal oblique, multifidus, rectus abdominis, erector spinae, rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius are activated in three synergies: 1) transition from upbeat to downbeat; 2) downbeat, and; 3) upbeat [29,34]. The muscular activation pattern between agonist and antagonist muscles in the trunk and the thigh during the UUS did not show co-activation in female competitive swimmers [58]. Yet, the muscular co-activation phase between agonist and antagonist muscles of rectus abdominis - erector spinae (*i.e.*, trunk) and rectus femoris - biceps femoris (*i.e.*, thigh) had small and moderate positive associations with UUS velocity, respectively [34] (*i.e.*, the higher the muscle co-activation, the higher the UUS velocity). These results were not consistent with the authors' hypothesis, as a negative association was expected. Hence, as the muscular co-activation was negatively correlated with Froude efficiency, it was postulated that swimmers increased UUS velocity by sacrificing the efficient muscular activation pattern (*i.e.*, reciprocal activation)[34].

Together with muscle force output, the tendinous elastic energy contributes to UUS velocity, as a stretch-shortening pattern during the execution of UUS has been observed in the vastus lateralis [59]. From these outcomes, swimmers should attempt to reduce the transition time between downbeat-upbeat to minimize the dissipation of the tendinous elastic energy. However, the potential role of other muscles involved in UUS performance remains unknown.

Limitations and future perspective

Future research should be conducted to address some limitations of previous research by: 1) stating clearly whether the sample used were male or female swimmers; and 2) considering the action of proximal segments when examining single elements (*e.g.*, the effect of knee action on the ankle, given that ankle restriction evokes an increase in knee flexion).

From a design standpoint, and based on the quality assessment (Table S6.3) future studies should: 1) clearly show the inclusion and exclusion criteria for the sample used; 2) describe the sample's performance level (*e.g.,* FINA points); and 3) identify and describe how to deal with potential confounders.

Future research should be conducted in an attempt to elucidate: 1) whether exist a maximal kick frequency that should not be surpassed; 2) the effects that UUS specific training could have on velocity, distance per kick, and kick frequency; 3) clarify the different contribution between the two upbeat phases; 4) whether there is an optimal level of joint mobility; 5) the importance of joint muscle strength on UUS performance; and 6) muscle activation during UUS.

Conclusion

This systematic review identifies the key factors of UUS performance and provides valuable information about UUS that could aid coaches and sports science practitioners to improve swimmers' performance. The UUS movement should be performed as a whip-like motion, maximizing the caudal momentum transfer (*i.e.*, body wave velocity) and vertical toe velocity. The upbeat duration should be reduced and not used as a mere recovery phase. To optimize the upbeat, the hips have to be extended before flexing the knees avoiding the horizontal displacement of the toes during the latter phase of the upbeat. Special attention should be given to the knee and hip angular velocities in this phase. It is possible to benefit from the tendinous elastic energy stored during the UUS movement by reducing the duration of the transition between phases.

The influence of kick frequency should be addressed when the movement is performed adequately, and not as a primary element when initiating the UUS movement. Higher kick frequency does not imply higher UUS velocity. The kick frequency is specific for each swimmer and the one that best fits every individual needs to be found. The UUS velocity can be improved by increasing the distance per kick while maintaining the swimmer's preferred kick frequency. The independence in UUS velocity between body positions suggests that the UUS movement must be trained in the same body position as the one used during competition. The amplitude of the kick should be driven by the range of motion of the hip and not the knee. The ankle joint mobility restriction evokes compensatory movements that negatively affect UUS performance. To enhance UUS performance, ankle plantar flexor and internal rotators strength have to be increased. However, there is no evidence about the other joints involved in UUS (*e.g.*, hips and knees). An acute enhancement of the UUS performance can be elicited through a high-intensity warm-up protocol. Finally, apart from the key factors described above, certain individual characteristics need to be taken into account to avoid imposing the same UUS technique on all swimmers.

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Supplementary material

Table S6.1. Search terms used in Web of Science, Scopus, and SPORTDiscus databases.

Web of Science
(((((Undulatory underwater swimming) OR (Undulatory underwater swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic)))
Scopus
(((((undulatory AND underwater AND swimming) OR (undulatory AND underwater AND swimming)) OR (dolphin AND kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range AND of AND motion)) OR (kinetic)))
SPORTDiscus
((((Undulatory underwater swimming) OR (Undulatory underwater swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic))

Table S6.2: Update search terms used in Pubmed, Web of Science, Scopus, and SPORTDiscus databases.

Pubmed
(((((Undulatory underwater swimming) OR (underwater undulatory swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic))) AND (("2020/09/30"[Date - Publication] : "2021/10/14"[Date - Publication]))
Web of Science
(TS=((((((Undulatory underwater swimming) OR (Underwater undulatory swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic))))) AND DOP=(2020-09-30/2021-10-14)
Scopus
TITLE-ABS-KEY ((((((undulatory AND underwater AND swimming) OR (underwater AND undulatory AND swimming)) OR (dolphin AND kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range AND of AND motion)) OR (kinetic))))) AND PUBYEAR > 2019
SPORTDiscus
((((Undulatory underwater swimming) OR (Underwater undulatory swimming)) OR (Dolphin kick))) AND (((((kinematic) OR (anthropometric)) OR (strength)) OR (range of motion)) OR (kinetic)) Limiters: Published Date: 20201001-20211031

* Scopus and SPORTDiscus did not allow the specific search day to be set, but rather the year and month, respectively. Hence, the articles included on this two databases were checked manually to avoid including articles that were already included in the initial search. One article found in Scopus had already been found in the initial search and therefore it was not taken into account in this process.

Table S6.3: Quality assessment of the articles included.

References	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Total	Total score	Category
Alves et al. [33]	0	0	1	1	0	0	1	1	4	0.50	Low quality
Atkinson et al. [7]	0	1	1	1	1	0	1	1	6	0.75	High quality
Arellano et al. [36]	0	0	0	1	0	0	1	0	2	0.25	Low quality
Connaboy et al. [6]	1	1	1	1	1	1	1	1	8	1.00	High quality
Crespo et al. [30]	0	1	1	1	1	1	1	1	8	0.88	High quality
Higgs et al. [5]	1	1	1	1	1	1	1	1	8	1.00	High quality
Houel et al. [35]	0	1	1	1	1	1	1	1	7	0.88	High quality
Ikeda et al. [31]	1	1	1	1	1	0	1	0	6	0.75	High quality
Shimojo et al. [15]	0	0	1	1	1	1	1	1	6	0.75	High quality
Shimojo et al. [39]	1	1	1	1	1	1	1	1	8	1.00	High quality
Wadrzykl et al. [37]	0	1	1	0	0	0	1	1	4	0.50	Low quality
Wadrzykl et al. [32]	0	1	1	1	0	0	1	1	5	0.63	Low quality
Wang et al. [40]	0	0	0	0	0	0	1	0	1	0.13	Low quality
Willems et al. [38]	1	1	1	1	1	0	0	1	6	0.75	High quality
Yamakawa et al. [34]	0	1	1	1	1	1	1	1	7	0.88	High quality
Criterion score (%)	33.33	73.33	86.66	86.66	66.66	46.66	93.33	80	5.66		

The criterion score was obtained by dividing the number of studies meeting the criteria by the total number of studies (*i.e.*, 15). 1: met the methodological quality criterion; 0: did not meet the methodological quality criterion.

CHAPTER 7:

Undulatory underwater swimming performance: Effects of in-water training *vs.* in-water and strength training

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Abstract

Purpose: This study aimed to evaluate the effect of a five-weeks training program on undulatory underwater swimming (UUS) in adolescent swimmers and to compare the specific effects prompted by two different training protocols on UUS performance and kinematics. ***Methods:*** Swimmers (n = 14) were divided in in-water only (WO)(18.6 ± 2.6 years, FINA points: 507 ± 60) and water + dry-land training groups (WD)(18.4 ± 2.6 years, FINA points: 508 ± 83). Three countermovement jumps (CMJ) and three maximal UUS trials were performed before and after a five-weeks training period. The training program comprised 14 × 30 min sessions, divided into two identical blocks of 15 min. WO repeated the same 15 min block twice, while WD performed one block of 15 min in the water and the other block on land performing lower limbs exercises with conical pulleys. Seven body landmarks were auto-digitalized during UUS by a neural network and 21 kinematic variables were calculated. Statistical significance level was set at $p < 0.05$. ***Results:*** Significant group × time interaction in favor of WD was observed for mean vertical toe velocity ($p = 0.035$, $\eta_p^2 = 0.32$). WD experienced enhancements in mean and maximum underwater velocity, kick frequency, maximum shoulder angular velocity, and mean and maximum vertical toe velocity ($p < 0.05$). The WO exhibited an enhancement in CMJ height ($p < 0.05$). ***Conclusions:*** UUS performance was improved in adolescent swimmers after five-weeks of specific training, only when combining water and conical pulleys exercises. Coaches should include dry-land specific lower limbs exercises in addition to in-water training to improve UUS performance.

Keywords: dolphin kick, swimmers, assessment, speed, biomechanics.

Introduction

In swimming, having well-developed acyclic phases (*i.e.*, start and turns) is considered an essential prerequisite to yield high performance in major international events [1–3]. These acyclic phases are often divided into subsections for in-depth analysis, such as diving, wall push-off, underwater, and breakout [4]. Among these subsections, start and turn performances clearly rely on the optimization of the underwater phase [5,6]. The prominence of this phase is frequently observed in major events, where most of the swimmers try to reach the limited 15 m after each wall [7] as an important contribution to the overall performance [7,8]. Therefore, coaches should consider that any improvements within the underwater phase would lead to an enhancement of the start and turn performances, thus having a crucial impact on the overall race success.

Except for breaststroke events, swimmers propel themselves forward throughout the underwater phase by performing the undulatory underwater swimming (UUS), also known as “dolphin kick”. The UUS consists of performing body undulations while holding a streamline body position with arms outstretched and held together over the head [9]. The propulsion is generated in a “whip-like” action and this “body wave” travels caudally throughout the body [10], resulting in a leg-dominated technique [11]. The UUS velocity can be enhanced increasing the magnitude of the propulsive impulse relative to the active drag experienced, hence, equal velocities can be reached in a number of different ways [12].

Among all the kinematic variables, kicking frequency, cycle length, joints amplitudes, range of motion (ROM), or maximum angular velocity seem to be related to UUS technique and/or performance [9,13]. Moreover, the fact that specific activation of lower limbs muscles enhance UUS performance [14] or the use of lower body strength exercises to enhance other swimming leg-dominated techniques such as flutter kicking [15] or swimming start [16,17] support the likely role of muscle strength in UUS performance [18]. Previous studies focused on finding the strongest predictors of UUS performance [9,11,12,19], nevertheless, the results were variable, partly due to inconsistencies in the kinematic parameters measured [20] or because of swimmers tend to employ different techniques when performing maximal UUS [12].

The effect of UUS training programs have been mostly studied in young swimmers [21–23] as the optimum age for learning swimming techniques ranges between 7 and 12 years old [24]. However, as well as it happens in the rest of the strokes, swimmers experience the dramatic improvement in UUS velocity throughout the adolescence [25]. Hence, it remains unclear how a period of UUS specific training might affect performance in this group of swimmers. Furthermore, as the propulsive force yielded while swimming relies on aquatic-based strength, directly related to dry-land strength [26,27], it is unknown the specific effect of lower limbs strength training on UUS performance. Therefore, this study aimed 1) to evaluate the effects of five-weeks UUS training program in adolescent swimmers and 2) to compare the specific effects prompted by two different training protocols on UUS performance and kinematics.

Methods

Design

A "pre/post testing" design was conducted with an intervention carried out over five-weeks. Swimmers were evaluated before (PRE) and after (POST) the five-weeks training period. The intervention period took place during the second macrocycle of the season, ending right before the beginning of the taper. Swimmers were randomly allocated into two groups: an only water group (WO), which conducted all the exercises in the water and a water + dry-land group (WD), which performed, during each specific session, half of the time in the water and half on land.

To avoid a possible "learning effect", swimmers were familiarized with the experimental procedures before the PRE. In both PRE and POST, testing were performed at the same time of the day to avoid possible biases due to circadian variation [28]. Furthermore, swimmers were instructed to refrain from intense exercise and/or vigorous physical activity and to abstain from stimulant beverages consumption 24 h before each testing. The intervention included a total of 14 sessions of 30 min each, that were part of the regular swimming training session. Throughout the intervention, swimmers were requested to assist at least 85% of the sessions (*i.e.*, 12 sessions) and to follow the whole training program set by their coach.

Participants

Nineteen (10 males and 9 females) trained and highly trained swimmers [29] volunteered to participate in the current study. From the initial 19 participants that were randomly assigned to each group, two females and two males did not meet the study criteria (*i.e.*, took part in less than 85% of the training sessions). Moreover, one female swimmer dropout due to an injury (not related with the study). Hence, a total of 14 swimmers, eight males and six females, were finally included in the study. The WO was composed by four males and three females (18.6 ± 2.6 years, 65.2 ± 8.7 kg of body mass, 169.8 ± 5.6 cm of height, and 50 m front crawl International Swimming Federation [FINA] points: 507 ± 60, performance level 4 [30]) and the WD comprised also four males and three females (18.4 ± 2.6 years, 63.7 ± 7.4 kg of body mass, 172.7 ± 7.3 cm of height, and 50 m front crawl FINA points: 508 ± 83, performance level 4 [30]). The protocol was explained to the swimmers and their parents (swimmers' under 18 years), prior to signing an informed written consent. The study was conducted according to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the protocol was approved by the university ethics committee.

Methodology

Training Protocol

In accordance with the swimmers' coach, the training protocol comprised, firstly, two weeks of four sessions per week (Monday, Wednesday, Friday, and Saturday) and then three weeks of two sessions per week (Monday and Wednesday). The training protocol was designed following the procedures employed by Ruiz-Navarro et al. [21] dividing the exercises in five groups ("body awareness", "gliding", "gliding + propulsion", "propulsion", and "speed"). Since the participants were skilled swimmers and the alignment and position of the swimmers' bodies were correctly performed (observed by a biomechanics researcher), the training protocol focused on "gliding + propulsion", "propulsion", and "speed" exercises. The contents of each session progressed in difficulty or intensity over the five training weeks. The whole protocol is available in Supplementary Material 7.1.

To make sure that both groups performed the same exercises, each UUS training session was divided into two identical blocks of 15 min. Hence, WO performed the two 15 min blocks in the water, while WD performed one block of 15 min in the water and the other one on land using the conical pulleys (RSP conic, Pontevedra, Spain). The dry-land exercises with the conical pulleys were performed unilaterally (*i.e.*, first one leg and then the other one), standing on their feet, and clinging to a partner, swimmers had to execute the downbeat action simulation (*i.e.*, hip flexion + knee extension) or the upbeat action simulation (hip extension + knee flexion)(Figure 7.1). The conical pulleys exercises were carried out alternately each day (*e.g.,* Monday: downbeat action simulation, Wednesday: upbeat action simulation). A researcher assisted to all the training sessions to ensure that the training protocol was properly performed.

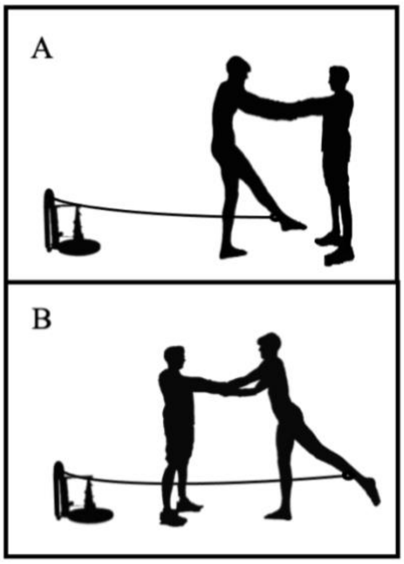

Figure 7.1. Lower limbs exercises on land using conical pulleys. A: downbeat action simulation (*i.e.*, hip flexion + knee extension); B: upbeat action simulation (hip extension + knee flexion).

Testing Protocol

On both testing sessions (*i.e.,* PRE and POST)(Figure 7.2), anthropometrics measurements were conducted by the same researcher using a stadiometer (Seca 799, Hamburg, Germany) on swimmers' arrival at the facilities. Participants were then marked with a 3 cm diameter circle of black oil-based hypoallergenic body paint at the styloid process of the ulna, head of the humerus, greater trochanter of the femur, the lateral epicondyle of the femur, the lateral malleolus of the fibula, and the 5th metatarsal phalangeal joint of the foot (5th MPJ) of the right side of the body. These specific points represent the joint centers of the wrist, shoulder, hip, knee, and ankle and the most distal point of the foot, respectively [31]. Subsequently, a standardized warm-up of dry-land exercises meant to activate and mobilize the core and lower limbs before performing maximal effort tests was conducted [21,32]: ankles, knees, hips, and shoulders joint mobility, 2 × 10 repetitions squats with 30 s rest, 2 × 10 repetitions lunge with 30 s rest, 2 × 30 s planks with 15 s rest, 2 × 30 s bird dog with 15 s rest, and three submaximal countermovement jumps (CMJ). Following the dry-land warm-up, five maximal CMJ with hands on hips and 1 min of rest between repetitions were recorded with an iPhone X (apple inc., California, USA) high-velocity camera in an adjacent room to the pool by the same researcher in both visits.

Swimmers then entered a 25 m swimming pool (25 m × 16.5 m; 28.0 and 27.8ºC water temperature, 31.0 and 30.6ºC air temperature, and 32 and 44% humidity in the PRE and POST, respectively) and performed an in-water warm-up comprising 400 m swim, 100 m pull, 100 m kick, 4 × 50 m increasing speed, four submaximal underwater trials familiarizing with the procedures, and 200 m easy swim. The UUS assessment was developed in the same pool and consisted of three maximum 15 m trials with 3 min of total recovery between trials [11]. Each trial was performed at 1 m depth beginning with the swimmers pushing prone from the wall at 1 m depth to remove wave drag effects [33]. Swimmers were asked to maintain the depth at 1 m throughout the 15 m otherwise they would be requested to perform an extra trial. Moreover, to avoid the velocity obtained during kicking being affected by the push-off from the wall, swimmers were asked to start kicking as soon as possible [34]. One stationary underwater camera (GoPro HERO 9, 60Hz, 2.7K, California, USA) was set at 7.5 m from the starting wall and 1 m below the surface with the optical axes perpendicular to the direction of swimming, recording the area between 5 and 10 m. This area ensured that two complete kick cycles per trial were recorded [13]. Hence, a total of six cycles (two cycles per trial) were captured for analysis guaranteeing a representative and reliable account of the UUS kinematics [13].

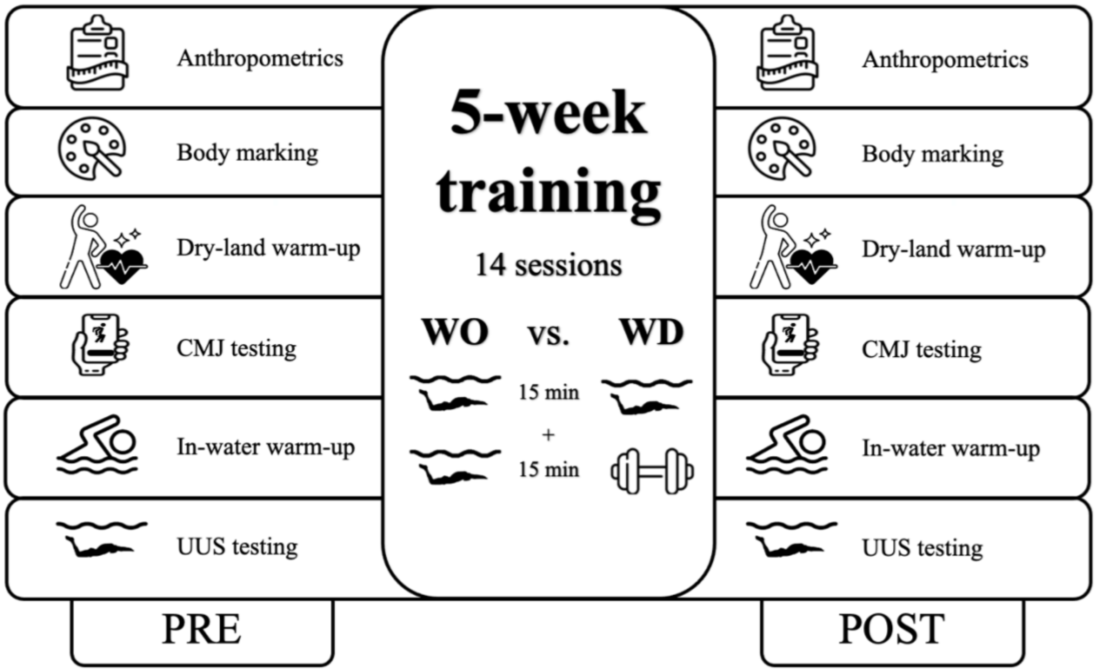

Figure 7.2. Study design and evaluations conducted. CMJ: countermovement jump; UUS: undulatory underwater swimming. PRE: before the five-weeks training period; POST: after the five-weeks training period.

Data Processing and Analysis

The CMJs were analyzed using MyJump 2 [35,36]. From the five CMJ analyzed, the highest and the lowest CMJ heights (CMJ_H) were removed, and the mean of the three remaining was calculated [37].

For the UUS analysis, bilateral symmetry was assumed [13] and only the right side was analyzed using a trained Neural Network in DeepLabCut™. The training procedures were conducted following the methods employed by Papic et al. [38] on a manually digitized subset of 400 frames taken from the UUS trials. The mean test error between manually digitized body landmarks and the neural network was 2.08 pixels or 5.5 mm. The “Cinalysis” software [39] was used to compute the calibration coefficients by applying a 2D direct linear transformation with a calibration plane (2.05 × 1.60 m) containing 37 calibration points in Matlab 2016 (MathWorks Inc., Natick, Mass., USA). The calibration error was assessed as the reprojection error, where root-mean-square error (RMSE) of the reconstructed calibration marker positions were for the x- and y-axis coordinates 3.1 mm and 2.9 mm, respectively. Per video recording, two full cycles were digitized. In addition, 15 frames before and after the start and end of the two kick cycles were also digitized to prevent minimize of the data during smoothing and subsequent calculation of time derivatives [40]. A fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz was employed to smooth the data [21].

Using the methods employed by Connaboy et al. [13], a total of 21 kinematic variables already identified as critical in UUS were calculated for each kick cycle: (1) mean (mean U), (2) maximum (max U), and (3) minimum (min U) swimming velocity, (4) cycle length, (5) kick frequency; vertical joint center amplitudes of (6) wrist, (7) shoulder, (8) hip, (9) knee, (10) ankle, and (11) 5th metatarsal phalangeal joint; maximum angular velocities of (12) shoulder, (13) hip, (14) knee, and (15) ankle; joint ranges of motion of (16) shoulder, (17) hip, (18) knee, and (19) ankle; (20) mean and (21) maximum vertical toe velocity. The calculation of variables was performed for each cycle in Python 3.9.

Statistical Analysis

The data are expressed as mean ± standard deviation (SD). Normality and homogeneity of variance across groups (WO *vs.* WD) of the data sets were verified using the Shapiro-Wilk and Levene tests, respectively. An independent t-test was used to compare swimmers' characteristics among groups. A 2 × 2 (group: WO, WD and time: PRE, POST) repeated measures analysis of variances (ANOVA) was estimated for each parameter and Bonferroni post-hoc test was used. Effect size for main effects and interactions was expressed as partial eta squared (η_p^2). Likewise, effect size was calculated using Cohen's *d* to estimate the magnitude of the training effect on the analyzed variables within each group. In this case, the effect size was categorized as follows: small if $0 \leq |d| \leq 0.5$, medium if $0.5 < |d| \leq 0.8$, and large if $|d| > 0.8$ [41]. All the statistical procedures were performed using SPSS 24.0 (IBM, Chicago, IL, USA) with the level of statistical significance set at $p < 0.05$.

Results

There were no statistical differences between groups baseline for age, height, body mass, or 50 m front crawl FINA points ($p > 0.05$). Significant group × time interaction in favor of WD was observed for mean vertical toe velocity ($p = 0.035$, $\eta_p^2 = 0.32$), whereas there was no group × time interaction for the rest of the variables ($p > 0.05$). Training resulted in a main effect of time in Mean U ($p = 0.003$, $\eta_p^2 = 0.53$), Max U ($p = 0.005$, $\eta_p^2 = 0.49$), kick frequency ($p = 0.033$, $\eta_p^2 = 0.32$), maximum shoulder angular velocity ($p = 0.013$, $\eta_p^2 = 0.41$), maximum knee angular velocity ($p = 0.028$, $\eta_p^2 = 0.34$), mean vertical toe velocity ($p = 0.035$, $\eta_p^2 = 0.32$) and maximum vertical toe velocity ($p = 0.035$, $\eta_p^2 = 0.32$). This main effect of time was only significant in WD group (Table 7.1). Mean values, differences between PRE and POST, relative change, and effect size for all variables are reported in Table 7.1.

Table 7.1. Mean ± standard deviation, changes in undulatory underwater swimming performance and kinematics and countermovement jumps from PRE to POST training for each group.

Variable	Group	PRE-test	POST-test	Difference [95% CI]; Δ%	*p*-value	Effect size
Mean U ($m \cdot s^{-1}$)	WO	1.53 ± 0.14	1.55 ± 0.16	0.02 [-0.02, 0.06]; 1.3%	0.295	0.32, small
	WD	1.50 ± 0.17	1.58 ± 0.17	0.08 [0.04 , 0.12]; 5.0%	0.001*	2.57, large
Max U ($m \cdot s^{-1}$)	WO	1.85 ± 0.18	1.89 ± 0.19	0.04 [-0.03 , 0.12]; 2.4%	0.212	0.57, medium
	WD	1.80 ± 0.15	1.92 ± 0.18	0.12 [0.05 , 0.19]; 6.7%	0.004*	1.21, large
Min U ($m \cdot s^{-1}$)	WO	1.17 ± 0.13	1.16 ± 0.16	-0.10 [-0.50 ,0.70]; -0.8%	0.723	0.17, small
	WD	1.11 ± 0.23	1.14 ± 0.21	0.03 [-0.02 , 0.09]; 3.3%	0.203	0.43, small
Cycle length (m)	WO	0.76 ± 0.08	0.77 ± 0.10	0.00 [-0.03 , 0.04]; 0.4%	0.873	0.06, small
	WD	0.72 ± 0.01	0.70 ± 0.07	-0.02 [-0.05 , 0.02]; -2.7%	0.273	0.40, small
Kick frequency (Hz)	WO	2.01 ± 0.26	2.04 ± 0.33	0.03 [-0.09 , 0.15]; 1.4%	0.613	0.19, small
	WD	2.09 ± 0.10	2.25 ± 0.16	0.16 [0.04 , 0.27]; 7.5%	0.014*	1.12, large
Wrist amplitude (m)	WO	0.06 ± 0.01	0.07 ± 0.02	0.01 [-0.01 , 0.02]; 9.4%	0.402	0.35, small
	WD	0.08 ± 0.03	0.09 ± 0.04	0.01 [-0.01, 0.02]; 13.1%	0.147	0.55, medium
Shoulder amplitude (m)	WO	0.06 ± 0.01	0.06 ± 0.01	0.00 [-0.01 , 0.01]; 9.7%	0.142	0.62, medium
	WD	0.06 ± 0.01	0.06 ± 0.01	0.00 [-0.01 , 0.01]; 10.3%	0.114	0.61, large
Hip amplitude (m)	WO	0.13 ± 0.01	0.14 ± 0.02	0.01 [-0.01 , 0.02]; 7.4%	0.107	0.53, medium
	WD	0.13 ± 0.03	0.13 ± 0.03	0.00 [-0.01 , 0.01]; 2.0%	0.638	0.25, small
Knee amplitude (m)	WO	0.26 ± 0.03	0.26 ± 0.03	0.00 [-0.01 , 0.02]; 1.7%	0.642	0.14, small
	WD	0.27 ± 0.04	0.27 ± 0.04	-0.00 [-0.02 , 0.01]; -2.0%	0.529	0.33, small
Ankle amplitude (m)	WO	0.43 ± 0.04	0.42 ± 0.06	-0.01 [-0.04 , 0.01]; -3.1%	0.371	0.29, small
	WD	0.41 ± 0.05	0.42 ± 0.04	-0.01 [-0.03, 0.02]; -0.7%	0.830	0.10, small
5^{th} MPJ amplitude (m)	WO	0.56 ± 0.05	0.55 ± 0.06	-0.01 [-0.03 , 0.02]; -1.0%	0.699	0.14, small
	WD	0.57 ± 0.05	0.56 ± 0.05	-0.01 [-0.03 , 0.02]; -1.4%	0.511	0.21, small
Max shoulder angular velocity ($^{o} \cdot s^{-1}$)	WO	177.58 ± 46.42	185.88 ± 37.76	8.29 [-0.833 , 24.91]; 4.7%	0.298	0.39, small
	WD	179.76 ± 65.91	202.69 ± 69.63	22.92 [6.30, 39.55]; 12.8%	0.011*	1.17, small
Max hip angular velocity ($^{o} \cdot s^{-1}$)	WO	463.02 ± 49.43	467.57 ± 59.56	4.54 [-55.47 , 64.56]; 0.9%	0.872	0.08, small
	WD	481.70 ± 75.67	505.78 ± 79.83	24.08 [-35.93 , 84.10]; 5.0%	0.399	0.27, small
Max knee angular velocity ($^{o} \cdot s^{-1}$)	WO	707.47 ± 130.60	766.82 ± 126.42	59.35 [-2.70 , 178.95]; 8.4%	0.180	0.49, small
	WD	720.43 ± 36.60	808.55 ± 116.70	88.12[-2.70 , 178.95]; 12.2%	0.056	0.84, large
Max ankle angular velocity ($^{o} \cdot s^{-1}$)	WO	677.81 ± 146.05	703.19 ± 177.08	25.38 [-60.95 , 111.72]; 3.7%	0.533	0.21, small
	WD	531.87 ± 108.19	603.67 ± 129.73	71.80 [-14.53 , 158.14]; 13.5%	0.095	0.82, large
Shoulder ROM (^{o})	WO	23.82 ± 8.86	26.31 ± 3.95	2.03 [-0.09 , 4.16]; -2.2%	0.060	0.63, medium
	WD	23.82 ± 8.86	24.96 ± 8.35	1.13 [-0.99, 3.26]; 4.7%	0.268	0.62, medium
Hip ROM (^{o})	WO	44.57 ± 1.55	47.39 ± 5.93	2.83 [-1.16 ,7.30]; 6.3%	0.192	0.43, small
	WD	48.58 ± 6.46	46.89 ± 5.57	-1.69 [-6.16, 2.77]; -3.5%	0.425	0.48, small
Knee ROM (^{o})	WO	82.22 ± 5.72	81.58 ± 5.94	-1.23 [-4.59 , 2.11]; -1.5%	0.437	0.29, small
	WD	81.55 ± 4.69	83.21 ± 4.53	-1.63 [-5.01 , 1.69]; -1.9%	0.301	0.41, small
Ankle ROM (^{o})	WO	45.82 ± 5.37	45.82 ± 7.80	0.00 [-3.49 , 3.49]; 0.0%	0.999	0.00, small
	WD	40.58 ± 5.87	42.99 ± 6.26	2.41 [-1.07 , 5.90]; 5.9%	0.158	0.83, large
Mean toe vertical velocity ($m \cdot s^{-1}$)	WO	113.26 ± 14.89	112.86 ± 14.12	-0.393 [-4.78 , 3.99]; -0.3%	0.849	0.05, small
	WD	119.70 ± 11.04	126.88 ± 12.69	7.17 [2.79 , 11.56]; 6.0%	0.004*	2.28, large
Max toe vertical velocity ($m \cdot s^{-1}$)	WO	403.62 ± 26.79	408.47 ± 30.01	4.85 [-15.24 , 24.94]; 1.2%	0.608	0.20, small
	WD	414.65 ± 24.93	440.76 ± 24.89	26.11 [6.02 , 46.19]; 6.3%	0.015*	1.04, large
CMJ_H (m)	WO	0.31 ± 0.10	0.33 ± 0.11	0.02 [0.00, 0.04]; 7.5%	0.023*	1.64, large
	WD	0.36 ± 0.07	0.37 ± 0.06	0.01 [-0.01, 0.03]; 2.6%	0.360	0.28, small

WO: in-water only; WD: water +dry-land; Mean U: mean undulatory underwater velocity;Max U: maximum undulatory underwater velocity;Min U: minimum undulatory underwater velocity; MPJ: metatarsal phalangeal joint; ROM: range of motion; CMJ_H: countermovement jump height.*significant differences.

Discussion

This study aimed to assess the effects of a five-weeks training protocol on UUS performance in adolescent swimmers and to compare the effects of two different training protocols on UUS performance and kinematics. The main finding of the current study indicates that adolescent swimmers' UUS performance was enhanced after five-weeks of specific training only when combining in-water and conical pulleys exercises. Therefore, these results provide relevant evidence to support the need of including specific UUS strength exercises for the lower limbs within the swimming training program to obtain further development of adolescent swimmers' performance.

The enhancement of UUS velocity could be achieved by either increasing propulsive force or decreasing the active drag experienced. Since the alignment and position of the body were correctly observed by a biomechanics researcher, the training protocol focused on improving the propulsive impulse. The enhancement of the propulsive force could be achieved by either increasing swimmer's muscular strength production or the ability to apply that force [26,42]. In terms of muscle strength, only WO group reached higher CMJ_H after the training period, which might indicate that lower limbs strength was not significantly developed by the conical pulley training on the WD group (Table 7.1). Nevertheless, it is important to mention that the study of propulsion in UUS relies mainly on the analysis of vortex, which has been positively related to vertical toe velocity (*i.e.*, the higher vertical toe velocity the greater propulsion) [43]. Indeed, our results showed a significant interaction for mean vertical toe velocity ($p = 0.035$, $\eta_p^2 = 0.32$). WD increased the mean vertical toe velocity (6.0%), while the WO showed almost identical results (-0.3%) after the training period, which might explain why UUS performance only improved in WD (Table 7.1). Hence, the conical pulley exercises combined with the in-water training enhanced mean vertical toe velocity and likely led to the Mean U and Max U improvement in WD (5.0 and 6.7%, respectively).

Often swimmers increase UUS velocity by increasing the kick frequency and reducing cycle length in a relatively lower proportion [44]. This process seems to require a period of adaptation since acute kick frequency changes are matched by cycle length reduction eliciting similar UUS velocity [45]. However, even after five-weeks of training, cycle length and kick frequency were similar in the WO group (Table 7.1). As the increase in kick frequency requires more internal work of locomotion [46], it is possible that swimmers in WO were not able to produce larger torque power that enabled them to reach higher kick frequency without compromising cycle length [45]. Nevertheless, WD increased kick frequency after the five-weeks, which together with the maintenance of cycle length (Table 7.1) explained the UUS performance improvement elicited by the training. It is possible then, that WD swimmers were able to produce higher torque in POST compared to PRE. This fact is indeed in line with the greater vertical toe velocity of WD observed in POST than in PRE.

Cycle length and kick frequency are modulated by joints amplitude, joints angular velocity, joints ROM, and vertical toe velocity [12,44]. Altogether, these kinematics variables represent swimmers' UUS technique, being therefore possible to attain the same UUS velocity in several different ways [12]. For instance, some swimmers may seek to perform large undulatory movements maximizing propulsive impulse production, which would lead to higher joints amplitude, whereas other swimmers may perform smaller movements (*i.e.*, lower joints amplitude and ROM) to produce a reduced amount of propulsive impulse but instead an active drag reduction [12]. Our results did not show significant changes in joints amplitude or ROM in any of the training groups (Table 7.1). Nevertheless, WD's maximum shoulder angular velocity exhibited a significant improvement and a positive trend in the rest of the maximum joints angular velocities after the training period (Table 7.1). Thus, the resulting amount of the positive trends obtained in all the maximum joints angular velocities [12] together with the increase in mean vertical toe velocity [44], after the training period, likely induced the development of higher kick frequency in WD. Conversely, the WO did not exhibit any change in joints angular velocities, which may explain the similar kick frequency observed in both moments (Table 7.1). Hence, five-weeks of only in-water training might not be enough time to induce technical changes in adolescent swimmers, or perhaps, the exercises included in our program should had been different to prompt significant changes.

Traditionally, tracking has been conducted using video analysis to acquire reliable quantitative and qualitative data on performance [47]. However, this methodology is computationally intensive, delaying the information to athletes [48]. Nevertheless, the development of neural networks allows performing kinematic tracking in a considerably short amount of time in a reliable and accurate way [38]. Hence, we were able to provide the coach and swimmers with the results before their main competition (less than two weeks).

Certain limitations should be acknowledged: 1) the low final sample analyzed, which could have reduced the statistical power. Indeed, some of the parameters showed positive tendency with a borderline p-value. Nevertheless, including swimmers with high percentage of missing sessions might have induced a risk of bias and negatively impacted the results. 2) UUS was evaluated in two-dimensions, hence, the likely effect on three-dimensional kinematics remained unknown [49]. However, besides the set-up requirements (*e.g,* number of cameras), as the training protocol was performed using flexo-extension exercises, the influence of rotation would likely be reduced.

Practical applications

These results highlight that coaches should provide stimuli on dry-land conditions to improve UUS performance. Therefore, this aspect moves away from the more traditional trends that ensure that the development of the swimmer has to be exclusively in the water and contributes to support the most current trends that comprehensively prioritize the development of swimmers, including a wide range of stimuli, both in the water and out of the water, to develop their physical and motor skills to the maximum.

Conclusion

Five-weeks of skill-specific training, including specific conical exercises, can induce performance enhancement in UUS, likely as a result of greater vertical toe velocity and kick frequency. However, only five-weeks of skill-specific in-water training does not enhance UUS performance. Five-weeks of in-water training could not be long enough or the exercises conducted in our research might not be adequate to induce changes in adolescent skilled swimmers. Thus, future studies should be conducted with longer training periods, including different in-water and dry-land exercises.

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Supplementary Material

Supplementary Material 7.1. Detailed training protocol.

SESSION: 1 – Monday Week 1

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.	4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.
8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before to stop perform 5 powerful dolphin kicks and glide again as far as possible.	8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before to stop perform 5 powerful dolphin kicks and glide again as far as possible.
4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.	4×10 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 0 weights.
8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before to stop perform 5 powerful dolphin kicks and glide again as far as possible.			

@: start every “X” time.

SESSION: 2 – Wednesday Week 1

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4×6 rep	@1’	Vertical kicks with fins and arms alongside the body.	4×6 rep	@1’	Vertical kicks with fins and arms alongside the body.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks with fins.	4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks with fins.
8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming with fins.	8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming with fins.
4×6 rep	@1’	Vertical kicks with fins and arms alongside the body.	4×10 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 0 weights.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks with fins.			
8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming with fins.			

@: start every “X” time.

SESSION: 3 – Friday Week 1

Only Water (WO)			**Water + Dry-land (WD)**		
Set	Rest	Exercise	Set	Rest	Exercise
4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.	4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.
8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before stopping perform 7 powerful dolphin kicks and glide again as far as possible.	8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before stopping perform 7 powerful dolphin kicks and glide again as far as possible.
4×50 m	@1’15”	Perform two powerful kicks and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and held together over the head. Repeat the action all the distance.	4×10 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 1 weight.
8×15 m	@1’	Push off from the wall in a streamline position and glide. Right before stopping perform 7 powerful dolphin kicks and glide again as far as possible.			

@: start every “X” time.

SESSION: 4 – Saturday Week 1

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
8×25 m	@1’	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 10 m in the shortest possible time using undulatory underwater swimming.	8×25 m	@1’	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 10 m in the shortest possible time using undulatory underwater swimming.
2×100 m	@2’	Freestyle, increasing the number of underwater kicks every turn (4,5,6,7 kicks per turn, respectively).	2×100 m	@2’	Freestyle, increasing the number of underwater kicks every turn (4,5,6,7 kicks per turn, respectively).
8×25 m	@1’	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 10 m in the shortest possible time using undulatory underwater swimming.	4×10 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 1 weight.
2×100 m	@2’	Freestyle, increasing the number of underwater kicks every turn (4,5,6,7 kicks per turn, respectively).			

@: start every “X” time.

SESSION: 5 – Monday Week 2

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
6×25 m	@1’10”	Push off from the wall in a streamline position at 1 m depth. Perform two powerful kicks and then glide for 2 s. Repeat the action all the lane along.	6×25 m	@1’10”	Push off from the wall in a streamline position at 1 m depth. Perform two powerful kicks and then glide for 2 s. Repeat the action all the lane along.
4×25 m	@1’15”	Push off from the wall in a streamline position at 1 m depth gliding until beginning to ascend to the surface, then kick all the lane along maintaining 1 m depth.	4×25 m	@1’15”	Push off from the wall in a streamline position at 1 m depth gliding until beginning to ascend to the surface, then kick all the lane along maintaining 1 m depth.
6×25 m	@1’10”	Push off from the wall in a streamline position at 1 m depth. Perform two powerful kicks and then glide for 2 s. Repeat the action all the lane along.	4×8 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 2 weights.
4×25 m	@1’15”	Push off from the wall in a streamline position at 1 m depth gliding until beginning to ascend to the surface, then kick all the lane along maintaining 1 m depth.			

@: start every “X” time.

SESSION: 6 – Wednesday Week 2

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4×6 rep	@1’	Vertical kicks with arms alongside the body.	4×6 rep	@1’	Vertical kicks with arms alongside the body.
4×8 rep	@1’	Push from the bottom of the pool and perform vertical kicks.	4×8 rep	@1’	Push from the bottom of the pool and perform vertical kicks.
8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming.	8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming.
4×6 rep	@1’	Vertical kicks with arms alongside the body.	4×8 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 2 weights.
4×8 rep	@1’	Push from the bottom of the pool and perform vertical kicks.			
8×15 m	@1’	Reach 15 m in the shortest possible time using undulatory underwater swimming.			

@: start every “X” time.

SESSION: 7 – Friday Week 2

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4×50 m	@1’30”	Perform two powerful kicks with fins and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and holding a paddle over the head. Odd cycles with the paddle in a vertical position and even repetitions with the paddle in a horizontal position. Repeat the action all the distance.	4×50 m	@1’30”	Perform two powerful kicks with fins and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and holding a paddle over the head. Odd cycles with the paddle in a vertical position and even repetitions with the paddle in a horizontal position. Repeat the action all the distance.
2×100 m	@1’45”	Freestyle, perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.	2×100 m	@1’45”	Freestyle, perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.
4×50 m	@1’30”	Perform two powerful kicks with fins and then glide for 2 s on the water surface using a snorkel in a prone streamline position with the arms outstretched and holding a paddle over the head. Odd cycles with the paddle in a vertical position and even repetitions with the paddle in a horizontal position. Repeat the action all the distance.	4×10 rep each leg	@2’30”	Downbeat action simulation (*i.e.,* hip flexion + knee extension) – 2 weights.
2×100 m	@1’45”	Freestyle, perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.			

@: start every “X” time.

SESSION: 8 – Saturday Week 2

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
6×15 m	@1'15"	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.	6×15 m	@1'15"	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.
3×100 m	@2'15"	On the back performing kicks with the arms down at the side. Perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.	3×100 m	@2'15"	On the back performing kicks with the arms down at the side. Perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.
6×15 m	@1'15"	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.	4×10 rep each leg	@2'30"	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 2 weights.
3×100 m	@2'15"	On the back performing kicks with the arms down at the side. Perform undulatory underwater swimming during the 5 m in and 10 m out of every turn.			

@: start every "X" time.

SESSION: 9 – Monday Week 3

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4×25 m	@1’	On the water surface, move a teammate in streamline position performing kicks with fins and snorkel in a prone streamline position with the arms outstretched and holding the colleagues' feet over the head.	4×25 m	@1’	On the water surface, move a teammate in streamline position performing kicks with fins and snorkel in a prone streamline position with the arms outstretched and holding the colleagues' feet over the head.
4×25 m	@1’	Perform undulatory underwater swimming with fins in a prone streamline position with the arms outstretched and holding a paddle vertically over the head.	4×25 m	@1’	Perform undulatory underwater swimming with fins in a prone streamline position with the arms outstretched and holding a paddle vertically over the head.
4×15 m	@1’	Perform undulatory underwater swimming in a prone streamline position with the arms alongside the body.	4×15 m	@1’	Perform undulatory underwater swimming in a prone streamline position with the arms alongside the body.
4×25 m	@1’	On the water surface, move a teammate in streamline position performing kicks with fins and snorkel in a prone streamline position with the arms outstretched and holding the colleagues' feet over the head.			
4×25 m	@1’	Perform undulatory underwater swimming with fins in a prone streamline position with the arms outstretched and holding a paddle vertically over the head.	4×6 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 4 weights.
4×15 m	@1’	Perform undulatory underwater swimming in a prone streamline position with the arms alongside the body.			

@: start every “X” time.

SESSION: 10 – Wednesday Week 3

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
8×15 m	@1’15”	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 15 m in the shortest possible time using undulatory underwater swimming.	8×15 m	@1’	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 15 m in the shortest possible time using undulatory underwater swimming.
2×100 m	@1’45”’	Freestyle, increase the number of underwater kicks every turn (6,7,8,9 kicks per turn, respectively).	2×100 m	@1’45”’	Freestyle, increase the number of underwater kicks every turn (6,7,8,9 kicks per turn, respectively).
8×15 m	@1’15”	Odd repetitions: swimming start with 15 m of underwater phase. Even repetitions: perform 5 kicks against the wall in a streamline body position and right after without breathing reach 15 m in the shortest possible time using undulatory underwater swimming.	4×6 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 4 weights.
2×100 m	@1’45”’	Freestyle, increase the number of underwater kicks every turn (6,7,8,9 kicks per turn, respectively).			

@: start every “X” time.

SESSION: 11 – Monday Week 4

Only Water (WO)			**Water + Dry-land (WD)**		
Set	Rest	Exercise	Set	Rest	Exercise
4×15”	@1’	Vertical kicks with fins with arms outstretched and held together above the head.	4×15”	@1’	Vertical kicks with fins with arms outstretched and held together above the head.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.	4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.
4×10”	@1’	Kick in a streamline body position against a teammate trying to displace him/her.	4×10”	@1’	Kick in a streamline body position against a teammate trying to displace him/her.
4×15”	@1’	Vertical kicks with fins with arms outstretched and held together above the head.	4×8 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 4 weights.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.			
4×10”	@1’	Kick in a streamline body position against a teammate trying to displace him/her.			

@: start every “X” time.

SESSION: 12 – Wednesday Week 4

Only Water (WO)			Water + Dry-land (WD)		
Set	Rest	Exercise	Set	Rest	Exercise
4× (3 rep + 10 m)	@1’30”	Push from the bottom of the pool, perform vertical kicks and then reach 10 m in the shortest possible time using undulatory underwater swimming with fins.	4× (3 rep + 10 m)	@1’30”	Push from the bottom of the pool, perform vertical kicks and then reach 10 m in the shortest possible time using undulatory underwater swimming with fins.
4×15 m	@2’	Competition between two swimmers per lane. Reach 10 m in the shortest possible time using undulatory underwater swimming with fins.	4×15 m	@2’	Competition between two swimmers per lane. Reach 10 m in the shortest possible time using undulatory underwater swimming with fins.
4× (3 rep + 10 m)	@1’30”	Push from the bottom of the pool, perform vertical kicks and then reach 10 m in the shortest possible time using undulatory underwater swimming with fins.	4×8 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 4 weights.
4×15 m	@2’	Competition between two swimmers per lane. Reach 10 m in the shortest possible time using undulatory underwater swimming with fins.			

@: start every “X” time.

SESSION: 13 – Monday Week 5

Only Water (WO)			**Water + Dry-land (WD)**		
Set	Rest	Exercise	Set	Rest	Exercise
4×6 rep	@1’	Vertical kicks with arms outstretched and held together above the head.	4×6 rep	@1’	Vertical kicks with arms outstretched and held together above the head.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.	4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.
4×15 m	@1’	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.	4×15 m	@1’	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.
4×6 rep	@1’	Vertical kicks with arms outstretched and held together above the head.	4×10 rep each leg	@2’30”	Downbeat action simulation (*i.e.*, hip flexion + knee extension) – 4 weights.
4×6 rep	@1’	Push from the bottom of the pool and perform vertical kicks.			
4×15 m	@1’	From the 5 m mark to the 20 m mark (without push-off) perform undulatory underwater swimming.			

@: start every “X” time.

SESSION: 14 – Wednesday Week 5

Only Water (WO)			**Water + Dry-land (WD)**		
Set	Rest	Exercise	Set	Rest	Exercise
1×12 rep	@1’15”	League between swimmers. In pairs, reach 12.5 m using undulatory underwater swimming before your teammate.	1×12 rep	@1’15”	League between swimmers. In pairs, reach 12.5 m using undulatory underwater swimming before your teammate.
1×12 rep	@1’15”	League between swimmers. In pairs, reach 12.5 m using undulatory underwater swimming before your teammate.	4×10 rep each leg	@2’30”	Upbeat action simulation (*i.e.*, hip extension + knee flexion) – 4 weights.

@: start every “X” time.

CHAPTER 8:

General discussion

General discussion

The current doctoral thesis contributes to a better understanding of the determinant factors of sprint swimming performance, providing different insights into its evaluation, training, and detraining. First, we investigated the relationship between tethered swimming, under more similar conditions to free swimming, and sprint swimming performance (**Chapter 3**). Second, we provided a comprehensive approach, between two swim-specific measures of anaerobic performance, dry-land strength, sprint swimming performance, and how sex may induce different results (**Chapter 4**). Third, based on our previous results, we studied the effect of a period of training cessation on these factors and how the detraining might impact sprint swimming performance (**Chapter 5**). Fourth, due to the importance of the underwater phase in sprint swimming performance, we provided an overview of the determinants of undulatory underwater swimming (UUS) and highlighted future perspectives that should be covered (**Chapter 6**). Lastly, based on the gaps identified in our systematic review, we studied the effects of two different training protocols on UUS performance (**Chapter 7**).

One of the main aspects developed in swimmers' training regimes is the muscle strength [1]. This is indeed, a determinant factor in sprint swimming performance [2]; however, due to the aquatic environment, its evaluation is highly complex, leading to dry-land assessments, which missed the specificity criteria [3], and/or to in-water assessments. Among the different in-water tests, tethered swimming excels as a valid and reliable test [4–7]. However, as discussed in **Chapter 1**, tethered swimming still presents some differences from free swimming. Hence, we combined tethered swimming with a swimming flume, which would lead to a closer situation to free swimming [8]. Our results showed that as the water flow speed was closer to the maximum free swimming speed, the correlation with sprint swimming performance increased (**Chapter 3**). Moreover, deepening into intra-individual results we noticed that some swimmers with high values at zero speed presented lower values at high water flow speed than their counterparts with relatively lower values at zero speed. Hence, as propulsive forces not only depend on the swimmer's muscular strength production [2] but also on the swimmer's ability to effectively apply that force in the water [9], we concluded that this difference was due to the swimmers' ability to apply the force in the water.

Based on the aforementioned results, we intended to reaffirm this statement and therefore the association of tethered forces at two different swimming conditions (*i.e.*, water flow speed) and dry-land strength was studied (**Chapter 4**). In this case, our sample consisted of both male and female swimmers and therefore the water flow speed had to be adjusted for the whole sample. The highest water flow speed used in **Chapter 3** (*i.e.*, 1.389 $m \cdot s^{-1}$) was too high for some female swimmers, consequently 1.124 $m \cdot s^{-1}$ was chosen for this study as it was the maximum speed that allowed the force of this group of swimmers to be recorded throughout the whole stroke. We found stronger correlations between dry-land exercises and tethered forces at zero than at 1.124 $m \cdot s^{-1}$ water flow speed. This result corroborated our previous conclusion (**Chapter 3**). During tethered swimming, both the ability to apply force in the water and muscle strength are manifested [10]; however, tethered forces at zero speed mostly indicates the swimmers' strength potential [8], whereas, in the flume, as the water flow approaches to free swimming speed the perception of the ability to apply force in the water is better than at zero speed. Moreover, in another study not included in this thesis, we proposed two different parameters to quantify swimmers' ability to apply force in the water regardless of swimmers' strength. These parameters were based on the reduction of the magnitude between tethered swimming conditions and the results further corroborated our conclusions [10].

In addition to propulsive forces assessment, tethered swimming can be used to evaluate anaerobic performance [11,12]. However, we were aware that not every swimming club may have access to these apparatus. Thus, we decided to examine whether other tests might be used instead. Together with the aforementioned association with dry-land strength, we studied the correlation between tethered swimming and anaerobic critical velocity (**Chapter 4**). These two tests presented a positive correlation, especially in males when using tethered forces at 1.124 $m \cdot s^{-1}$ water flow speed, likely as the exercise mode greatly affects physiological outcome variables [13]. On the other hand, females' correlations were not as strong as males' correlations. As discussed in **Chapter 4**, it is possible that our female swimmers relied more on their legs' strength than males, or perhaps, females struggled to give their maximum effort in the swimming flume as a consequence of the water flow. Unfortunately, most of the studies are conducted with male swimmers and further studies are required with females.

Chapter 5 showed the effects of a typical period of training cessation. Up to that moment, most of the studies had focused on middle and long distance events, likely due to the importance of the aerobic contribution; however, the knowledge about sprint events and their determinants was scarce. The results provided in **Chapter 5** aid to understand how sprint swimming performance is impaired after such a short period of training cessation. Hence, although the off-season is required to allow a physiological and mental recovery, such impairments, as the ones reported in **Chapter 5,** could compromise the performance of the following competitive season and therefore specific activities should be conducted during the training cessation period. However, these activities require further study, since, unlike previously stated in 400 m [14], the deterioration in sprint swimming performance was not attenuated in the most physically active swimmers during the off-season. It is worth highlighting that during the POST evaluation sessions, swimmers commented to the research team the activities they had performed during the off-season. Running or riding a bike were the most frequently performed activities, but always at a relatively low intensity without stressing the anaerobic pathways. Unfortunately, as this information was not systematically collected, we could not report it.

Since 2009, when Connaboy et al. [15] published their review, the amount of literature published regarding UUS raised. Hence, the conduct of the systematic review provided an up-to-date overview of the determinant factors of UUS providing valuable information to coaches and sports sciences practitioners to improve UUS performance (**Chapter 6**). Nevertheless, despite the increase in publications in recent years, we identified several gaps that remained to be elucidated. First, there was a lack of longitudinal studies, which might explore the effects of UUS specific training on performance. Indeed, the previous longitudinal studies were conducted with age group swimmers [16–18]. Second, the importance of joints' muscle strength on UUS performance. Although muscle strength and resistance training are well-studied topics in free swimming and the acyclic phases (*i.e.,* start and turn) there was scarce knowledge about the importance of lower limbs strength in UUS performance. Indeed, only one study explored the association between ankle strength and UUS velocity. Hence, **Chapter 7** was conducted to cover these two gaps in the literature.

The specific training protocol lasted five weeks, which is approximately the duration of one training mesocycle [19]. The in-water only group allowed us to understand whether specific UUS training performed by swimmers would be enough to enhance UUS performance. Meanwhile, the combination of in-water and conical exercises would provide relevant information about the importance of muscle strength in UUS (**Chapter 7**). The results demonstrated that only five-weeks of UUS skill-specific training might not be enough to induce performance improvements in adolescent swimmers. Hence, coaches should be aware that more time or different exercises might be needed. On the other hand, the inclusion of specific resistance exercises replicating the underwater action can induce performance enhancement in UUS. This kind of exercise could be excellent stimuli to provide further developments of UUS performance (**Chapter 7**). Hence, this result highlights the importance of lower limbs strength in UUS performance and supports the integral development of swimmers, including a wide range of stimuli, both in the water and out of the water, to develop their physical and motor skills to the maximum.

General limitations

Several strengths and limitations have been noted throughout the different chapters of the current doctoral thesis. Nonetheless, there are general limitations that should be highlighted:

- The performance level of the swimmers included in our chapters was ~500 FINA points, performance level 4 [21]. We are unaware whether higher level swimmers might present different results. Nevertheless, it is highly complex to access higher level swimmers and our results are of benefit to most of the competitive swimming population.

- In general, most of the studies are conducted with male swimmers, and even though we tried to keep gender parity, female samples were smaller than male samples.

- The sample sizes were relatively small in the studies included in this doctoral thesis. However, all of the swimmers belonged to the same swimming club under the direction of the same coach which allowed us to have controlled conditions and control confounding factors.

- Front crawl was the only stroke analyzed in Chapters 1-3, remaining the rest of the strokes unstudied.

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CHAPTER 9:

Conclusions / Conclusiones

Conclusions

This doctoral thesis provides new insights into the understanding of the determinants of sprint swimming for coaches and the research community. Altogether these findings provide valuable information for better training plans and monitoring procedures, intending to improve sprint swimmers' performance.

- The propulsive force is highly associated with sprint swimming performance. The propulsive force depends on the swimmers' muscular strength production and the swimmers' ability to effectively apply that force in the water. Hence, both should be taken into consideration when training and monitoring.

- Tethered swimming at zero speed mostly indicates the swimmer's strength potential, whereas, in the flume, as the water flow approaches to free swimming speed the ability to apply force in the water becomes more relevant.

- The anaerobic critical velocity can be used as a non-invasive, non-expensive, and easy tool to monitor swimmers' anaerobic performance.

- Countermovement jumps and pull-ups are valuable testing tools that should also be used as training exercises.

- The sex-induced differences need to be kept in mind when training and monitoring sprint swimming performance.

- The off-season could compromise the performance of the following competitive season. Coaches should design specific plans that allow swimmers to recover physiologically and mentally while minimizing swimmers' performance impairments.

- Individual characteristics need to be considered when performing undulatory underwater swimming. The same speed can be reached in different ways and imposing the same undulatory underwater swimming technique to all swimmers must be avoided.

- The caudal momentum transfer, as well as vertical toe velocity, should be maximized to enhance undulatory underwater swimming performance. On the other hand, the kick frequency should not be addressed as a primary element when initiating the development of the undulatory underwater swimming movement.

- Five-weeks of skill-specific in-water training is not enough to enhance undulatory underwater swimming performance in adolescent swimmers.

- The inclusion of specific conical exercises together with skill-specific in-water training induces performance enhancement in undulatory underwater swimming performance. Coaches should provide stimuli on dry-land conditions to improve undulatory underwater swimming performance

Conclusiones

Esta tesis doctoral aporta nuevos conocimientos sobre los factores determinantes de las pruebas de velocidad para los entrenadores y la comunidad investigadora. En conjunto, estos hallazgos proporcionan información valiosa para mejorar los planes de entrenamiento y la monitorización, con la intención de mejorar el rendimiento de los nadadores velocistas.

- La fuerza propulsiva está altamente asociada con el rendimiento de las pruebas de velocidad. La fuerza propulsiva depende tanto de la fuerza muscular como de la habilidad para aplicar dicha fuerza en el agua. Por tanto, ambos aspectos deben tenerse en cuenta en el entrenamiento y la monitorización.

- El nado atado a velocidad cero permite evaluar mayormente el potencial de la fuerza muscular, mientras que, en el canal, a medida que aumenta la velocidad de flujo se manifiesta más la habilidad para aplicar fuerza en el agua.

- La velocidad critica anaeróbica puede ser utilizada como una herramienta no invasiva, barata y fácil de utilizar para monitorizar el rendimiento anaeróbico de los nadadores.

- El salto con contramovimimiento y las dominadas son valiosas herramientas de evaluación que también deberían ser implementadas como ejercicios en el entrenamiento de los nadadores velocistas.

- Se debe de tener en cuenta las diferencias inducidas por el sexo durante el entrenamiento y la evaluación del rendimiento de las pruebas de velocidad.

- El periodo transitorio entre temporadas puede comprometer el rendimiento de la siguiente temporada. Los entrenadores deberían diseñar planes específicos que permitan a los nadadores velocistas recuperar fisiológica y mentalmente mientras que se minimizan las pérdidas del rendimiento.

- Se deben de considerar las características individuales de los nadadores cuando se realiza el nado ondulatorio subacuático. La misma velocidad puede ser alcanzada de diferentes formas y por tanto debe de evitarse el imponer la misma técnica de nado ondulatorio subacuático a todos los nadadores.

- La transferencia del momento caudal al igual que la velocidad vertical del pie deben de maximizarse para mejorar el rendimiento del nado ondulatorio subacuático. La frecuencia de patada no debe abordarse como un elemento primordial al iniciar el desarrollo del nado ondulatorio subacuático.

- Cinco semanas de entrenamiento específico en agua no son suficientes para mejorar el rendimiento del nado ondulatorio subacuático en nadadores adolescentes.

- La inclusión de ejercicios de fuerza simulando la acción del batido, en polea cónica, combinado con un entrenamiento especifico en agua mejoran el rendimiento del nado ondulatorio subacuático. Los entrenadores deberían de proporcionar estímulos en seco para mejorar el rendimiento del nado ondulatorio subacuático

CHAPTER 10:

Suggestions for future research

Suggestions for future research

During the current doctoral thesis, different issues related to sprint swimming performance have been corroborated and clarified, however, many questions still remain unresolved. Hence, future research should aim to cover the following ideas:

- To study the effects of specific training in swimmers ability to apply force in the water. This would provide more knowledge to improve swimming training plans, leading to similar/greater gains in shorter periods of training.

- To investigate the association between tethered swimming, dry-land strength, and swimming performance in the remaining three other strokes. Front crawl is the most studied stroke, but knowledge of the rest of the strokes is scarce.

- To analyze the time required after an off-season to recover from the detraining. That would provide a better understanding of the competition results at the beginning of a new season, knowing from which point onwards performance improvements could be expected.

- To find the most suitable strategy during the off-season that allows swimmers to recover physiologically and mentally while reducing performance impairments. This would prevent performance from being compromised the following season. Physiological and mental recovery is essential to avoid burnout during the following season. Therefore, the best balance between recovery and impairments reduction must be found.

- To deepen the importance of muscle strength in undulatory underwater swimming. Many questions need to be answered, such as the type of resistance training, the minimum training period required to elicit enhancements, or the importance of the core muscles in undulatory underwater swimming.

- To conduct the analysis of this current doctoral thesis with higher performance level swimmers and to compare the results between different level swimmers. This would provide further insights into overall performance.

- In general, female swimmers are underrepresented in swimming research and therefore further studies are required to better understand the sex-induced differences. That would aid in female swimmers' performance development.

ANNEXES

SHORT CURRICULUM VITAE

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*These two authors equally contributed to this manuscript.

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Book chapters

[1] **Ruiz-Navarro JJ,** Gay A. Iniciación al waterpolo. In: López-Contreras G. et al. Perfeccionamiento Deportivo: Natación. Copideporte; **2021**. ISBN: 978-84-18471-70-4.

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Reviewer activity

[1] Scandinavian Journal of Medicine and Science in Sport.

- Sport Sciences 13/124; Q1.

[2] Scientific Reports.

- Multidisciplinary Sciences 17/73; Q1

[3] Sport Sciences for Health.

- Not indexed in JCR.

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Research projects

2018-2022	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, Spain.
2018-2022	Project research staff of the swimming performance evaluation of regional and national swimmers from the Swimming Andalusian (FAN) and National Federations (RFEN).
2018-2019	Project research staff of DEP2014-59707-P ‘SWIM: Specific Water Innovative Measurements applied to the Development of the International Swimmers in Short Swimming Events (50 and 100 m)’.
2019-2021	Project research staff of PGC2018-102116-B-I00 ‘SWIM II: Specific Water Innovative Measurements: Applied to the Performance Improvement’.
2021-2023	Project research staff of SWIM FOR LIFE: Efecto de la práctica de la natación de competición en la calidad de vida de las personas adultas.

Research stays

2020	Three months international internship at Faculty of Health sciences, University of Sydney. Supervisor: Professor Ross Sanders

University teaching

- Subject: **Fundamentals of sports 1: Swimming** (30 hours of teaching, 3 credits ECTS). Degree: Physical Activity and Sport Sciences, University of Granada (Spain). Academic course: 2018/2019.

- Subject: **Fundamentals of sports 1: Swimming** (50 hours of teaching, 5 credits ECTS). Degree: Physical Activity and Sport Sciences, University of Granada (Spain). Academic course: 2019/2020.

- Subject: **Sports training** (60 hours of teaching, 6 credits ECTS). Degree: Physical Activity and Sport Sciences, University of Granada (Spain). Academic course: 2020/2021

- Subject**: Fundamentals of sports 1: Swimming** (20 hours of teaching, 2 credits ECTS). Degree: Physical Activity and Sport Sciences, University of Granada (Spain). Academic course: 2021/2022.

- Subject: **Sports specialization: Swimming** (20 hours of teaching, 2 credits ECTS). Degree: Physical Activity and Sport Sciences, University of Granada (Spain). Academic course: 2021/2022.

Other merits

- Six posters in international congress.

- 2021 and 2022 Invited lecturer in the Master's in Research in Sports and Physical Activity: Advanced research in aquatic sports. University of Granada, Spain. 2 hours each year.

- 2021 and 2022 race analyst of the Spanish Swimming Team in national and international championships.

- Author of more than 15 transfer reports.

- Second award in the XXXVIII International congress of the Spanish swimming coaches association.

UNIVERSIDAD DE GRANADA

FACULTAD DE CIENCIAS DEL DEPORTE
DEPARTAMENTO DE EDUCACIÓN FÍSICA Y DEPORTIVA

EXAMPLE OF REPORTS PROVIDED TO SWIMMERS

Jesús Juan Ruiz Navarro

Aquatics lab
Facultad de Ciencias del Deporte
Universidad de Granada

The relationship between muscle strength and undulatory underwater swimming performance

Estimado **"anonimity"**, de parte de todo el grupo de investigación del Aquatics Lab, y en especial de mi persona, nos gustaría agradecerte tu predisposición y contribución en el desarrollo de esta investigación. A continuación, encontrarás los resultados de los test realizados, así como una breve explicación de las variables obtenidas. Ante cualquier duda, pregúntanos!

1º- ANTROPOMETRIA Y FUERZA

Los valores aportados son los valores máximos obtenidos

ANTROPOMETRIA	
Peso (kg)	67,1
Estatura (cm)	187,9
IMC (%)	19,01
FUERZA PIERNAS	
Flexión de rodilla (N)	208
Extensión de rodilla (N)	629
Flexión de cadera (N)	164
Extensión de cadera (N)	233
Altura del salto (m)	0,38
FUERZA DEL CORE	
V-sit (s)	143
Biering-Sorensen (s) - lumbar	102

2º- NADO ONDULATORIO SUBACUATICO

Los valores aportados a continuación son los valores promedios de todas las repeticiones. El batido completo hace referencia a todo el movimiento, la fase descendente hace referencia al periodo comprendido entre la posición más alta de los pies hasta la más baja y la fase ascendente se refiere al periodo comprendido entre la posición más baja de los pies hasta la más alta

	BATIDO COMPLETO	**FASE DESCENDENTE**	**FASE ASCENDENTE**
Velocidad promedio (m/s)	1,29	1,26	1,31
Velocidad pico (m/s)	1,66	1,66	1,44
Velocidad mínima (m/s)	0,76	0,76	1,24
Distancia recorrida por patada (m)	0,74	0,31	0,43
Frecuencia de patada (Hz)	1,74	4,10	3,04
Amplitud de patada (cm)	67,16	63,02	67,16
RANGO DE MOVIMIENTO			
Cadera (º)	50,07	42,24	33,08
Rodilla (º)	79,92	70,72	45,55
Tobillo (º)	50,54	38,15	11,08
VELOCIDAD ANGULAR PROMEDIO			
Cadera (º/s)	140,05	266,91	177,94
Rodilla (º/s)	373,81	439,76	199,81
Tobillo (º/s)	264,43	306,61	61,30

VELOCIDAD ANGULAR MÁXIMA			
	BATIDO COMPLETO	**FASE DESCENDENTE**	**FASE ASCENDENTE**
Cadera (º/s)	565,54	565,54	249,07
Rodilla (º/s)	597,07	596,59	540,84
Tobillo (º/s)	621,22	621,22	119,27
VELOCIDAD VERTICAL DEL PIE			
Media (m/s)	1,17	2,58	2,04
Máxima (m/s)	4,35	4,35	2,94

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