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Use of wetsuit: Its effect on swimming performance under different experimental conditions

Uso del neopreno: Su efecto en el rendimiento en natación bajo diferentes condiciones experimentales

International Doctoral Thesis
Tesis Doctoral Internacional

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A los que con Amor, siempre han creído en mí.
One Life, Live It.

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RESEARCH PROJECTS AND FUNDING

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LIST OF PUBLICATIONS

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2. **Gay, A.,** Zacca, R., Arturo, A., Morales-Ortiz, E., López-Contreras, G., Fernandes, R., & Arellano, R. Swimming with swimsuit and wetsuit at typical vs cold-water temperatures (26 vs 18ºC). *International Journal of Sports Medicine*. 2021;42, 1-8. doi: 10.1055/a-1481-8473. (Impact Factor: 2.556, Journal Ranking: 2nd Quartil, Sport Sciences).

3. **Gay, A.,** Arturo, A., Zacca, R., Morales-Ortiz, E., López-Contreras, G., Fernandes, R., & Arellano, R. Acute effects of water temperature in swimming performance: a biophysical analysis (peer review). Study presented at the *XIII th International Symposium on Biomechanics and Medicine in Swimming (BMS),* Japan. 2018. (Peer review article).

4. **Gay, A.**, Zacca, R., Abraldes, A., Morales-Ortiz, E., López-Contreras, G., Cuenca-Fernández, F., Fernandes, R., Arellano, R. Physiology and biomechanics to determine the effect of wetsuit Speedo Thinswim® when swimming in a cold-water flume (peer review). Abstract presented at *the XXV European College of Sport Sciences*. Book of Abstracts, Sevilla. 2020. (Peer review abstract).

5. **Gay, A.,** Ruiz-Navarro, J., Fernandes, R., & Arellano, R. Use of wetsuit in swimming performance, a systematic review.

6. **Gay, A.,** Ruiz-Navarro, J., Cuenca-Fernández, F., Abraldes, A., Fernandes, R., & Arellano, R. 400 m front crawl swimming determinants when using a wetsuit.

LIST OF SYMBOLS AND ABBREVIATIONS

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Aerobic contribution	Aer
Amplitude of the fast $\dot{V}O_2$ component	Ap
Anaerobic alactic contribution	AnAl
Anaerobic lactic contribution	AnL
Analysis of variance	ANOVA
Blood lactate concentration	[La-]
Body mass	M
Body mass index	BMI
Borg rating of perceived exertion scale	RPE
Cardiac output	Q
Cohen’s Kappa coefficient	κ
Confidence interval	CI
Constant for O_2 equivalent of $[La\text{-}]_{net}$	β
Correlation coefficient	r
Determination coefficient	R^2
Energy cost of swimming	C
Energy expenditure	E
Exercise duration	t
Heart rate	HR
Heaviside step function	*H*
International Swimming Federation	FINA
International Swimming Federation points	FINA points

International Triathlon Federation	ITU
Kilojoules	kJ
Kilometer	km
Kilowatt	kW
Maximal blood lactate concentration	$[La^-]_{max}$
Maximal heart rate	HR_{max}
Maximal oxygen consumption	$\dot{V}O_{2peak}$
Meter	m
Minimal velocity that elicits $\dot{V}O_{2max}$	$v\dot{V}O_{2max}$
Minute	min
Minute ventilation	$\dot{V}E$
Number of participants	n
Oxygen uptake	$\dot{V}O_2$
Oxygen content of the arterial blood	Ca_2
Oxygen content of the venous blood	CvO_2
Phosphocreatine	PCr
Propelling efficiency	ηp
Respiratory exchange ratio	RER
Respiratory frequency	RF
Second	s
Standard deviation	SD
Statistical package for the social sciences	SPSS
Stroke frequency	SF
Stroke index	SI

Stroke length	SL
Swimming speed	v
Time constant of the fast $\dot{V}O2$ component	τp
Time delay of the fast $\dot{V}O_2$ component	TDp

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Chapter 4

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SF \cdot l) \cdot 2/\pi] \cdot 100$$

Chapter 6

$$\dot{V}O_2(t) = A_0 + H\left(t - TD_p\right) \cdot A_P(1 - e^{-(t-TD_p)/\tau_p})$$

$$AnL = [La^-]_{net} \cdot \beta \cdot M$$

$$AnAL = PCr \cdot (1 - e^{-t/\tau}) \cdot M$$

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SF \cdot l) \cdot 2/\pi] \cdot 100$$

Chapter 7

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SF \cdot l) \cdot 2/\pi] \cdot 100$$

Chapter 9

$$\dot{V}O_{2max} = Q \cdot (Ca_2 - CvO_2)$$

Equations of interest

Swimming velocity ($m \cdot s^{-1}$): v = d · t-1
FINA points: $P = 1000 \cdot (B/T)^3$
Stroke rate (Hz): $SR = \text{time in 3 cycles} \cdot 60^{-1}$
Stroke length (m): $SL = v \cdot SR^{-1}$
Stroke index ($m^2 \cdot s^{-1}$): $SI = SL \cdot v$
Total energy expenditure: E = Aer + AnL + AnAL
Body mass index: BMI = Weight (kg) / Height (m^2)

ABSTRACT / RESUMEN

ABSTRACT

Introduction: Wetsuits are used in swimming mainly to avoid hypothermia, with open water and triathlon competitions as wearing them often. It use in these sports varies, being mandatory, optional or prohibited depending on the water temperature, existing full body, sleeveless long and short wetsuits designs. The wetsuit also improves swimming performance due to the increased buoyancy, allowing better hydrodynamic position and decreased hydrodynamic drag. The overall aim of this Doctoral Thesis is to study the effect of wearing a wetsuit and a swimsuit on 400 m front crawl performance. **Methods:** A systematic review was developed to find out what had been studied on the area and then, 95 open water swimmers and triathletes swam 400 m front crawl with wetsuit and swimsuit in a 25 m swimming pool and in a swimming flume at different water temperatures. Anthropometric, biomechanical and physiological variables were analyzed. **Results:** Swimmers increased their swimming speed by 0.07 $m \cdot s^{-1}$ with wetsuit compared to conventional swimsuit, resulting in a 6% of improvement on 400 m front crawl performance (20.1 s). Stroke rate and the wetsuit thickness in females better explained the improvement on 400 m front crawl performance while using wetsuit. In the other hand, swimming in cold water with wetsuit do not produce physiological alterations that may impair performance, recommending its use when the water temperature is between 18-20ºC. Swimming at 18ºC without a wetsuit might influence the 400 m front crawl performance as lower maximal blood lactate concentrations, ratio of perceived exertion and exergy expenditure were observed. In addition, when using the wetsuit Speedo Thinswim®, the higher value on propelling efficiency could be due to the reduction on hydrodynamic drag, inducing in a decrease in energetic contributions and so higher velocity might be reached with the same effort on 400 m front crawl, using this specific wetsuit. **Conclusions:** Swimming with wetsuit improves performance on 400 m front crawl and it use is recommended in open water and triathlon competitions. These findings increase our knowledge in understanding how the wetsuit change the swimming technique or influence the physiological responses while swimming comparing to the swimsuit, which is important to improve the swimmers daily training and thus, the results in open water swimming and triathlon competitions.

RESUMEN

Introducción: El neopreno se utiliza en natación principalmente para evitar la hipotermia, siendo las competiciones de aguas abiertas y de triatlón las que más los utilizan. Su uso en estos deportes varía, siendo obligatorio, opcional o prohibido en función de la temperatura del agua, existiendo diseños que cubren el cuerpo completo, neoprenos largos sin mangas y cortos. El neopreno también mejora el rendimiento en natación debido al aumento de la flotabilidad, permitiendo una mejor posición hidrodinámica y la disminución de la resistencia hidrodinámica. El objetivo general de esta Tesis Doctoral es estudiar el efecto del uso del neopreno y del bañador sobre el rendimiento en 400 m crol. **Métodos:** Se desarrolló una revisión sistemática para conocer lo estudiado en el área y posteriormente, 95 nadadores de aguas abiertas y triatletas nadaron 400 m crol con neopreno y bañador en una piscina de 25 m y en una piscina contracorriente a diferentes temperaturas de agua. Se analizaron variables antropométricas, biomecánicas y fisiológicas. **Resultados:** Los nadadores aumentaron su velocidad de nado en 0.07 $m \cdot s^{-1}$ con neopreno en comparación con el bañador convencional, lo que supuso una mejora del 6% en el rendimiento de los 400 m crol (20.1 s). La frecuencia de brazada y el grosor del neopreno en las mujeres fueron los que mejor explicaron el incremento en el rendimiento en 400 m crol con el uso del neopreno. Por otro lado, nadar en agua fría con neopreno no produce alteraciones fisiológicas que puedan perjudicar el rendimiento, recomendando su uso cuando la temperatura del agua está entre 18-20ºC. Nadar a 18ºC sin neopreno podría influir en el rendimiento de los 400 m crol, ya que se observaron menores concentraciones máximas de lactato en sangre, ratio de esfuerzo percibido y gasto energético. Además, cuando se utiliza el neopreno Speedo Thinswim®, el alto valor de la eficiencia propulsiva podría deberse a la reducción de la resistencia hidrodinámica, induciendo una disminución de las contribuciones energéticas y, por tanto, se podría alcanzar una mayor velocidad con el mismo esfuerzo en los 400 m crol usando neopreno específico. **Conclusiones:** Nadar con neopreno mejora el rendimiento en 400 m crol y se recomienda su uso en competiciones de aguas abiertas y triatlón. Estos resultados aumentan nuestro conocimiento en la comprensión de cómo el neopreno cambia la técnica de natación o influye en las respuestas fisiológicas durante la natación en comparación con el bañador, lo cual es importante para mejorar el

entrenamiento diario de los nadadores y, por lo tanto, los resultados en competiciones de aguas abiertas y triatlón.

CHAPTER 1: General introduction

CHAPTER 1: General introduction

Open water swimming encompasses any competition that takes place in rivers, lakes, oceans or water channels [1]. Since the beginning of long distance and endurance swimming, many events have been developed over the years. The first event took place in the famous Catalina Channel in California in January 1927 when a group of 101 swimmers braved the cold waters of the 21 miles crossing from the California coast to Catalina Island. Since then, the event has been successfully run 113 times. In the years that followed, many other famous international water competitions have been conquered by intrepid marathon swimmers, such as the Bering Strait, the Cab of Good Hope, the Magellan Strait and Windermere Lake (among the most interesting). But the most important crossing throughout history is the English Channel (the channel that separates England from France). This 20 miles crossing has been attempted between 4000 and 5000 times, of which 800 have been unsuccessful. But despite its importance, the first crossing of this channel took place more than half a century after the first event ('Catalina Channel' in 1927) [2].

Although the large number of events developed throughout history, it was not until 1986 when the International Swimming Federation (FINA) recognized long distance swimming as an aquatic discipline with the first long distance swimming World Cup in the 'Windermer' lake in England. Subsequently, the first Open Water Swimming World Championships were held in Perth, Australia. However, it was not until the 2008 Olympic Games in Beijing when the 10 km open water distance when the discipline was introduced at an Olympic Games [3]. In short, long-distance swimming is defined as freestyle swimming over distances of more than 400 m [3]. At the professional level, FINA establishes 5, 10 and 25 km as official open water competition distances. However, any freestyle over 400 m would meet the criteria required to be considered open water competition [4]. In the other hand, triathlon is an individual endurance sport that combines three sequential sport disciplines (swimming, cycling and running) [5] and was introduced in the Olympic Games in Sidney 2000 with the called Olympic distance (characterized by 1500 m of open water swimming).

Swimming in open water, both in the discipline of swimming or triathlon, requires a series of swimwear regulations, mainly to avoid hypothermia [6]. The neoprene material of wetsuits is composed of small bubbles of gases (such as air, nitrogen and hydrogen) that insulate against the cold by creating a thermal layer between the swimmers body and the water. It induces thermal insulation as a result of heat reduction and convective heat loss [7]. Its use is regulated depending on the water temperature, i.e. both FINA for open water swimming and International Triathlon Federation (ITU) for triathlon, which establish different temperature ranges defining its use as mandatory, optional or prohibited in competitions (Table 1A and B detail the temperatures ranges of each modality). In addition, not all known types of wetsuits can be used for open water swimming and triathlon, with the thickness being limited to 5 mm for both disciplines [8,9].

Table 1. Open water (A) and triathlon (B) swimming rules for the wetsuit use depending on the water temperature.

Water Temperature	**Use of Wetsuit**
< 16ºC	Competition Cancelled
16 - 17.9ºC	Mandatory
18 - 20ºC	Optional
> 20ºC	Forbidden

A: FINA rules [8].

		Use of Wetsuit regarding Water Temperature		
Category	**Swim length**	Forbidden	Mandatory	Optional
Elite, under 23, junior and youth	up to 1500 m	≥ 20ºC	≤ 15.9ºC	16 - 19.9ºC
	1501m and longer	≥ 22ºC	≤ 15.9ºC	16 - 21.9ºC
Age group athletes	up to 1500 m	≥ 22ºC	≤ 15.9ºC	16 - 19.9ºC
	1501m and longer	≥ 24.6ºC	≤ 15.9ºC	16 - 21.9ºC

B: ITU rules [9].

In addition to the hypothermia prevention, the wetsuit use also improves performance [6,10-12], because the additional buoyancy of the neoprene material, providing a more horizontal position of the swimmers thus, resulting in a better hydrodynamic body position. This improved hydrodynamic position reduces drag and, as a consequence, the energy cost of swimming (C) [13]. Hence, swimming with wetsuit might increase swimming performance due to the biomechanical and physiological changes. To understand the characteristics and the wetsuit effects in swimming performance, a systematic review was developed (**Chapter 3**). It were included swimmers, triathletes, pools and open water environments and the types of wetsuits allowed to be used in competitions: full body (covers the trunk, lower limbs until the ankles and upper limbs until the wrists, but not the head); sleeveless long (covers the trunk and lower limbs until the ankles but not the upper limbs) and sleeveless short (covers only trunk and lower limbs until the knees) [14-17] (see Figure 1).

Figure 1. From left to right: full body, sleeveless long and short wetsuits, and swimsuit.

The results of the systematic review showed different issues to address this Doctoral Thesis. Firstly, wetsuit improves performance but differently for experienced, inexperienced swimmers and for triathletes [10,15]. Secondly, the effect of the type of wetsuit used (full body, sleeveless long or short) influences swimming performance otherwise for swimmers and triathletes [14,16,17]. Thirdly, the distance evaluated differs from competitive distances. As discussed above, the official distances recognized by FINA for open water swimming competitions range from 400 m to 25 km [4] however, competitive distances in triathlon vary from 250 m to 3900 m in the swimming segment [9]. It means that the measurements of the wetsuit effects are not always adapted to the competition distances, being shorter in numerous studies as it can be observed in Table 2 of **Chapter 3**. Fourthly, the swimming place and its similarity to real competition. Swimmers and triathletes compete in open water, though the environment constraints induce researchers to test in swimming pools (either 25 m or 50 m) or swimming flumes rather than in open water [12,18-20]. To finish, fifthly, the water temperature in indoor pools is around 26 - 27ºC (see Table 2 of **Chapter 3**) but in competitions the water temperature is usually much lower (Table 1A and B of this chapter).

Throughout the chapters of the current Doctoral Thesis we attempt to analyze and discuss those issues. The first purpose was to determine the physiological and biomechanical differences between the use of wetsuit compared to swimsuit in a 25 m swimming pool and in a swimming flume where the continuous swimming without turns is possible simulating real competition (**Chapter 4**). As literature confirms, the full body wetsuit gives the best performance in swimming [10,14,15], thus the studies develop in this thesis were focused on this kind of wetsuit. The sample was composed of swimmers and triathletes and they swam 400 m front crawl with both suits as it is well related with the velocity that elicits maximal oxygen consumption ($\dot{V}O_{2max}$), a valid indicator of aerobic power [21,22].

Derived from this study, it was aimed to solve the question how the improvement on 400 m front crawl produced by the wetsuit might be influenced by the biomechanical, physiological and/or anthropometrical variables. In addition, it was aimed to study the possible associations between these variables, analysing this for the total sample but also differentiating by sexes (**Chapter 5**). The importance of this study is based on, as has been studied, greater thickness allows greater buoyancy [10,23] and also due to the thicker the wetsuit, the greater the buoyancy that can be obtained [7]. Therefore, the increase in performance provided by the wetsuit could be explained by changes in biomechanical, physiological and anthropometric variables plus by the age of the participants. Since the information on this topic is scarce, it is of interest to establish a model that clarifies which variables are mainly responsible for the improved performance with the use of wetsuit in swimming.

To solve the problem with the water temperature (issue five comment above), **Chapters 6** and **7** aimed to analyze the physiological and biomechanical changes while swimming at 18 and 26ºC with wetsuit and swimsuit in the swimming flume. The temperatures selected were 18ºC (optional use in open water swimming competitions) [8], thus the decision on its use is important for swimming performance and 26ºC (usual indoor pool water temperature). As a results of the physiological and biomechanical variables studied were modified by the use of the swimming flume compared to 25 m swimming pool in the previous study (**Chapter 4**), the aim was to investigate the effect of swimming with wetsuit in the swimming flume where the analysis of respiratory exchanges, $\dot{V}O_{2max}$ and energetic contributions induce fewer measurement constrains that measuring in the swimming pool [24] (**Chapters 6 and 7**). The acute biophysical effects of different water temperatures (18 and 26ºC) on 400 m front crawl swimming only with swimsuit was explore in the **Chapter 7**.

The physiological changes that cold water produces in our bodies when we enter it might influence our performance in open water and triathlon events, due to the cold-shock response [25]. For this reason, using wetsuit might be a determining factor when choosing whether or not to use it (depending on the water temperature). In addition, its use is also related to the ability to swim with it, as discussed in **Chapter 3**. In turn, knowing the $\dot{V}O_{2max}$ (as a determinant of maximal metabolic aerobic performance capability [26], the energy contributions (aerobic, anaerobic lactic and alactic), blood lactate concentrations ([La-]) and maximal heart rate (HR_{max}) provide very important information for determining the efficiency of swimming with and without wetsuit and in cold and warm water temperatures, which is especially relevant for designing swimmers training [27].

To supplement the biophysical analysis of the effect of wetsuit on swimming performance, it is presented a justification of the use of the same type of wetsuit (brand and model; **Chapter 8**). The reasons of this pilot study was due to most of the participants used their own wetsuit, thus each one had specific thickness characteristics in upper and lower limbs and torso. As it can be observed in the Table 4 of the **Chapter 3**, there are many studies that use a particular brand for the whole sample [10,17,18] and it might clarify the effects produced by a specific wetsuit model. This pilot study was performed with four male swimmers who wore the same wetsuit Speedo Thinswim®, which is characterized by 2 mm of thickness throughout the suit. The information obtained here helps us to better understand the benefits of this wetsuit and therefore to plan the training loads in open water swimming [28].

To understand the results obtained in the current Doctoral Thesis, a general discussion is proposed**,** including main limitations (**Chapter 9**). In the **Chapter 10,** conclusions are exposed and finally, general applications and suggestions for future research are detailed in **Chapter 11**. In addition, in the **Appendices I to IV** are shown complementary information derived from the current Doctoral Thesis (i.e., Publications and knowledge transfer reports derived from the research group Aquatics Lab CTS-527: 'Actividad Física y Deportiva en el Medio Acuático' during the current Doctoral Thesis; Ethics committee for the first and the entire thesis data collection; Consent forms of the first and second data collection (adults and under 18-years old); Reports to participants (Example of report from the study: 'Swimming with swimsuit and wetsuit at typical vs cold-water temperatures (26 vs 18ºC)'; and Curriculum vitae of the candidate, respectively.

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CHAPTER 2: Aims / Objetivos

CHAPTER 2: Aims

Aims of the current International Doctoral Thesis

Overall aim

To study the effect of swimming with wetsuit and swimsuit on 400 m front crawl performance. This overall aim is addressed in six specific aims which correspond to six thesis chapters.

Specific aims

- **Specific aim I:** To examine the effect of wearing different types of wetsuits on front crawl swimming performance in different distances and water environments (swimming pool, flume and in open water). Besides, to clarify the improvement related to biomechanics and physiological aspects to recommend its use in open water swimming events (**Chapter 3**).

- **Specific aim II:** To analyze the changes in performance, general biomechanical and physiological variables when using a wetsuit, both in swimming pool and swimming flume conditions (**Chapter 4**).

- **Specific aim III:** To clarify which determinants could explain the wetsuit advantages during swimming, we have purposed to conduct a biomechanical, physiological and anthropometrical characterization (including the age) of the 400 m front crawl using wetsuit. Afterwards, we aim to observe the associations between the selected variables studied, analysing this for the total sample and differentiating by sex (**Chapter 5**).

- **Specific aim IV:** To compare 400 m front crawl swimming performance at two water temperatures (18 and 26ºC) with and without wetsuits in the swimming flume (**Chapter 6**).

- **Specific aim V:** To explore swimmers technical and physiological behavior at cold and temperate water temperatures with swimsuit, by analyzing some relevant front crawl biophysical related variables on 400 m (**Chapter 7**).

- **Specific aim VI:** To assess the biophysical comparison between the wetsuit Speedo Thinswim® (2 mm of thickness in upper limbs, trunk and lower limbs, Nottingham, United Kingdom) and a training swimsuit when swimming at 18ºC water temperature (**Chapter 8**).

CHAPTER 2: Objetivos

Objetivos de la presente Tesis Doctoral Internacional

Objetivo general

Estudiar el efecto de nadar con neopreno y bañador convencional sobre el rendimiento en 400 m crol. Este objetivo general se aborda en seis objetivos específicos que corresponden a seis capítulos de la tesis.

Objetivos específicos

- **Objetivo específico I:** Examinar el efecto del uso de diferentes tipos de neopreno en el rendimiento en natación (nado crol) en diferentes distancias y entornos acuáticos (piscina de 25 y 50 m, piscina contracorriente y en aguas abiertas). Además, aclarar la mejora relacionada con los aspectos biomecánicos y fisiológicos para recomendar su uso en eventos de natación en aguas abiertas (**Capítulo 3**).

- **Objetivo específico II:** Analizar los cambios en el rendimiento y las variables biomecánicas y fisiológicas generales cuando se utiliza neopreno, tanto en piscina de 25 m como en piscina contracorriente (**Capítulo 4**).

- **Objetivo específico III:** Aclarar qué determinantes podrían explicar las ventajas del neopreno durante la natación, con el objetivo de realizar una caracterización biomecánica, fisiológica y antropométrica (incluyendo la edad) de los 400 m crol utilizando neopreno. Posteriormente, pretendemos observar las asociaciones entre las variables estudiadas, analizándolas para la muestra total y diferenciando por sexo (**capítulo 5**).

- **Objetivo específico IV:** Comparar el rendimiento de la natación de 400 m crol en dos temperaturas del agua (18 y 26ºC) con y sin neopreno en la psicina contracorreinte (**Capítulo 6**).

- **Objetivo específico V:** Determinar el comportamiento biomecánico y fisiológico de los nadadores en temperaturas de agua fría y templada con bañador, analizando algunas variables biofísicas relevantes relacionadas con el nado crol en 400 m (**Capítulo 7**).

- **Objetivo específico VI:** Evaluar la comparación biofísica entre el neopreno Speedo Thinswim® (2 mm de grosor en las extremidades superiores, tronco y extremidades inferiores, Nottingham, Reino Unido) y un bañador convencional al nadar a 18ºC de temperatura del agua (**Capítulo 8**).

CHAPTER 3: Use of wetsuit in swimming performance, a systematic review

CHAPTER 3: Use of wetsuit in swimming performance, a systematic review

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Abstract

This systematic review aims to examine the effect of wearing different types of wetsuits on front crawl swimming performance in different distances and environments (swimming pool, flume and open water). The Web of Science (WOS), PubMed, Scopus and the Proceedings of International Symposium on Biomechanics and Medicine in swimming (BMS) databases were searched. From the total of 938 studies found, 23 articles were finally included for eligibility. The use of full body wetsuit was the suit more studied and the results showed an increment from 3.23 to 12.9% on front crawl swimming performance in distances from 25 to 1500 m, incremental tests, continuous swimming of 5 and 30min and in open water swimming events. Also, the sleeveless long wetsuit also induce a performance enhancement as shown on 400 and 800 m compared to full body wetsuit. Higher stroke rate (SR), stroke length (SL) and stroke index (SI) were observed while using wetsuit compared to swimsuit. Energy cost (C) showed lower values with the use of full body wetsuit by contrast with swimsuit. The improvement achieved by the use of the wetsuit in biomechanics and physiological parameters induce to the increase in speed when wearing the full body, sleeveless long and short wetsuits, compared to use swimsuit.

Keywords: Open water, triathlon, neoprene, wet suit, physiology, biomechanics,

Introduction

The wetsuit was originally used in open water swimming to prevent hypothermia [1] and it use is mandatory both by the International Swimming Federation (FINA) [2,3] and by the International Triathlon Union (ITU) [4]. In both cases, the use of wetsuit depends on the water temperature (see Table 1A and B, **Chapter 1**) to maintain core body temperature [5]. Regulations also determines the maximal thickness allowed in competitions, it is five millimeters as maximum for open water swimming and triathlon competitions [3,4]. Previous researches confirm that the use of wetsuit implies an improvement in performance mainly due to the increase in buoyancy which induce the reduction in drag and so the decrease in the energy cost of swimming (C) and the increase in propelling efficiency (ηp) [6,7]. As it was studied, these advantages produce a 5 to 7% performance improvement from 400 m to 30 min swimming events when wearing a wetsuit [8-11].

As referred above, there are not only differences in the wetsuit thickness, but also in the model and structure. A distinction can be made between full body wetsuit (covering both upper limbs and lower limbs up to the ankles), sleeveless long (not covering the upper limbs) and sleeveless short (only covering the torso and lower limbs until the knees). All of them have been evaluated for competition by different studies as Trappe at al. [12] and have been validated by the respective federations [3,4]. It is important to highlight that the election of the model is not only influenced by the thickness but also by the fabric. The composition of the wetsuit is made of neoprene fabrics with small gas bubbles contained in synthetic rubber which induce thermal insulation as a result of the reduction and convective heat loss. But some of them are not only composed by rubber but also with single jersey knitted fabrics besides the uniform or non-uniform composition of the material in the suit, which is a guarantee of the thermal properties [13].

In addition, the use of wetsuit by the athletes is also based on the comfort of wearing it and, in turn, the comfort is related to the frequency of use and its incorporation in the daily training. This perception of comfort is usually assessed using the subjective effort perception scale [14], dividing between swimmers and triathletes related to the technical abilities [8,15,16] or by asking case-by-case to the athletes. The greater muscle mass in the upper limbs in swimmers is one of the reasons of the popular use of sleeveless long wetsuit between swimmers rather than in triathletes. In addition to the fact that the level of the swimmer is also related to the use of the model without sleeves rather than the full body [8,15]. Hence, that improvements produced by wearing wetsuit in different athletes (swimmer or triathlete) is a variable to observe while assessing the enhancement in swimming performance.

Scientific literature has demonstrated biomechanics and physiological effects on swimming while wearing wetsuit. Nevertheless, it is required to understand the situations from which we can obtain better performance both for training and/or competition. Also discerning between different types of wetsuit, level and discipline of swimming (swimmer or triathlete). As a result, coaches and athletes could design their training routines with wetsuit and the strategies for open water swimming competitions. Thus, the purpose of the present review was to examine the effect of wearing different types of wetsuits on front crawl swimming performance in different distances and water environments (swimming pool, flume and in open water). Besides, to clarify the improvement related to biomechanics and physiological aspects to recommend its use in open water swimming events.

Material and Methods

Search Strategy

The present systematic review was conducted following to the Preferred Reporting Items for Systematic Reviews and Meta – analysis (PRISMA). The Web of Science (WOS), PubMed, Scopus and the Proceedings of International Symposium on Biomechanics and Medicine in swimming (BMS, peer review publications) databases were searched up to and including the November 13, 2020. This review includes studies about the effect of wetsuit on swimming performance. The key-terms used to search the appropriate publications were: ‘swimming’ AND ‘wetsuit’; ‘swimming’ AND ‘wet suit’; ‘swimming’ AND ‘wet-suit’; ‘swimming’ AND ‘neoprene’; ‘swimming’ AND ‘thermal swimsuit’ and ‘swimming’ AND ‘floating swimsuit’. The search strategy was adapted to the four data bases. The search was conducted in tittles, abstracts and key words. Furthermore, additional relevant studies which were not identified in the database search were included as additional records (see Figure 1).

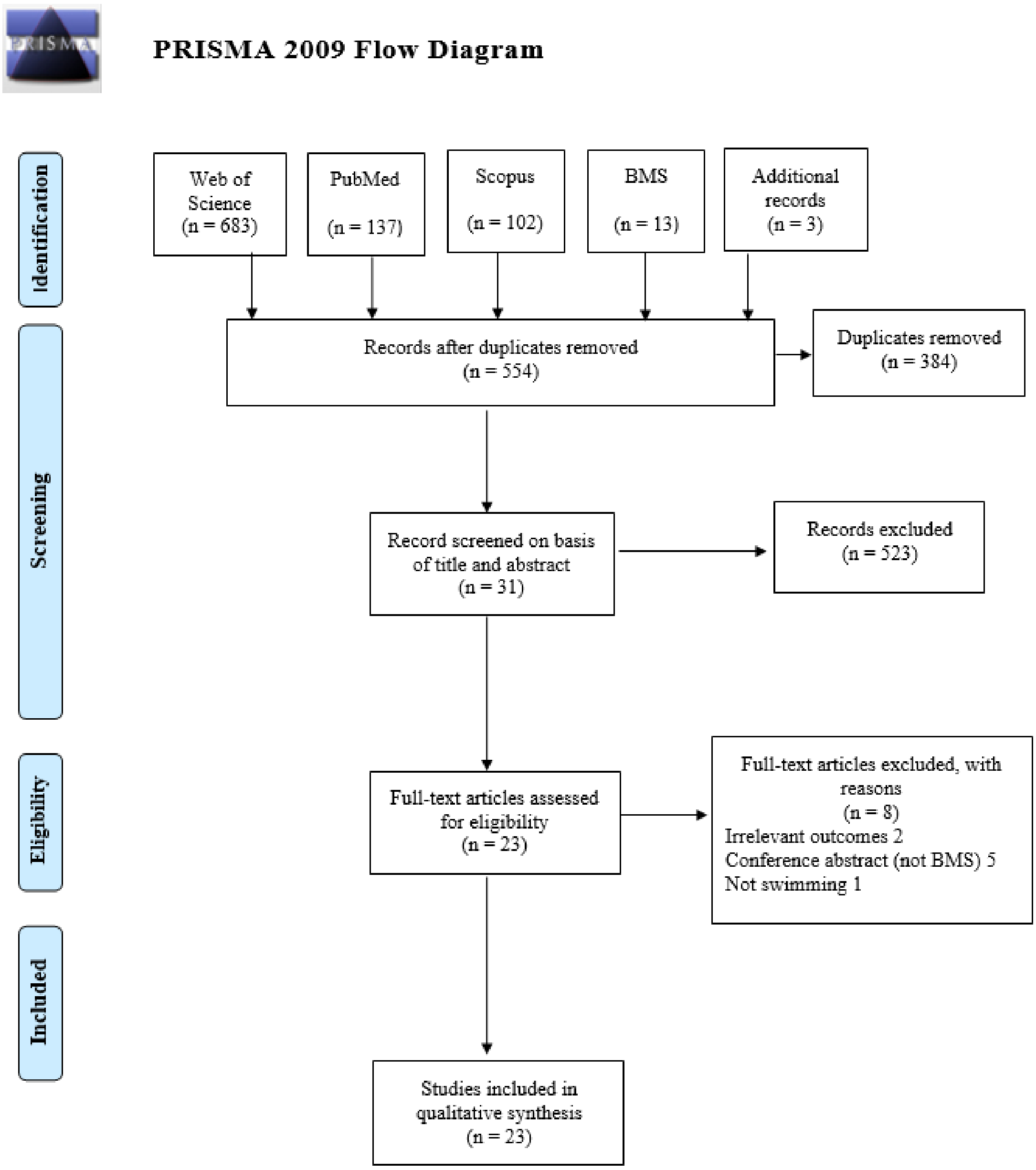

Figure 1. PRISMA flow diagram of the studies selected.

Eligibility Criteria

The studies included in the present review fulfil the following inclusions requirements: (i) published in a peer-review journal; (ii) studies that aimed to assess front crawl swimming performance while wearing wetsuit; (iii) the methodology developed were conducted in 25 or 50 m swimming pool, swimming flume or open water environment (lake, river, water channel or sea) and at any water temperature; and (iv) the wetsuits used could be full body, sleeveless long or sleeveless short. As an exclusion criteria was used: (i) review articles (qualitative and systematic reviews and meta-analysis); (ii) congress contributions, with the exception of the BMS (the most prominent swimming research conference in the world) articles; (iii) studies that evaluated the effect of wearing wetsuit performing water immersions or the effect of wetsuit in the subsequent cycling or running related to triathlon events; and (iv) studies related to the wetsuit use in other disciplines or fields (non-swimming or triathlon).

Study selection

The review process was conducted by two independent researchers in two different stages. During the first stage, duplicate articles were identified and removed from the articles obtained in the initial searched. Titles and abstracts were then checked to identify those manuscript likely to be included. The second stage consisted of checking the full text of the remaining articles to certify those articles that would be finally included in this review. The additional records which were included in the final selection were discussed. Both researchers applied the eligibility criteria during the entire process. In case of disagreements, a consensus meeting was conducted to resolve them.

Data Extraction

The selection of the data extracted was conducted by a researcher and then checked by the rest of the researchers. The items extracted and recorded were defined as follow: (i) study reference; (ii) sample characteristics (age, gender, swimming level and discipline specialization: swimmer or triathlete); (iii) type of wetsuit used; (iv) water environment and water temperature; (v) procedures; and (vi) biomechanics and physiological outcomes. It was identified the publications which compared between two or three types of wetsuits and also between swimmers and triathletes. In case of disagreement of the data extracted, it was solved in a consensus meeting.

Quality Assessment

The quality assessment of the selected studies was conducted by the Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews [17] as it has been specifically designed to assess the quality of cross-sectional studies. It consists of eight items related to sample characteristics, methods and outcomes. Three possible answers were possible on each question: (i) yes, (ii) no or (iii) not applicable. A study was considered as 'high quality' when the quality score was at least 0.75, whereas studies were considered as 'low quality' when the quality score was lower than 0.75 [18]. Furthermore, a summary score of each criterion was calculated by dividing the number of positively scored by the total number of included studies, to provide an overview of how well the included literature scores on each criterion. Two independent reviewers conducted this process and disagreements were discussed until consensus was reached. Moreover, inter-rater reliability for the initial agreement between both researchers was assessed using Cohen's Kappa coefficient (κ) statistical analysis.

Results

Study identification

From the initial searched, 935 studies were identified (WOS: 683 studies; PubMed: 137 studies; Scopus: 102 studies; and BMS: 13 studies). 551 articles remained after duplicates removal. After the screening process a total of 20 articles were finally included in this systematic review plus 3 additional records which were included at the discretion of the authors due to they were not on the data base but the topic is related with this systematic review. In the final screening, 23 full-text articles assessed were included for eligibility, of which the data of 276 subjects and 1714 participants of an open water swimming events were recollected. The study selection process is described in Figure 1.

Quality assessment

Cohen's Kappa coefficient (κ) used to measure inter-rater reliability for the categorical items evaluated, presented that the reliability for the agreement between both researchers was categorized as substantial, following Landis and Gary [19] with $\kappa = 0.60$. Among the articles included, 40% were categorized as ‘high quality’ and 60% as ‘low quality’. Table 1 shows the evaluations of the agreement between the two researchers of studies assessed.

Table 1. The quality assessment of the selected studies after being consensus by the two researchers.

Authors (year)	Question 1	Question 2	Question 3	Question 4	Question 5	Question 6	Question 7	Question 8	Tot
Chatard et al. (1995) [8]	1	1	1	1	0	0	1	1	
Cordain and Kopriva (1991) [9]	1	1	1	1	1	0	1	1	
De Lucas et al. (2000) [10]	1	1	1	1	0	0	1	1	
Gay et al. (2020) [11]	0	1	1	1	1	0	1	1	
Hue, Benavente and Chollet (2003) [21]	1	1	1	1	0	0	1	1	
Hatteau et al. (2007) [22]	0	1	1	1	0	0	1	1	
Nicolaidis, Sousa and Knechtle, (2018) [32]	1	1	1	1	1	0	1	1	
Parsons et al. (1986) [1]	0	1	1	1	0	0	0	1	
Perrier and Monteil (2004) [23]	0	1	1	1	0	0	1	1	
Perrier and Monteil (2002) [20]	0	1	1	1	0	0	1	1	
Perrier and Monteil (2001) [15]	0	1	1	1	0	0	1	1	
Santos, Bento and Rodacki (2011) [28]	0	1	1	1	1	1	1	1	
Tomikawa and Nomura (2009) [24]	0	1	1	1	0	0	1	1	
Tomikawa et al. (2003) [25]	1	1	0	1	0	0	0	1	
Tomikawa, Shimoyama and Nomura (2008) [26]	0	1	1	1	1	1	1	1	
Toussaiunt et al. (1989) [6]	0	1	1	1	0	0	1	1	
Trappe et al (1996) [12]	0	1	1	1	0	0	1	1	
Trappe et al. (1995) [25]	0	1	1	1	0	0	1	1	
Ulsamer et al (2014) [33]	0	0	0	1	1	0	0	1	
Yamamoto et al. (1999) [31]	0	0	1	0	0	0	1	1	

Question 1 (1: Were the criteria for inclusion in the sample clearly defined?; Question 2: Were the study subjects and the setting described in detail?; Question 3 way? Question 4: Were objective, standard criteria used for measurement of the condition?; Question 5: Were confounding factors identified?; Question 6: Were Question 7: Were the outcomes measured in a valid and reliable way? Question 8: Was appropriate statistical analysis used?; Total Score: ≥ 0.75 'High Quality'; researchers.

Sample characteristics

The study sample contains 23 publications from 1986 as the oldest to 2020 as the recent one published (Table 2). From the total sample, the age of participants was 24.05 ± 5 average years old (+50 years old in one study). The swimming level of the participants were regional in five studies [1,10,11,15,20], national in 11 studies [1,9,10,15,20-26], international in 8 studies [1,8,21,23-27], elite in one study [1], amateur in two studies [28,29], students in two studies [14,30], beginners in one study [31], triathletes from a club in a study [27] and four studies did not provide information about the sample level [6,12,32,33]. From the total sample, 15 of the studies has swimmers as participants [6,8-12,14,15,20,28-33] and 16 triathletes [1,6,8,10,11,15,21-29,32]. The wetsuit used in 15 of the studies was full body cover [8-12,14,15,20-23,25,26,28,30], 10 studies used sleeveless long [1,6,9,10,12,14,15,20,27,29] and only in one study sleeveless short was used [12]. In three studies no information was provided about the wetsuit used [31-33]. A brief summary related to the sample type of participants can be observed in the Table 3. Furthermore, Table 4 shows details, thickness and mean ± standard deviation (SD) of each wetsuit used in the different studies.

Table 2. General characteristics of the studies included (sample size details, performance assessment, envi developed, water temperature and wetsuits information), n = 23.

Authors (year)	**Sample Size** **Mean Age ± SD (years)** **Level**	**Performance assessment**	**Environme** **Water temperature**
Chatard et al. (1995) [8]	8 swimmers (21±3.1) and 8 triathletes (21±1.5) International	400m with wetsuit and swimsuit	50m swimming 26 – 26.5ºC
Cordain and Kopriva (1991) [9]	14 females swimmers (19.9±0.9)	400m and 1500m with wetsuit and swimsuit	25 yard (22.86m) swi 26 – 28ºC
De Lucas et al. (2000) [10]	12 males (20.7±4.4) 7 females (22.0±3.1) From which 8 triathletes national and 11 swimmers regional	1500m maximal 3x200m incremental 30m maximal with wetsuit and swimsuit	25 and 50m swimm 25 – 26ºC
Gay et al. (2020) [11]	33 triathletes and open water swimmers 13 females (26.7±10.3) and 20 males (26.3±12.8)	2x400m with wetsuit and swimsuit in the swimming pool and 2x400m with wetsuit and swimsuit in the swimming flume	25m swimming and swimming f 27ºC
Hue, Benavente and Chollet (2003) [21]	12 males triathletes (23.7±3.1) national and international	800, 100 and 50m with wetsuit and swimsuit	25m swimming ---
Hatteau et al. (2007) [22]	7 males triathletes (21±4) national	3x400m maximal with swimsuit, wetsuit and tri-function suit	25m swimming 27ºC
Nicolaidis, Sousa and Knechtle, (2018) [32]	1,130 open-water ultra-distance swimmers 180 females (35.9±11.9) 950 males (40.0±10.2)	14.3km of the 'Strait of Gibraltar' since 1950 to 2018	Open water envir ---

Parsons et al. (1986) [1]	16 triathletes 14 males, 2 females (from 20 to +50) beginners to elite	2x30min swimming with sleeveless long wetsuit and swimsuit	66y (60.35m) swimr 18ºC
Perrier and Monteil (2004) [23]	8 males triathletes (24.8±3.7) National to international	2x1500m with wetsuit and swimsuit	50m swimming 26ºC
Perrier and Monteil (2002) [20]	23 swimmers (23±4.8) Regional to national	3x400m with wetsuit, sleeveless long and swimsuit	25m swimming 26ºC
Perrier and Monteil (2001) [15]	8 swimmers (23±6) regional 8 triathletes (23±4) national	3x400m maximal with full body wetsuit, sleeveless long and swimsuit	25m swimming 26ºC
Santos, Bento and Rodacki (2011) [28]	20 participants (12 males triathletes and 8 males swimmers) (22±6.6) amateur	4x400m (2 maximal and 2 submaximal, both with wetsuit and swimsuit)	25m swimming 29ºC
Tomikawa and Nomura (2009) [24]	8 males triathletes (20±1) 4 females triathletes (21±3) Total (20±1) national and international	Incremental with wetsuit and swimsuit (competitive swimsuit) in swimming flume 2x25m sprints 400m with wetsuit and swimsuit	Swimming flum 25m swimming 25.7 – 27.7º
Tomikawa et al. (2003) [25]	8 males triathletes (19.6±1.8) national and international	Incremental with wetsuit and swimsuit in swimming flume 400m with wetsuit and swimsuit	Swimming flum 25m swimming
Tomikawa, Shimoyama and Nomura (2009) [26]	9 males triathletes (21.7±3.5) 4 females triathletes (21.8±1.0) Total (21.7±2.9) national and international	Incremental with wetsuit and swimsuit (competitive swimsuit) 2x5 min with wetsuit and swimsuit (60 and 80% vVO2max)	Swimming flu ---
Toussaint et al. (1989) [6]	12 swimmers and triathletes	10x23m at constant velocity (from 1.0 to 1.8m· s^{-1}) and	25m swimming 26ºC

	(8 males and 4 females) (26.4±4.12) --	23m with wetsuit and swimsuit at 1.10, 1.25 and 1.50m· s^{-1}	
Trappe et al (1996) [12]	5 males swimmers (26.1±1.3) ---	4x5min swims at 0.9, 1.05, 1.18±0.01 and 1.31±0.02m· s^{-1} with full body, sleeveless long and short wetsuit and swimsuit	Swimming flu 26.5±1.0ºC
Trappe et al. (1995) [29]	9 triathletes and swimmers (7 males and 2 females) (31.8±4.1)	30m with wetsuit and swimsuit (competitive swimsuit)	25 yard (22.86m) swim 20.08±0.03, 22.73± 25.59±0.05º
Ulsamer et al (2014) [33]	300 swimmers in 26.4km race 284 swimmers in the 3.8km race ---	Analyse the use of wetsuit vs swimsuit in the participants of the 'Marathon Swim' and 'LOST-Race', 26.4 and 3.8km respectively	Open water enviro ---
Yamamoto et al. (1999) [31]	8 beginner swimmers (21±1)	5x7min in the swimming flume at constant velocity (0.4, 0.6, 0.8, 1.0 and 1.1m· s^{-1}) with wetsuit and swimsuit 2x400m maximal in 25m swimming pool with wetsuit and swimsuit	25m swimming po swimming flu 30ºC
Nicolau, Kozusko and Bishop (2001) [14]	9 females swimmers (19.6±1.7) University swim team	3x800m with full body, sleeveless long wetsuits and swimsuit	50m swimming 27ºC
Pavlik, Pupis and Pavlovic. (2015) [30]	4 students ---	2x100m maximal with wetsuit and swimsuit (2 times with 1 month of difference in between)	25m swimming 26ºC
Lowdon, McKenzie and Ridge (1992) [27]	12 males triathletes (28.6±6.37) International to club competitors	1500m maximal with racing swimsuit, thigh-length lycra suit and sleeveless long wetsuit	50 and 25m swimm 17 (±1.14), 21.3 (±0 (±0.23)ºC

Table 3. Summary of the studies with the different types of wetsuits and athletes (n = 23).

	Type of Wetsuit			
Athlete	**Full body wetsuit**	**Sleeveless long**	**Sleeveless short**	**Other/no info**
Swimmers	8, 9, 10, 11, 20, 15, 28, 12, 14, 30 (10)	9, 10, 20, 14, 6, 12, 29, 14 (8)	12 (1)	32, 33, 31 (3)
Triathletes	8, 10, 11, 21, 22, 23, 15, 28, 25, 26 (10)	10, 1, 15, 6, 29 (5)	-	32 (1)
Swimmers and triathletes	8, 10, 11, 15, 28 (5)	10, 15, 6, 29 (4)	-	32 (1)

Each number indicated the study reference and the total number of studies is show between parentheses.

Table 4. Wetsuit details and mean ± standard deviation (SD) of the wetsuit thickness (n = 23).

Type of Wetsuit	Thickness Upper limbs (mm)	Thickness Trunk (mm)	Thickness Lower limbs (mm)
Aqua Man® [8,21,23,20,15]	3([8,21,15]); 1.5([23]); 5([20])	5	3([8,21]); 5([23,20,15])
Scott Tinley [9]	3	3	3
Ironman® [10]	3	5	3
Personal Full body [11]	2.20 ± 0.61	2.72 ± 0.94	2.58 ± 0.81
Orca® [22]	5	5	5
Personal wetsuit [32,33]	-	-	-
Sleeveless long [1]	-	-	-
Mormaii [28]	1.5	1.5	1.5
Full body Custom-made [24,26]	2 to 3	5	2 to 3
Full body Custom-made [25]	-	-	-
Sleeveless long Aqua Man® [6]	-	-	-
Quintana Roo® [12]	3-4	3-4	3-4
Quintana Roo® [29]	-	3	4
Floating swimsuit [31]	-	-	-
Ironman® [14]	3	5 (2-3 in the back)	3
Aquaspare [30]	4	4	4
Sleeveless long Shinklow™ [27]	2	2	2
Mean ± SD	3.01 ± 1.11	3.71 ± 1.25	3.21 ± 1.03

Concerning the environment in which they performed, 25 m swimming pool was used in 15 cases (two in yards) [6,9-11,15,20-22,24,25,27-31], contrary to long course (50 m swimming pool) which was used only in six times (one in yards) [1,8,10,14,23,27]. A swimming flume was used in six cases [11,12,24-26,31] and natural environment was conducted in two cases (analysis the use of wetsuit in real competitions) [32,33]. The water temperature ranged from 21 to 30ºC on the studies selected but only in one study the water temperature was 18ºC [1] and in another it was 17ºC [27]. It could be observed that the results which reported physiological information were detail in 14 studies and with biomechanical outcomes in 20. Finally, 12 studies analyze both parameters (Tables 5 and 6).

Table 5. Biomechanical parameters related to the wetsuit improvement in the experimental conditions of the

	Distance							
Variable	**1500 m**	**800 m**	**400 m**	**100 m**	**25m (23m[6])**	**50 m**	**Incremental**	**3**
Time improved	35.18s – 3.23% [9*] 47s – 3.7% [10*] 80s – 6.5% [23*] 24.44s – 10% faster with wetsuit vs lycra swimsuit [27*] 27.34s – 10% faster with wetsuit vs swimsuit [27*]	22.3s less with full body vs swimsuit; 39.7s less with sleeveless long vs swimsuit; [14*]	Without and with full body wetsuit swimmers faster than triathletes [8*] 14.92 s – 4.96% [9*] 20.08s – 6% [11*] 37.3s – 12% [22*] 21.5s – wetsuit vs swimsuit [20] 25.4s – wetsuit vs swimsuit [20] 1..4% higher sleeveless long vs wetsuit [20] 18s – 6.4% wetsuit (maximal) vs swimsuit [28*] 6.9% wetsuit vs swimsuit [24*] 21.3s - 6.8% swimsuit vs wetsuit [25*]	14.75s – 12.9% [30*]	4.3% wetsuit vs swimsuit [24*]	-	+77.4s with wetsuit [25*] 5.4% higher with wetsuit [26*]	l we v V w 9
v (m· s^{-1})	Higher with wetsuit [10*] 1.17±0.08 without wetsuit	1.38±0.05 with wetsuit and 1.36±0.03 without wetsuit [21]	1.24±0.16 with wetsuit and 1.17±0.16 without wetsuit in swimming pool [11*]	1.63±0.08 with wetsuit and 1.61±0.07 without wetsuit [21]	1.70±0.09 with wetsuit; 1.63±0.11 without wetsuit [24*]	1.70±0.08 with wetsuit and 1.66±0.08 without wetsuit [21]	1.12±0.15 without wetsuit 1.18±0.16 with wetsuit [26*]	I v 1. v v

	1.21±0.08 with wetsuit [10*] 1.26±0.15 without wetsuit and 1.37±0.13 with wetsuit in the first 100m [23*] 1.15±0.11 without wetsuit and 1.24±0.11 with wetsuit in the last 100m [23*]	1.28±0.06 with swimsuit; 1.31±0.03 with full body; 1.36±0.07 with sleeveless long [14*]	1.30±0.09 with wetsuit and 1.16±0.07 without wetsuit [22*] 1.30±0.13 without wetsuit; 1.40±0.13 with full body wetsuit and 1.42±0.14 with sleeveless long wetsuit [20] 1.36±0.07 without wetsuit; 1.44±0.08 with wetsuit (maximal) [28*] 1.23±0.06 without wetsuit; 1.24±0.06 with wetsuit (submaximal) [28] 1.36±0.09 with wetsuit; 1.27±0.09 without wetsuit [24*] 1.30±0.16 without wetsuit; 1.39±0.14 with wetsuit [25*]					1. v
SR (Hz/strokes·min^{-1})	35.8±3.2 without wetsuit and 36.7±2.4 with wetsuit in the first 100m [23] 37.1±2.4 without wetsuit and 38.9±3.3	35.9±3.7 with wetsuit and 36.4±4.2 without wetsuit [21]	Without wetsuit higher for swimmers than triathletes [8*] With full body wetsuit equal in both [8] 0.62±0.09 with wetsuit and 0.61±0.07 without wetsuit in swimming pool [11] 0.52±0.07 with wetsuit and 0.52±0.06 without	47.2±4.7 with wetsuit and 48.3±4.2 without wetsuit [21]	-	51.5±4.2 with wetsuit and 51.9±2.7 without wetsuit [21]	Lower with wetsuit [25]	

	with wetsuit in the last 100m [23*]		wetsuit in swimming flume [11] 0.46±0.05 with wetsuit and 0.46±0.04 without wetsuit [22] 0.63±0.05 without wetsuit; 0.64±0.05 with full body wetsuit and 0.63±0.05 with sleeveless long wetsuit [20] 36.4±4.54 without wetsuit; 36.35±4.52 with wetsuit (maximal) [28] 30.65±3.7 without wetsuit; 28.20±3.70 with wetsuit (submaximal) [28*] 34.7±1.7 with wetsuit; 33.9±1.6 without wetsuit [24*] Higher with wetsuit [25*]					
SL (m)	2.12±0.2 without wetsuit and 2.24±0.19 with wetsuit in the first 100m [23*] 1.87±0.23 without wetsuit and 1.93±0.24 with wetsuit in the last 100m [23*]	2.34±0.2 with wetsuit and 2.27±0.2 without wetsuit [21] Equal in conditions [14]	1.84±0.23 with wetsuit and 1.76±0.20 without wetsuit in swimming pool [11*] 2.48±0.45 with wetsuit and 2.30±0.32 without wetsuit in swimming flume [11*] 1.24±0.11 with wetsuit and 1.14±0.11 without wetsuit [22*] 1.93±0.91 without wetsuit; 2.07±0.29 with full body wetsuit and	2.09±0.2 with wetsuit and 2.02±0.2 without wetsuit [21*]	-	1.99±0.1 with wetsuit and 1.93±0.1 without wetsuit [21*]	-	v v a w 9

			2.12±0.23 with sleeveless long wetsuit [20] 2.27±0.26 without wetsuit; 2.39±0.27 with wetsuit (maximal) [28*] 2.46±0.28 without wetsuit; 2.69±0.28 with wetsuit (submaximal) [28*] 2.32±0.21 with wetsuit; 2.27±0.20 without wetsuit [24*] Higher with wetsuit [25*]				
SI ($m^2 \cdot s^{-1}$)	2.69±0.5 without wetsuit and 3.07±0.5 with wetsuit in the first 100m [23*] 2.16±0.45 without wetsuit and 2.40±0.49 with wetsuit in the last 100m [23*]	3.25±0.3 with wetsuit and 3.09±0.4 without wetsuit [21*] Equal in conditions [14]	2.10±0.47 with wetsuit and 1.90±0.40 without wetsuit in swimming pool [11*] 3.22±0.91 with wetsuit and 2.78±0.67 without wetsuit in swimming flume [11*] 3.09±0.41 without wetsuit; 3.51±0.41 with wetsuit (maximal) [28*] 3.05±0.41 without wetsuit; 3.34±0.49 with wetsuit (submaximal) [28*]	3.43±0.4 with wetsuit and 3.26±0.4 without wetsuit [21*]	-	3.40±0.3 with wetsuit and 3.21±0.3 without wetsuit [21*]	-
ηp (%)	-	-	40.00±7.51 with wetsuit and 40.63±6.25 without wetsuit in swimming pool [11] 52.41±11.16 with wetsuit and 51.56±11.30 without wetsuit in swimming flume [11]	-	-	-	-

IdC	-17.7±8 without wetsuit and -20.6±6 with wetsuit in the first 100m [23] -12.6±8 without wetsuit and -18.4±1 with wetsuit in the last 100m [23]	-11.7±3.7 with wetsuit and -9.6±3.8 without wetsuit [21*]	-	-7.2±3.7 with wetsuit and -5.1±4.4 without wetsuit [21]	-	-5.7±4.5 with wetsuit and -5.6±5.2 without wetsuit [21]	-	
Active Drag (N)	-	-	-	-	79.1±18.1 with wetsuit; 79.4±23.8 without wetsuit [24] 32.9±6.7 without wetsuit; 27.7±6.9 with wetsuit at 1.1 $m\cdot s^{-1}$ (16%) [6*] 48.7±9.5 without wetsuit; 41.8±9.3 with wetsuit at 1.25 $m\cdot s^{-1}$ (14%) [6*] 73.3±13.9 without wetsuit; 64.3±12.9 with wetsuit at 1.5 $m\cdot s^{-1}$ (12%) [6*]	-	-	4 v v 5 w
Passive Drag (N)	-	-	Without wetsuit lower for swimmers than triathletes [8*] With full body wetsuit equal in both [8]	-	0.34±0.05 with wetsuit; 0.37±0.08 without wetsuit [24]	-	-	(v v (w

PO$_{max}$ (W)	-	-	-	-	135.6±36.9 with wetsuit; 131.2±46.2 without wetsuit [24]	-	-
F$_d$ (N)	-	-	-	-	27.2±5.4 without wetsuit; 22.9±5.7 with wetsuit at 1.1 $m \cdot s^{-1}$ [6]* 31.2±6.1 without wetsuit; 26.8±6.0 with wetsuit at 1.25 $m \cdot s^{-1}$ [6]* 32.6±6.2 without wetsuit; 28.5±6.1 with wetsuit at 1.5 $m \cdot s^{-1}$ [6]*	-	-

Swimming speed (v), stroke rate, length and index (SR, SL and SI), propelling efficiency (ηp), index of coordination (IdC), power output (PO$_{max}$) and relation be between conditions.

Table 6. Physiological parameters related to the wetsuit improvement in the experimental conditions of the st

	Distance						Time	
Variable	**1500m**	**800 m**	**400 m**	**100 m**	**Incremental**	**30 min**	**2x5 min**	**4x**
$\dot{V}O_{2max}$ (mL · kg^{-1}· min^{-1}/ l/min^{-1})	-	-	Without wetsuit higher for swimmers than triathletes [8*] With full body wetsuit equal in both [8]	-	59.8±5.0 with wetsuit; 58.7±3.6 without wetsuit [24] 3.83±0.24 without wetsuit; 4.0±0.50 with wetsuit [25] 3.33±0.60 without wetsuit; 3.0±0.60 with wetsuit [26] -	2.75±0.21 with swimsuit; 2.72±0.23 with wetsuit at 20.1ºC [29] 2.96±0.24 with swimsuit; 2.95±0.21 with wetsuit at 22.7ºC [29] 2.89±0.22 with swimsuit; 2.84±0.19 with wetsuit at 25.6ºC [29]	-	0. 1. 1. 2.
v$\dot{V}O_{2max}$ (m· s^{-1})	-	-	-	-	1.24±0.07 with wetsuit; 1.17±0.08 without wetsuit [24*]	-	-	
$\dot{V}E$ (l/min^{-1})	-	-	-	-	-	-	-	3

								4 5 6
[La⁻]peak (mmol·l⁻¹)	-	-	Without wetsuit higher for swimmers than triathletes [8*] With full body wetsuit equal in both [8] 8.05±2.55 with wetsuit and 8.89±2.86 without wetsuit in swimming pool [11] 5.82±3.23 with wetsuit and 5.94±2.99 without wetsuit in swimming flume [11] 8.8±2.2 without wetsuit;	-	7.6±1.5 with wetsuit; 7.1±1.4 without wetsuit [24] 8.3±2.0 without wetsuit; 8.6±2.3 with wetsuit [25] 7.21±1.48 without wetsuit; 7.36±1.57 with wetsuit [26]	7.15±0.55 with swimsuit; 6.57±0.73 with wetsuit at 20.1ºC [29] 7.21±0.94 with swimsuit; 6.18±0.76 with wetsuit at 22.7ºC [29] 6.50±0.70 with swimsuit; 5.55±0.69 with wetsuit at 25.6ºC [29]	2.18±0.59 with wetsuit; 2.46±0.88 without wetsuit at 60% vVO2max [26] 4.7±1.5 with wetsuit; 4.31±1.38 without wetsuit at 80% vVO2max [26]	

			8.8±2.79 with wetsuit (maximal) [28] 5.3±1.65 without wetsuit; 3.8±1.21 with wetsuit (submaximal) [28*] 9.2±1.3 with wetsuit; 8.0±1.0 without wetsuit [24*] 8.8±1.1 without wetsuit; 10.1±1.6 with wetsuit [25*]					
RPE (0-10 scale/6-20 scale)	-	Equal in conditions [14]	7.91±1.23 with wetsuit and 7.88±0.86 without wetsuit in swimming pool [11] 6.36±1.66 with wetsuit and 6.33±1.68 without wetsuit in swimming flume [11] 17.5±2 without	-	-	Similar in 3 conditions [29]	12±1 with wetsuit; 12±1 without wetsuit at 60% vVO2max [26] 15±2 with wetsuit; 15±1 without wetsuit at 80% vVO2max [26]	7 sh 9 sh 11

			wetsuit; 17.3±1.7 with full body wetsuit and 17±2.2 with sleeveless long wetsuit [20] 17.1±1.71 without wetsuit; 17.1±1.59 with wetsuit (maximal) [28] 12.2±2.12 without wetsuit; 10.75±1.88 with wetsuit (submaximal) [28*] 17.4±1.2 without wetsuit; 17.6±0.7 with wetsuit [25]					
HR_{max} (beats·min^{-1})	Higher in 21.3 vs 17ºC [27*] Higher in 29.5 vs 17ºC [27*] Higher with wetsuit vs lycra suit [27*]	Equal in conditions [14]	179.50±11.96 with wetsuit and 175.80±13.78 without wetsuit in swimming pool [11] 166.76±15.77 with wetsuit and 167.52±14.80 without	2 subject higher with wetsuit and 2 lower with wetsuit [30]	-	Similar in 3 conditions [29]	-	9 s s

			wetsuit in swimming flume [11] 177±11 without wetsuit; 179±8 with full body wetsuit and 177±10 with sleeveless long wetsuit [20] 172±11.13 without wetsuit; 169.±17.14 with wetsuit (maximal) [28] 149±17.96 without wetsuit; 134±19.45 with wetsuit (submaximal) [28*] Lower with wetsuit [31*]					s
RER	-	-	-	-	-	-	-	0 0

								0 0
C (kJ · m^{-1} / ml · kg^{-1}· min^{-1})	-	-	Without wetsuit lower for swimmers than triathletes [8*] With full body wetsuit lower for swimmers than triathletes [8*]	-	-	-	41±9 with wetsuit; 48±12 without wetsuit (14.4%)at 60% vVO2max [26*] 47±9 with wetsuit; 51±10 without wetsuit (7.5%) at 80% vVO2max [26*]	
T_C	Lower in 17 vs 29.5ºC [27*] Lower in 21.3 vs 29.5ºC [27*] Lower in 17 vs 21.3ºC [27*] Higher with wetsuit vs swimsuit [27*] Higher with wetsuit vs lycra suit [27*]	-	-	-	-	38.01±0.28 with swimsuit; 38.17±0.23 with wetsuit at 20.1ºC [29] 38.04±0.26 with swimsuit; 38.65±0.17 with wetsuit at 22.7ºC [29*] 38.68±0.21 with swimsuit; 38.67±0.21 with wetsuit at 25.6ºC [29*]	-	

T_t	Lower in 17 vs 29.5ºC [27*] Lower in 21.3 vs 29.5ºC [27*] Lower in 17 vs 21.3ºC [27*]	-	-	-	-	20.58 with swimsuit; 24.96±0.28 with wetsuit at 20.1ºC [29*] 23.17 with swimsuit; 26.92±0.51 with wetsuit at 22.7ºC [29*] 26.08 with swimsuit; 29.12±0.44 with wetsuit at 25.6ºC [29*]	-
T_R	Higher in 29.5 vs 21.3ºC [27*] Higher in 21.3 vs 17ºC [27*] Higher in 29.5 vs 17ºC [27*] Higher with wetsuit vs swimsuit [27*] Higher with wetsuit vs lycra suit [27*]	-	-	-	-	-	-

Maximal oxygen consumption ($\dot{V}O_{2max}$), velocity at maximal oxygen consumption ($v\dot{V}O_{2max}$), ventilation ($\dot{V}E$), peak blood lactate concentrations ([La-]peak), Bor
heart rate (HR_{max}), respiratory exchange ratio (RER), energy cost (C), core temperature (Tc), trunk temperature (T_t), rectal temperature (T_R). *Differences betwe

The improvements while using wetsuits

The use of full body wetsuit is the more studied (Table 2) and the results showed an improvement in performance compared to swimsuit and other type of wetsuit (20 of the 23 studies included), with an increment from 3.23 to 12.9% in front crawl swimming performance in different distances from 25 to 1500 m, incremental tests, continuous swimming of 5 and 30 min and in open water swimming events. The sleeveless long wetsuit also induced a performance increment as it is showed in 400 and 800 m compared to full body wetsuit and swimsuit [14,15,20] (Table 5). Related to biomechanical aspects, the higher values were found in stroke rate (SR) [24-26] and higher stroke length (SL) [11,21-25,28] while using full body wetsuit compared to swimsuit and also higher values of these variables while using sleeveless long wetsuit compared to swimsuit [29]. Accordingly, stroke index (SI) also was higher with full body wetsuit compared to swimsuit [11,21,23,28]. Related to active drag, only one study showed lower values with sleeveless long wetsuit compared to wetsuit and also lower values in the relation between drag and swimming velocity (F_d) [6].

Related to the effect in physiology (Table 6), maximal oxygen consumption ($\dot{V}O_{2peak}$) was higher only in swimmers while using wetsuit in 400 m test compared to swimsuit [8]. Different values were found at different velocities and between full body wetsuit and swimsuit on 4 x 5 min swim with full body, sleeveless long and short wetsuits [12] and also in 5 x 7 min swims with full body wetsuit [31], both in the swimming flume. Only three studies showed differencies in peak blood lactate concentrations ($[La\text{-}]_{peak}$), being lower with full body wetsuit compared to swimsuit [8,24,28] but in only in one case the results were higher using full body wetsuit [25]. Related to heart rate (HR), two studies showed differences, in two cases lower with full body wetsuit than with swimsuit [28,31] and in one case, it was higher compared to swimsuit [27]. C was measured only in two of the studies, which showed lower values while wearing full body wetsuit [8,26] comparing with swimsuit. Finally, concerning corporal temperature, the studies showed differences between sleeveless long wetsuit and swimsuit in different temperatures (ranged from 17 to 29.5º) and during long swim (30 min) [27,29] (Table 6).

Swimmers vs triathletes using wetsuit

From the total sample of 23 studies, only two studies distinguished between swimmers and triathletes [8,15]. The details for swimmers and triathletes are shown in the Tables 5.1 and 6.1 (about biomechanical and physiological parameters, respectively). Swimmers performed lower time with full body wetsuit than triathletes [8]. In addition, swimmers were also faster with full body wetsuit compared to triathletes but no differences were found between swimmers and triathletes in Borg rating of perceived exertion (RPE), $[La-]_{peak}$ nor SR [8]. In addition, results showed higher values in velocity, SR and SL with sleeveless long wetsuit for swimmers and triathletes compared to full body wetsuit and swimsuit [15] (Table 5.1).

Table 5.1. Biomechanical parameters comparisons for swimmers and triathletes individually.

	Swimmers	Triathletes
Variable	**400 m**	**400 m**
Time improved	253.9±8.0 without wetsuit 252.5±4.5 with full body wetsuit [8] 17.2s - 6.3% swimsuit vs full body wetsuit [15*] 22.9s - 8.5% swimsuit vs sleeveless long wetsuit [15*]	19s less with wetsuit, 304.8 ± 30.1 without wetsuit 285.8 ± 33.9 with full body wetsuit, 6% faster with wetsuit [8*] 23.8s - 8.5% swimsuit vs full body wetsuit [15*] 26.3s - 9.5% swimsuit vs sleeveless long wetsuit [15*]
v (m· s^{-1})	1.38±0.04 without wetsuit; 1.46±0.04 with full body wetsuit and 1.50±0.06 with sleeveless long wetsuit [15*]	1.32±0.07 without wetsuit; 1.43±0.06 with full body wetsuit and 1.44±0.08 with sleeveless long wetsuit [15*]
SR (Hz)	No differences [8] 0.62±0.03 without wetsuit; 0.63±0.05 with full body wetsuit and 0.62±0.03 with sleeveless long wetsuit [15*]	40.3 ± 1.2 without wetsuit 42.3 ± 1.4 with full body wetsuit [2*] 0.64±0.04 without wetsuit; 0.66±0.04 with full body wetsuit and 0.66±0.03 with sleeveless long wetsuit [15*]
SL (m)	2.01±0.09 without wetsuit; 2.14±0.08 with-full body wetsuit and 2.27±0.14 with sleeveless long wetsuit [15*]	1.88±0.15 without wetsuit; 2.04±0.21 with full body wetsuit and 2.05±0.14 with sleeveless long wetsuit [15*]
Passive Drag (N)	No differences [8]	Lower with wetsuit [8*]

Swimming speed (v), stroke rate, length and index (SR, SL and SI). *Differences between conditions.

Table 6.1. Physiological parameters comparisons for swimmers and triathletes individually.

	Swimmers	Triathletes
Variable	**400 m**	**400 m**
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	5.3 ± 0.4 without wetsuit 4.9 ± 0.3 with full body wetsuit [8*]	No differences [8]
$[La^-]_{peak}$ ($mmol \cdot l^{-1}$)	12.3 ± 1.5 without wetsuit 10.9 ± 2.1 with full body wetsuit [8*]	No differences [8]
RPE	17.3±2 without wetsuit; 17.5±1.6 with full body wetsuit and 17.1±1.4 with sleeveless long wetsuit [15]	16.9±1.5 without wetsuit; 17.2±1.1 with full body wetsuit and 17.6±1 with sleeveless long wetsuit [15]
HR_{max} ($beats \cdot min^{-1}$)	179±11 without wetsuit; 179±9 with full body wetsuit and 179±10 with sleeveless long wetsuit [15]	177±12 without wetsuit; 180±8 with full body wetsuit and 180±9 with sleeveless long wetsuit [15]
C ($kJ \cdot m^{-1}$)	No differences [8]	Lower with wetsuit [8*]

Maximal oxygen consumption ($\dot{V}O_{2max}$), peak blood lactate concentrations ([La-]peak), Borg rating of perceived exertion scale (RPE), maximal heart rate (HR_{max}), energy cost (C). *Differences between conditions.

Discussion

The investigation about the use of wetsuit is quite diverse, including researches form the medical perspective with the use or the design of different regeneration devices, variety of sports as diving or surfing, and swimming performance as competitive discipline in open water swimming and triathlon. Thus, the aim of the present systematic review was to clarify the effects of wearing wetsuit on front crawl swimming performance in different distances and environment (swimming pool, flume and in open water). Form the total sample studied, the main funding was that the use of full body wetsuit produce an increment from 3.23 to 12.9% in front crawl swimming performance in distances from 25 to 1500 m, incremental tests, continuous swimming of 5 and 30 min and in open water swimming events. Furthermore, sleeveless long wetsuit also produce a performance advantages in comparison with full body wetsuit [14,15,20].

Effect of wetsuit on swimming time performance related to the body cover

The importance in thermoregulation of the wetsuit depends on its composition and structure as discussed above, also wetsuits with thickness from higher than 4 mm presented better hydrophobic properties. In turn, the more body surface area covered by the wetsuit, the greater the thermal properties [13]. In this regard, it is understandable that higher body cover wetsuit (i.e., full body wetsuit) induce to higher biomechanical changes, as reported [14,15]. The results of the present review detail the variables modified by using wetsuits and it can be observed how the full body wetsuit (the more study suit), produce changes in the most of biomechanics and physiological parameters comparing with swimsuit. On average, higher values of SR, SL and SI are obtained while using full body wetsuit, lower values of C, [La-] and HR_{max}. Thus, these results induce to the improvement in swimming velocity.

However, the sleeveless long wetsuit was seen to benefit more to swimmers than triathletes [14,15], which might be due to the swimming skills of the athletes as discusses below. This kind of wetsuit is gaining popularity for the comfort provide in the shoulder movement in open water swimming and triathlon competitions as swimmers reported [14], so further research are needed in this context. Lastly, information about sleeveless short is scarce with only one study included in this review [12] which report the higher values of $\dot{V}O_{2max}$ and ventilation ($\dot{V}E$) with the sleeveless short wetsuit compared to sleeveless long and full body wetsuit in four different velocities (ranged from 0.9 to 1.31 m· s^{-1}).

Swimmers vs triathletes

Chartard et al., was the first to compare the swimming agility level between competitive swimmers and triathletes [8]. He reported that full body wetsuit improves performance in inefficient swimmers (triathletes) but the wetsuit also generates more benefit in swimmers than in triathletes, showing also lower C values. In addition, without wetsuit, $\dot{V}O_{2max}$, [La-] and SR were higher with lower C and passive drag for swimmers compared to triathletes. The lower hydrodynamic lift showed in the triathletes compared to the swimmers justify the technical abilities of swimming (i.e., poor horizontal position), producing higher hydrodynamic drag and, as a consequence lower buoyancy [6,7]. Moreover, the neoprene fabrics properties, increase buoyancy due to the composition of synthetic rubber [13], it could be the reason why the wetsuit benefit triathletes more than swimmers due to the better hydrodynamic position caused by the higher technical ability.

Few years later, another study showed data of swimmers and triathletes but it does not compared between groups [15]. These authors confirmed the previous research [8], explaining that swimmers with lower hydrodynamic lift (< 10 N) and weak swimming speed (< 1.30 $m \cdot s^{-1}$) improve swimming performance more with the use of wetsuit. Furthermore, using sleeveless wetsuit, the more experienced swimmer will reach better performance than with full body wetsuit, which related to the discomfort of wearing wetsuit due to shoulder movement limitations and also with the shoulder overload related to the increase in SR. Using full body wetsuit, the improvement in performance was associated to the increase in velocity (7.1 and 11.3% for swimmers and triathletes respectively) and SL (6.4 and 8.4% for swimmers and triathletes respectively). Contrary to the use of sleeveless long wetsuit which increase 11.8% in velocity for swimmers compared to swimsuit. As it can be observed, from the total studies included in this review, only one study compare between swimmers and triathletes, so it should be more explore due to the technical differences in practical abilities on swimming which determine the effect on swimming performance for swimmer or triathletes.

Biomechanical parameters influenced by the wetsuit use

The use of wetsuit influence swimming technique as demonstrated [8,11,22,24,25,28] with, in general, higher values with the use of wetsuit on SR and SL and, as a consequence in SI. Swimmers who generally swim with higher SL will benefit more using sleeveless long wetsuit than full body wetsuit [15]. This is related to the ability to use wetsuit and the frequency of use because of the adaptation to it. Indeed, the more horizontal position adapted by the use of wetsuit due to the buoyancy of the suit, more reduction of the hydrodynamic drag and increment of the efficiency in the propulsive phases [21]. Thus, at higher SL with wetsuit, the magnitude of propulsive forces might be higher. This could be also related to the thickness, as it is shown on the Table 4, the wetsuits studied have ~3.31 mm of thickness on average which might facilitate the adaptation to it, especially for swimmers who are more skilled as discussed above.

Focus on efficiency, ηp was calculated only in one study [11] and no differences were found between full body wetsuit and swimsuit in both swimming pool and flume, although authors showed higher values while using full body wetsuit on SL and SI which might be the responsible of the higher velocity reached on 400 m front crawl [11]. The scarce information about this variable, induce that it should be consider for future analysis while using wetsuit because as a determinant of C might determine the model or type of wetsuit which better fit the swimmer or triathlete [7]. Related to the index of coordination (IdC), only in two studies of the present review analysed it, on 1500 m front crawl with no differences found between full body wetsuit and swimsuit [23]. However, when studied 50, 100 and 800 m front crawl [21], were observed lower values while using wetsuit only on 800 m in catch-up coordination. This results suggest that adaptation exist to the wetsuit, however, the information is scarce and more data is necessary to conclude, which might be useful for training purposes.

Physiological parameters influenced by the wetsuit use

Maximal oxygen consumption ($\dot{V}O_{2max}$) as a determinant of maximal metabolic aerobic performance capability [34], is a crucial variable to analyse in triathletes and open water swimmers performing with or without wetsuit. From the total sample, seven studies analyzed $\dot{V}O_{2max}$ in different trials, where it was found lower values for swimmers while using full body wetsuit on 400 m [8], also lower with full body, sleeveless long and short wetsuit while performing 4 x 5 min swims (and also ventilation, ($\dot{V}E$)) [12] and lower with wetsuit in 5 x 7 min swims in the swimming flume [31], all compared to swimsuit (Table 6). The result suggest that the use of wetsuit reduce the energy requirements in these distances. Furthermore, it is important to highlight that, although it was study only in one article, the velocity to the maximal oxygen consumption ($v\dot{V}O_{2max}$) was higher with wetsuit with equal $\dot{V}O_{2max}$ [24], another reason that justifies the advantages of wetsuit in swimming performance. The first study which detailed the $\dot{V}O_2$ kinetics, E and C in open water swimming condition while using wetsuit did not studied the effect of wetsuit because the swimming speed was not controlled but the lower C values observed during 5 km in open water might been affected by the wetsuit use [37].

Higher and lower values of blood lactate concentrations ([La-]) were observed while using wetsuits (see Table 6) for swimming 400 m front crawl comparing to swimsuit [24,25,28]. Similar results were found in maximal heart rate (HR_{max}) [27,28,31], with higher values on 1500 m but lower on 400 m and on 5 x 7 min swims compared to swimsuit. These inconsistent results could be influenced by the fact that the wetsuit produce a compression in the body which could modified the results [35]. Indeed, although a lower [La-] and HR is expected while using wetsuit due to the reduction on energy requirements as was discussed above, it is no clear because the corporal temperature is affected by the suit and it will depend mainly on the water temperature which might produce higher physiological responses at higher water temperatures, thus the results might be altered easily. Furthermore, in relation with the RPE, as a subjective indicator, might show useful information to know the personal comfort of the swimmer while using the wetsuit and for training purposes. Only in two cases of the sample from the present review were found lower values with wetsuit compared to swimsuit [12,28] which might explain the discomfort of using wetsuit or the higher effort perceived as a consequence of the higher velocity reach by the wetsuit.

Energy cost of swimming and Drag

The reduction in drag force induce the reduction in C, besides the higher swimming speeds might be sustained by a swimmer with elevated ηp and low hydrodynamic drag (i.e., low C), as it occurs while using wetsuit [36]. Only few studies included in the present review analyse C. However, the one which measured passive drag with lower values found with wetsuit compared to swimsuit for triathletes, obtained also lower C in the same trial [8]. This is in accordance with affirmation of lower hydrodynamic lift swimmers use full body wetsuit [8,15], because this full suit might provide more benefits to that swimmers reducing their higher drag and C. The lower values found on active drag and the lower relation between drag and swimming velocity (F_d) with the use of full body wetsuit on short trials of 23 m also confirm the improvement in efficiency, probably due to the increase in ηp [6]. As it was recently studied, to achieve the desired kinematic swimming fluctuations for 5 km (mainly in velocity and SR), changes are needed at total energy expenditure (E), which affect $\dot{V}O_2$, HR and [La-] [37], thus it might be influenced by the ability to use wetsuit, an important key to introduce in the daily training. In the measurement of active drag, it is important to consider that the measurement of active drag (MAD) system induces an increase in stroke efficiency but, in turn, requires mechanical adaptations (due to the placement of the paddles) which leads to a reduction in SR and an increase in SL besides the measurement is limited to the arm pull forces [38,39].

Another predictor and influencer of C is intracycle velocity variations as it describes the speed fluctuations resulting from changes in drag during an arm stroke. However, this has not been measured in any of the selected studies in this sample, so it might be interesting to measure with and without wetsuit because those changes in the swimming speed, produces changes in the hydrodynamic resistance (composed by: form, friction and wave drag) and in consequence the energy expenditure E will also change [7]. In this context, the speed reached on 400 m front crawl is the minimum velocity that elicits $\dot{V}O_{2max}$ [7], indeed it strengthens the use of this protocol is commonly used in the studies of this sample [8,9,11, 22, 20, 15, 28, 24, 25, 31].

As higher taller swimmer, lower wave drag, so the velocity will increase and leg sinking torque will be reduced (as the parameter related to the static position the body assumes when immersed in water) and thus, lower C values. Thus, as wetsuit reduced leg sinking torque, higher hydrodynamic drag will be reached as a consequence of lower C [7]. Also, the wetsuit use might reduce the local fatigue, which is associated with the increase in velocity and, as a result lower C [39]. That is another advantage of the use of wetsuit which might be in consideration for open water swimming competitions

Core temperature and cold water

The importance to avoid hypothermia during competitions induce to study the minimum temperature in which the use of wetsuit should be determinant, being mandatory it use when the water temperature is below 16ºC as ITU rules stablish from January 2017 (see Table 1A and B, **Chapter 1**) [5]. In that context, the studies about the wetsuit use, should focus on the temperatures which simulated the real competitions because the normal water temperature in indoor pools (~26ºC) are no the real scenario in open water swimming events. The selected studies in the present review, only two of them were performed on cooler temperatures, at 18ºC [1] were triathletes swam 7% faster with sleeveless long wetsuit compared to swimsuit and at 17ºC [27] in which triathletes swam 10% faster with sleeveless long wetsuit compared to lycra swimsuit and swimsuit. Also, HR_{max} was lower in 17ºC compared to warmer temperatures, contrary to core, trunk and rectal temperatures which were lower at 17ºC [27]. But as recently studied, swimming 400 m front crawl with swim and wetsuit at 18ºC does not induce physiologic and biomechanical disadvantages comparing to 26ºC, the use of wetsuit increase performance at 18ºC water temperature, thus its use is recommended in open water swimming competitions when the water temperature is 18-20ºC [40].

These results suggest that using wetsuit increase corporal temperature as the same time that increase water temperature and also at the same time that HR_{max}, so it does not produce cold-shock response, where lower beats are shown. Important to highlight, the use of tight wetsuit produces an increase in the compression forces that induce an increase in venous return. Thus, the use of wetsuit is consider as risk factor of swimming performance as it is cold water swimming [35]. For that reason, the high temperatures (more than 20ºC in open water swimming or higher and equal of 24.6ºC in triathlon event) probably should not be consider for studies with practical applications in training and/or competitive purposes. More studies are need in this context as the brief study where a full body wetsuit Speedo Thinswim® was study at 18ºC [41], temperature in which the use of wetsuit is optional according to FINA rules. Although the values found were similar, the higher value of ηp using wetsuit could be due to the reduction on hydrodynamic drag as discussed above.

Limitations of the Study

The limitations observed in the present systematic review were: (i) a limited number of studies and most of the them with poor samples size; (ii) heterogeneity in the samples used, with different swimming levels and high range of age; (iii) different performance methods used in the studies due to the different competitive distances in which the use of wetsuit is allowed; (iv) lack of physiology information analyzed, probably due to the complex equipment required in the water environment; (v) deficiency of studies in cooler water temperatures were the use of wetsuit is optional according to FINA and ITU rules (see Table 1A and B, **Chapter 1**); and (vi) the studies developed on short and long course swimming pool and swimming flume which are not real competition environment.

Conclusions

According to the results observed in the systematic review, the biomechanics and physiological changes produced by the wetsuit use induce to the increase in swimming speed when wearing the full body, sleeveless long and short wetsuits, compared to use swimsuit. This enhancement is reached thanks to the buoyancy increment and the hydrodynamic drag reduction while swimming with wetsuit. Indeed, the technical adaptations are determinant to swim with less energy requirement while using wetsuit and it might result in the improvement in swimming performance.

The findings of the present systematic review provide useful information for coaches, swimmers and triathletes about the use of full body, sleeveless long and short wetsuits. The three models improve swimming performance compared to swimsuit on different swimming distances and water environments. Interesting to highlight that in 15 of the studies included, it was use the same brand and model of wetsuit for the participants, which might reflect the specific characteristics of a concrete wetsuit but, in the other side, the actual brands more used in open water swimming and triathlon competitions are probably not the ones use in these estudies (e.g., Arena® or Speedo®) [37,39]. Thus, the information provided by the rest of the studies which use personal wetsuit also might be interesting for an overview of its improvements and might be apply to different level of swimmers and triathletes. In addition, more studies are necessary to compare the effect of wetsuit on different skilled swimmers and/or triathletes which might be useful for training.

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CHAPTER 4: Is swimmers´ performance influenced by wetsuit use?

CHAPTER 4: Is swimmers´ performance influenced by wetsuit use?

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Abstract

Purpose: The aim of the current study was to observe the changes in performance, physiological and general kinematical variables induced by the wetsuit vs swimsuit use in both swimming pool and swimming flume conditions. Methods: Following a randomized and counterbalanced order, 33 swimmers (26.46 ± 11.72 years old) performed 2 x 400 m maximal front crawl in a 25 m swimming pool (with wetsuit and swimsuit) and its mean velocities were used afterwards in two swimming flume trials with both suits. Velocity, blood lactate concentrations ([La-]), heart rate (HR), Borg scale (RPE), stroke rate (SR), stroke length (SL), stroke index (SI) and propelling efficiency (ηp) were evaluated. Results: Swimming pool 400 m performance was 0.07 $m \cdot s^{-1}$ faster when using the wetsuit than swimsuit, evidencing a reduction of ~6% in time performed ($p < 0.001$). HR_{max}, $[La-]_{max}$, RPE, SR and ηp were similar when using both swimsuits but SL and SI presented higher values with the wetsuit both in swimming pool and swimming flume. Comparing swimming conditions, HR_{max} and $[La-]_{max}$ were lower, and SL, SI and ηp were higher, while swimming in the flume than in the pool both with wet and swimsuit. Conclusions: The 6% velocity improvement was the result of an increase of 4% in SL. Swimmers reduced SR and increased SL to benefit from the hydrodynamic reduction of the wetsuit and increase the swimming efficiency. The wetsuit might be utilized during the training seasons to improve the adaptations while swimming.

Keywords: Swimming flume, open water, triathlon, propelling efficiency, front crawl.

Introduction

In triathlon and open water swimming official events it is permitted to compete using a wetsuit depending on water temperature, swimming length and age-group (to prevent hypothermia) [1]. Previous research on wetsuit effect focused on performance improvement due to increased buoyancy, which is closely related to lower hydrodynamic body drag [2]. Moreover, wetsuit use reduces hydrodynamic resistance, raising the gliding length and decreasing the energy cost in inefficient swimmers with low buoyancy [3]. In fact, it seems that when wearing a wetsuit there is a reduction in body drag, improving the 400 and

1500 m, and the 30 min, front crawl performances [4-6]. This is especially important as the 400 m distance is well related with the intensities corresponding to the time to exhaustion at the minimum velocity that elicits maximal oxygen consumption ($\dot{V}O_{2max}$) [7] and to the critical velocity [8], both frequently used as index of aerobic performance [9].

Open water swimming events with and without wetsuit could be replicated by using a swimming flume. It was observed that the use of a full body wetsuit (covering both upper and lower limbs until the ankles) leads to lower $\dot{V}O_2$ and heart rate (HR) values comparing to long wetsuit (covering trunk and lower limbs until the ankles) and to short wetsuit (covering trunk and lower limbs until the knees) [10], eventually implying lower energy expenditure due to the modified physiological variables ($\dot{V}O_2$ and HR). The wetsuit use also leaded to biomechanical changes in swimming pool, particularly an increase of the stroke rate (SR) and the stroke length (SL) in a 1500 m front crawl time-trial [11]. However, none of the previously referred studies analyzed propelling efficiency (ηp, the ratio of the useful power – the used to overcome drag – to the total power output), one of the major determinants of swimming energy cost [12].

When swimming in a flume, a specific pace is maintained constant during the entire effort, by contrast with what happens in a swimming pool, where swimmers might change speed due to a number of constraints (as fatigue [13]). As a result, changes in the swimming technique are produced while performing in the swimming flume. Furthermore, evaluating swimmers technique is easier in the swimming flume than in the swimming pool particularly because in this latter swimmers are propelling themselves along the pool [13,14]. Therefore, an accurate measurement of the wetsuit effect in both swimming conditions might be relevant to increase the efficiency of triathletes and open water swimmers training process.

In the current study, changes in performance, physiologic and general kinematic variables were analyzed when using a wetsuit, both in swimming pool and in swimming flume conditions. It was hypothesized that using a wetsuit would enhance the 400 m front crawl performance, reduce physiological responses and increase swimming efficiency. Complementarily, lower physiological and higher technical variables values were expected with performance in the swimming flume compared with performance in the swimming pool, evidencing a more economic effort.

Methods

Participants

Thirty-three triathletes and open water swimmers (13 females and 20 males) voluntarily participated in the current study. Female and male physical characteristics were 26.69 ± 10.34 vs 26.3 ± 12.8 years old, 165.15 ± 6.12 vs 175.86 ± 7.47 m of height, 58.45 ± 7.55 vs 72.78 ± 9.98 kg of body mass and 15.04 ± 3.22 vs 13.92 ± 2.46% of body fat. Swimmers were engaged in a six to seven weekly training frequency and had 76.15 ± 10.39% for the 100 m front crawl as personal best. Participants or parents (when the subjects were under 18 years old) provided a written informed consent to participate and the Institutional Ethical Review Board approved the study design (which has been performed according to the Code of Ethics of the World Medical Association - Declaration of Helsinki).

Design

Two 400 m front crawl time-trials, using full body wetsuit (thickness of 2.20 ± 0.61, 2.72 ± 0.94 and 2.58 ± 0.81 mm in upper limbs, trunk and lower limbs, respectively) and swimsuit, were performed in a 25 m swimming pool (with in-water starts and 48 h rest in-between). Afterwards, the corresponding 400 m velocities and time durations were used in two trials (with wetsuit and swimsuit) in a swimming flume. As the swimming flume had a pre-defined velocity range, 400 m trials mean velocities were adjusted to the closest one available so swimmers could perform at the same pace than in the swimming pool. An individual warm-up of 15 min of low to moderate intensity followed by 10 min of passive rest was always performed before testing [15], and conditions were randomly and counterbalanced performed both between trials and vestment conditions. Participants had previous experience in swimming in the flume and abstained taking caffeinated drinks and practicing exhausting exercise before the experiments.

Methodology

A Panasonic (Full-HD HX-A500, Osaka, Japan) 50 Hz underwater camera recorded the sagittal plan of the swimmers displacement at the center of both pools (12.50 and 2.35 m in the swimming pool and flume, respectively). Pre-calibrated spaces 5 and 1 m long situated in the center of the swimming pool and flume (respectively) were used for video analysis, and reference points were drawn at the participants' shoulders, hips and wrists for technical variables determination. The swimming flume (Endless Pool Elite Techno Jet Swim 7.5 HP, Aston PA, USA) was 2.4 x 4.7 m of length, with flow velocity being measured at 0.30 cm depth using an FP101 flow probe (Global Water, Gold River, CA) [16]. The water temperature was set at 27ºC in both conditions since it is the recommended (and frequently used) water temperature in indoor swimming pools.

Data Analysis

The 400 m front crawl were recorded with a camera Nikon 1J1 (Nikon Corp., Japan) at 60 frames per second. Timing pads (Alge Timing, Training Pad TP980 Lustenau, Austria) were situated in both sides of the pool. A specific database was developed to measure the video time code and calculate the average velocity at 85 m of each 100 m lap (Filemaker v14.5, California, United States). The time performed in the swimming pool was used to determine the distance which swimmers had to accomplish in the swimming flume (with and without the wetsuit). The mean velocity performed in the swimming pool in both conditions was controlled with the swimming flume monitor.

HR was recorded using CardioSwim (Freelap, Fleurier, Switzerland) with the maximal HR (HR_{max}) obtained from the average of the last 30 s of the trials. Participants pointed out the Borg rating of perceived exertion scale (RPE) [17] immediately after the efforts and, at the third min of recovery, capillary blood samples (25 μL) for blood lactate concentration ([La-]) analysis were collected from the fingertip (using a Lactate Pro, Arkray, Inc., Kyoto, Japan) to obtain its maximal values ($[La^-]_{max}$) [15].

SR was obtained by considering three upper limb cycles and dividing it for the time taken to complete the three cycles in every 25 m lap corresponding to the 50, 200 and 400 m partials in both swimming pool and flume. SL was obtained from the ratio between the velocity and SR [18]. Stroke index (SI) was calculated by multiplying the swimming velocity by the SL) [19]. ηp was estimated as follows [12] :

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SF \cdot l) \cdot 2/\pi] \cdot 100 \qquad (1)$$

where *l* is the distance between the shoulder and wrist during the upper limbs insweep.

Statistical Analysis

Using the IBM SPSS Statistics (Version 20, IBM SPSS, Chicago, USA), Kolmogorow-Smirnov confirmed the data normality and homogeneity. A Pair Student's t-test was computed to compare 400 m front crawl performance with the wetsuit and swimsuit. ANOVA repeated measures was selected to compare the use of a wetsuit and a swimsuit both in swimming pool and flume conditions. Sphericity (homogeneity of variance and covariance) was verified by means of the Mauchley test and, when it was not met the significance of the F-ratios, was adjusted according to the Greenhouse-Geisser procedure. When a significant F value was achieved, Bonferroni post hoc procedures were performed to locate the pairwise differences between the means ($P < 0.05$). The Cohen´s d effect was calculated with the following criteria: 0 to 0.19 trivial, 0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, 2.0 to 3.9 very large and > 4.0 nearly perfect [20].

Results

Data concerning swimming performance, as well as physiological and technical variables, are presented in Table 1. On average swimmers were faster with the wetsuit than with the swimsuit (in the swimming pool), evidencing a reduction of 20.08 s (~6%) in the time endured at the 400 m front crawl. HR_{max}, $[La-]_{max}$, RPE, SR and ηp were similar between suits conditions (in both pool and flume). SL and SI were higher when wearing the wetsuit (both in the swimming pool and flume). Data data shown in Figure 1 complement the information in Table 1.

When comparing swimming conditions, HR_{max}, $[La-]_{max}$, SR and RPE were lower when performing in the flume (for both suits), showing a nearly perfect and very large effect size for the physiological variables, and large and moderate effect size for RPE (with wet and swimsuit, respectively). By contrast, SL, SI and ηp were higher when performing in the flume, a nearly perfect effect was in evicence for ηp. Data are described in Table 1, and the corresponding comparisons are shown in Figure 1.

Table 1. Values of 400 m maximum front crawl performance and related physiological and technical variabl in both swimming pool and flume conditions.

SWIMMING POOL						
Variable	**Wetsuit**	**Swimsuit**	**Difference [95%CI]; %Δ**	**Effect size (d)**	**Wetsuit**	**Swimsu**
Time endured (s)[1]	328.05 ± 42.85	348.13 ± 46.46***	-20.08 [-24.34, -15.81]; 6.1%	-1.67[b]	---	---
Velocity ($m \cdot s^{-1}$)	1.24 ± 0.16	1.17 ± 0.16***	0.07 [0.05, 0.09,]; -5.6%	0.16	1.28 ± 0.16	1.19 ± 0.
$\mathbf{HR_{max}}$ (beats·min-[1])	179.50 ± 11.96	175.80 ± 13.78	3.69, [-3.04, 10.43]; -2.1%	11.93[d]	166.76 ± 15.77	167.52 ± 1
$\mathbf{[La\text{-}]_{max}}$ ($mmol \cdot l^{-1}$)	8.05 ± 2.55	8.89 ± 2.86	-0.84, [-1.81, 0.13]; 10.4%	2.55[c]	5.82 ± 3.23	5.94 ± 2
RPE	7.91 ± 1.23	7.88 ± 0.86	0,03 [-0.59, 0.65]; -0.4%	1.23[b]	6.36 ± 1.66	6.33 ± 1
SR (Hz)	0.62 ± 0.09	0.61 ± 0.07	0.01, [-0.01, 0.03]; -1.6%	0.12	0.52 ± 0.07	0.52 ± 0
SL (m)	1.84 ± 0.23	1.76 ± 0.20*	0.07 [0.01, 0.14,]; -4.3%	0.21	2.48 ± 0.45	2.30 ± 0.3
SI ($m^2 \cdot s^{-1}$)	2.10 ± 0.47	1.90 ± 0.40**	0.20 [0.07, 0.34,]; -9.5%	0.48	3.22 ± 0.91	2.78 ± 0.6
ηp (%)	40.00 ± 7.51	40.63 ± 6.25	-0.62 [-3.07, 1.83,]; 1.6%	7.40[d]	52.41 ± 11.16	51.56 ± 1

Maximal heart rate (HR_{max}); maximal blood lactate concentration ($[La\text{-}]_{max}$); Borg rating of perceived exertion scale (RPE); stroke rate, length and index (SR, SL and SI); p effect size: [a]moderate, [b]large, [c]very large and [d]nearly perfect. The time-elapsed values were similar in swimming pool and flume conditions. Mean differences between suits f

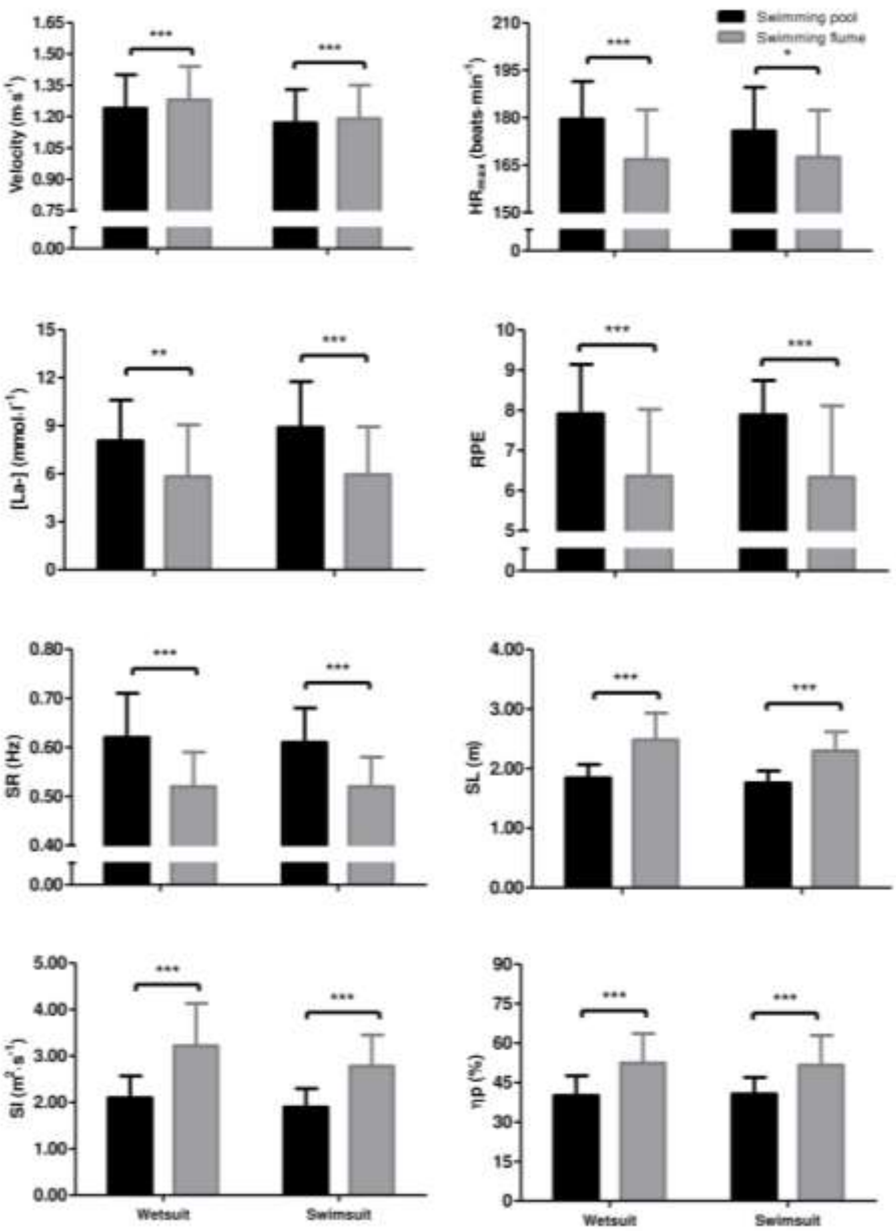

Figure 1. Means and standard deviation of physiological and technical variables plotted with wet and with swimsuit. Black bars represents the swimming pool and grey bars the swimming flume condition. Maximal heart rate (HR_{max}), maximal blood lactate concentrations ($[La-]_{max}$), Rating of perceived exertion (RPE), stroke rate (SR), stroke length (SL), stroke index (SI) and propelling efficiency (ηp). *, ** and *** mean differences between suits for $p < 0.05$, 0.01 and 0.001.

Discussion

The current study aimed to analyze the differences in 400 m maximum front crawl performance, and related physiological and general kinematical variables, when using a wetsuit compared with a swimsuit in two typical training conditions (swimming pool and flume). As expected, our swimmers were faster when using the wetsuit, which is consistent with the 5-6% improvement in 400 m [3,5] and 7% in 30 min front crawl [4] (previously described). Therefore, the current data corroborate the scientific literature that states that using a wetsuit allows obtaining advantage at aerobic events, probably due to better hydrodynamics [2]. In addition, differences between pools (with and without wetsuit) were also analyzed, being observed for similar velocities a reduction of physiological values and an increment of some technical variables in the swimming flume condition (using both suits).

When comparing physiologically wetsuit and swimsuit, it was not observed differences in HR_{max}, $[La-]_{max}$ and RPE (in both swimming pool and flume), which is contrary to our hypothesis. This could be justified by the fact that the velocity improvement is caused by the hydrodynamic drag reduction [3-6], and not by physiological changes. However, even if the ~10 and 2% $[La-]_{max}$ reduction when using wetsuit in the pool and in the flume (respectively) did not had statistical meaning, it could be relevant for training purposes, for instance justifying the inclusion of higher intensity sets during the training process. Moreover, the obtained $[La-]_{max}$ values are in accordance with the literature for 400 m trials events [3,7,15] but not HR_{max}, whose values were lower with wetsuit and higher with swimsuit comparing with previous results [7,10] (that could be explained by the higher velocities implemented in these studies). In addition, RPE values are similar to those found after swimming 400 m front crawl in a swimming pool with swimsuit [8], supporting the results of the current study. Swimmers RPE is similar with and without wetsuit probably due to their similar energy expenditure requirements between trials as HR_{max} and $[La-]_{max}$ corroborate.

When comparing suits focusing on technical variables, it was observed similar SR values (in swimming pool and in flume), which does not corroborate studies in which higher values were found with wetsuit [3,21], probably because different 400 m front crawl protocols were implemented and different swimmers levels were used. SL presented higher values in the wetsuit condition compared to swimsuit (~4 and ~7%, swimming pool and flume respectively), in accordance with data from the 30 min and 400 m front crawl studies [21,22]. The buoyancy increase imposed by the wetsuit use and the reduction in hydrodynamic drag seems to lead changes in the body position, producing technical adaptations of the swimmers who do not modified their SR. Hence, the swimming efficiency was similar in both situations. On the contrary, SL was 4.3% with wetsuit comparing with swimsuit in the swimming pool, which might be the responsible of the higher velocity reached in the 400 m test with wetsuit.

Swimming efficiency is fundamental to reach high performances (as it is strongly associated with low values of energy cost) and SI is frequently used as an easy to obtain strategy to measure it [19,23,24] . In the current study, SI was higher when using the wetsuit vs swimsuit (in both pools) as expected as it depends on SL, and was similar to data previously reported for the 400 m front crawl [25]. Furthermore, a better efficiency has been observed for the long suits (compared to sleeveless or short suits) due to the enhanced buoyancy and reduction in friction drag [10]. Notwithstanding the observed SI differences between suits, ηp did not differ, probably because swimmers had to modify their technique based on the swimming conditions (swimming pool or swimming flume) and the suit wear. That might be the reason why neither the SR nor ηp were modified. Its values were similar to the literature regardless the methodology used for its assessment, particularly using the Zamparo et al.[12] and measurement of active drag (MAD) system methods [26,27].

Concerning the second aim of the current study – comparing front crawl swimming at similar velocities in different pools – it was observed lower physiological variables values in the flume (independently of the suit used). This seems to express that swimming at high intensity in a flume is more economic, probably due to the constant pace imposed by the water flow and the absence of turns. These swimming flume constraints induced a better energy balance, as observed by the reduction of ~33% of $[La^-]_{max}$ and might be truly important for the training process of triathletes, because they are more engaged in long distance events and have lower vital capacity and skinfold thickness (and therefore, less buoyancy [28]). The lack of difference in physiological variables migh be also due to the participants do not performed the test maximally in the swimming pool and, as a consequence, niether in the swimming flume. In addition, swimming against a current in such a reduced place might produce additional propulsion when the water rebounds off the wall of the flume. It avoids swimmers using additional energy to propel themselves or change direction. Therefore, as this study suggested, physiological responses could be reduce due to flume swimming (Table 1). Complementarily, RPE was higher in the swimming pool compared to the flume probably due to the different swimming strategies (free swimming in the pool, in which swimmers determine the swimming pace vs imposed pace in the swimming flume), this contrast with a previous study [17]. This might be related to previous experience when in swimming at the flume (our subjects were accustomed to perform there) and to the characteristics of the different water channels.

Related to technical variables, the increment of the efficiency in the flume can be explained by the possible mechanical constraints induced by the flume, because the narrow displacement of the water impelled and consequent direction of the water around the swimmers body [13]. In addition, differences between pools limit the use of the flume to in comparing data in both conditions. As Figure 1 shows, all the variables are statistically different, probably due to characteristics of the flume of the reduced dimensions and small water impeller.

Practical Applications

Our results add more precision to the adaptation of training loads when using wetsuits, considering the reduction of 10% of $[La\text{-}]_{max}$ and improvements in technical efficiency. These results suggest that there are technical adaptations that swimmers should focus on for improving efficiency while swimming with the wetsuit. A 6% increase in velocity is produced by an increase of 4.3% in SL with similar values of SR. Swimmers could reduce SR and increase SL to benefit from the hydrodynamics characteristics of wetsuits and improve their swimming efficiency. A recommendation for trained swimmers, as the simple size used in this study, is to use a wetsuit during the training season, swimming at different intensities and distances to improve the adaptations, while swimming with the wetsuit.

Conclusions

Our data confirmed that wearing a wetsuit leads to a 400 m front crawl performance increment. In addition, it was observed that physiological variables reached lower values (using both suits) and technical variables (except SR) were higher in the swimming flume.

The swimmers improved their velocity by 6% with the wetsuit due to the suit itself, because they do not change their swimming technique, as the results show. Rather, they increase SL, and, as a consequence, their velocity was higher. This can be explained by the reduction in hydrodynamic resistance and changes in body position; however, these variable were not measured in this study. More information is needed concerning the influence of wetsuits in swimming performance, particularly by implementing biomechanical and physiological analysis at lower temperatures for a better understanding of the mechanisms underlying open water and triathlon competitions.

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CHAPTER 5: 400 m front crawl swimming determinants when using a wetsuit

CHAPTER 5: 400 m front crawl swimming determinants when using a wetsuit

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Abstract

In the current study was aimed to conduct a biomechanical, physiological and anthropometrical characterization (including the age) of the 400 m front crawl using wetsuit. Eleven females and 20 males performed two 400 m front crawl bouts in a 25 m swimming pool using a wetsuit and a swimsuit. Anthropometric characteristics, stroke rate (SR), stroke length (SL), stroke index (SI), propelling efficiency (ηp), maximal blood lactate concentrations ($[La-]_{peak}$) and maximal heart rate (HR_{max}) were assessed. Pearson correlation coefficients and stepwise regression analyses were performed. For the total sample, 48% of the 400 m front crawl performance variance improvement (20.09 ± 8.95 s) was explained by the SR change ($r = 0.484$, $p < 0.01$) and the wetsuit upper limbs thickness ($r = -0.491$, $p < 0.05$). In females, the 62% of the time improved on 400 m front crawl was explained by the wetsuit lower limbs thickness ($r = -0.784$, $p < 0.05$), while in males the SR difference ($r = 0.559$, $p < 0.01$) and the age ($r = 0.428$, $p < 0.05$) explained 48% of this improvement. Furthermore, associations were observed for the time improved on 400 m front crawl and the age ($r = 0.384$, $p < 0.05$), International Swimming Federation (FINA) points ($r = -0.638$, $p < 0.01$), SL ($r = -0.392$, $p < 0.05$) and ηp differences ($r = -0.370$, $p < 0.05$) for the total sample. For females, the associations were between this time improved and FINA points ($r = -0.554$, $p < 0.05$) and wetsuit upper limbs thickness ($r = -0.784$, $p < 0.05$). Finally, in males the associations were between this time improved and FINA points ($r = -0.639$, $p < 0.01$) and SL difference ($r = -0.441$, $p < 0.05$). In conclusion, SR and the wetsuit thickness better explained the improvement on 400 m front crawl performance while using wetsuit for triathletes and open water swimmers.

Keywords: Wet suit, predictors of performance enhancement, body composition, open water, swimming technique.

Introduction

Wetsuits are frequently used at open water swimming competitions and triathlon events for preventing hypothermia [1,2], since the neoprene fabrics is permeable to a thin water layer that acts as a thermal insulation [3,4]. The wetsuits use also leads to a swimming performance enhancement (compared to wearing traditional swimsuits), with 5-7% velocity increments observed for different distances (like the 400, 800 and 1500 m and also the 30 min swim [5-8]). However, even if it is well-known that the wetsuit use leads to relevant swimming technique changes (particularly affecting stroke rate (SR), stroke length (SL) and upper limbs coordination [5-9]), research on the topic is scarce.

The most referred benefit of swimming with a wetsuit is the augmented buoyancy, leading to hydrodynamic drag reduction and, consequently, to a better propelling efficiency (ηp) and lower energy cost of swimming [5,10,11,13]. In addition, maximal heart rate (HR_{max}) is lower when swimming at the same velocity with a wetsuit comparing to a swimsuit, eventually leading to lower maximal oxygen consumption ($\dot{V}O_{2max}$) values [12]. This physiological variable is a very important determinant of aerobic performances, such as open water swimming and triathlon competitions, in which wetsuits are frequently used [13,14]. Of course the magnitude of these technical and physiological modifications depends on swimmers level and on the wetsuit frequency use and model selected [5,8-11].

Thermal temperature is of crucial importance in long distance swimming, with body fat contributing to its maintenance and affecting the final performance [15]. Since the wetsuit use attenuates the decrease of the core temperature along 30 min swimming at ~20-26ºC water temperatures [16], studies relating swimmers anthropometric characteristics and wetsuit use are welcome. In fact, higher skinfold thickness permits greater buoyancy [5,17], indicating that specific anthropometric features might provide an additional benefit on the wetsuit use effect in swimming performance [5]. Indeed, it was observed that swimmers with higher body mass benefit less than learners when wearing wetsuit though no relationships with swimsuits were reported. Moreover, inverse relationships between body density and the 400 and 1500 m front crawl times were also found (notwithstanding that the regression analysis has not been studied [6]).

Aiming to clarify which determinants could explain the wetsuit advantages during swimming, we have purposed to conduct a biomechanical, physiological and anthropometrical characterization (including the age) of the 400 m front crawl using wetsuit. Afterwards, we aim to observe the associations between the selected variables studied, analysing this for the total sample but also for per sex. We hypothesized that the increase in performance provided by the wetsuit could be explained by changes in biomechanical, physiological and anthropometric variables plus by the age of the participants.

Methods

Experimental approach to the problem

After an anthropometric characterization, swimmers performed two 400 m front crawl bouts, one using full body wetsuit (covering upper limbs until the wrist, lower limbs until the ankles and torso) and other with swimsuit. All the wetsuits used by the participants were similar and conformed to the official International Swimming Federation (FINA) and International Triatlon Union (ITU) thickness standards [1,2]. Trials were performed in a 25 m swimming pool (with 27ºC water temperature), using in-water start and resting 48 h in-between, and its execution was randomized and counterbalanced. Before testing, an individualized in-water warm-up composed of 15 min of low to moderate intensity followed by 10 min of passive rest was performed [8]. Participants were asked to abstain from taking caffeinated drinks and to participate in exhausting exercise 24 h before the experiments.

Subjects

The sample was composed by 31 triathletes and open water swimmers (11 females and 20 males) that voluntarily participated in the current study (their ages were 27.00 ± 11.85, 28.27 ± 10.35 and 26.30 ± 12.80, respectively). Swimmers were engaged on a six to seven weekly training frequency and were accustomed to wear wetsuit in training and competitions. Participants and parents (when the subjects were under 18 years old) provided a written informed consent to participate in the study and the Institutional Ethical Review Board approved the experimental design, which was performed in accordance to the Code of Ethics of the World Medical Association - Declaration of Helsinki (project code: 125/CEIH/2016).

Procedures

Anthropometric measurements were conducted by the same researcher, with participants being barefoot and wearing their swimsuit. A stadiometer (Seca 213 Portable Stadiometer Height-Rod, Hamburg, Germany) and a portable scale (model 803 digital scale, Hamburg, Germany) were used to measure height and body mass (with body mass index calculated as kg/m^2). A meter and a caliper (Caliper Bozeera, Arnhem, Nederland) allowed obtaining arm spam and skinfold thickness (using the three measures average of the biceps, triceps, subscapular, suprailiac, supraspinal, abdominal, thigh and calf skinfolds [19]). With the data obtained, body fat, bone mass, skeletal muscle mass and residual mass were estimated.

The 400 m front crawl bouts were recorded using two cameras, one placed above water (Nikon 1J1, Nikon Corp., Japan) and the other underwater (Panasonic,Full-HD HX-A500, Osaka, Japan), working at 60 and 50 Hz (respectively). A pre-calibrated space was used and reference points were attached at the participants shoulders, hips and wrists for technical variables determination [8]. Three upper limb cycles were measured in the 50, 200 and 400 m splits to assess SR. Afterwards, SL and stroke index (SI) were calculated [20]. In addition, ηp was estimated based on a previous methodology [21]. The difference values between conditions (i.e., swimsuit minus wetsuit) was calculated for the following variables: 400 m front crawl, HR_{max}, maximal blood lactate concentrations ($[La-_{peak}]$), SR, SL, SI and ηp using subtraction. Finally, related to the swimming time, it was also subtracted the time between swimming with swimsuit minus wetsuit and it was defined as time improved on 400 m front crawl. CardioSwim (Freelap, Fleurier, Switzerland) was used to measure HR. The HR_{max} was obtained from the average of the last 30 s of the trials [8]. Blood lactate concentrations ([La-]) analysis were collected from the same fingertip (Lactate Pro, Arkray, Inc., Kyoto, Japan) and capillary blood samples (25 μL) were obtained to find maximal value [8].

Statistical Analysis

IBM SPSS Statistics (version 20, IBM SPSS, Chicago, USA) was used to performed data analysis. Kolmogorov-Smirnov analysis and Levene tests confirmed the normality and homogeneity of the sample (respectively), therefore parametric statistical analysis was adopted. Pearson correlation coefficients (r) were computed between selected variables and linear regression analyses were applied to evaluate the potential associations for the total sample and by sex. A stepwise regression analysis was used to determine the strongest predictors of the time improved on 400 m front crawl. Then, multiple regression analysis with two blocks was conducted: (i) in the first block the predictor of the first stepwise was included using the enter method; and (ii) in the second block the variables which were significantly correlated with the difference in time improved on 400 m front crawl were included in a stepwise method. The level of significance was set at $p < 0.05$ with 95% of confidence interval (CI).

Results

The mean ± standard deviation (SD) values of the variables for the total sample and divided by sex and the relationships of the time improved on 400 m front crawl and biomechanical, physiological and anthropometrical variables are presented in Table 1. Regarding the total sample, age and SR difference were positively associated with the time improved on 400 m front crawl (20.09 ± 8.95 s), while negative associations were observed for FINA points, wetsuit upper limbs thickness, SL and ηp differences. In females, a negative associations were also found for FINA points and wetsuit upper and lower limbs thickness. Moreover, in males negative associations were found for FINA points and SL difference while positive relationships were found for age and SR difference.

Table 1. Sample performance and anthropometric characteristics (mean ± SD) and Pearson correlations ou
front crawl and age, biomechanical, physiological and anthropometrical variables of the total sample size and

Dimension	Total sample (n=31)		Females (n=11)		
	Mean ± SD	Time improved on 400 m front crawl (s)	Mean ± SD	Time improved on 400 m front crawl (s)	Me
Age (years)	27.00 ± 11.85	0.384*	28.27 ± 10.35	0.463	26,3
Time 400m front crawl swimsuit (s)	348.32 ± 47.19	-	354.28 ± 47.02	-	345.0
Mean velocity with swimsuit ($m \cdot s^{-1}$)	1.17 ± 0.16	-	1.15 ± 0.14	-	1.1
Time 400m front crawl wetsuit (s)	326.53 ± 42.74	-	337.02 ± 42.44	-	320.
Mean velocity with wetsuit ($m \cdot s^{-1}$)	1.25 ± 0.16	-	1.21 ± 0.14	-	1.2
Time improved on 400m front crawl (s)	21.79 ± 10.19	-	17.26 ± 8.78	-	24.2
FINA points	281.34 ± 116.30	-0.638**	316.64 ± 112.97	-0.554*	261.9
Wetsuit upper limbs thickness (mm)	2.68 ± 0.55	-0.491*	2.75 ± 0.46	-0.784*	2.6
Wetsuit trunk thickness (mm)	3.04 ± 0.74	0.037	3.13 ± 0.83	0.255	2.9
Wetsuit lower limbs thickness (mm)	2.94 ± 0.59	0.025	2.75 ± 0.46	-0.784*	3.0
Wetsuit average thickness (mm)	2.89 ± 0.49	-	2.88 ± 0.35	-	2.9
Height (cm)	172.30 ± 8.15	0.113	165.84 ± 4.66	-0.187	175.
Weight (kg)	67.69 ± 11.36	0.074	58.45 ± 7.22	-0.281	72.
Body max index (kg/m^2)	22.64 ± 2.17	0.017	21.19 ± 1.97	-0.262	23.4
Arm span (cm)	177.64 ± 9.56	0.066	169.56 ± 5.00	-0.305	182.
Body fat (kg)	9.73 ± 2.76	0.041	8.87 ± 2.91	-0.280	10.2
Bone mass (kg)	7.37 ± 1.24	0.147	6.32 ± 0.56	-0.089	7.9
Skeletal muscle mass (kg)	34.94 ± 5.20	0.028	30.87 ± 3.11	-0.191	37.
Residual mass (kg)	15.64 ± 3.30	0.123	12.38 ± 1.60	-0.355	17.4
Body fat (%)	14.27 ± 2.78	0.018	14.91 ± 3.31	-0.237	13.9
Bone mass (%)	10.927 ± 0.88	0.148	10.88 ± 0.80	0.335	10.9
Skeletal muscle mass (%)	51.84 ± 2.60	-0.194	53.02 ± 2.78	0.276	51.
Residual mass (%)	22.96 ± 1.56	0.209	21.19 ± 0.96	-0.259	23.9

HR_{max} difference (beats·min^{-1})	-3.92 ± 14.14	0.037	-1.26 ± 4.46	-0.231	-5.3
[La-$_{peak}$] difference (mmol·l^{-1})	0.79 ± 2.03	-0.220	1.13 ± 1.72	-0.067	0.6
SR difference (Hz)	-0.14 ± 0.04	0.484**	-0.03 ± 0.04	0.149	-0.0
SL difference (m)	-0.07 ± 0.15	-0.392*	-0.05 ± 0.14	-0.188	-0.0
SI difference (m^{2}·s^{-1})	-0.21 ± 0.28	-0.193	-0.21 ± 0.26	-0.066	-0.2
ηp difference (%)	0.56 ± 5.09	-0.370*	1.68 ± 4.77	-0.418	-0.0

International Swimming Federation points (FINA) of best competitive performance on 400 m freestyle in short-course; maximal heart rate (HR$_{m}$
wetsuit tests); peak blood lactate concentrations ([La-]$_{peak}$); stroke rate (SR); stroke length (SL) and propelling efficiency (ηp). * and ** $p<0.05$ an

Table 2. Multiple regression output of the time improved on 400 m front crawl for the total sample size and divided by sex.

Variables	B	p
Time improved on 400 m front crawl (s)		**Total sample (n=31)**
SR difference (Hz)	0.487	0.009**
Wetsuit upper limbs thickness (mm)	-0.432	0.018*
Time improved on 400 m front crawl (s)		**Females (n=11)**
Wetsuit lower limbs thickness (mm)	-0.784	0.021*
Time improved on 400 m front crawl (s)		**Males (n=20)**
SR difference (Hz)	0.542	0.007**
Age (years)	0.405	0.034*

Stroke rate (SR) * and ** $p<0.05$ and 0.01.

Linear regression analyses showed that only the FINA points were included in the model (see Figures 1 to 3). The upper and lower limbs were accounted for a 61% of the variance (r = 0.78) in the time improved on 400 front crawl in females (Figure 2) and for FINA points in a 41% of the variance (r = 0.64) in the time improved on 400 front crawl in males (Figure 3). No relevant associations were found for the total sample (Figure 1). Multiple regression analysis for total sample and divided by sex are showed in Table 2. Results revealed that 48% of the variance (r = 0.69) of the time improved on 400 m front crawl was explained by the SR difference and the wetsuit upper limbs thickness (for the total sample). In females, 62% (r = 0.78) of this improvement was explained by the wetsuit lower limbs thickness, while in males, the SR difference and the age explained 48% (r = 0.69) the time improved on 400 m front crawl.

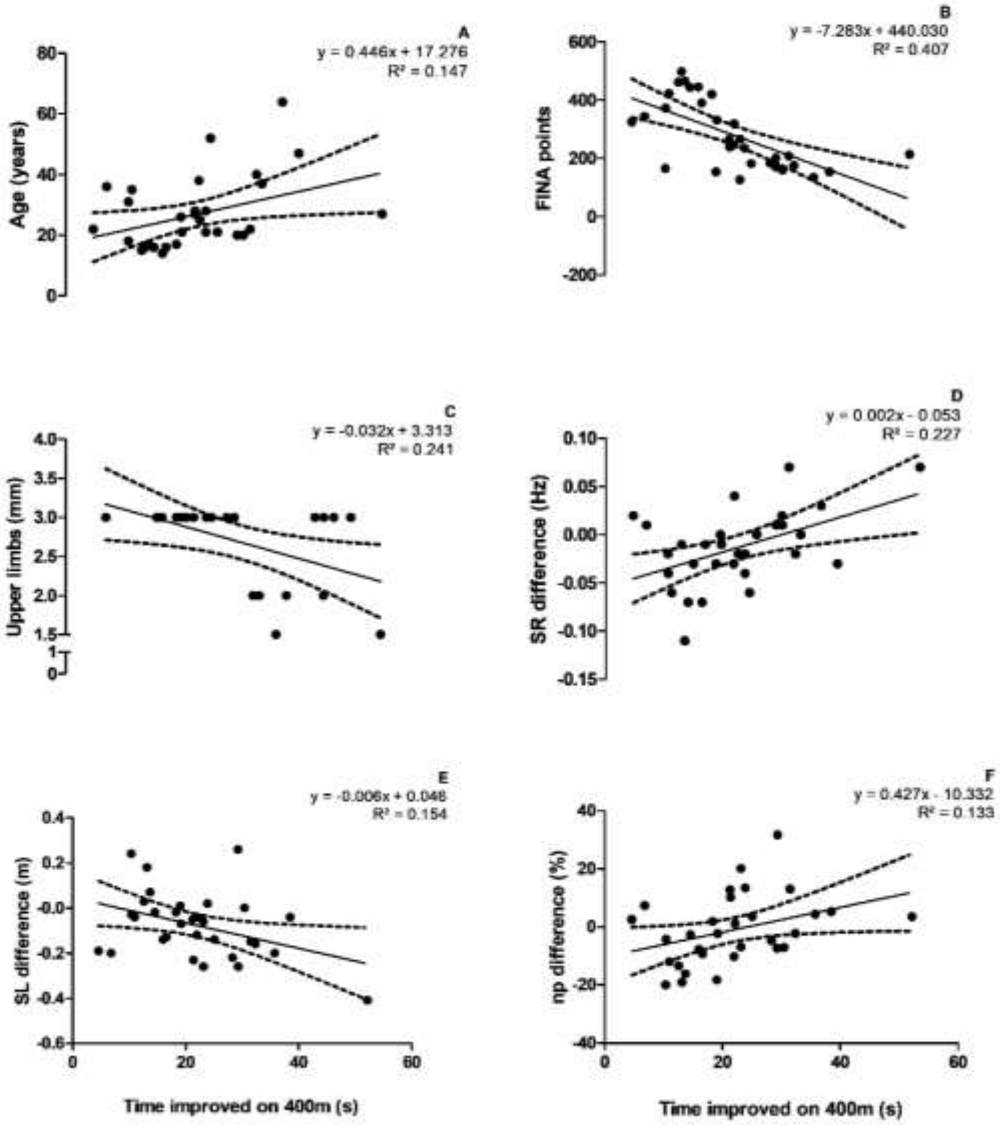

Figure 1. Linear regressions for the total sample size (n = 31) between the time improved on 400 m front crawl and the age (panel A); International Swimming Federation points (FINA points, panel B); wetsuit upper limbs thickness (panel C); stroke rate difference (SR, panel D); stroke length difference (SL, panel E) and propelling efficiency difference (ηp, panel F). Individual value (continuous lines) and 95% confidence intervals (dashed lines) are represented.

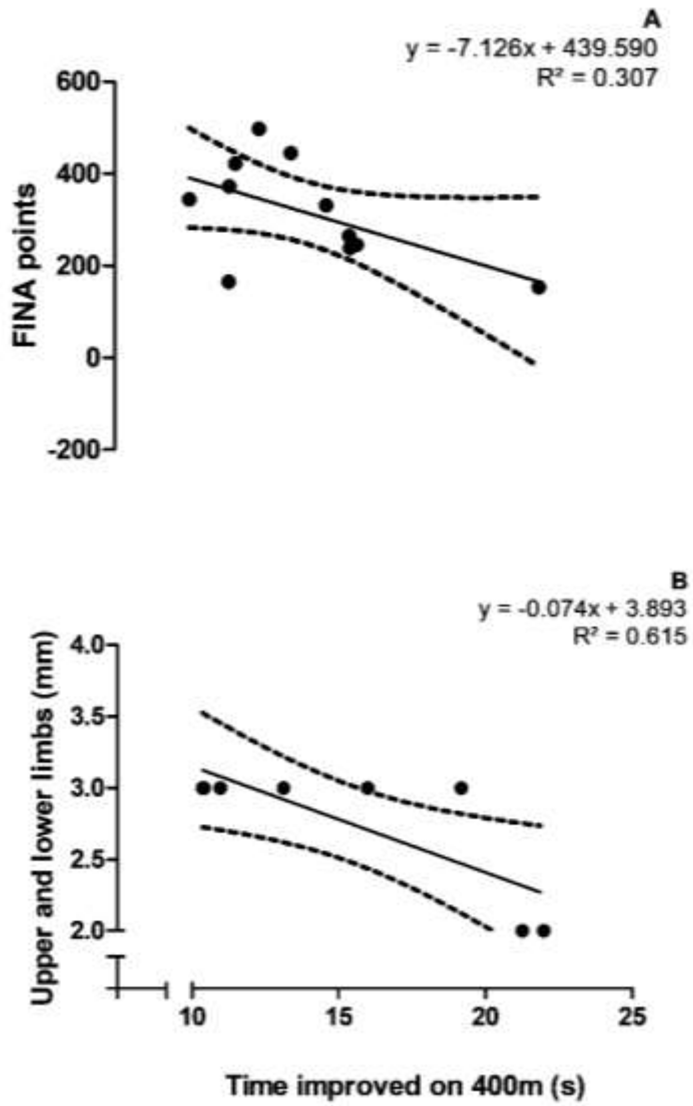

Figure 2. Linear regressions for females (n = 11) between the time improved on 400 m front crawl and the International Swimming Federation points (FINA points, panel A) and wetsuit upper and lower limbs thickness (panel B). Individual value (continuous lines) and 95% confidence intervals (dashed lines) are represented.

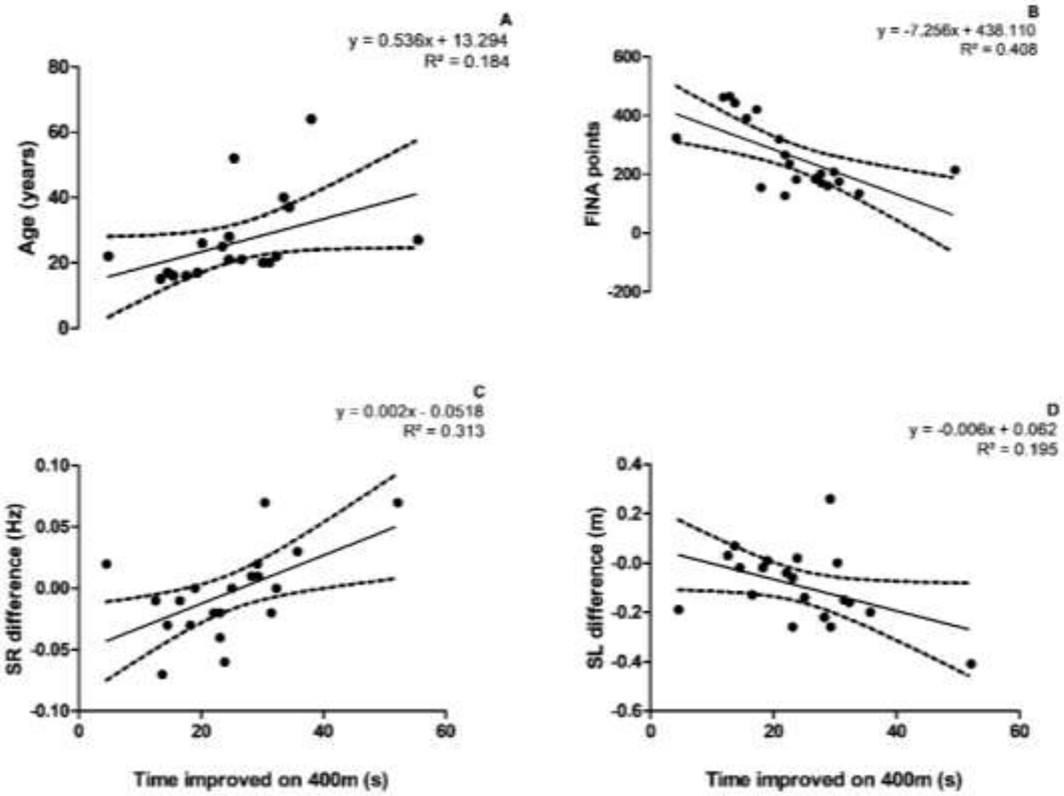

Figure 3. Linear regressions for males (n = 20) between the time improved on 400 m front crawl and the age (panel A); International Swimming Federation points (FINA points, panel B); stroke rate difference (SR, panel C) and stroke length difference (SL, panel D). Individual value (continuous lines) and 95% confidence intervals (dashed lines) are represented.

Discussion

The purpose of the present study was to conduct a biomechanical, physiological and anthropometrical characterization (including the age) of the 400 m front crawl using wetsuit, aiming to clarify which determinants could explain the wetsuit advantages during swimming. In addition, it was aimed to observe the associations between the selected variables studied, analysing this for the total sample but also for per sex, once it was studied that the wetsuit use improves performance on 400 m front crawl [8]. The physiological variables (i.e., HR_{max} and [La-]) did not explain the difference in performance, contrary as hypothesized. However, the SR showed to have an influence, especially on the male group (Table 2). Also, the thickness of the different parts of the wetsuit seems to affect the enhancement elicited while swimming with the wetsuit (upper limbs thickness for the total sample and lower limbs thickness for females). Contrary to what was hypothesized, physiologic and anthropometric variables did not have an effect on the time improved on 400 m front crawl however, FINA points showed a negatively association for the three groups (Table 1).

The use of wetsuit induces different changes in HR_{max} and [La-] as previously reported varying with higher and lower values [5,11-12,22]. These differences could be explained by the temperature of the swimming pools because wetsuit performances are usually studied in water temperatures around 25-29ºC [7-8,23], although it use is not permitted in open water and triathlon competitions at the above temperatures [1-2]. In this regard, the lack of relationships obtained in the present study between HR_{max} and [La-] with the time improved on 400 m front crawl could be explained by the water temperature, since higher temperatures (in addition of wearing wetsuit) might induce to increases in trunk temperature [16] and, as a consequence, higher physiological responses (as observed in Table 1 with negative means for the HR_{max} differences in the three groups), thus higher values with wetsuit were obtained [16,24].

The reduction of hydrodynamic drag generated by the buoyancy of the wetsuit and consequently the reduction of C should help the swimmer to swim more efficiently and therefore, changes in swimming technique could be observed [5,11,25]. However, related to females, SR was no relevant to explain the tme improved on 400 m front crawl (Table 2), perhaps due to the small size of the group and the minor variations undergone by the SR, even when large changes in stroke length occurs [26-27]. As it was reported, the use of wetsuit is also important in open water swimming competitions but the improvement that it provides might change depending on the sex because the buoyancy would be different due to the body fat percentage [28]. Interestingly, the swimming efficiency (neither ηp nor SI) seemed not to explain the differences of performance in the present study, even though it is known that swimming performance appeared to be dependent on swimming efficiency [29]. Probably, because the enhancement in efficiency would depend not only on the swimming technique, but also on the frequency of use wetsuit as discussed above.

The percentage values of body fat for the total sample, females and males were similar as reported [11,16] but as females have lower skeletal muscle mass and probably, higher body fat, it might induces higher buoyancy and a better body positioning [28]. This is in accordance with a higher swimming economy related to the time limit to $\dot{V}O_{2max}$ for females [13]. Nevertheless, the higher percentage of skeletal muscle mass in females of the present study might be due to the fact that all of them were swimmers, by contrast to males which were swimmers and triathletes. In this regard, lean subjects benefit more by the use of wetsuit than fatter subjects [6], which can be observed in the results of the correlations, with more associations reported in males than in females (Figure 3 and 2).

Besides, the body fat percentage does not change after a week performing nine trials with swimsuit, lycra suit or wetsuit at different water temperatures (~17, ~21 and, ~30ºC) [22], hence training must be focus on increasing skeletal muscle mass instead of reducing body fat, since this is related to better performance in swimming, as reported [18]. As a consequence, the same might occurred while using wetsuit. Although the age has explained the time improved on 400 m front crawl performance with SR only in male swimmers, it might be an interesting variable to take into account along with technique, because masters swimmers are able to maintain higher levels of performance in longer distances rather than in shorter ones which might be related to the upper limbs as major source of propulsion for front crawl in master swimmers [30]. In this context, a deeper analysis of the anthropometrics variables (e.g., girths, breadths and somatotype) should be studied to better understand the associations with the advantages produced by the wetsuit and its relations to swimming technique.

Practical applications

The 48% of the variance of the time improved on 400 m front crawl performance (20.09 ± 8.95 s) was explained by the SR difference (for the total sample size and males), suggested that SR is the variable which better explained this enhancement while using wetsuit. Thus, a higher maintenance of the SR might induce to higher velocities reached by the wetsuit. This confirmed the importance of biomechanical factors (SR, SL, SI and ηp) as reported which might determine the improvement while using wetsuit for triathletes and open water swimmers [29]. Also, the 62% of this improvement is explained by the wetsuit lower limbs thickness in females and the 48% by the wetsuit upper limbs thickness in males stage the importance in selecting a specific model of wetsuit according to the subject characteristics and technique.

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Conflict of interest

Authors have no conflicts of interest to report.

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CHAPTER 6: Swimming with swimsuit and wetsuit at typical vs cold-water temperatures (26 vs 18ºC)

CHAPTER 6: Swimming with swimsuit and wetsuit at typical vs cold-water temperatures (26 vs 18ºC)

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Abstract

The study aimed to compare three swimming conditions in a swimming flume with water at 26ºC (using swimsuit) and 18ºC (randomly with swimsuit and wetsuit). Seventeen swimmers (32.4 ± 14.7 years old, 175.6 ± 0.06 cm height and 70.4 ± 9.8 kg body mass) performed the three bouts until exhaustion at 400 m front crawl pace (24 h intervals). ANOVA repeated measures compared the experimental conditions. Swimming at 26ºC with swimsuit evidenced a higher metabolic demand (total energy expenditure; (E)), comparing to 18ºC swimsuit ($p = 0.05$) and with 18ºC wetsuit ($p = 0.04$). The 26ºC swimsuit condition presented higher peak oxygen uptake ($\dot{V}O_{2peak}$), blood lactate concentrations ($[La-]_{peak}$), rate of perceived exertion (RPE), maximal heart rate (HR_{max}), anaerobic lactic energy (AnL), E, energy cost (C), $\dot{V}O_2$ amplitude (Ap) and stroke rate (SR), but lower stroke length (SL) and stroke index (SI) than 18ºC wetsuit. The 18ºC swimsuit condition (comparing to wetsuit) lead to higher $\dot{V}O_{2peak}$, $[La-]_{peak}$, HR_{max}, E, C, Ap and SR but lower SL and SI. Swimming at aerobic power intensity with swim and wetsuit at 18ºC does not induce physiologic and biomechanical disadvantages comparing to 26ºC, The results suggested that the use of wetsuit might increase performance at 18ºC water temperature for competitive master swimmers. Thus, its use is recommended in open water swimming competitions when the water temperature is 18-20ºC.

Keywords: Wet suit, Energetics, Biomechanics, Swimming Flume, Open water, Neoprene.

Introduction

The use of wetsuits in open water swimming events is very frequent due to the enhancement in speed compared to swimsuits. The properties of a wetsuit include increased buoyancy and reduced hydrodynamic drag. Wetsuits also improve the propelling efficiency (ηp), which reduces the energy cost of swimming (C) [1,2,3]. In fact, both former and contemporary studies showed a 5 to 7% of performance improvement on 400 m to 30 min swimming events when wearing a wetsuit [1,4-6], probably due to body drag reduction caused by the buoyancy increment [1]. However, there is a high variety of wetsuits models (full body, sleeveless long, and short), some of which are more economic to swim with (presenting lower C values) than others, related to the body cover [4,7,8].

The use of wetsuits in open water competitions is mandatory, allowed and forbidden depending on water temperature (lower than 18, from 18 to 20, and higher of 20ºC, respectively) [9]. The reason is to avoid hypothermia in cold-water temperatures [10]. When the immersion in with cold-water lead to the 'cold-shock' physiological phenomenon that is characterized by 1-3 min of hyperventilation and tachycardia followed by an inspiratory gasp and by a heart rate (HR) decrease due to a blood flow volume reduction [11]. However, these responses are only observed when swimming at temperatures ≤ 15ºC and in deep immersions [12,13] but it is not clarified if there are physiologic and biomechanical modifications when swimming with a wetsuit at 18ºC.

Open water swimming is different compared to pool swimming since there are no turns and wall push-off glide, as the water volume is higher and water temperatures varies, leading to particular cardiovascular and technical responses [14,15]. Therefore, swimming in a flume at different water temperatures could be a good strategy to simulate the typical continuous open water swimming both during training and testing. It was recently observed that performing in a swimming flume and in a 25 m pool is physiological and biomechanically different (independently of the suit used) [6]. In addition, differences in fluid flow characteristics and the changes in their swimming technique during continuous swimming might appear when fatigue occurs [16,17].

Knowing that the 400 m front crawl pace is well related with the velocity that elicits maximal oxygen consumption ($\dot{V}O_{2max}$) and is a valid indicator of aerobic power (one of the most important swimming training zones) in which the anaerobic contribution range between 17 and 40% of the total energy expenditure [18,19], the aim of this study was to compare swimming performed at two water temperatures (18 and 26ºC) with and without wetsuits. It was hypothesized that: (i) swimming with a swimsuit at 26 vs 18ºC implies lower physiological demands and higher ηp; and (ii) swimming at 18ºC with swimsuit is less efficient and economic than performing with a wetsuit.. Water temperatures of 26 and 18ºC were selected since they represent the usual value at indoor swimming pools and the limit under which the use of wetsuit is mandatory in open water swimming competitions [9].

Methods

Participants

Seventeen competitive master swimmers (15 males and 2 females) voluntarily participated in the current study. Their main physical and performance characteristics were 32.4 ± 14.7 years of age, 175.6 ± 0.06 cm of height, 70.4 ± 9.8 kg of body mass, 181.1 ± 7.1 cm of arm span, 23.03 ± 2.35 kg/m^2 of body mass index, and 273 ± 130 International Swimming Federation (FINA) points of best competitive performance on 400 m freestyle performance in short-course, with a training time frequency ~8-10 h per week. The Institutional Ethical Review Board approved the study design that has been performed according to the Code of Ethics of the World Medical Association - Declaration of Helsinki (project code: 125/CEIH/2016) and the study follows the ethical standards in sport and exercise science research [20]. A written informed consent was given by all participants.

Experimental Design

After a standard in-water warm up of 1000 m at 26ºC [6], subjects performed three front crawl time-trials in a swimming flume (with 24 h rest in-between) at a water speed simulating each swimmer 400 m front crawl pace (the best time obtained in a 400 m freestyle competition). The distance selected was assumed to be an aerobic power pace [18,19]. Due to specific constraints to cool down the water, subjects firstly swam at 26ºC using a swimsuit and, after the water temperature was decreased to 18ºC, they randomly and counterbalanced perform the trials with a personal swimsuit and wetsuit (2.24 ± 0.89, 2.87 ± 1.18 and 2.64 ± 1.07 mm of upper limbs trunk and lower limbs thickness accordingly to FINA rules). In the three conditions swimmers were asked to stay at the center of the swimming flume and to continue swimming until they were not able to keep the pace. Swimmers had previous experience in flume swimming, using a breathing snorkel and a nose clip, and abstained to take stimulant drinks and practice exhaustive exercise 48 h prior to the trials. The trials were conducted at the same time of day (at a room with 24 ± 1.5ºC air temperature and 51 ± 2.7% relative air humidity) and prior 24 h nutrition was controlled.

Methodology

Experimental trials were conducted in a 2.4 x 4.7 m Endless Pool (Elite Techno Jet Swim 7.5 HP, Aston PA, USA), with its flow speed measured at 0.30 cm depth using an FP101 flow probe device (Global Water, Gold River, CA) [21]. A K4b^2 (Cosmed, Rome, Italy) breath-by-breath portable gas analyzer which allows the direct measurement of respiratory and pulmonary gas exchange variables, being suspended at 1.8 m above the water surface (Figure 1). The gas analyzer was attached to a low hydrodynamic resistance respiratory snorkel and valve system (Aquatrainer®, Cosmed, Rome, Italy) [14,22] and it was calibrated with 16% O_2 and 5% CO_2 concentration gases before each testing session. HR was measured using telemetry (Polar Wearlink, Kempele, Finlandia) synchronized with the portable gas analyzer. A surface and underwater cameras (Nikon Corporation, Japan and Panasonic Full-HD HX-A500, Osaka, Japan), operating at 50 Hz and placed on the swimming flume frontal and sagittal plans (respectively), were used to assess the biomechanical variables (see below). A pre-calibrated space was used as a reference for video analysis with one meter wide and 14 points used for calibrations, situated in the center of the swimming flume [6].

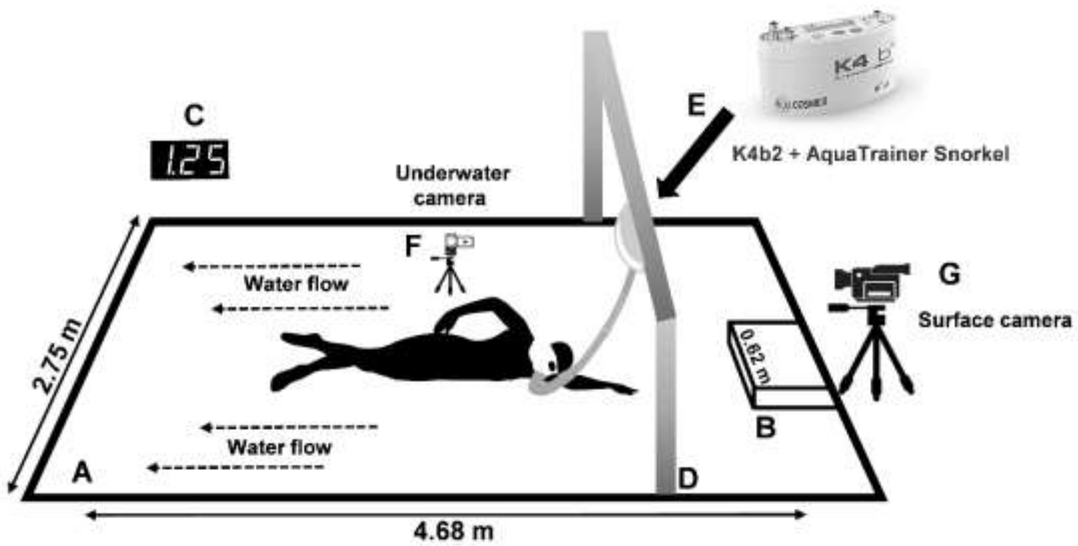

Figure 1. Graphic representation of the swimming flume. A: space for the swimmer; B: water channel; C: flume monitor where swimming speed was selected; D: mobile structure attached to the apparatus; E: K4b^2 and Aquatrainer® respiratory snorkel; F: underwater sagittal camera; and G: surface front camera. Dashed arrows represent the water flow direction.

Data Analysis

$\dot{V}\mathbf{O_2}$ data was analyzed using the $\dot{V}\mathbf{O_2}$FITTING open and free software [23], with a mono-exponential model adjusting the best profile for the three experimental conditions (equation 1):

$$\dot{V}O_2(t) = A_0 + H\left(t - TD_p\right) \cdot A_P(1 - e^{-(t-\mathrm{TD}_p)/\tau_p}) \quad (1)$$

where $\dot{V}O_2$ (t) represents the relative $\dot{V}O_2$ at the time t, A_0 is the rest $\dot{V}O_2$ (the pre-exercise last 2 min average), H represents the Heaviside step function and Ap, TDp and τ_p are the fast $\dot{V}O_2$ component amplitude, time delay and time constant (respectively) [23]. $\dot{V}O_2$ values included only those between $\dot{V}O_2 \pm 4$ SD, decreasing the noise between breaths caused when swimmers swallow water, cough or the signal is interrupted [24]. Then, individual breath-by-breath $\dot{V}O_2$ responses were smoothed using a three-breath moving average and time averaged every 10 s [23,24] allowing the highest incidence of $\dot{V}O_2$ plateau occurrence regardless the distance performed [24]. Peak oxygen consumption ($\dot{V}O_{2peak}$) and other physiological variables, as maximal heart rate (HR_{max}) and respiratory exchange ratio (RER), were obtained from the last 30 s of each trial.

The total energy expenditure (E) was estimated as the sum of aerobic (Aer), anaerobic lactic (AnL) and anaerobic alactic (AnAL) energy contributions, with the first two calculated, respectively, from the time integral of the net $\dot{V}O_2$ vs time relationship and using the following equation [25,26]:

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

where $[La^-]_{net}$ is the difference between the blood lactate concentration ($[La^-]$) before and after exercise ($[La\text{-}]_{peak}$), β is the constant for O_2 equivalent of $[La^-]_{net}$ ($2.7\ ml \cdot kg \cdot min^{-1}$) and M is the swimmer body mass in kilograms. Afterwards, these energy contributions were expressed in kJ assuming an energy equivalent of $20.9\ kJ \cdot L^{-1}$ [19]. The AnAL was estimated from the maximal phosphocreatine splitting in the contracting muscle, using this equation [25]:

$$\mathrm{AnAL} = \mathrm{PCr} \cdot (1 - e^{-t/\tau}) \cdot \mathrm{M} \qquad (3)$$

where PCr is the rest phosphocreatine concentration, t is the exercise time, τ is the PCr splitting time constant at exercise onset (23.4 s) and M is the body mass. Then, AnAL was expressed in kJ by assuming an energy equivalent of 0.468 kJ · mM and a phosphate/oxygen ratio of 6.25 [27]. C was obtained as the ratio between E and distance swam at 400 m front crawl pace [28]. Capillary blood samples (25 μL) were collected from the fingertip immediately after each trial (and at the 1, 3, 5 and 7 min of the recovery period) using a portable lactate analyzer (Lactate Pro analyzer, Arkray, Inc., Kyoto, Japan) to assess $[La^-]_{peak}$ [6,29]. In addition, immediately after each trial, swimmers rated their perceived exertion (RPE) on a Borg scale [24].

Stroke rate (SR) was obtained measuring three consecutive upper limbs cycles, stroke length (SL) was calculated from the ratio between v and corresponding SR [14] and stroke index (SI), a measure of swimming efficiency, was calculated by multiplying v by SL [19]. Finally, ηp was estimated as follow [30]:

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SR \cdot l) \cdot 2/\pi] \cdot 100 \quad (4)$$

where *l* is the distance between the shoulder and wrist during the insweep (with the hand situated exactly under the shoulder) Reference points were drawn at the shoulders, hips and wrists to allow a proper biomechanical analysis. The distance between the points were calculated with 2D motion analysis software Kinovea (version 0.8.15). For both upper limbs due to a mirror was use to digitalize the upper limb of the left side of the swimming flume.

Statistical Analysis

IBM SPSS Statistics (version 20, IBM SPSS, Chicago, USA) was used to data analysis, with Shapiro-Wilk confirming its normality and homogeneity. ANOVA repeated measures was computed to compare the three experimental conditions. Sphericity was verified by means of the Mauchly test and adjusted according to the Greenhouse-Geisser procedure when the significance of the F-ratios were not met. Bonferroni post hoc was performed to locate the pairwise differences between the means ($p < 0.05$) with 95% of confidence interval (CI). The Cohen´s *d* effect was calculated (0 to 0.19 trivial, 0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, 2.0 to 3.9 very large and > 4.0 nearly perfect) [6]. The relationships between the time endured in the different trials and the corresponding energetic contributions were assessed with Pearson correlations coefficients (r) and linear regression analysis.

Results

Comparisons between experimental conditions conducted at different temperatures and swimming suits at the 400 m front crawl pace are presented in Table 1. Bonferroni post hoc analysis showed that E was different between the three comparisons. Nevertheless, $\dot{V}O_{2peak}$, HR_{max}, $[La-]_{peak}$, C, Ap, SR, SL and SI were different in between 26 swimsuit and 18ºC swimsuit and between 18 swimsuit and 18ºC wetsuit conditions (Table 2). In Table 1 it could be observed the percentual contribution of each energy system for the overall swimming performance at each water temperature and suit condition. However, only the AnL contribution showed differences between 26 swimsuit and 18ºC wetsuit conditions (Table 2). Complementarily, in the 26ºC swimsuit condition, the time endured at the aerobic power pace was directly related with Aer ($r = 0.69$; $p < 0.001$; Figure 2, panel C) and inversely related with AnAL ($r = -0.62$; $p < 0.001$; Figure 2, panel A). No statistically relationships were observed between swimming performance and energetic contributions in the two other studied conditions (18ºC swimsuit and 18ºC wetsuit) as shown in Figure 2.

Table 1. Mean ± SD, effect sizes and power values of the comparison between the three conditions studied (n = 17).

	26º swimsuit	18ºC swimsuit	18ºC wetsuit	Time effect			
Variable	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	***F***	***P***	**Eta²**	**Power**
Time endured (s)	304.91 ± 78.38	330.83 ± 52.97	334.11 ± 52.13	1.58	0.22	0.09	0.31
v ($m\cdot s^{-1}$)	1.23 ± 0.21	1.23 ± 0.17	1.24 ± 0.21	0.44	0.55	0.03	0.10
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	47.70 ± 11.80†	44.70 ± 8.40β	39.10 ± 8.30†β	12.64	0.00	0.44	0.99
$\dot{V}E$ (l/min^{-1})	129.60 ± 31.10†	119.70 ± 32.70	101.00 ± 26.70†	9.08	0.00	0.36	0.96
$\Delta\dot{V}E$ (l/min^{-1})	125.80 ± 30.60†	114.90 ± 33.40β	95.10 ± 27.40†β	10.72	0.00	0.40	0.98
$[La^-]_{basal}$ ($mmol\cdot l^{-1}$)	2.25 ± 0.78	2.22 ± 1.08	2.18 ± 1.14	0.04	0.97	0.00	0.05
$[La^-]_{peak}$ ($mmol\cdot l^{-1}$)	10.25 ± 3.45†	7.99 ± 4.38β	5.21 ± 2.65†β	14.36	0.00	0.47	1.00
$\Delta[La^-]$ ($mmol\cdot l^{-1}$)	8.00 ± 3.53†	5.77 ± 4.39	3.03 ± 2.68†	12.57	0.00	0.44	0.99
RPE	7.12 ± 1.32*†	5.35 ± 1.73*	6.00 ± 2.09†	9.38	0.00	0.37	0.97
HR_{max} ($beats\cdot min^{-1}$)	181.88 ± 19.24†	182.88 ± 18.79β	154.18 ± 12.08†β	15.98	0.00	0.50	0.99
ΔHR ($beats\cdot min^{-1}$)	105.47 ± 18.39†	109.76 ± 21.71β	74.12 ± 15.14†β	21.32	0.00	0.57	1.00
RF ($breaths\cdot min^{-1}$)	57.98 ± 19.27	51.61 ± 13.92	51.43 ± 15.76	2.12	0.14	0.12	0.40
ΔRF ($breaths\cdot min^{-1}$)	50.63 ± 19.90†	43.33 ± 14.36	41.43 ± 16.12†	3.70	0.04	0.19	0.64
RER	1.20 ± 0.20	1.30 ± 0.30	1.20 ± 0.30	0.69	0.51	0.04	0.16
ΔRER	0.50 ± 0.20	0.40 ± 0.30	0.40 ± 0.30	2.34	0.11	0.13	0.44
AnAL (kJ)	29.25 ± 4.08	29.25 ± 4.09	29.25 ± 4.09	1.72	0.20	0.10	0.24
AnL (kJ)	31.72 ± 14.73†	23.06 ± 18.78	12.18 ± 11.01†	12.99	0.00	0.45	0.99
Aer (kJ)	309.47 ± 97.08	314.02 ± 66.20	273.59 ± 57.60	2.43	0.10	0.13	0.45
AnAL (%)	8.69 ± 3.38	8.20 ± 1.48	9.60 ± 2.43	1.98	0.16	0.11	0.38
AnL (%)	8.60 ± 3.54†	6.15 ± 4.15	3.88 ± 3.34†	12.20	0.00	0.43	0.99
Aer (%)	82.72 ± 5.38	85.65 ± 4.36	86.52 ± 4.63	4.23	0.02	0.21	0.70
E (kJ)	370.44 ± 105.88*†	366.34 ± 74.16*β	315.02 ± 60.71†β	4.20	0.02	0.21	0.70
C ($kJ \cdot m^{-1}$)	0.93 ± 0.26†	0.92 ± 0.19β	0.79 ± 0.15†β	4.20	0.02	0.21	0.70
Ap ($ml \cdot kg^{-1} \cdot min^{-1}$)	42.40 ± 12.30†	37.00 ± 5.90β	32.20 ± 6.80†β	15.87	0.00	0.50	0.99
TDp (s)	18.98 ± 8.35	18.02 ± 6.90	16.44 ± 0.79	0.70	0.51	0.04	0.16
τp (s)	25.20 ± 12.17	26.21 ± 17.60	23.55 ± 15.46	0.18	0.83	0.01	0.08
SR (Hz)	0.56 ± 0.08†	0.55 ± 0.07β	0.51 ± 0.07†β	19.99	0.00	0.56	1.00
SL (m)	2.25 ± 0.43†	2.28 ± 0.38β	2.48 ± 0.48†β	16.81	0.00	0.51	1.00
SI ($m^2\cdot s^{-1}$)	2.83 ± 1.04†	2.86 ± 0.84β	3.15 ± 1.17†β	8.45	0.00	0.35	0.95
ηp (%)	46.55 ± 8.96	45.90 ± 8.35	48.90 ± 10.93	3.16	0.06	0.16	0.56

Swimming speed (v), maximal oxygen consumption ($\dot{V}O_{2peak}$) ventilation ($\dot{V}E$), delta ventilation ($\Delta\dot{V}E$), basal blood lactate concentrations ([La-]basal), peak blood lactate concentrations ([La-]peak), delta blood lactate concentrations (Δ[La-]), Borg rating of perceived exertion scale (RPE), maximal heart rate (HR_{max}), delta heart rate (ΔHR), respiratory frequency (RF), delta respiratory frequency (ΔRF), respiratory exchange ratio (RER), delta respiratory exchange ratio (ΔRER), anaerobic alactic, anaerobic lactic and aerobic contributions (AnAL, AnL and Aer), total energy expenditure (E), energy cost (C), amplitude, time delay and tau of the oxygen consumption (Ap, TDp and τp), stroke rate, length and index (SR, SL and SI) and propelling efficiency (ηp). *,† and βDifferences between 26 vs 18ºC swimsuit, 26ºC swimsuit vs 18ºC wetsuit and 18ºC swimsuit vs wetsuit.

Table 2. Mean difference, coefficient intervals (CI) and effect sizes of the significant pairwise comparisons (n = 17).

Variable	Difference [95%CI]; %Δ	p	Effect size (d)
26 swimsuit vs 18ºC swimsuit			
RPE	1.76 [0.81, 2.72]; -24.79%	0.000	1.16, Moderate
E (kJ)	4.11 [-59.93, 68.14]; -1.11%	0.050	0.04, Trivial
26 swimsuit vs 18ºC wetsuit			
$\dot{V}O_{2peak}$ (mL · kg^{-1}· min^{-1})	8.62 [3.86, 13.39]; -18.07%	0.001	1.17, Moderate
VE (l/min)	28.57 [11.41, 45.73]; -22.05%	0.001	1.08, Moderate
ΔVE (l/min)	30.71 [14.05, 47.36]; -24.41%	0.000	1.20, Large
$[La^-]_{peak}$ (mmol·l^{-1})	5.04 [3.09, 6.99]; -49.2%	0.000	1.68, Large
$\Delta[La^-]$ (mmol·l^{-1})	4.97 [2.93, 7.02]; -62.13%	0.000	1.58, Large
RPE	1.12 [0.02, 2.21]; -15.7%	0.045	0.66, Moderate
HR_{max} (beats·min^{-1})	27.70 [14.60, 40.81]; -15.23%	0.000	1.37, Large
ΔHR (beats·min^{-1})	31.35 [16.95, 45.75]; -29.72%	0.000	1.41, Large
ΔRF (breaths·min^{-1})	9.2 [-0.26, 18.65]; -18.17%	0.050	0.63, Moderate
AnL (kJ)	19.54 [11.56, 27.52]; -61.6%	0.000	1.59, Large
AnL (%)	4.72 [2.24, 7.19]; -54.87%	0.000	1.24, Large
E (kJ)	55.42 [-1.25, 112.09]; -14.96%	0.050	0.63, Moderate
C (kJ · m^{-1})	0.14 [0, 0.28]; -14.96%	0.050	0.63, Moderate
Ap (ml · kg^{-1}· min^{-1})	10.1 [4.98, 15.23]; -23.86%	0.000	1.28, Large
SR (Hz)	0.05 [0.02, 0.08]; -8.68%	0.001	1.21, Large
SL (m)	-0.23 [-0.37, -0.1]; 10.39%	0.001	-1.11, Moderate
SI (m^2·s^{-1})	-0.32 [-0.51, -0.14]; 11.33%	0.001	-1.11, Moderate
18 swimsuit vs 18ºC wetsuit			
$\dot{V}O_{2peak}$ (mL · kg^{-1}· min^{-1})	5.62 [1.22, 10.03]; -12.57%	0.011	0.83, Moderate
ΔVE (l/min)	19.8 [0.44, 39.17]; -17.24%	0.044	0.66, Moderate
$[La^-]_{peak}$ (mmol·l^{-1})	2.79 [0.15, 5.43]; -34.88%	0.037	0.69, Moderate
HR_{max} (beats·min^{-1})	28.70 [11.24, 46.18]; -15.69%	0.001	1.07, Moderate
ΔHR (beats·min^{-1})	35.64 [18.24, 53.06]; -32.47%	0.000	1.33, Large
E (kJ)	51.31 [2.02, 100.6]; -14.01%	0.040	0.67, Moderate
C (kJ · m^{-1})	0.13 [0.01, 0.25]; -14.01%	0.040	0.68, Moderate
Ap (ml · kg^{-1}· min^{-1})	4.76 [2.09, 7.43]; -12.86%	0.001	1.16, Moderate
SR (Hz)	0.04 [0.02, 0.05]; -6.83%	0.000	1.86, Large
SL (m)	-0.2 [-0.31, -0.09]; 8.59%	0.001	-1.15, Moderate
SI (m^2·s^{-1})	-0.3 [-0.57, -0.02]; 10.34%	0.034	-0.70, Moderate

Borg rating of perceived exertion scale (RPE), total energy expenditure (E), Maximal oxygen consumption ($\dot{V}O_{2peak}$), ventilation ($\dot{V}E$), delta ventilation ($\Delta\dot{V}E$), peak blood lactate concentrations ([La-]peak), delta blood lactate concentrations (Δ[La-]), maximal heart rate (HR_{max}), delta heart rate (ΔHR), delta respiratory frequency (ΔRF), anaerobic lactic contribution (AnL), energy cost (C), amplitude of the oxygen consumption (Ap), stroke rate, length and index (SR, SL and SI).

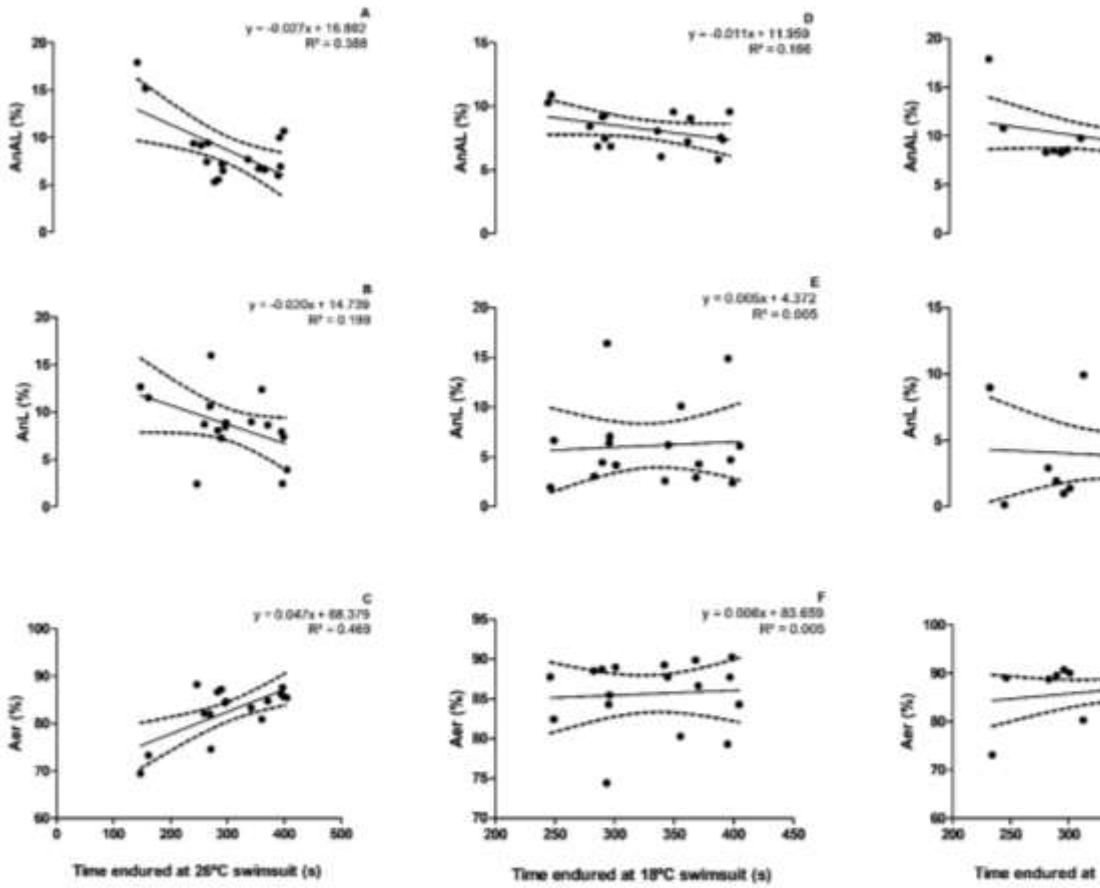

Figure 2. Relationships between the times endured on 400 m front crawl (at 26 and 18ºC with swimsuit energetic contribution percentages. Anaerobic alactic energy (AnAL; panels A, D and G); Anaerobic lactic and; Aerobic energy (Aer; panels C, F and I). Individual values (continuous lines) and 95% confidence inte (n = 17).

Discussion

The main aim of the current study was to assess relevant physiological and biomechanical variables while swimming to exhaustion at each individual 400 m front crawl pace (i.e., at the aerobic power intensity) using swim and wetsuits at typical and cold-water temperatures. Contrary to our expectation, swimming with a swimsuit at 18ºC did not increase swimmers physiological demands (even enduring 20-25 s longer) compared to performing at representative swimming pool water temperature (26ºC). In addition, as anticipated, swimming at 18ºC with swimsuit was less economic than with wetsuit (and lower physiological variables values and better technical characteristics were observed in this latter condition) accordingly with previous reports of better performances when wearing wetsuits [1,4,6].

As referred before, using a wetsuit at open water competitions with 18ºC water temperature is optional [9]. It is known that subjects submerged in cold-water suffer a cold-shock response that might lead to vasoconstriction and blood flow reduction [11], particularly when using regular swimsuits that do not give any relevant protection against low water temperatures. However, only RPE and E showed differences between the 26 and 18ºC swimsuit conditions. The reason might be that this water temperature was not sufficient to cause significant cold-shock responses and/or the exposure time was enough to reduce the metabolic responses of cold water (which is studied to be subsided after the first 5 min of immersion time [31]) and in the current study, the maximum time swam at 18ºC water temperature was ~6.40 min. Still, when using a wetsuit at 18ºC, an evident decrease of the cardiorespiratory and technical variables was found, evidencing that this condition required lower E and C values compared to 18º swimsuit as it can be observed in Table 2 ($p = 0.04$; $d = 0.67$ and $p = 0.04$; $d = 0.68$, respectively) (i.e., it was more economic than swimming with a swimsuit both at 26 and 18ºC).

Regarding oxygen kinetics at the primary cardiorespiratory response, it was observed that τ_p was > 20 s (as reported before [32]), with no differences between the three experimental conditions. TDp also was similar between conditions, with values ~10-20 s. However, the higher Ap values for the conditions 26ºC swimsuit vs 18ºC wetsuit and 18ºC swimsuit vs 18ºC wetsuit might indicate that the Aer contribution was accentuated by cold water and wetsuit use. In addition, the AnL contributions were higher at 26 compared to 18ºC wetsuit, in accordance with the $[La^-]_{peak}$ values, an indicator of anaerobic energy requirement [27]. This, plus the use of wetsuit in the cooler condition, might justify why swimmers were able to maintain the time endured in all experimental conditions. When swimming at 18ºC without wetsuit, swimmers maintained the pace eventually due to the cold-shock response that lead to higher HR_{max} values [11].

In fact, when wearing a wetsuit, swimmers lower limbs sinking torque is less expressive, decreasing their hydrodynamic drag and, consequently, the C for the same speed [33]. This was observed in the current study with a SL and SI increment (and a SR decrease) at the 18ºC wetsuit condition even if usually the wetsuit thickness limits the shoulder range of motion leading to a SR increase [34]. This is in line with previously reported data when using a wetsuit comparing to swimsuit in a flume at the aerobic power intensity [6]. As time to exhaustion at $\dot{V}O_{2max}$ is directly influenced by C, SL and SI [17,18,33], the lower values in time endured at 26ºC swimsuit seems to express that swimmers experienced it as the most difficult metabolic and technical condition. This can be observed by the higher RPE, $[La^-]_{peak}$, $\dot{V}O_{2max}$ and SR values (also with higher values of power), although the learning effect might also influenced the results since the warmer condition was performed first.

In accordance with these data, a swimming efficiency rise at the 18ºC wetsuit exertion was expected. However, when comparing the ηp at the different conditions, the p value although very close to 0.05 fell short of statistical meaning (with lower eta^2 and power). This might be justified by methodological constraints, particularly by the fact that the ηp calculation was limited to the SR, neither considering technical aspects responsible for propulsion nor thrust-producing vortices. Complementarily, the lower values of *l* might have induced higher efficiency values [30], for which the swimming ability is an important factor. Eventually, if another ηp assessment method was used (e.g., by assessing the ratio of the speed of the center of mass to three dimensional speed of the right and left upper limbs during underwater phase [29]) the results might be different.

It is also important to highlight that, even if a swimming flume allows to better set and control the swimmers pace, it has some specificities that might influence both physiological and biomechanical variables. In fact, the hydrodynamic resistance that swimmers need to overcome is different from free swimming due to its non-laminar water flow, consequently influencing swimmers technique and E [6,16]. The higher the water temperature, the lower the water density and, consequently, the lower the hydrodynamic resistance [35]. However, at higher temperatures the body temperature increases, and more energy requirement might be necessary for self-regulation, probably explaining the higher energetics requirement values at the 26ºC condition.

Furthermore, flume swimming does not include the start and turn phases, which might also influence swimmers E comparing to swimming in a pool. However, these swimmers participate in open water and triathlon competitions hence, swimming in a flume might replicate real swimming events. In addition, though our swimmers had considerable experience using the swimming flume and the breathing snorkel, we could accept that their technique might be affected and, in consequence, their energy requirements could be different from swimming unimpeded in a pool, but as the aim of the study is related to open water, the used of a swimming flume could be a more ecologically valid method to measure continuous swimming than swimming pool. In conclusion, when using a wetsuit at 18ºC, an evident decrease of the cardiorespiratory and technical variables was found, demonstrating that this condition require lower E and C values. Thus, it was more economic than swimming with a swimsuit both at 26 and 18ºC. The results suggested that the use of wetsuit might increase performance at 18ºC water temperature for competitive master swimmers.

Practical applications

The current study underscored the importance of using wetsuits at 18 °C for open water swimming competitions, since it allows for better technique and economy of effort (compared to wearing a swimsuit), meaning that for the same energy input its use enables better performance. Also, since the anaerobic threshold pace happens at ~90 % of the 400-m intensity [18, 19], the physiologic and biomechanical variable values displayed in our study could be useful for evaluating the open water swimmer and triathletes' performance, which typically happens below or at that boundary [14, 15]. Notwithstanding the swimming flume particularities (that should be considered when analyzing data), its use makes the process of evaluating swimmers easier in both physiologic and biomechanical areas. For this reason, swimmers in general (and open water specialists, in particular) should use it on a regular basis as a followup to their training process.

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Conflict of interest

Authors have no conflict of interest to report.

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CHAPTER 7: Acute effects of water temperature in swimming performance: a biophysical analysis

CHAPTER 7: Acute effects of water temperature in swimming performance: a biophysical analysis

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Abstract

The aim of the current study was to explore the acute biophysical effects of different water temperatures in swimming. Ten male swimmers (28.20 ± 13.15 years old) completed two front crawl time-trials in a flume (24 h rest in-between) at 18 and 26ºC water temperature, both without wetsuit. The speed was common at both conditions and established according to a 400 m pre-test in a 25 m swimming pool (1.28 ± 0.13 $m \cdot s^{-1}$). The peak oxygen uptake $(\dot{V}O_{2peak})$, maximal heart rate (HR_{max}), blood lactate concentrations ([La-]), energy cost (C) and energy expenditure E were assessed. Stroke rate (SR), stroke length (SL), stroke index (SI), propelling efficiency (ηp) and the Borg rating of perceived exertion scale (RPE) were calculated. Pair Student's t-test was computed to compare both conditions. Time endured and $\dot{V}O_{2peak}$ were similar for 18 and 26ºC conditions (313.44 ± 40.10 vs 282.27 ± 58.61 s; mean difference: 31.16 s; 95% CI: -32.12 to 94.45 s; p = 0.294; 47.54 ± 7.93 vs 51.91 ± 12.49 $mL \cdot kg{-}1 \cdot min^{-1}$; mean difference: -4.37 $mL \cdot kg{-}1 \cdot min^{-1}$; 95% CI: -10.10 to 1.37 s; p = 0.119). However, lower $[La\text{-}]_{peak}$ (7.46 ± 3.33 vs 11.40 ± 1.58 $mmol \cdot l^{-1}$; p = 0.002; Cohen's d: -1.42) and RPE (5.10 ± 1.91 vs 7.10 ± 1.29; p = 0.001; Cohen's d: -1.60) values were observed at 18ºC. The aerobic contribution (Aer) was higher (86.20 vs 81.90%; p = 0.037; Cohen's d: 0.77) and anaerobic lactic (AnL) influence lower (5.80 vs 9.82%; p = 0.001; Cohen's d: -1.46) when swimming at 18ºC, but E (383 ± 60 vs 397 ± 98 kJ) and C (0.96 ± 0.15 vs 0.99 ± 0.25 $kJ \cdot m^{-1}$) remained similar within conditions. Furthermore, swimming at 18 and 26ºC was not different from a general kinematical point of view (SR: 0.54 ± 0.04 vs 0.55 ± 0.06 Hz; p = 0.115; Cohen's d: -0.55; SL: 2.39 ± 0.20 vs 2.32 ± 0.20 m; p = 0.176; Cohen's d: 0.46; SI: 3.06 ± 0.53 vs 2.96 ± 0.44 $m^2 \cdot s^{-1}$; p = 0.145; Cohen's d: 0.50 and ηp: 47 ± 4.7 vs 48 ± 6.4%; p = 0.325; Cohen's d: -0.33). The tendency for lower values at 18ºC are not in agreement with the literature and could be affected by the reduction of the blood flow volume in cold water and also due to methodological issues, particularly the learning effect regarding the use of the flume and breathing apparatus.

Keywords: Physiology, biomechanics, swimming flume, cold water.

Introduction

Open water swimming events take place in rivers, lakes and water channels [1], with wetsuits being mandatory when water temperature is < 18ºC and optional between 18 and 20ºC [2]. When swimming in cold water swimmers suffer a cold-shock response characterized by a 1 to 3 min hyperventilation and tachycardia besides an inspiratory gasp [3]. Despite that, open water swimmers should have the ability to swim long distances at 80-90% of maximal oxygen uptake ($\dot{V}O_{2max}$), requiring a high propelling efficiency and a low energy cost to maintain that intensity [4].

Another recent study showed that maximum respiratory frequency (beats·min^{-1}) and average heart rate (HR) were higher when swimming 200 m front crawl at 10 than at 28ºC, and the time to reach the maximal HR (HR_{max}) was shorter, regardless the swimming expertise level [5]. These results suggested that swimming after the cold-shock response required a higher energy expenditure (E) than at temperate conditions.

Elite open-water swimmers are anthropometrically lighter and smaller compared to the swimming pool counterparts [6], possessing relevant aerobic metabolic characteristics that enhances long-distance swimming performances. This study aimed to clarify swimmers physiological and technical behavior at different water temperatures, by analyzing some relevant front crawl biophysical related variables at cold and temperate water temperatures. We hypothesized that swimming at 18ºC would produce an increment on physiological demands and reduce swimming efficiency comparing to performing at 26ºC.

Methods

Participants

Ten male swimmers 28.2 ± 13.1 years old, 175.9 ± 5.1 cm of height and 72.4 ± 9.4 kg of body mass participated voluntarily in this study. All were engaged in a six to seven weekly training frequency and had 77.9 ± 11.6% of the 100 m front crawl world record as personal best. Participants provided written informed consent and the Institutional Ethical Review Board approved the study design (which has been performed according to the Code of Ethics of the World Medical Association - Declaration of Helsinki).

Design

Two front crawl time-trials in a flume (24 h rest in-between) at 18 and 26ºC water temperature were performed at a common speed (1.28 ± 0.13 $m \cdot s^{-1}$) obtained during a 400 m pre-test in a 25 m swimming pool. All participants performed firstly the 26ºC trial due to swimming flume constraints (the water temperature was lowered afterwards). They abstained taking caffeinated drinks and practicing exhausting exercise during the testing days. Before testing, an individual warm-up of 15 min of low to moderate intensity was conducted, followed by 10 min of passive rest (ensuring that previous exercise had no influence on testing performances) [7]. Participants had previous experience in performing in the swimming flume.

Methodology

Respiratory and pulmonary gas-exchange variables were directly measured using the $K4b^2$ breath-by-breath portable gas analyzer attached to an Aquatrainer® respiratory snorkel and valve systems (Cosmed, Rome, Italy) [8], as displayed in Figure 1. An underwater camera (Panasonic Full-HD HX-A500, Osaka, Japan) working at 50 Hz was located on the sagittal plan of the swimmers displacement in the center of both pools (12.50 and 2.35 m in swimming pool and flume, respectively) to analyze technical variables. A 5 and 1 m long pre-calibrated spaces situated in the center of the swimming pool and swimming flume (respectively) were used as a reference for video analysis. The swimming flume (Endless Pool Elite Techno Jet Swim 7.5 HP, Aston PA, USA) was 2.4 x 4.7 m of length, with flow velocity measured at 0.30 cm depth using an FP101 flow probe (Global Water, Gold River, CA) [9].

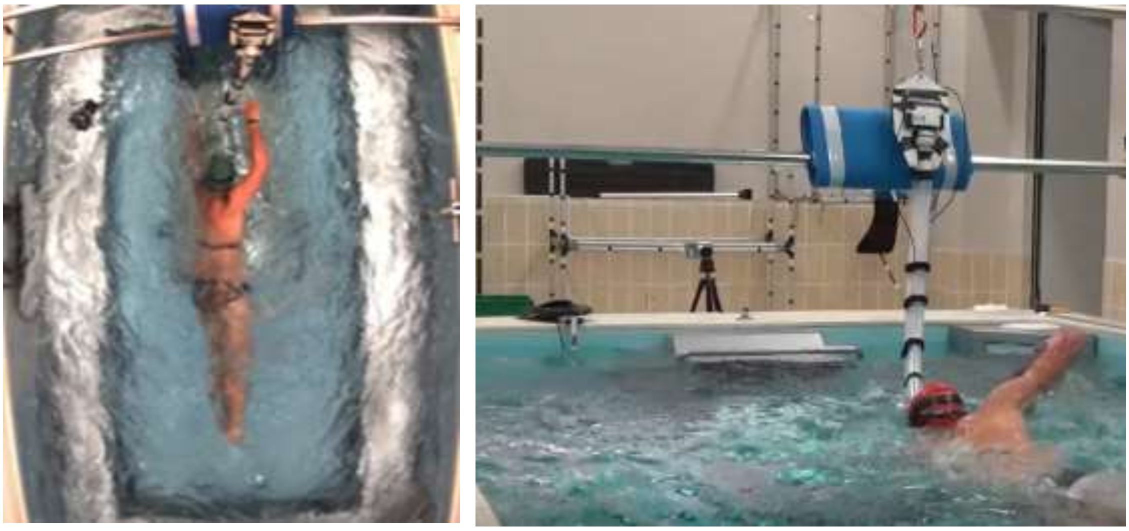

Figure 1. Swimmer using an Aquatrainer® respiratory snorkel attached to the K4b^2 portable gas analyzer.

Data analysis

A mono-exponential model fitting was used for treating the $\dot{V}O_2$ data. E was obtained through the addition of the net $\dot{V}O_2$ and blood lactate concentration ([La-]) values, with energy cost (C), i.e., the energy expended to cover one-unit distance at a given speed [4] determined by dividing E to swimming distance. HR was monitored and registered through a HR monitor system (Polar S610i, Finland), with HR_{max} obtained from the average of the last 30 s of the effort (the same procedure was used to obtain $\dot{V}O_{2peak}$ and the maximal respiratory exchange ratio - RER).

Capillary blood samples (25 μL) for [La-] analysis were collected from the fingertip immediately after the trial and at the 1, 3, 5 and 7 min during the recovery period using a portable lactate analyzer (Lactate Pro, Arkray, Inc., Kyoto, Japan) to find the maximal [La-] ($[La\text{-}]_{peak}$). Immediately after the trials, participants pointed out the Borg rating of perceived exertion scale (RPE) [10].

Swimming velocity was computed in the middle of every 100 m of the 400 m pre-test to obtain the mean velocity and adjust it afterwards during the swimming flume trials. Stroke rate (SR) was obtained measuring three upper limbs cycles and subsequently stroke length (SL) and stroke index (SI) were calculated. Propelling efficiency (ηp) was estimated according with Zamparo et al. as follow [11]:

$$\eta_p = [(v \cdot 0.9 / 2\pi \cdot SF \cdot l) \cdot 2/\pi] \cdot 100 \quad (1)$$

where *l* is the distance between the shoulder and wrist during the in sweep. Reference points were drawn at the shoulders, hips and wrists to help the analysis of the technical variables.

Statistical analysis

Using the IBM SPSS Statistics (Version 20, IBM SPSS, Chicago, USA), pair Student's t-test was computed to compare physiological and technical variables at different water temperature conditions, and Bonferroni post hoc procedures performed to locate the pairwise differences between the means ($\alpha = 0.05$). Cohen's d effect was calculated with the following criteria: 0 to 0.19 trivial, 0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, 2.0 to 3.9 very large and > 4.0 nearly perfect [12].

Results

Data concerning physiological and technical variables are presented in Table 1. Times endured in the swimming flume were similar for 18 and 26ºC condition and also the physiological variables $\dot{V}O_{2peak}$, HR_{max}, RER, E and C. Nevertheless, $[La\text{-}]_{peak}$ and RPE were lower in the 18ºC condition which explains the lower anaerobic lactic contribution (AnL) at this colder temperature. Swimming at 18 and 26ºC was not different from a general kinematical point of view, with similar SR, SL and SI values, and also regarding ηp.

Table 1. Changes in the physiological and technical variables at 18 and at 26ºC trials.

Variable	18ºC	26ºC	t-test (p)	Difference [95%CI]; %Δ	Effect size (d)
Time endured (s)	313.44 ± 40.10	282.27 ± 58.61	0.294	31.16 [-32.12, 94.45]; -10%	0.35, Small
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	47.54 ± 7.93	51.91 ± 12.49	0.119	-4.37 [-10.10, 1.37]; 9.2%	-0.54, Small
$[La^-]_{peak}$ ($mmol \cdot l^{-1}$)	7.46 ± 3.33	11.4 ± 1.58	0.002	-3.94 [-5.92, -1.96]; 52.8%	-1.42, Large
RPE	5.10 ± 1.91	7.10 ± 1.29	0.001	-2 [-2.89, -1.11]; 39.2%	-1.60, Large
HR_{max} ($beats \cdot min^{-1}$)	164.65 ± 9.99	171.18 ± 11.61	0.081	-6.53 [-14.03, 0.98]; 4%	-0.62, Moderate
HR_{max} (%)	87.6 ± 6.3	91.1 ± 8	0.084	-3.53 [-7.64, 0.58]; 4 %	-0.61, Moderate
RER	0.98 ± 0.08	1.03 ± 0.08	0.139	-0.05 [-0.12, 0.02]; 5.3%	-0.51, Small
AnAL (kJ)	30.09 ± 3.89	30.09 ± 3.88	0.425	0.01 [-0.01, 0.02]; -0.02 kJ	0.26, Small
AnL (kJ)	22.54 ± 17.28	38.01 ± 11.14	0.001	-15.46 [-22.92, -8]; 68.6%	-1.48, Large
Aer (kJ)	330.60 ± 57.12	329.29 ± 94.81	0.971	1.32 [-78.87, 81.51]; -0.4 kJ	0.01, Trivial
AnAL (%)	8 ± 1.44	8.28 ± 3.64	0.806	-0.28 [-2.81, 2.24]; 3.5 %	-0.08, Trivial
AnL (%)	5.80 ± 4.05	9.82 ± 2.63	0.001	-4.02 [-6, -2.05]; 69.4%	-1.46, Large
Aer (%)	86.20 ± 4.69	81.9 ± 5.60	0.037	4.30 [0.32, 8.28]; -5%	0.77, Moderate
E (kJ)	383 ± 60	397 ± 98	0.712	-14.14 [-98.15, 69.87]; 3.7%	-0.12, Trivial
C ($kJ \cdot m^{-1}$)	0.96 ± 0.15	0.99 ± 0.25	0.698	-0.04 [-0.25, 0.17]; 3.9%	-0.13, Trivial
SR (Hz)	0.54 ± 0.04	0.55 ± 0.06	0.115	-0.02 [-0.04, 0.01]; 3.4%	-0.55, Small
SL (m)	2.39 ± 0.20	2.32 ± 0.20	0.176	0.07 [-0.04, 0.18]; -3%	0.46, Small
SI ($m^2 \cdot s^{-1}$)	3.06 ± 0.53	2.96 ± 0.44	0.145	0.10 [-0.04, 0.24]; -3.2%	0.50, Small
η_p (%)	47 ± 4.7	48 ± 6.4	0.325	-1.07 [-3.38, 1.25]; 2.3%	-0.33, Small

Peak oxygen uptake ($\dot{V}O_{2peak}$), peak blood lactate concentrations ($[La^-]_{peak}$), Borg rating of perceived exertion scale (RPE), maximal heart rate (HR_{max}), percentage of HR_{max} ($HR_{max;}$ %), respiratory exchange ratio (RER), anaerobic alactic (AnAL), anaerobic lactic (AnL), aerobic (Aer), energy expenditure (E), energy cost (C), stroke rate (SR), stroke length (SL), stroke index (SI), propelling efficiency (η_p).

Discussion

The current study aimed to evaluate the biophysical effects of cold and temperate water temperatures (18 and 26ºC, respectively) in front crawl swimming. 18ºC is the temperature that swimmers have to decide whether to use or not the wetsuit in open water swimming events. We have observed a statistically non-significant difference in the swimming time although a difference of 31 s was evident between conditions. Data showed that swimming at 18ºC without a wetsuit might influence the 400 m front crawl performance as lower $[La\text{-}]_{peak}$ and RPE were observed. Although $\dot{V}O_{2peak}$, HR_{max} and RER did not evidence statistical differences when swimming in cold and temperate waters, a tendency for higher values were observed at 26ºC (it was found ~9, 4 and ~5% differences for $\dot{V}O_{2peak}$, HR_{max} and RER, respectively). Technique related variables showed a similar behavior within conditions without statistically differences found for SR, SL, SI and ηp.

These unexpected results may be due to a water temperature of 18ºC not being sufficiently cold to elicit a cold-chock response. In fact, temperatures cooler than 15ºC are usually utilized for this kind of studies. In addition, there is still a lack of information about the physiological responses while swimming in cold waters because the majority of the studies focus on cold water immersion after exercise rather than performing on it (see Bleakley and Davison, and Broatch et al., for a review on the topic [13,14]).

Ferrara et al., investigated how muscle contraction requires less oxygen at 25ºC than at 37ºC [15]. Although this study was not with humans, it could support how lower values were obtained in cold water in the current study. Besides the fact that a vasoconstriction appeared as a consequence of the cold exposure which reduced the blood flow volume [16]. As a result, [La-] production and AnL may have been influenced by the cold water.

Another justification for the obtained values may be related to the methodological issues, particularly the eventual learning effect regarding the use of the flume, which could induce some mechanical constraints when swimming in that pool for the first times [17]. In fact, although swimmers had an experimental period of adaptation in the swimming flume, their technique could be affected in their first test condition (at 26º) and, in consequence, their energy requirements could be increased as confirmed by AnL values. The use of the Aquatrainer® respiratory snorkel (see Ribeiro et al., for a detailed description [8]) with non-elite swimmers might also justify the obtained data.

In the future, we will try to overcome these limitations using a randomized and counterbalanced testing order and select a higher sample size with best prepared and experienced swimmers. As swimming front crawl at 18ºC has a significant importance for open water (and triathlon) training and competition, future studies should also consider testing both physiological and biomechanical variables and swimming with and without a wetsuit to clarify whether its use is recommended or not with the objective of benefiting from it when its use is elective (between 18 and 20ºC).

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CHAPTER 8: Physiology and biomechanics to determine the effect of wetsuit speedo Thinswim® when swimming in a cold-water flume

CHAPTER 8: Physiology and biomechanics to determine the effect of wetsuit speedo Thinswim® when swimming in a cold-water flume

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Introduction

To avoid hypothermia, the Fédération Internationale de Natation (FINA) allows the use of wetsuit in swimming events when the water temperature is between 16 to 20ºC. However, improvements in performance produced by the wetsuit use in different distances highlights the importance in selecting the wetsuit according to thickness and fabric [1,2]. The purpose of the current study was to assess the biophysical comparison between the wetsuit Speedo Thinswim® (2 mm of thickness in upper limbs, trunk and lower limbs, Nottingham, United Kingdom) and a training swimsuit when swimming in at 18ºC water temperature.

Methods

Four male swimmers (age: 22.2 ± 4.1 years; height: 180 ± 0.04 cm; body mass: 79.4 ± 10.3 kg; arm spam: 191 ± 11 cm; 400 m freestyle personal best time: 78 ± 6% of the World Record) performed two front crawl trials at 18ºC (with wetsuit and swimsuit) in the swimming flume (randomized order; 24 h rest in-between), with swimmers 400 m front crawl best time (298 ± 54 s) and respective mean swimming speed (v, 1.44±0.33 m·s-1) being used for define the swimming flume trials. Peak oxygen uptake ($\dot{V}O_{peak}$) and minute ventilation ($\dot{V}E$) were assessed breath-by-breath using a telemetric portable gas analyzer and snorkel ($K4b^2$ + AquaTrainer®; Cosmed, Rome, Italy), with maximal heart rate (HR_{max}; Polar Electro Oy, Kempele, Finland), peak blood lactate concentrations ([La-]; Lactate Pro analyzer, Arkray, Inc., Kyoto, Japan) and rate of perceived exertion (RPE) being obtained. Oxygen consumption ($\dot{V}O_2$) data were modelled using the mono-exponential model with VO_2FITTING [3]. Thus, energy cost (C) and energy expenditure (E) were obtained. Stroke rate (SR), stroke length (SL), stroke index (SI) and propelling efficiency (ηp) were calculated.

Results

No differences were found on $\dot{V}O_{peak}$ (wetsuit Speedo Thinswim®: 53.3 ± 11.4 vs swimsuit: 51.8 ± 3.0 $mL\cdot kg^{-1}\cdot min^{-1}$, p = 0.80, Cohen‘s d: 0.14), $\dot{V}E$ (104 ± 32 vs 107 ±

23 l·min^{-1}, p = 0.67, d: -0.23), C (0.8 ± 0.13 vs 0.85 ± 0.2 kJ · m^{-1}, p = 0.33, d: -0.57), E (318 ± 53 vs 340 ± 78 kJ, p = 0.33, d: -0.57), HR_{max} (145 ± 17 vs 173 ± 37 beats·min^{-1}, p = 0.16, d: -0.93) and [La-] (4.1 ± 3.4 vs 6.4 ± 6.6 mmol·l^{-1}, p = 0.26, d: -0.68). Regarding biomechanics, ηp was higher while using wetsuit (67 ± 14 vs 56 ± 15%, p = 0.046, d: 1.65), while SR (26.2 ± 3.27 vs 28.26 ± 3.43 cycles·min^{-1}, p = 0.20, d: -0.82), SL (3.3 ± 0.6 vs 3.0 ± 0.7 m, p = 0.14, d: 0.99) and SI (4.90 ± 1.86 vs 4.25 ± 1.69 m^2·s^{-1}, p = 0.21, d: 0.78) were similar between conditions.

Conclusion

Although the similar physiological and technical values found, the higher value on ηp using the wetsuit Speedo Thinswim® could be due to due to the low wetsuit thickness studied besides the reduction on hydrodynamic drag, inducing in a decrease in energetic contributions, thus higher velocity might be reached with the same effort on 400 m front crawl.

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CHAPTER 9: General discussion

CHAPTER 9: General discussion

The current Doctoral Thesis contributes to a better understanding of the effect of the wetsuit use while swimming 400 m front crawl (compared to swimsuit), assessing the issues raised by the systematic review (**Chapter 3**). In addition, we address relevant gaps that have been unperceived so far in scientific literature in swimming while using wetsuit. Of note, the specificity and research constraints that arise in the different assessment conditions of swimming tests to obtain data for certain parameters, such as analysis of respiratory exchanges, $\dot{V}O_{2max}$ and energetic contributions.

The effect of wetsuit in swimming performance as a function of the type of suit and swimmer

As mentioned in **Chapter 1**, there are different types of wetsuits on which research has focused over the years (Figure 1). The most studied model has been the full body [1,2], followed by the sleeveless long [3,4] and sleeveless short wetsuits [5] (Table 2 of **Chapter 3**). Although the wetsuit models studied are different (Table 4 of **Chapter 3**), the thickness complies with both FINA and ITU competition regulations in all cases (5 mm maximum thickness) [6,7]. As discussed in that chapter, though the sleeveless long wetsuit improves swimming performance compared to the full body wetsuit, it is the latter which improves performance the most respect to the swimsuit. The full body wetsuit shows an enhancement on front crawl swimming performance from 3.23 to 12.9% in distances from 25 to 1500 m, incremental tests, continuous swimming of 5 and 30 min and in open water swimming events [2,4,8]. Due to these results, full body wetsuit was consider for study throughout this Doctoral Thesis.

Observable differences between swimmers and triathletes have been discussed in the literature [1,2]. On the one hand, studies report that swimmers feel discomfort in the shoulder joint when swimming with wetsuit, therefore it is concluded that sleeveless long or short wetsuits helps them more than triathletes [2,4,9] and, different results were obtained in swimming performance comparing swimmers with triathletes using the same suit [1,2]. These results are likely to be more observable when swimmers are pool specialists rather than open water swimmers (more accustomed to wearing wetsuit). However, only two studies of the 23 included in the systematic review (**Chapter 3**) compared the effects of wetsuit between swimmers and triathletes [1,2]. Hence, more studies are needed to clarify the differences between these athletes, especially between specialists of open water swimming and triathletes.

As we have seen in **Chapter 3**, the distances used for assessing the effect of the wetsuit use vary from 23 m to 30 min continuous in swimming pool trials [3,10,11], from 5 min to 400 m, including continuous progressive swimming test in a swimming flume [5,12] and also analyzing open water swimming competitions [13,14] (see Table 2 of **Chapter 3**). This lead to the conclusion that there is no standard distance to evaluate the effect of the wetsuit use in swimming, which is understandable due to the wide range of distances; for open water swimming the FINA regulations allow the use of wetsuits in 5, 10 and 25 km [6] and from 250 to 3900 m according to the ITU triathlon regulations [7]. Therefore, for research in this area, should be evaluated a distance which represents the continuous swimming speed at an intensity above the lactate threshold, which elicits the velocity at $\dot{V}O_{2max}$ [15] (see below). It is the point at which blood lactate first starts to rise during incremental exercise [16], thus exercise below lactate threshold correspond to any domain in which a classical steady state is achieved.

The distance assessed and the study environment

In **Chapter 4**, the first swimming trials were carried out with wetsuit in both the 25 m swimming pool and in the swimming flume to analyze the effect of the wetsuit use compared to swimsuit. As a result of $\dot{V}O_2$ kinetics, four intensity domains have been predefined by incremental tests [17,18]: i) low-moderate: intensities under lactate threshold, distances covered in 30 minutes or more; ii) heavy: intensities above lactate threshold but below the swimming velocity that allows $\dot{V}O_{2max}$, distances covered in maximum 15 min (e.g., 800 and 1500 m); iii) severe: intensities corresponding at $\dot{V}O_{2max}$, distances covered in about 3-6 min (e.g., 400 m); and iv) extreme: intensities above $\dot{V}O_{2max}$ during ≤ 2 min (e.g., 200, 100 and 50 m). We have focused on the severe intensity domain as it corresponds to the speed that elicits $\dot{V}O_{2max}$, pace that characterize long distance events and the steady state is delayed [18,19]. It has been studied how in the last step of the 7 x 200 m incremental test (usually used as the gold standard in swimming to obtain the velocity to $\dot{V}O_{2max}$) [15,20,21], physiological and biomechanical results are similar to those obtained in a 400 m front crawl. Thus, 400 m distance as a valid indicator of aerobic power, can be used to study the effect of wetsuit use in swimming [22].

The use of the swimming flume has made possible to simulate the continuous swimming without turns characteristic of open water and triathlon swimming and differences were found between swimming in the 25 m pool and in the swimming flume and between both suits (wetsuit and swimsuit) in this thesis. Firstly, it was corroborated, as previously studied, how swimmers increase their swimming speed by 0.07 $m \cdot s^{-1}$ with wetsuit compared to conventional swimsuit, resulting in a 6% of improvement on 400 m front crawl performance, which correspond to a 20.1 s of advantage (**Chapter 4**). Although physiological variables were similar between suits in both pools, SL and SI were higher while using wetsuits in both pools. On the contrary, swimming in the flume instigate a reduction in physiological responses (i.e., HR_{max} and $[La-]_{peak}$) compared to the 25 m pool and using both suits. As discussed in that study, the reduction in SR and the increase in SL might explain the increase in efficiency with the use of wetsuit [23-25].

Subsequently, the aim was to investigate further how the biomechanical, physiological and anthropometric variables, including age, could interfere in the improvement produced by the wetsuit in swimming performance and it was establish an explanatory model for this improvement in **Chapter 5**. Although physiological variables do not explain the improvement in timed improved on 400 m front crawl while using wetsuit, the biomechanical parameters, specifically the stroke rate (SR), justifies this change (the greater the SR, the greater the improvement with wetsuit). The increase in SR due to the enhancement in buoyancy provided by the neoprene material [26] and also the elevated SR to reach higher swimming paces with the same stroke length (SL) might justify this results [27]. Besides, the influence of the wetsuit thickness is a factor that affects the improvement in performance but differently for men (upper limbs) and women (lower limbs), which is related to their higher fat mass [13]. Finally, it was concluded that the older the swimmer, the greater the improvement as the results showed, which might be related to the swimming experience with wetsuit.

Oxygen consumption and the influence of water temperature on the use of the wetsuit on swimming performance

The inclusion of further physiological analysis in the subsequent studies allows to clarify additional concepts derived from the systematic review conducted (**Chapter 3**). In this physiological context, it is important to clarify several concepts. Firstly, the importance of oxygen consumption ($\dot{V}O_2$) measurement in sport, specifically in swimming. Since, the main representative measure of cardiorespiratory fitness is $\dot{V}O_2$ [28], it might determine performance in sport. As defined, $\dot{V}O_2$ refers to how much oxygen (O_2) our body absorbs, transports and consumes and therefore, $\dot{V}O_{2max}$ is the maximum amount of O_2 that the body is able to absorb, transport and consume per unit of time, usually expressed in absolute units (ml·min) or relative units (ml·kg·min). The Fick equation shows the following [29]:

$$\dot{V}O_{2max} = Q \cdot (Ca_2 - CvO_2) \qquad (1)$$

where Q is the cardiac output expressed the product of HR and stroke volume, CaO_2 and CvO_2 are the O_2 content of the arterial and venous blood, respectively. Hence, when the intensity increases with exercise, stroke volume increases and therefore higher HR will be observed. In short, an indicator parameter of the functional capacity of aerobic power is $\dot{V}O_{2max}$ and thus, the aerobic performance limitations is the ability to obtain O_2 from the tissues, being $\dot{V}O_2$ the most representative measure for this [28], justifying the use of this variable in the analysis of swimming performance while using wetsuit. Complementarily, the study of [La-], which represents balance between lactate appearance and lactate clearance [16] and the HR_{max} which show a kinetics similar to $\dot{V}O_2$ [30], completed the information on the swimming energetics with and without a wetsuit and at different water temperatures.

In relation to **Chapters 6** and **7**, the study of the energetic variables and swimming in cold water (18ºC) are the most important issues to highlight. Firstly, as discussed in the cited chapters, immersion in cold water produces physiological responses caused by the thermal shock between the water and the body temperature [31]. Initially, the first studies were carried out to determine the temperatures above which the use of wetsuit should be mandatory in open water and triathlon events [32]. However, at present there are no studies in the literature that indicate how the use of wetsuit, within a temperature range optional by the different federations [6,7], can be used as a strategy during competition, which is of utmost importance for training. Furthermore, studies concerning swimming and cold water are not focused on swimming, but on immersion [33,34].

In **Chapter 6** it has been concluded that the use of wetsuit is recommended when the temperature is between 18 and 20ºC (permitted by FINA [35]). This is because although swimmers did not increase their physiological demands by swimming without wetsuit, it was less economical than swimming with wetsuit due to lower physiological values were found and better technical characteristics were observed while swimming with wetsuit in cold water compared to 26ºC. The justifications are mainly based on the buoyancy provided by the neoprene material itself, hydrodynamic drag is reduced and, as a result, greater swimming efficiency is achieved, resulting in a reduction of physiological variables and, consequently, lower C [26]. Furthermore, in **Chapter 7**, where no wetsuit was used, lower values of [La-] and energy expenditure (E) were obtained while swimming at 18ºC, suggesting that lower temperatures might not produce elevated physiological responses during a severe intensity test (400 m front crawl), contrary to as studied [36,37]. Thus, swimming at 18°C might be adequate to benefit from the wetsuit properties with no physiological alterations that may impair performance.

Using the same methodology, in **Chapter 8** it was studied the physiological and biomechanical effects of swimming with the wetsuit Speedo Thinswim®, which was 2 mm of thickness in both upper and lower limbs and trunk. Comparisons between this specific wetsuit and a swimsuit while swimming at 18ºC showed similar values for all variables and both suits, except for propelling efficiency (ηp), with higher values with the use of the wetsuit. This result is probably due to the reduction of the hydrodynamic drag due to the buoyancy produced by the neoprene fabric. It might lead to an increase in swimming velocity and, therefore, an improvement in performance on 400 m crawl could be reached with the wetsuit Speedo Thinswim® [38]. Altough np estimation is limited to the swimming hand velocity ratio, without considering related propulsion components such as drag, ligt and vortex forces [39]. However, this specific wetsuit is one of many that exist and not one of the most commonly used in open water swimming competitions [9]. Hence, it simply shows an approach to this specific model, which is characterized by its thinness, which should avoid the shoulder discomfort and constraints most often experienced by swimmers [2,4,9].

Main limitations

Several strengths and limitations have been specifically noted for each study throughout the different chapters of the current Doctoral Thesis. Nonetheless, there are general limitations which deserve more attention:

- Further assessment of anthropometry (i.e., girths, breadths, body composition and somatotype) could provide more information that could be relevant to establish relationships with improvement in performance with the wetsuit use (**Chapter 5**).

- The hydrodynamic resistance that swimmers need to overcome in the swimming flume is different from free swimming due to its non-laminar water flow, consequently influencing swimmers technique and E. Although the swimming flume allows to better set and control the swimmers pace, it has some specificities that might influence both physiological and biomechanical variables (**Chapter 6**).

- The no randomized and counterbalanced testing order which could not performed due to the characteristics of the flume, the procedures constraints and the small sample size used (**Chapter 7**).

- The pilot study, in which only four swimmers participated, gives us very specific information about the sample however, a larger sample could provide more insight and extrapolate the results to a larger population (**Chapter 8**).

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CHAPTER 10: General conclusions / Conclusiones generales

CHAPTER 10: General conclusions

The findings of the current Doctoral Thesis provides a greater insight to the sport and research community of the wetsuit use during swimming to generate biomechanical and physiological adaptations, with the aim of improving both technically and tactically in open water and triathlon competitions when the use of this suit is optional. It can be concluded that:

- The effects of wetsuits in swimming have been studied over time, showing different effects depending on the sample (swimmers and triathletes), the type of wetsuit used (full body, sleeveless long and short), the distance measured, the field of study (swimming pool, flume or open water) and the water temperature for swimming.

- The biomechanics and physiological changes produced by the wetsuit use induce to the increase in swimming speed when wearing the full body, sleeveless long and short wetsuits, compared to use swimsuit. This enhancement in speed is reached thanks to the buoyancy increment and the hydrodynamic drag reduction while swimming with wetsuit. Indeed, the technical adaptations are determinant to swim with less requirement of energy while using wetsuit and it might result in the improvement on swimming performance.

- The three types of wetsuits (full body, sleeveless long and short) improve swimming performance compared to swimsuit on different swimming distances and water environments.

- Wearing a wetsuit produce a reduction of 20.1 s on 400 m front crawl performance (~6%) compared to swimsuit. Physiological variables were reduced (using both suits) and technical variables (except SR) were higher in the swimming flume. Also, SL and SI were higher when wearing a wetsuit (in both 25 m swimming pool and in swimming flume).

- Stroke rate and the wetsuit thickness better explained the improvement on 400 m front crawl performance while using wetsuit for triathletes and open water swimmers. Thus, a higher maintenance of the SR might induce to higher velocities reached by the wetsuit. The 62% of this improvement explained by the wetsuit lower limbs thickness in females and the 48% by the wetsuit upper limbs thickness in males stage the importance in selecting a specific model of wetsuit according to the subject characteristics and technique.

- When using a wetsuit at 18ºC, an evident decrease of the cardiorespiratory and technical variables was found, demonstrating that this condition require lower E and C values. Thus, it was more economic than swimming with a swimsuit both at 26 and 18ºC. The results suggested that the wetsuit use might increase performance at 18ºC water temperature for competitive master swimmers.

- Swimming at 18ºC without a wetsuit might influence the 400 m front crawl performance as lower $[La-]_{peak}$ and RPE were observed. Although $\dot{V}O_{2peak}$, HR_{max} and RER did not evidence statistical differences when swimming in cold and temperate waters. Technique related variables showed a similar behavior within conditions without statistically differences found for SR, SL, SI and ηp.

- Using the the wetsuit Speedo Thinswim®, the values of ηp were higher, inducing in a decrease in energetic contributions and thus higher velocity might be reached with the same effort on 400 m front crawl compared to swimsuit. However, physiological and technical variables were not different between suits which might be due to the low wetsuit thickness studied.

CHAPTER 10: Conclusiones generales

Los resultados de la presente Tesis Doctoral aportan una mayor visión para la comunidad deportiva e investigadora sobre del uso del neopreno en natación para generar adaptaciones biomecánicas y fisiológicas, con el objetivo de mejorar tanto técnica como tácticamente en las competiciones de aguas abiertas y triatlón cuando el uso del mismo es opcional. Se puede concluir que:

- A lo largo del tiempo se han estudiado los efectos del neopreno en natación, lo que nos muestra diferentes efectos en función de la muestra (nadadores y triatletas), tipo de neopreno utilizado (completo, sin mangas largo y corto), la distancia medida, el ámbito de estudio (natación, piscina contracorriente y aguas abiertas) y la temperatura del agua.

- Los cambios biomecánicos y fisiológicos producidos por el uso del neopreno inducen al aumento de la velocidad de nado cuando se usa el neopreno completo, largo sin manga y corto, en comparación con el uso del bañador. Esta mejora de la velocidad se consigue gracias al aumento de la flotabilidad y a la reducción de la resistencia hidrodinámica al nadar con neopreno. De hecho, las adaptaciones técnicas son determinantes para nadar con un menor requerimiento de energía mientras se utiliza el neopreno y podría resultar en la mejora del rendimiento de la natación.

- Los tres modelos de neopreno (completo, largo sin mangas y corto) mejoran el rendimiento de natación en comparación con el bañador convencioanl en diferentes distancias de natación y entornos acuáticos.

- El uso del neopreno produjo una reducción de 20.1 s en el rendimiento en 400 m crol (~6%) en comparación con el bañador convencional. Las variables fisiológicas se redujeron (utilizando ambos trajes) y las variables técnicas (excepto SR) fueron mayores en la piscina contracorriente. Además, SL y SI fueron mayores cuando se utilizó el neopreno (tanto en la piscina de 25 m como en la piscina contracorriente).

- La frecuencia de brazada y el grosor del neopreno explican mejor la mejora del rendimiento en los 400 metros de crol cuando se utiliza el neopreno en triatletas y nadadores de aguas abiertas. Así, un mayor mantenimiento de SR podría inducir a mayores velocidades alcanzadas por el neopreno. El 62% de esta mejora se explicada por el grosor de las extremidades inferiores del neopreno en las mujeres y por el 48% del grosor de las extremidades superiores del neopreno en los hombres, ponen de manifiesto la importancia de seleccionar un modelo específico de neopreno en función de las características y la técnica del sujeto**.**

- Al utilizar neopreno a 18ºC, se encontró una evidente disminución de las variables cardiorrespiratorias y biomecánicas, demostrando que esta condición requiere menores valores de E y C. Por lo tanto, fue más económico nadar con neopreno que nadar con bañador tanto a 26 como a 18ºC. Los resultados sugieren que el uso del neopreno podría aumentar el rendimiento a 18ºC de temperatura del agua para los nadadores que compiten en categoría máster.

- Nadar a 18ºC sin neopreno podría influir en el rendimiento de los 400 m crol, ya que se observó menores valores de $[La\text{-}]_{peak}$ y RPE. Aunque el $\dot{V}O_{2peak}$, HR_{max} y RER no mostraron diferencias estadísticas al nadar en agua fría y templada. Las variables relacionadas con la técnica mostraron un comportamiento similar en las diferentes condiciones sin que se encontraran diferencias estadísticas para SR, SL, SI y ηp.

- Utilizando el neopreno Speedo Thinswim®, los valores de ηp fuero más altos, lo que induce a una disminución de las contribuciones energéticas y, por lo tanto, se podría alcanzar una mayor velocidad con el mismo esfuerzo en los 400 m crol en comparación con el bañador convencional. Sin embargo, las variables fisiológicas y técnicas no fueron diferentes entre los trajes, lo que podría deberse al bajo grosor del neopreno estudiado.

CHAPTER 11: General applications and suggestions for future research

CHAPTER 11: General applications and suggestions for future research

General applications

There are propose some swimming training applications derived from the current Doctoral Thesis:

- Swimming with wetsuit required technical adaptations that swimmers should focus on to improve the efficiency while swimming with it. Swimmers might reduce SR and increase the SL to benefit of the hydrodynamics characteristic of the wetsuit and improve the efficiency while swimming. A recommendation for trained swimmers and coaches is to use the wetsuit during the training seasons, swimming at different intensities and distances to improve the adaptations while swimming with this suit.

- Since the 400 m distance is a valid indicator of aerobic power, it might be used to study the effect of the wetsuit use in swimming. Hence, the physiologic and biomechanical variables analyzed in our studies could be useful to evaluate the open water swimmers and triathletes performances. This distance might also simplified the longer protocols of measurement.

- The effects of the wetsuit on swimming performance differs depending on the swimmers characteristics, thus it is very important to select the right wetsuit (whether full body, sleeveless long or short), to obtain the maximum benefits.

Suggestions for future research

During the curren Doctoral Thesis, different issues related to the wetsuit use in swimming have been corroborated and clarified, however, there are still many questions that remain unresolved. Therefore, it is important to highlight that future research should aim the following ideas:

- To analyze the same type of wetsuit in a sample which has the same training conditions and/or speciality (open water swimmers and triathletes). In this case, the most commonly used wetsuit in open water swimming competitions could be used for research as it can be observed in the most important open water swimming championships.

- To study the kinetics of the technique during a 400 m crawl swimming with wetsuit and with a conventional swimming, to know in detail the modification of the technique with the use of the wetsuit throughout the trial. To assess whether fatigue or discomfort in the shoulder due to the wetsuit is responsible for the modification of front crawl technique.

- To assess the $\dot{V}O_2$ during the recovery of the swimming tests with and without wetsuit in a 25 m swimming pool, analyzing by off-kinetics extrapolation. This method solve the difficulties of using these devices in a 25 m swimming pool.

- To compare data of swimming with and without wetsuit at 18 and 26ºC in the swimming flume and also in the swimming pool, using off-kinetics extrapolation method and therefore, to perform a comparison between the kinetics vs off-kinetics measurements.

- To explore the effect of the wetsuit use in a real situation (open water channel or lake) aiming to obtain physiological data as possible and biomechanical measurements over a predefined distance and to stablish a comparison between wetsuit and swimsuit.

- To study the performance enhancement with the use of wetsuit in the optional temperature ranges proposed by the ITU, according to the sample age and the triathlete level, to conclude about the wetsuit use when its use is optional for triathletes.

- To distinguish the results obtained between open water swimmers specialist and triathletes to investigate the differences for both groups with and without wetsuit on front crawl swimming performance.

APPENDIX I: Publications and knowledge transfer reports

APPENDIX I: Publications

Publications derived from the Research group Aquatics Lab CTS-527: 'Actividad Física y Deportiva en el Medio Acuático' during the current International Doctoral Thesis

1. Cardoso, F., Coelho, E., **Gay, A.,** Vilas-Boas, J., Pinho, J., Pyne, D., and Fernandes, R. A jaw protruding dental splint improves running physiology and kinematics. *International Journal of Sports Physiology and Performance* (under review). 2021.

2. López-Belmonte, O., **Gay, A.,** Ruiz-Navarro, J.J., Cuenca-Fernández, F., González-Ponce, A., and Arellano, R. Pacing profiles, variability and progression in 400, 800, and 1500-m swimming events at the 2021 European Championships. *International Journal of Sports Physiology and Performance* (under review). 2021.

3. Ruiz-Navarro, J.J., López-Belmonte, O., **Gay, A**., Cuenca-Fernandez, F., and Arellano, R. A new model of performance clarification to standardize the research results in swimming. *European Journal of Sport Sciences* (under review). 2021.

4. Ruiz-Navarro, J.J., Cuenca-Fernández, F., Papic, C., **Gay A**., Morales-Ortiz, E., López-Contreras, G., & Arellano, R. Does jumping conducted before the swimming start elicit underwater enhancement? *International Journal of Sports Science & Coaching* (under review). 2021.

5. Cuenca-Fernández, F., Ruiz-Navarro, J.J., González-Ponce, A., López-Belmonte, O., **Gay, A**, Arellano, R. Variability and performance progression between heats, semi-finals and final at the 2021 European Swimming Championships. *Sports Biomechanics* (under review). 2021.

6. Cuenca-Fernández, F., Boullosa, D., Ruiz-Navarro, J. J., **Gay, A**., Morales-Ortíz, E., López-Contreras, G., & Arellano, R. Lower fatigue and faster recovery of ultra-short race pace swimming training sessions. *Research in Sports Medicine*. 2021; 1-14. doi:10.1080/15438627.2021.1929227

7. Cuenca-Fernández, F., Ruiz-Navarro, J.J., **Gay, A**., Morales-Ortíz, E., López-Contreras, G., Arellano, R. Swimming performance after an eccentric post-activation training protocol. *Apunts Educación Física y Deportes.* 2020*;*2(140): 44-51. doi: 10.5672/apunts.2014-0983.es(2020/2).140.07. ESCI (Emerging Sources Citation Index).

8. Cuenca-Fernández, F., Ruiz-Navarro, J., **Gay, A**., Arellano, R. The effect of different loads on semi-tethered swimming and its relationship with dry-land performance variables. *International Journal of Performance Analysis in Sport.* 2020;20(1):90-106. doi: 10.1080/24748668.2020.1714413

9. Cuenca-Fernández, F., **Gay, A.,** Ruiz-Navarro, J.J., Morales-Ortiz, E., López-Contreras, G., Arellano, R. Protocolización de la post-activación potenciación estimulada en natación y su relación con la fuerza relativa. *Revista Andaluza de Medicina del Deporte.* 2020;13:150-154. doi: 10.33155/j.ramd.2020.02.003

10. Cuenca-Fernández, F, **Gay, A**, Ruiz-Navarro, J.J., Morales, E, López-Contreras, G, Arellano, R. Potenciación post-activación en natación. *Revista Técnica de Natación y Actividades Acuáticas*. 2019;17(1):13-19.

11. Ruiz-Navarro, J.J., Lorente-ferrón, F., Bilbao-lucuix, P., Cuenca-Fernández, F., **Gay, A.,** Lopez-contreras, G., Morales-Ortiz, E., Arellano, R. Evaluación de la fuerza producida en el agua. Su relación con el rendimiento. *NSW: Natación, Saltos/Sincro, Waterpolo*. XLII. 2019;2:10-14.

12. Cuenca-Fernández, F., **Gay, A.,** Ruiz-Navarro, J.J., Morales-Ortiz, E., López-Contreras, G., Arellano, R; Postactivation potentiation in sprint swimming. *1st SCS Annual Conference – New Horizons on Strength and Conditioning Science (SCS).* 2018.

13. Arellarno, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** Cuenca-Fernández, F., López Contreras, G. Short course 50 m female freestyle performance comparison between national and regional swimmers (peer review). *XIII th International Symposium on Biomechanics and Medicine in Swimming Proceeding.* 2018:48-355.

14. Arellarno, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** Cuenca-Fernández, F., López Contreras, G. Short course 50 m female freestyle performance comparison between national and regional swimmers (peer review). *ISBS Proceedings Archive*. 2018;36(1)614.

15. Szczepan, S., Zaton, K., Cuenca-Fernández, F., **Gay, A**., Arellano, R. The effects of concurrent visual versus feedback on swimming strength task execution. *Baltic Journal of Health and Physical Activity*. 2018;10(4). ESCI (Emerging Sources Citation Index). doi: 10.29359/BJHPA.10.4.05

16. Arellano, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** López-Contreras, G. Una nueva propuesta de modelos de rendimiento y planificación en natación para pruebas de 50 y 100 m, basados en resultados competitivos. *Revista Técnica de Natación y Actividades Acuáticas*. 2016;39.6-19.

Chapters of books

1. **Gay, A.,** Cuenca-Fernandez, F. Aguas abiertas. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

2. **Gay, A.,** Ruiz-Navarro, J.J. Natación Artística. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

3. Cuenca-Fernandez, F., **Gay, A**. Virajes. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

4. Ruiz-Navarro, J.J., **Gay, A**. Waterpolo. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

Knowledge transfer reports

1. 2019 - Apoyo biomecánico y Análisis Individualizado del Rendimiento del Equipo Nacional Absoluto de Natación durante el Ámsterdam Open (Ámsterdam, Holanda), prueba clasificatoria para los JJOO de Tokio 2020, realizado bajo contrato: "Evaluación del rendimiento de nadadores del Equipo Nacional Absoluto" Real Federación Española de Natación – Fundación General – Universidad de Granada. 10-14/10/2019. [C-4656-00].

2. 2019 - Trofeo Internacional Granada Ciudad Universitaria. Primer circuito Luso-Andaluz de Natación. Entidad Financiadora: Grupo de Investigación CTSD-527 y Plan Nacional DEP2014-59707-P. Investigadores: Raúl Arellano, Gracia López, Esther Morales, Francisco Cuenca, **Ana Gay,** Pedro Bilbao y Francisco Lorente. Granada (España). 12/01/2019 - 13/01/2019.

3. 2018 - Trofeo Internacional Granada Ciudad Universitaria. Primer circuito Luso-Andaluz de Natación. Entidad Financiadora: Grupo de Investigación CTSD-527 y Plan Nacional DEP2014-59707-P. Investigadores: Raúl Arellano, Gracia López, Esther Morales, Francisco Cuenca, **Ana Gay**, Pedro Bilbao y Francisco Lorente. Granada (España). 03/02/2018 - 04/02/2018.

APPENDIX II: Ethics committee

APPENDIX II: Ethics committee

Ethics committee for the first data collection

Universidad de Granada   Vicerrectorado de Política Científica e Investigación

COMITE DE ETICA EN INVESTIGACION
DE LA UNIVERSIDAD DE GRANADA

La Comisión de Ética en Investigación de la Universidad de Granada, analizado el informe preliminar del Presidente del Comité en Investigación Humana, emite informe favorable a la metodología en la investigación titulada 'EFECTO DEL TRAJE DE NEOPRENO EN EL RENDIMIENTO DE NATACIóN EN NADADORES DE LARGA DISTANCIA Y TRIATLETAS.' que dirige D./Dña. ANA GAY PÁRRAGA, con NIF 77.374.127-B, quedando registrada con el nº: 125/CEIH/2016.

Granada, a 05 de Febrero de 2016.

EL PRESIDENTE
Fdo: Enrique Herrera Viedma

EL SECRETARIO
Fdo: Fernando Cornet Sánchez del Águila

Ethics committee for the entire thesis data collection

UNIVERSIDAD DE GRANADA — Vicerrectorado de Investigación y Transferencia

COMITE DE ETICA EN INVESTIGACION
DE LA UNIVERSIDAD DE GRANADA

La Comisión de Ética en Investigación de la Universidad de Granada, analizado el informe preliminar del Presidente del Comité en Investigación Humana, emite informe favorable a la metodología en la investigación titulada 'USO DEL TRAJE DE NEOPRENO; SU EFECTO EN EL RENDIMIENTO EN NATACIÓN BAJO DIFERENTES CONDICIONES EXPERIMENTALES' que dirige D./Dña. ANA GAY PÁRRAGA, con NIF 77.374.127-B, quedando registrada con el nº: 302/CEIH/2017.

Granada, a 06 de Abril de 2017.

EL PRESIDENTE
Fdo: Enrique Herrera Viedma

EL SECRETARIO
Fdo: Fernando Cornet Sánchez del Águila

APPENDIX III: Consent forms

APPENDIX III: Consent forms

Consent form of the first data collection (adults)

CONSENTIMIENTO INFORMADO PARA TRIATLETAS Y NADADORES

Título: Efecto del neopreno en el rendimiento de natación en nadadores de larga distancia y triatletas.

Nombre del investigador: Ana Gay Párraga.

Director del Proyecto: Raúl Arellano Colomina.

Departamento: Educación Física y Deportiva.

Estimado/a participante:

Mediante la presente usted es invitado a participar en el estudio de investigación que Ana Gay Párraga, estudiante del Máster de Investigación en Actividad Física y Deporte en la Universidad de Granada.

Este estudio tiene como objetivo analizar los cambios técnicos, fisiológicos y psicológicos que se producen con el uso del neopreno en pruebas de natación de 400 metros en estilo crol y sus diferencias en cuanto al nado en la piscina convencional y en la piscina contracorriente. En base a la información obtenida, se desea generar conocimiento basado en investigación que permita la mejora del rendimiento en competiciones de triatlón y aguas abiertas.

Si decido participar en el estudio, comprendo que durante el proceso deberé de comprometerme a:

1. Asistir a la totalidad de las sesiones de entrenamiento (adaptación al nado en la piscina contracorriente así como en la piscina de 25 m, uso del neopreno en las mismas y toma de datos: peso, estatura, envergadura, análisis de la composición corporal y área de mano y pie dominante).

2. Informar con antelación a los investigadores de mi intención de abandonar el estudio en caso necesario.
3. Indicar cualquier problema, síntoma o condición que sea relevante de mi estado de salud que pueda afectar directamente mi seguridad o rendimiento durante el ejercicio.
4. No ingerir antes de las sesiones de evaluación (desde la noche anterior) café, té u otro tipo de bebida estimulante como RedBull o similar. No consumir alcohol ni ningún tipo de droga.
5. Ajustarme al calendario de evaluación elaborado, consistente en:
    a. Realización de dos test en la piscina de 25 m de 400 m, uno de ellos con neopreno y otro sin neopreno.
    b. Realización de otros dos test en la piscina contracorriente de 5 min de duración, uno con neopreno y otro sin neopreno.
    c. Todos ellos consisten en: filmación en vídeo, toma de frecuencia cardiaca, percepción subjetiva del esfuerzo (RPE) y niveles de lactato en sangre. Cada uno de los test se realizará por orden aleatorio.

Posibles riesgos

Los riesgos que podrían desarrollarse en las actividades llevadas a cabo en este estudio son los mismos que los que podrían aparecen en cualquier práctica deportiva de entrenamiento y competición, asumidos por una federación del deporte a practicar.

Formulario de consentimiento informado

Si decido participar en el estudio, recibiré información por parte del equipo investigador sobre mi estado y rendimiento en las variables analizadas.

Soy consciente de que la participación es totalmente voluntaria y que podré dejar de participar en el estudio en cualquier momento. Ningún dato de este estudio será utilizado para otros fines manteniéndose la información obtenida en completa confidencialidad.

He leído el documento, entiendo las declaraciones contenidas en él y la necesidad de hacer constar mi consentimiento, para lo cual lo firmo libre y voluntariamente, recibiendo en el acto copia de este documento ya firmado.

D./Dña, ……………………..., con D.N.I. …………………………………, consiento en participar en la investigación descrita anteriormente.

Granada, a ………. de ……………………………………….. del 201_.

Firma:

Teléfono:

Email:

Consent form of the first data collection (under 18-years old)

CONSENTIMIENTO INFORMADO PARA TRIATLETAS Y NADADORES

Título: Efecto del neopreno en el rendimiento de natación en nadadores de larga distancia y triatletas.

Nombre del investigador: Ana Gay Párraga.

Director del Proyecto: Raúl Arellano Colomina.

Departamento: Educación Física y Deportiva.

Estimado/a participante:

Mediante la presente usted es invitado a participar en el estudio de investigación que Ana Gay Párraga, estudiante del Máster de Investigación en Actividad Física y Deporte en la Universidad de Granada.

Este estudio tiene como objetivo analizar los cambios técnicos, fisiológicos y psicológicos que se producen con el uso del neopreno en pruebas de natación de 400 metros en estilo crol y sus diferencias en cuanto al nado en la piscina convencional y en la piscina contracorriente. En base a la información obtenida, se desea generar conocimiento basado en investigación que permita la mejora del rendimiento en competiciones de triatlón y aguas abiertas.

Si decido participar en el estudio, comprendo que durante el proceso deberé de comprometerme a:

1. Asistir a la totalidad de las sesiones de entrenamiento (adaptación al nado en la piscina contracorriente así como en la piscina de 25 m, uso del neopreno en las mismas y toma de datos: peso, estatura, envergadura, análisis de la composición corporal y área de mano y pie dominante).
2. Informar con antelación a los investigadores de mi intención de abandonar el estudio en caso necesario.
3. Indicar cualquier problema, síntoma o condición que sea relevante de mi estado de salud que pueda afectar directamente mi seguridad o rendimiento durante el ejercicio.

4. No ingerir antes de las sesiones de evaluación (desde la noche anterior) café, té u otro tipo de bebida estimulante como RedBull o similar. No consumir alcohol ni ningún tipo de droga.
5. Ajustarme al calendario de evaluación elaborado, consistente en:
    a. Realización de dos test en la piscina de 25 m de 400 m, uno de ellos con neopreno y otro sin neopreno.
    b. Realización de otros dos test en la piscina contracorriente de 5 min de duración, uno con neopreno y otro sin neopreno.
    c. Todos ellos consisten en: filmación en vídeo, toma de frecuencia cardiaca, percepción subjetiva del esfuerzo (RPE) y niveles de lactato en sangre. Cada uno de los test se realizará por orden aleatorio.

Posibles riesgos

Los riesgos que podrían desarrollarse en las actividades llevadas a cabo en este estudio son los mismos que los que podrían aparecen en cualquier práctica deportiva de entrenamiento y competición, asumidos por una federación del deporte a practicar.

Formulario de consentimiento informado

Si decido participar en el estudio, recibiré información por parte del equipo investigador sobre mi estado y rendimiento en las variables analizadas.

Soy consciente de que la participación es totalmente voluntaria y que podré dejar de participar en el estudio en cualquier momento. Ningún dato de este estudio será utilizado para otros fines manteniéndose la información obtenida en completa confidencialidad.

He leído el documento, entiendo las declaraciones contenidas en él y la necesidad de hacer constar mi consentimiento, para lo cual lo firmo libre y voluntariamente, recibiendo en el acto copia de este documento ya firmado.

D./Dña, …………………….., con D.N.I……………………….…….., padre/madre o tutor/a de ……………........................…………………..…, autorizo a que participe en la investigación descrita anteriormente.

Granada, a……….. de………………………………………. del 201_.

Firma:

Teléfono:

Email:

Consent forms of the second data collection (adults)

CONSENTIMIENTO INFORMADO PARA TRIATLETAS Y NADADORES

Título: Analysis of $\dot{V}O_2$ in the swimming flume with wetsuit and swimsuit at different temperatures.

Nombre del investigador: Ana Gay Párraga.

Director de la Tesis Doctoral: Raúl Arellano Colomina.

Departamento: Educación Física y Deportiva.

Estimado/a participante:

Mediante la presente usted es invitado a participar en el estudio de investigación que Ana Gay Párraga, estudiante del programa de Doctorado en Biomedicina en la Facultad de Ciencias del Deporte de la Universidad de Granada, va a realizar para el desarrollo de su Tesis Doctoral.

Este estudio tiene como objetivo analizar los cambios técnicos, fisiológicos y psicológicos que se producen con el uso del neopreno en pruebas de natación de 400 metros en estilo crol y sus diferencias en diferentes temperaturas en la piscina contracorriente. En base a la información obtenida, se desea generar conocimiento basado en investigación que permita la mejora del rendimiento en competiciones de triatlón y aguas abiertas.

Si decido participar en el estudio, comprendo que durante el proceso deberé de comprometerme a:

1. Asistir a la totalidad de las sesiones de entrenamiento de adaptación al nado en la piscina contracorriente así como en la piscina de 25 m, uso del neopreno en las mismas y toma de datos iniciales: peso, estatura, envergadura.
2. Informar con antelación a los investigadores de mi intención de abandonar el estudio en caso necesario.
3. Indicar cualquier problema, síntoma o condición que sea relevante de mi estado de salud que pueda afectar directamente mi seguridad o rendimiento durante el ejercicio.

4. No ingerir antes de las sesiones de evaluación (desde la noche anterior) café, té u otro tipo de bebida estimulante como RedBull o similar. No consumir alcohol ni ningún tipo de droga.
5. Ajustarme al calendario de evaluación elaborado, consistente en:

    1º parte consistirá en la realización de un test máximo de 400 m en la piscina de 25 m con bañador convencional.

    2º parte estará formada por 3 pruebas de una duración aproximada de 5 min en la piscina contracorriente:

    a) Nado a 27º con bañador convencional.

    b) Nado a 18º con neopreno.

    c) Nado a 18º con bañador convencional.

Todos ellos consisten en: filmación en vídeo, toma de frecuencia cardiaca, percepción subjetiva del esfuerzo (RPE) y niveles de lactato en sangre junto con análisis de gases en las pruebas en la piscina contracorriente.

Posibles riesgos

Los riesgos que podrían desarrollarse en las actividades llevadas a cabo en este estudio son los mismos que podrían aparecen en cualquier práctica deportiva de entrenamiento y competición, asumidos por una federación del deporte a practicar.

Formulario de consentimiento informado

Si decido participar en el estudio, recibiré información por parte del equipo investigador sobre mi estado y rendimiento en las variables analizadas.

Soy consciente de que la participación es totalmente voluntaria y que podré dejar de participar en el estudio en cualquier momento. Ningún dato de este estudio será utilizado para otros fines manteniéndose la información obtenida en completa confidencialidad.

He leído el documento, entiendo las declaraciones contenidas en él y la necesidad de hacer constar mi consentimiento, para lo cual lo firmo libre y voluntariamente, recibiendo en el acto copia de este documento ya firmado.

CONSENTIMIENTO POR ESCRITO DEL PACIENTE O PARTICIPANTE

Título del estudio: Analysis of $\dot{V}O_2$ in the swimming flume with wetsuit and swimsuit at different temperatures.

Yo, (nombre y apellidos) ...., con D.N.I. nº……………………………

He hablado con el profesional responsable del estudio

…..…………..

He leído la hoja de información que se me ha entregado.

He podido hacer preguntas sobre el estudio.

He recibido suficiente información sobre el estudio.

Comprendo que mi participación es voluntaria.

Comprendo que puedo retirarme del estudio:

1. Cuando quiera.
2. Sin tener que dar explicaciones.
3. Sin que esto repercuta en mis cuidados médicos.

Presto libremente mi conformidad para participar en el estudio.

Las muestras obtenidas en este estudio sólo serán utilizadas para los fines específicos del mismo.

Fecha Firma del paciente o participante

Fecha Firma del profesional responsable del estudio y D.N.I.

Consent forms of the second data collection (under 18-years old)

CONSENTIMIENTO INFORMADO PARA TRIATLETAS Y NADADORES

Título: Analysis of $\dot{V}O_2$ in the swimming flume with wetsuit and swimsuit at different temperatures.

Nombre del investigador: Ana Gay Párraga.

Director de la Tesis Doctoral: Raúl Arellano Colomina.

Departamento: Educación Física y Deportiva.

Estimado/a participante:

Mediante la presente usted es invitado a participar en el estudio de investigación que Ana Gay Párraga, estudiante del programa de Doctorado en Biomedicina en la Facultad de Ciencias del Deporte de la Universidad de Granada, va a realizar para el desarrollo de su Tesis Doctoral.

Este estudio tiene como objetivo analizar los cambios técnicos, fisiológicos y psicológicos que se producen con el uso del neopreno en pruebas de natación de 400 metros en estilo crol y sus diferencias en diferentes temperaturas en la piscina contracorriente. En base a la información obtenida, se desea generar conocimiento basado en investigación que permita la mejora del rendimiento en competiciones de triatlón y aguas abiertas.

Si decido participar en el estudio, comprendo que durante el proceso deberé de comprometerme a:

1. Asistir a la totalidad de las sesiones de entrenamiento de adaptación al nado en la piscina contracorriente así como en la piscina de 25 m, uso del neopreno en las mismas y toma de datos iniciales: peso, estatura, envergadura.
2. Informar con antelación a los investigadores de mi intención de abandonar el estudio en caso necesario.
3. Indicar cualquier problema, síntoma o condición que sea relevante de mi estado de salud que pueda afectar directamente mi seguridad o rendimiento durante el ejercicio.

4. No ingerir antes de las sesiones de evaluación (desde la noche anterior) café, té u otro tipo de bebida estimulante como RedBull o similar. No consumir alcohol ni ningún tipo de droga.
5. Ajustarme al calendario de evaluación elaborado, consistente en:

   1º parte consistirá en la realización de un test máximo de 400 m en la piscina de 25 m con bañador convencional.

   2º parte estará formada por 3 pruebas de una duración aproximada de 5 min en la piscina contracorriente:

   a) Nado a 27º con bañador convencional.
   b) Nado a 18º con neopreno.
   c) Nado a 18º con bañador convencional.

Todos ellos consisten en: filmación en vídeo, toma de frecuencia cardiaca, percepción subjetiva del esfuerzo (RPE) y niveles de lactato en sangre junto con análisis de gases en las pruebas en la piscina contracorriente.

Posibles riesgos

Los riesgos que podrían desarrollarse en las actividades llevadas a cabo en este estudio son los mismos que podrían aparecen en cualquier práctica deportiva de entrenamiento y competición, asumidos por una federación del deporte a practicar.

Formulario de consentimiento informado

Si decido participar en el estudio, recibiré información por parte del equipo investigador sobre mi estado y rendimiento en las variables analizadas.

Soy consciente de que la participación es totalmente voluntaria y que podré dejar de participar en el estudio en cualquier momento. Ningún dato de este estudio será utilizado para otros fines manteniéndose la información obtenida en completa confidencialidad.

He leído el documento, entiendo las declaraciones contenidas en él y la necesidad de hacer constar mi consentimiento, para lo cual lo firmo libre y voluntariamente, recibiendo en el acto copia de este documento ya firmado.

CONSENTIMIENTO POR ESCRITO DEL REPRESENTANTE

Título del estudio: Analysis of $\dot{V}O_2$ in the swimming flume with wetsuit and swimsuit at different temperatures.

Yo, (nombre y apellidos) ...., con D.N.I. nº……………………………

en calidad de (relación con el participante) ....

de (nombre del participante) ....

He hablado con el investigador responsable del estudio

....

He leído la hoja de información que se me ha entregado.

He podido hacer preguntas sobre el estudio. /profesional responsable del estudio

He recibido respuestas satisfactorias a mis preguntas.

He recibido suficiente información sobre el estudio.

Comprendo que la participación es voluntaria.

Comprendo que puede retirarse del estudio:

4. Cuando quiera.
5. Sin tener que dar explicaciones.
6. Sin que esto repercuta en sus cuidados médicos.

Y presto mi conformidad con que (nombre del participante) ....

.... participe en este estudio.

Fecha Firma del representante

Fecha Firma del profesional responsable del estudio y D.N.I.

APPENDIX IV: Reports to participants

APPENDIX IV: Reports to participants

Example of the reports provided to the participants of the study: 'Swimming with swimsuit and wetsuit at typical vs cold-water temperatures (26 vs 18ºc)'

NOMBRE: ----

- **TEST A 26ºC SIN NEOPRENO**

Tiempo de nado: 4 min 09 s

Tiempo real de nado: 4 min 09 s

Velocidad de nado (velocidad en 100 m): 54 s

Percepción subjetiva del esfuerzo (0-10): 6

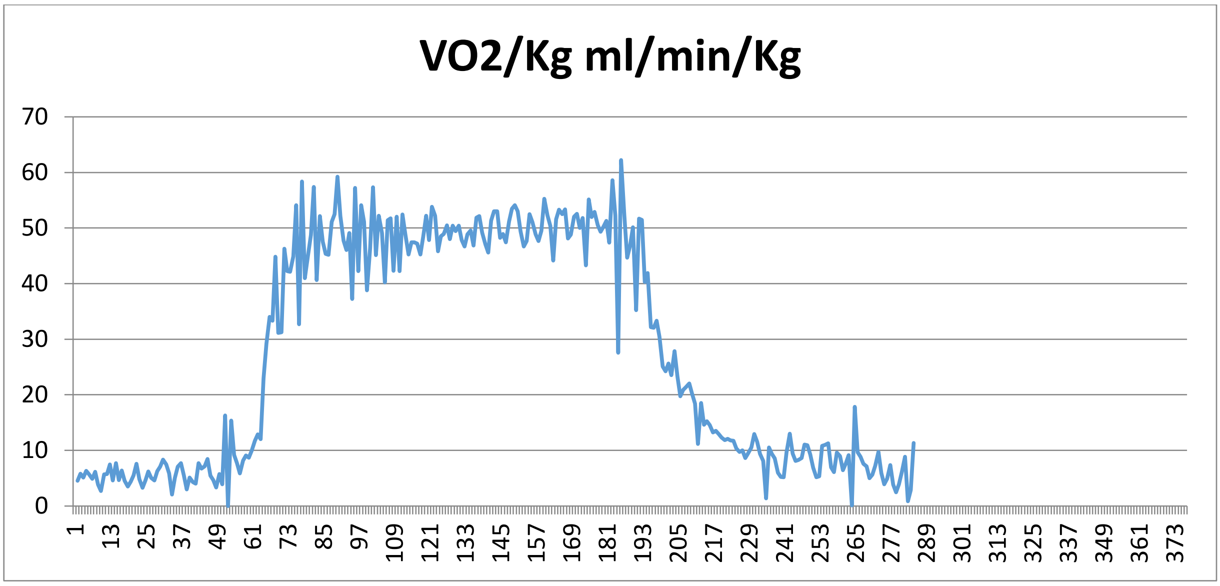
Lactato máximo ($mmol·l^{-1}$)[*1]: 5.1

Frecuencia cardíaca máxima (últimos 30 s test): 152

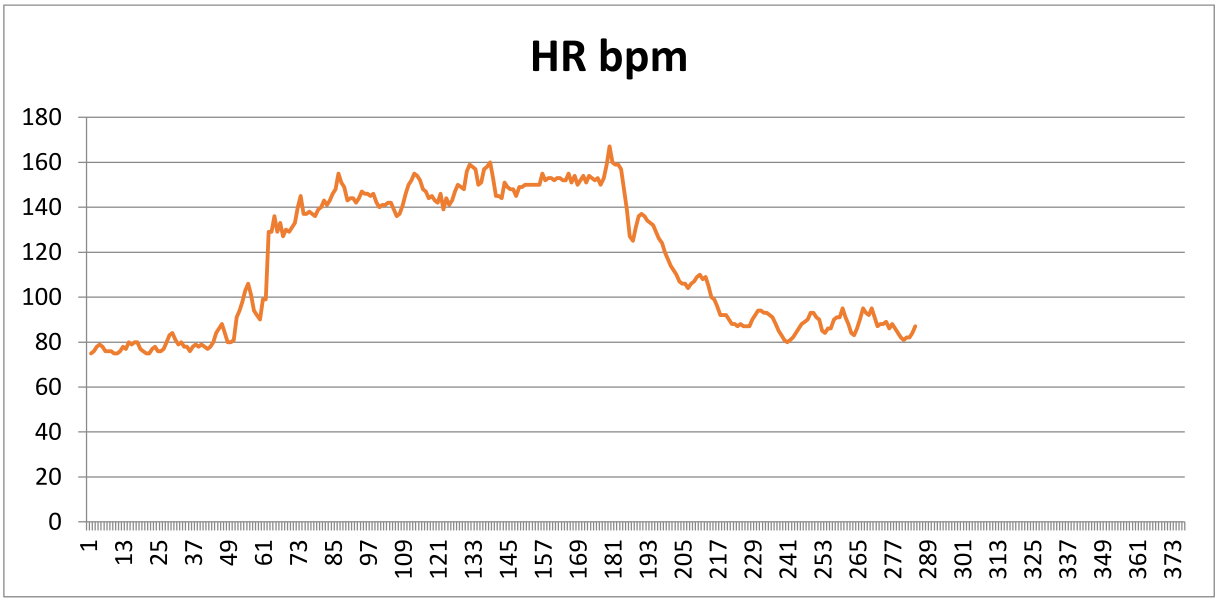
Consumo de O_2 máximo (ml/kg/min) (últimos 30 s test): 50.65

Cociente respiratorio (últimos 30 s test)[*2]: 0.93

Comportamiento consumo de oxígeno ($\dot{V}O_2$; incluye consumo basal, test y recuperación):



Comportamiento frecuencia cardíaca (HR; incluye basal, test y recuperación):



- **TEST A 18ºC SIN NEOPRENO**

Tiempo de nado: 4 min 09 s

Tiempo real de nado: 4 min 09 s

Velocidad de nado (velocidad en 100 m): 1 min 02 s

Percepción subjetiva del esfuerzo (0-10): 4

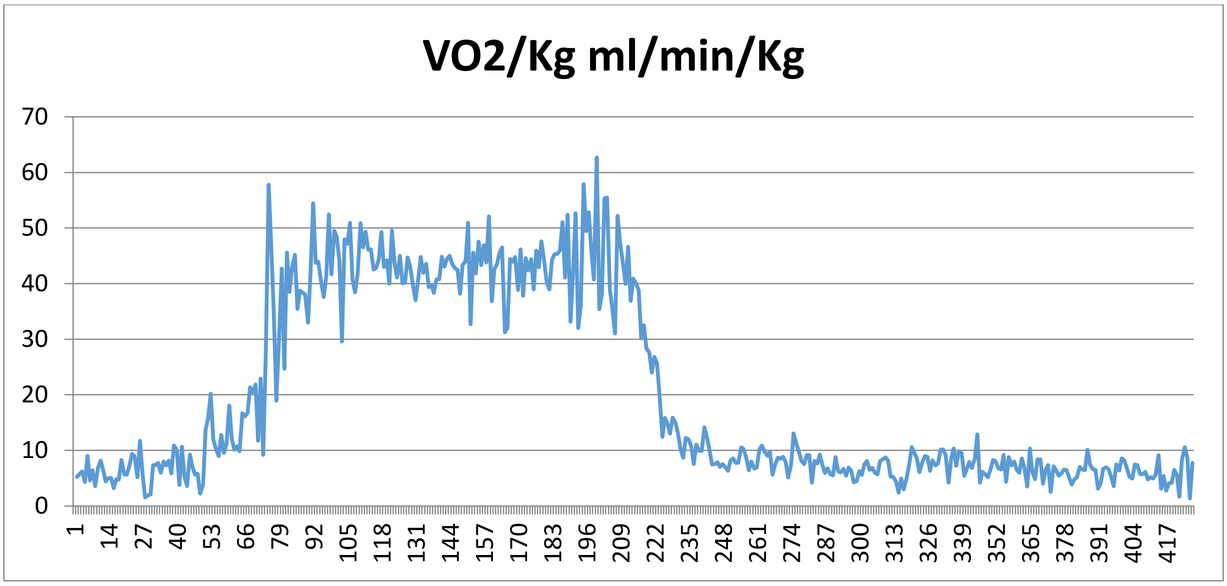
Lactato máximo ($mmol \cdot l^{-1}$)[*1]: 2.7

Frecuencia cardíaca máxima (últimos 30 s test): 185

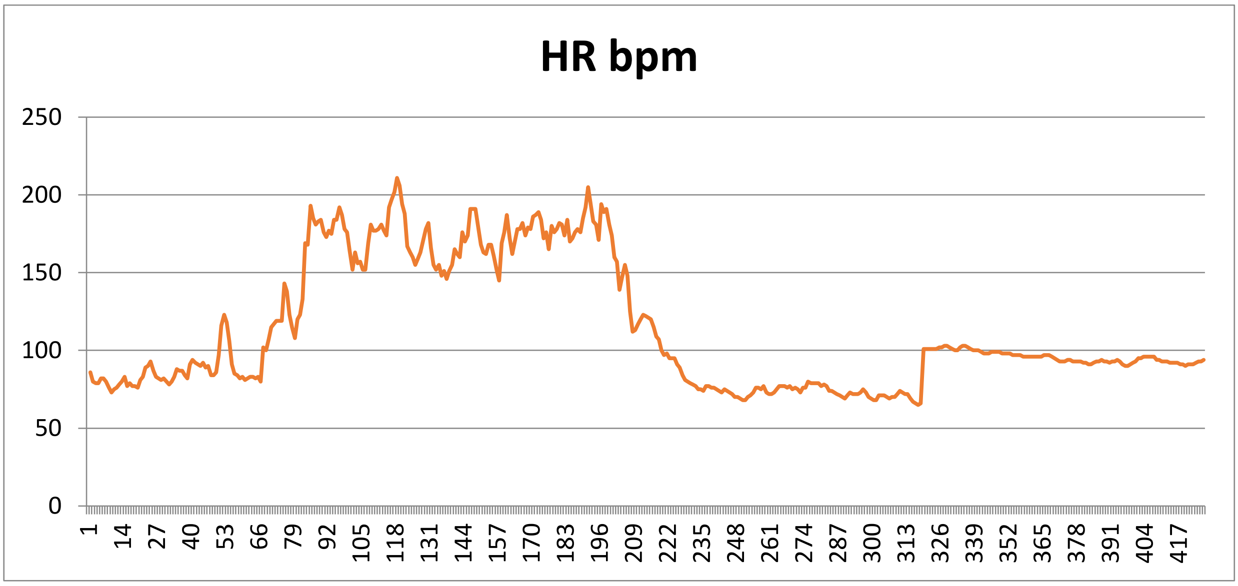
Consumo de O_2 máximo (ml/kg/min) (últimos 30 s test): 46.42

Cociente respiratorio (últimos 30 s test)[*2]: 0.85

Comportamiento consumo de oxígeno ($\dot{V}O_2$; incluye consumo basal, test y recuperación):



Comportamiento frecuencia cardíaca (HR; incluye basal, test y recuperación):



- **TEST A 18ºC CON NEOPRENO**

Tiempo de nado: 4 min 09 s

Tiempo real de nado: 4 min 09 s

Velocidad de nado (velocidad en 100 m): 54 s

Percepción subjetiva del esfuerzo (0-10): 4

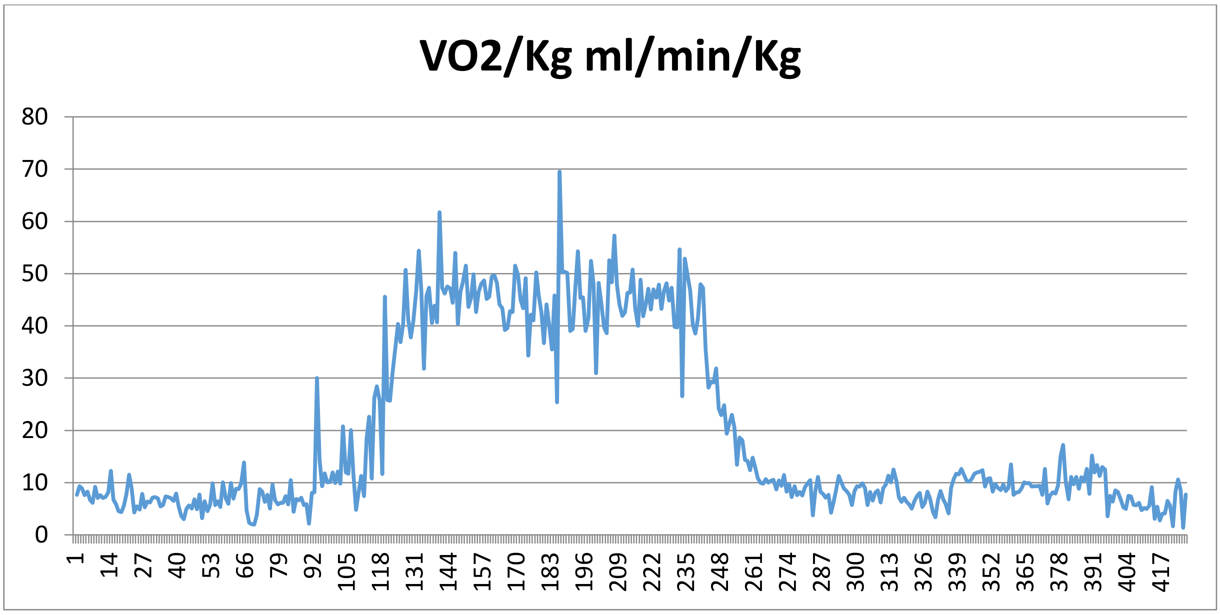
Lactato máximo ($mmol \cdot l^{-1}$)[*1]: 2

Frecuencia cardíaca máxima (últimos 30 s test): 139

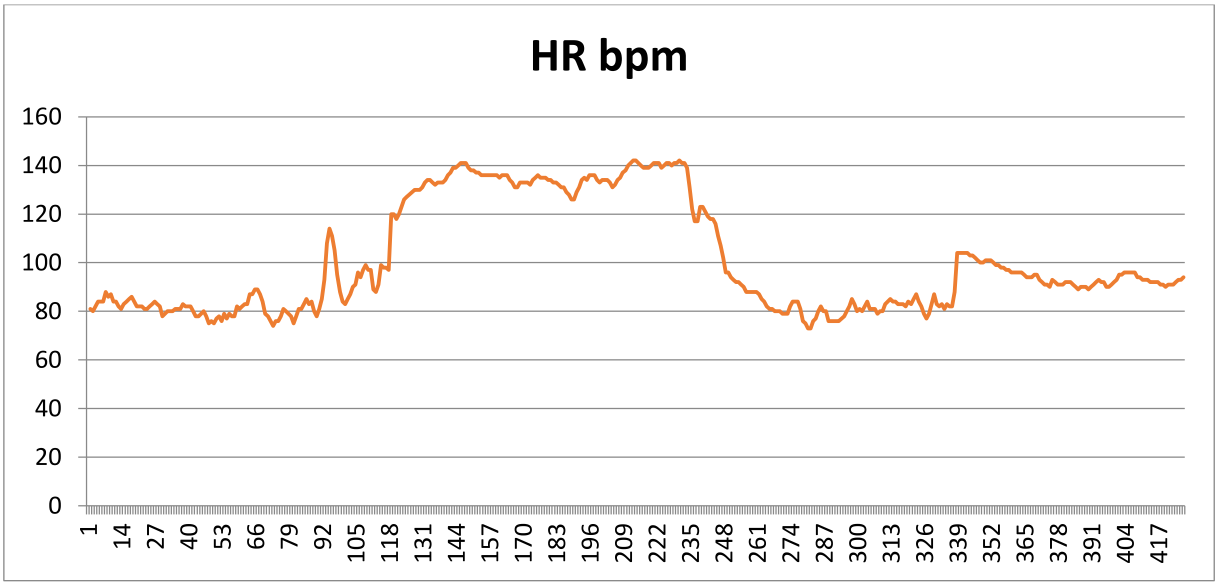
Consumo de O_2 máximo (ml/kg/min) (últimos 30 s test): 45.01

Cociente respiratorio (últimos 30 s test)[*2]: 0.83

Comportamiento consumo de oxígeno ($\dot{V}O_2$; incluye consumo basal, test y recuperación):



Comportamiento frecuencia cardíaca (HR; incluye basal, test y recuperación):



*Nota 1: concentración de lactato en sangre, cuanto más alta más intenso ha sido el esfuerzo realizado (esfuerzo máximo >8 mmol·l^{-1} aproximadamente).

*Nota 2: cociente respiratorio varía de 0 a 1, cuanto más se acerca a 1, mayor es la intensidad del esfuerzo (puede superar el 1).

APPENDIX V: Curriculum Vitae

APPENDIX V: Curriculum Vitae

PERSONAL DATA

Name:	Ana Gay Párraga
Email:	anagayparraga@gmail.com
Birth Date:	11/04/1992
Birth Place:	Jaén
Nationality:	Spanish
ORCID/Research ID:	0000-0003-4881-4620
Research Gate:	Ana Gay Párraga

CURRENT AFILIATIONS

PhD candidate	At the Faculty of Sport Sciences, University of Granada, Spain. From 2016 - Present
Funding	Spanish Ministry of Economy and Competitiveness
Department	Physical Education and Sports
Supervisors	Professor Dr. Raúl Arellano Colomina
	Professor Dr. Ricardo J. Fernandes

EDUCATION

2016 - present	PhD in Biomedicine, University of Granada, Spain
2015 - 2016	Master's Degree in Research in Sports and Physical Activity. Specialization in swimming sports. University of Granada, Spain
2010 - 2015	Degree in Physical Activity and Sport Sciences, University of Granada, Spain

INTERNSHIPS

2019 - 2019	Three months international internship for the Ph.D. in Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D), Faculty of Sport, University of Porto, Porto, Portugal.
2012 - 2013	Nine months exchange Erasmus Program at University School of Physical Education in Krakow, Poland.

RESEARCH / INTERESTS

My research activities are focused on the study of open water swimming performance in swimmers and triathletes with the use of wetsuits and conventional swimsuits. The main aim is to study the biomechanical and physiological changes with different models of suits (full body, sleeveless long and short wetsuits), test distances, water temperatures (at which the different federations allow their use) and environments (25 m swimming pool, swimming flume and open water). In addition, my research group Aquatics Lab CTS-527 is interested in the study of swimming performance and its application for training purposes. The research activity carried out by the group works with swimmers of amateur, regional and specialists at national and international level in the evaluation of the four swimming strokes, focus mainly on swimming competition analysis of 50 and 100 m sprint to 3000 m events, providing a detailed analysis of competition performance every 5 m. At the same time, we works in knowledge transfer activities evaluating swimmers through the Andalusian and Spanish Swimming Federation, providing scientific knowledge for implementation in the daily training and improving the competitions results.

PROFESSIONAL POSITTIONS AND PARTICIPATION IN RESEARCH PROJECTS

2016 - present	Ph.D. Full-time in Biomedicine at the University of Granada, Spain.
2019 - 2021	Project Research staff of the project: PGC2018-102116-B-I00 'SWIM II: Specific Water Innovative Measurements: Applied to the Performance Improvement'.
2016 - 2021	Project Research staff of the research group Aquatics Lab CTS-527: 'Actividad Física y Deportiva en el Medio

Acuático'.Department of Physical Activity and Sports, Faculty of Sport Sciences, University of Granada, Spain.

2016 - 2021 Project Research staff of the swimming performance evaluation of regional and national swimmers from the Swimming Andalusian (FAN) and National Federations (RFEN).

2015 - 2019 Project Research staff of the project: DEP2014-59707-P 'SWIM: Specific Water Innovative Measurements applied to the Development of the International Swimmers in Short Swimming Events (50 and 100 m)'.

2017 - 2018 Project Research staff of the evaluation of the suits and equipment of Aqua Lung ® Aqua Sphere ®. 'Swimming Suits Evaluation and Report (Xpresso MP, Mizumo and Arena)' Soc La Spirotechnique (Francia)– Fundación General Empresa – Universidad de Granada.

CHAPTER OF BOOKS

- ✓ **Gay, A.,** Cuenca-Fernandez, F. Aguas abiertas. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.
- ✓ **Gay, A.,** Ruiz-Navarro, J.J. Natación Artística. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

- ✓ Cuenca-Fernandez, F., **Gay, A**. Virajes. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.
- ✓ Ruiz-Navarro, J.J., **Gay, A**. Waterpolo. En: López-Contreras, G. Perfeccionamiento Deportivo: Natación. Copideporte; 2021. ISBN: 978-84-18471-70-4.

CONTRIBUTION TO INTERNATIONAL AND NATIONAL CONGRESSES

- ✓ **Gay, A.** Salud, deporte y rendimiento: El uso del neopreno en natación. *I workshop internacional mujeres investigadoras innovan*. 2021. *International Congress*

- ✓ López-Contreras, G., **Gay, A.**, Moralez-Ortiz, E., Escobar, R., Piñar, M., Feriche, B., Moreno, P., delCuerpo. Salud, deporte y rendimiento: Departamento de Educación Física y Deportiva. *I workshop internacional mujeres investigadoras innovan*. 2021. *International Congress*

- ✓ **Gay, A.**, Zacca, R., Abraldes, A., Morales-Ortiz, E., López-Contreras, G., Cuenca-Fernández, F., Fernandes, R., Arellano, R. Physiology and biomechanics to determine the effect of wetsuit Speedo Thinswim® when swimming in a cold-water flume (peer review). *Abstract presented at the XXV European College of Sport Sciences. Book of Abstracts, Sevilla*. 2020. (Peer review abstract). *International Congress.*

- ✓ **Gay, A**., Arturo, A., Zacca, R., Morales-Ortiz, E., López-Contreras, G., Cuenca-Fernández, F., Ruiz-Navarro, J.J., Fernandes, R., Arellano, R. Análisis biofísico del nado en la piscina contracorriente: efecto de la temperatura del agua. *Revista Técnica de Natación y Actividades Acuáticas*. 2019;3:6-10. *National Congress.*

- ✓ Ruiz-Navarro, J.J., Lorente-Ferrón, F., Bilbao-Lucuix, P., Cuenca-Fernández, F., **Gay, A.,** López-Contreras, G., Morales-Ortiz, E., Arellano, R. Evaluación de la fuerza producida en el agua. Su relación con el rendimiento. *Revista Técnica de Natación y Actividades Acuáticas*. 2019; 42(2):10-14. *National Congress.*

- ✓ Cuenca-Fernández, F., **Gay, A.,** Ruiz-Navarro, J.J., Morales-Ortiz, E., López-Contreras, G., Arellano, R. Potenciación post-activación en natación. *Revista Técnica de Natación y Actividades Acuáticas*. 2019;17(1):12-19. *National Congress.*

- ✓ **Gay, A.,** Arturo, A., Zacca, R., Morales-Ortiz, E., López-Contreras, G., Fernandes, R., & Arellano, R. Acute effects of water temperature in swimming performance: a biophysical analysis (peer review). Study presented at the XIII th *International Symposium on Biomechanics and Medicine in Swimming* (BMS), Japan. 2018. (Peer review article). *International Congress.*

- ✓ Arellarno, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** Cuenca-Fernández, F., López Contreras, G. Short course 50 m female freestyle performance comparison between national and regional swimmers (peer review). *XIII th International Symposium on Biomechanics and Medicine in Swimming Proceeding.* 2018:48-355. Tsukuba, Japan, 17-21 September 2018. *International Congress.*

- ✓ Arellarno, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** Cuenca-Fernández, F., López Contreras, G. Short course 50 m female freestyle performance comparison between national and regional swimmers (peer review). *ISBS Proceedings Archive*. 2018;36(1)614. Auckand, New Zealand, 10-14 September 2018. *International Congress.*

- ✓ **Gay, A.,** Abraldes, A., Zacca, R., Morales-Ortiz, E., Fernandes, R., Arellano, R. Análisis biofísico del nado en la piscina contracorriente: efecto de la temperatura del agua. *III Jornadas / I Congreso Nacional Investigadores en Formación Fomentando la interdisciplinariedad (JIFFI)*. ISBN 978-84-17293-45-1. 2018. *National Congress*

- ✓ **Gay, A.,** Arellano, R., López-Contreras, G. Efecto del uso del neopreno en pruebas de 400 m en la piscina contracorriente. *NSW, Natación Saltos y Waterpolo*. 2017;40(1):15-18. *National Congress.*

- ✓ **Gay, A.,** Arellano, R. Influencia del neopreno en el rendimiento en natación. *I Jornadas Internacionales de Actualización del Conocimiento*. 2017. *International Congress*

- ✓ Arellano, R., Ruiz-Teba, A., Morales-Ortiz, E., **Gay, A.,** López-Contreras, G. Una nueva propuesta de modelos de rendimiento y planificación en natación para pruebas de 50 y 100 m, basados en resultados competitivos. Revista técnica de natación y actividades acuáticas. *NSW, Natación Saltos y Waterpolo.* 2016;39:6-19. *National Congress.*

GRANTS AND PERSONAL AWARDS

2018	Third prize in the XXXVIII National Congress of the Swimming Spanish Federation (€100).
2017	Contract of technical support and management staff, within the framework of the national youth guarantee system and the operational programme for youth employment. Department of physical education and sports, University of Granada, Spain.
2016	Second prize in the XXXVI National Congress of the Swimming Spanish Federation (€200).

2016 | Mention for the best Master's thesis of the Master’s Degree in Research in Sports and Physical Activity. Specialization in swimming sports, University of Granada, Spain.

2015 - 2016 | Collaboration grant, granted by the Ministry of Education. Department of physical education and sports, University of Granada, Spain.

2015 | Icaro Scholarship in collaboration with the degree co-ordination. Department of physical education and sports, University of Granada, Spain.

TEACHING EXPERIENCE

2021 | Practical tutor of a master student in the Master Research in Sports and Physical Activity and teaching compulsory secondary education, vocational training and language teaching (physical education). Department of Physical Education and Sports, University of Granada, Spain (50 h).

2021 | Teacher of ‘Fundamentos de los deportes IV: Ciclismo’ in the Faculty of Sport Sciences. Department of Physical Education and Sports, University of Granada, Spain (20 hours).

2021 | Teacher in the Course of Biomechanics applied to the triathlon. Triathlon Andalusian Federation (4 h).

2021	Teacher in the Master's Degree in Research in Sports and Physical Activity: Advanced research in water sports. Department of Physical Education and Sports, University of Granada, Spain (4 hours).
2020	Teacher of 'Fundamentos de los deportes I: Natación' in the Faculty of Sport Sciences. Department of Physical Education and Sports, University of Granada, Spain (40 hours).
2020	Lecture of Triathlon: Training and Planning. Faculty of Sport, University of Porto, Portugal (2 h).
2020	Lecture of Swimming in the Swimming Flume: A Biophysical Analysis. Triathlon Andalusian Federation (2 h).
2019	Teacher of 'Fundamentos de los deportes IV: Ciclismo' in the Faculty of Sport Sciences. Department of Physical Education and Sports, University of Granada, Spain (60 hours).
2019	Teacher in the Course of Swimming Instructor, Level I. Swimming Andalusian Federation (4 h).
2018-2019	Teacher of 'Entrenamiento Deportivo' in the Faculty of Sport Sciences. Department of Physical Education and Sports, University of Granada, Spain (60 hours).

PREVIOUS STAYS IN OTHER CENTERS

2014 – present	Department of Physical Activity and Sports, Faculty of Sport Sciences, University of Granada.
2018	5 days in the Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D), Faculty of Sport, University of Porto, Porto, Portugal.
2017	12 days in the Centre of Research, Education, Innovation and Intervention in Sport (CIFI2D), Faculty of Sport, University of Porto, Porto, Portugal.
2012 – 2013	University School of Physical Education in Kraków, Poland.

SCIENTIFIC JOURNAL REVIEWER

2021	International Journal of Sports Physiology and Performance (Impact Factor: 3.528, Journal ranking: 1st Quartil, Sport Sciences)

SPECIFIC SOFTWARE OR TECHNOLOGIES USED

- ✓ $\dot{V}O_2$FITTING: A free and open-source software for modelling oxygen uptake kinetics in swimming.
- ✓ Gas analyzer K4b^2 and Aquatrainer® respiratory snorkel.
- ✓ Automatic System Performance Analysis (A.S.P.A). REF.: IE_57161.
- ✓ Statistical Package for the Social Sciences (SPSS).
- ✓ Kinovea.
- ✓ FileMaker.
- ✓ Python language.

ACKNOWLEDGMENTS / AGRADECIMIENTOS

ACKNOWLEDGMENTS / AGRADECIMIENTOS

A mis queridos padres, **Mari Lola Párraga Fernández** y **Miguel Gay Gay** por haber luchado humildemente durante sus vidas para que yo siempre cumpla mis sueños.

A mi hermana **María Dolores Gay Párraga**, porque has sido, eres y serás siempre mi mejor ejemplo de constancia y dedicación.

Al Profesor **Dr. Raúl Arellano** por haberme abierto las puertas del mundo de la natación, por mostrarme su amor hacia este deporte, por enseñarme sus conocimientos y por haber hecho posible que hoy esté aquí.

Al Profesor **Dr. Ricardo Fernandes** por su paciencia y enseñanza durante todo este proceso, por inculcarme su disciplina en la escritura científica.

To Professor ***Dr. Ricardo Fernandes*** *for your patience and teaching throughout this process, for instilling in me your discipline in scientific writing.*

A los miembros del Presente Tribunal, **Dra. María Perla Moreo Arroyo, Dra. Raquel Escobar Molina, Dr. José Andrés Sánchez Molina, Dr. Roberto Cejuela Anta** y **Dr. Argyris Toubekis** por su implicación y colaboración para que este acto pueda llevarse a cabo. Igualmente **a Dr. Palma Chillón Garzón** y **Dr. Flávio Antônio de Souza Castro** por comprometerse como tribunal suplente.

To the Doctoral Thesis Comittee, ***Dr. María Perla Moreo Arroyo, Dr. Raquel Escobar Molina, Dr. José Andrés Sánchez Molina, Dr. Roberto Cejuela Anta*** *and* ***Dr. Argyris Toubekis*** *for their involvement and collaboration in making this act possible. I would also like to thank* ***Dr. Palma Chillón Garzón*** *and* ***Dr. Flávio Antônio de Souza Castro*** *for their commitment as alternate judges.*

A los evaluadores internacionales **Dr. Pedro Figueiredo** and **Dr. Bruno Mezêncio** por su colaboración en la evaluación de la Presente Tesis.

*To the international reviewers **Dr. Pedro Figueiredo** and **Dr. Bruno Mezêncio** for their collaboration in the evaluation of the Present Thesis.*

Al presente coordinador del Doctorado en Biomedicina, **Dr. Enrique José Cobos del Moral**, por solucionar las infititas dudas relacionadas con este proceso y de forma tan clara. Al resto de compañeras/os de la Escuela Internacional de Posgrado y del Vicerrectorado de Investigación y Transferencia.

A la Profesora **Dra. Gracia López Contreras**, por sus enseñanzas en el ámbito de la natación sobre cómo enseñar este deporte, por sus consejos, ayuda y por mostrar siempre su inteligencia emocional ante las diferentes situaciones.

A la Profesora **Dra. Esther Morales Ortiz**, por introducirme en este deporte durante el primer curso en la piscina de Fuentenueva, por su ayuda y colaboración en las investigaciones derivadas de esta tesis.

Al profesor **Dr. Arturo Abraldes Valeiras** por enseñarme a utilizar los instrumentos necesarios para analizar gases en natación y por su colaboración en los estudios derivados de esta tesis.

A mi compañero **Dr. Francisco Cuenca Fernández**, por sus consejos, historias y su ayuda durante estos años.

A mi compañero doctorando **Jesús Juan Ruiz Navarro**, por sus risas y comentarios que han hecho más ameno el día a día en el laboratorio y por su siempre atenta amabilidad en ayudar.

A mi compañero doctorando **Óscar López Belmonte**, por hacer que juntos formemos un equipo de investigación sobre aguas abiertas.

A mi compañera **Ángela González Ponce** y mi compañero **Néstor Arellano Pardillo**, gracias a sus conocimientos seguimos creciendo como equipo, siendo más eficientes tanto en la toma como en el análisis de datos.

A mi primera compañera del Laboratorio de Natación **Ana Ruiz Teba**, por enseñarme lo necesario durante los primeros pasos.

A todas/os las/los **nadadoras/es** y **triatletas** que desinteresadamente han participado en las tomas experimentales de la Presente Tesis, por mostrar su colaboración e interesarse por el mundo de la investigación científica en natación. Sin vosotras/os esto no hubiera sido posible.

A las **Profesoras** y **Profesores** del Departamento de Educación Física y Deportiva de la Facultad de Ciencias del Deporte, por sus saludos diarios, su interés en mi proceso educativo y deportivo y por hacerme sentir querida.

Al **Dr. Rodrigo Zacca**, por ser un gran amigo e investigador, incitándome siempre a la mejora de mis estudios, sin olvidar a los entrenadores/as.

*To Dr**. Rodrigo Zacca**, for being a great friend and researcher, always encouraging me to improve my studies, without forgetting the coaches.*

Al mis compañeras y compañeros de Oporto **Dr. João Vilas-Boas, Dra. Susana Soares, Filipa Cardoso, Eduardo Coelho, Diogo Duarte** y **Sofía Monteiro** por su compañía durante mi estancia allí y por integrarme en sus proyectos.

*To my colleagues from Porto **Dr. João Vilas-Boas, Dr. Susana Soares, Filipa Cardoso, Eduardo Coelho, Diogo Duarte and Sofía Monteiro** for their company during my stay there and for integrating me in their projects.*

A mi primer compañero de esta facultad **Dr. Pedro Pablo Acosta Manzano**, por su paciencia resolviendo mis dudas en la fase final de este proceso.

Al **personal PAS** de la Facultad de Ciencias del Deporte, por su ayuda y paciencia y a **Maria del Carmen** y **Cristina**, por sus visitas diarias al laboratorio de Natación y su amabilidad.

A las compañeras **María Sagrario Avilés Rodríguez, Amadora Gómez Lozano** y **Ana María Peregrín González** de la Biblioteca de la Facultad del Deporte, igualmente por interesarse en mi proceso educativo y deportivo y por su siempre atenta disposición.

A **Santiago Valenzuela Masana**, por mostrarme su pasión hacia la natación, por sus ideas, por incitarme siempre a mejorar y por su gran apoyo.

A todas y todos aquellas/os que se han cruzado en este camino, ya sean **investigadoras/es, profesoras/es, compañeras/os, amigas/os** o **alumnas/os**, los cuales tienen un recuerdo en mi mente pues fueron parte de mis estudios de doctorado.

*To all those who have crossed this path, whether **researchers, professors, colleagues, friends** or **students**, who have a memory in my mind because they were part of my doctoral studies.*

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