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Fuerza, potencia y entrenamiento vibratorio en nadadores adolescentes

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Tesis Doctoral

FUERZA, POTENCIA Y ENTRENAMIENTO VIBRATORIO EN NADADORES ADOLESCENTES

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FUERZA, POTENCIA Y ENTRENAMIENTO VIBRATORIO EN NADADORES ADOLESCENTES

STRENGTH, POWER AND WHOLE-BODY VIBRATION TRAINING IN ADOLESCENT SWIMMERS

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Borja Muñiz Pardos

A mis directores y supervisores, Germán, José Antonio, Bruton y Yannis, y a mis compañeros del grupo GENUD, ejemplos a seguir

A mi familia, especialmente a mi madre y a mis tíos Alejandro, Enrique, Luís, Andrés y María Muñiz, por un apoyo incondicional y por hacer esto posible

A mi padre, mi fuerza

Es mejor saber después de haber pensado y discutido que aceptar los saberes que nadie discute para no tener que pensar.

Fernando Savater

Un poco más de persistencia, un poco más de esfuerzo, y lo que parecía irremediablemente un fracaso puede convertirse en un éxito glorioso

Elbert Hubbard

Fuerza, potencia y entrenamiento vibratorio en nadadores adolescentes

Strength, power and whole-body vibration training in adolescent swimmers

DIRECTOR DE TESIS:
Dr. Germán Vicente Rodríguez
Facultad de Ciencias de la Salud y
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GERMÁN VICENTE RODRÍGUEZ, PROFESOR TITULAR DE LA UNIVERSIDAD DE ZARAGOZA, CERTIFICA:

Que la Tesis Doctoral titulada *"Fuerza, potencia y entrenamiento vibratorio en nadadores adolescentes."* que presenta D. **BORJA MUÑIZ PARDOS** al superior juicio del Tribunal que designe la Universidad de Zaragoza, ha sido realizada bajo mi dirección durante los años 2014-2019, siendo expresión de la capacidad técnica e interpretativa de su autor en condiciones tan aventajadas que le hacen merecedor del Título de Doctor, siempre y cuando así lo considere el citado Tribunal.

Fdo. Germán Vicente Rodríguez

En Zaragoza a 28 de mayo de 2019

Publicaciones incluidas en la Tesis Doctoral [Doctoral Thesis publications]

Chapter 4.1

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Chapter 4.2

Muniz-Pardos, B, Gómez-Bruton, A, Matute-Llorente, A, Gonzalez-Aguero, A, Gomez-Cabello, A, Gonzalo-Skok, O, José A. Casajús, Vicente-Rodríguez G. Swim-specific resistance training and swimming performance: A systematic review. ***J Strength Cond Res.*** [*Accepted for publication*].

Chapter 4.3

Muniz-Pardos B, Gómez-Bruton A, Matute-Llorente A, González-Agüero A, Olmedillas H, Gómez-Cabello A, Sutehall S, Pitsiladis Y, Casajús JA, Vicente-Rodríguez G. Lower-body strength and power contribution in sprint swimming performance in trained adolescent swimmers. ***J Strength Cond Res***. [*Submitted*].

Chapter 4.4

Muniz-Pardos B, Gómez-Bruton A, Matute-Llorente A, González-Agüero A, Gómez-Cabello A, Casajús JA, Vicente-Rodríguez G. Long-term effects of whole-body vibration in trained adolescent swimmers. Does it increase strength, power or swimming performance? ***Int J Sports Physiol Perf.*** [*Submitted*].

Chapter 4.5

Muniz-Pardos B, Lozano-Berges G, Marín-Puyalto J, González-Agüero A, Vicente-Rodríguez G, Casajús JA, Garatachea N. Validity and reliability of an optoelectronic system to measure movement velocity during bench press and half squat in a Smith machine. ***Proc Inst Mech Eng P J Sport Eng Technol***. [*Submitted*].

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Proyecto de Investigación

La Tesis Doctoral que se presenta a continuación se enmarca dentro del siguiente proyecto de investigación:

"***Re**percusión del entrenamiento y la práctica de la **na**tación sobre el desarrollo metabólico y estructural del hueso en cre**cimiento**. Beneficios de la incorporación de entrenamiento pliométrico o vibratorio. (Acrónimo: RENACIMIENTO)*"

Este proyecto nacional de 3 años de duración fue financiado por el *Ministerio de Ciencia e Innovación (DEP2011-29093)*, cuyo investigador principal fue ***Germán Vicente Rodríguez.***

Research Project

The present Doctoral Thesis is within the frame of the research project:

"Swimming repercussion on metabolic and structural bone development; benefits of the incorporation of whole body vibration or plyometric training: the RENACIMIENTO project."

This three-year national project was funded by the **Spanish Ministry of Science and Innovation (DEP2011-29093)**, whose principal researcher was ***Germán Vicente Rodríguez***.

Resumen General

La fuerza y la potencia de las extremidades inferiores han demostrado tener un papel fundamental en el rendimiento en nadadores, principalmente durante las fases la salida y los virajes. No obstante, existe discrepancia en cuanto al tipo de variables de fuerza y potencia que mejor podrían explicar el rendimiento en pruebas de natación, así como al tipo de entrenamiento más adecuado para mejorar la fuerza y el rendimiento en nadadores. Por otro lado, el entrenamiento vibratorio de todo el cuerpo parece ser beneficioso para la mejora de la fuerza y potencia de las extremidades inferiores, aunque los efectos crónicos de este método en la fuerza y el rendimiento deportivo, a día de hoy, todavía no han sido examinados en nadadores.

El principal objetivo de esta tesis doctoral es analizar la importancia de la fuerza en el rendimiento en natación, así como mostrar los efectos crónicos del entrenamiento vibratorio en la fuerza y el rendimiento en nadadores.

En primer lugar, los capítulos 4.1 y 4.2 tratan de contextualizar y mostrar el estado actual de la literatura científica en cuanto a las asociaciones entre la fuerza y el rendimiento, así como los tipos de entrenamiento de fuerza existentes en natación. El capítulo 4.3 utiliza una muestra de 44 nadadores adolescentes para examinar la asociación entre variables de fuerza y potencia con el rendimiento en 50 y 100 m. En el capítulo 4.4 se exponen los resultados de un entrenamiento vibratorio de todo el cuerpo de 6 meses (3 veces por semana) en 20 nadadores adolescentes, mientras que un grupo control compuesto por 17 nadadores proseguían con su rutina de entrenamiento acuático. Por último, en el capítulo 4.5 se muestra un estudio de validación y fiabilidad de un sistema optoelectrónico para medir la velocidad de desplazamiento durante el ejercicios de fuerza con 22 sujetos con experiencia en entrenamiento de fuerza.

Los resultados principales de la presente Tesis Doctoral muestran que la potencia de las extremidades inferiores guarda una gran relación con el rendimiento en competición de nadadores chicos adolescentes. En nuestro estudio longitudinal, el entrenamiento vibratorio de 6 meses no produjo efectos en la fuerza, potencia o rendimiento deportivo en nadadores. Finalmente, el aparato optoelectrónico demostró ser un sistema válido y fiable para medir la velocidad de desplazamiento durante ejercicios de fuerza.

General Abstract

The lower-body strength and power have shown to play a decisive role in athletic performance in swimmers, especially during the start and turn phases. However, the type of strength and power-related variables that better explain swimming performance, and the most effective training practices to improve strength, power and swimming performance are still under debate. Whole-body vibration training seems to be beneficial to improve lower-body strength and power, although the long-term effects of this method are yet to be confirmed in swimmers.

The main aim of the present Doctoral Thesis is to broaden the scientific knowledge related to the importance of strength and power to swimming performance, as well as to examine the long-term effects of a whole-body vibration training program on strength, power and swimming performance.

Firstly, the purpose of the chapters 4.1 and 4.2 are to examine the current state of knowledge in relation to the association between strength, power, and swimming performance, and also the existing strength- and power-related training interventions aiming to improve swimming performance. Chapter 4.3 includes a sample of 44 swimmers to study the association between strength, power and swimming performance in 50 and 100 m. For chapter 4.4, we performed a 6-month whole-body vibration training protocol (3 sessions per week) in 20 adolescent swimmers, while the 17 swimmers included in the control group continued with the habitual swimming routine. Lastly, chapter 4.5 shows a validity and reliability study of an optoelectronic system to measure movement velocity during bench press and half squat in 22 male adults experienced in resistance training.

The results of the present Doctoral Thesis show that lower-body power has a strong relationship with swimming performance in male adolescent swimmers. In our longitudinal study, a 6-month whole-body vibration training protocol did not elicit any improvements in strength, power or swimming performance in adolescent swimmers. Finally, an optoelectronic device showed to be valid and reliable to measure movement velocity during different resistance exercises.

Listado de Abreviaturas

ATP	Adenosín trifosfato.
ATPasa	Adenosina trifosfatasa
ANCOVA	Análisis de las covarianzas
ANOVA	Análisis de las varianzas
CEA	Ciclo estiramiento-acortamiento.
CEICA	Comité de Ética de la Investigación de la Comunidad Autónoma de Aragón
TE	Tamaño del efecto
FINA	Federación Internacional de Natación
OLP	Mínimos productos ordinarios
PCr	Fosfocreatina
RFD	Tasa de producción de fuerza
SPSS	Paquete estadístico para las ciencias sociales
MCA	Mínimo cambio apreciable
WBV	Vibración del cuerpo entero
1RM	1 repetición máxima

*Abbreviations in English language are shown within Chapter 4.

Capítulo 1

Introducción y Justificación

1

1.1. *Natación*

1.1.1. *Historia de la natación*

La Real Academia Española define el término “natación” como “la acción y efecto de nadar” [1], definiendo “nadar” como “la acción por parte de personas o animales de trasladarse en el agua, ayudándose de los movimientos necesarios, y sin tocar el suelo ni otro apoyo” [1]. Sin embargo, entendiendo la natación dentro del ámbito deportivo, Arellano (1992) matizó: “práctica de un deporte olímpico reglamentado, con el objetivo de desplazarse de la forma más rápida posible en el agua, gracias a las fuerzas propulsivas que genera con los movimientos de los miembros superiores, inferiores y cuerpo, que le permiten vencer las resistencias que se oponen al avance del nadador” [2].

Counsilman y Counsilman (1994) [3] citaban en su libro: “Los peces y otros animales marinos están equipados con aletas que son relativamente pequeñas en comparación con el tamaño de su cuerpo, los humanos tenemos unos miembros superiores e inferiores largos y delgados que proporcionan muy poca superficie con la que interactuar con el agua”. Esta cita pone de manifiesto el pobre diseño del cuerpo del ser humano para nadar de forma eficiente. Los primeros registros históricos relativos a la práctica de la natación por el ser humano se remontan a las pinturas rupestres realizadas sobre los acantilados de Gilf Kebir (Egipto) en el año ~ 5.000 a.C., también llamadas “cuevas de los nadadores” [4]. Sin embargo, la práctica de la natación en este contexto se basaba en una acción de mera supervivencia, destacando la caza de alimentos, la búsqueda de materias primas y la fuga ante enemigos.

No es hasta el s. XIX cuando la natación se populariza extensivamente como práctica deportiva. Este acontecimiento fue causado principalmente por las primeras grandes travesías a nado (especialmente la del Canal de la Mancha), por el papel que los militares le otorgan a la natación durante su preparación física, y por la aparición de los primeros clubes, piscinas y competiciones regladas [5]. En referencia a este último acontecimiento, en el año 1837 tuvo lugar la fundación de la "National Swimming Association" en Inglaterra, lo que promovió la construcción de la primera piscina de la era moderna en 1845 [5].

La consolidación definitiva de la natación como práctica deportiva a nivel internacional culminó con la celebración de los primeros Juegos Olímpicos de la Era Moderna en Atenas (1896), donde se celebró una competición en mar abierto de 1200 m a nado libre. La fundación de la FINA se realizó tras la celebración de la IV edición de los Juegos Olímpicos de 1908 en Londres. El s. XX se caracterizó por una expansión masiva en el número de practicantes, piscinas, clubes y federaciones en los cinco continentes. Esta popularización a lo largo del último siglo se refleja claramente en la actual participación de 209 miembros federativos nacionales registrados por la FINA en enero del año 2018 [6] (**Figura 1**).

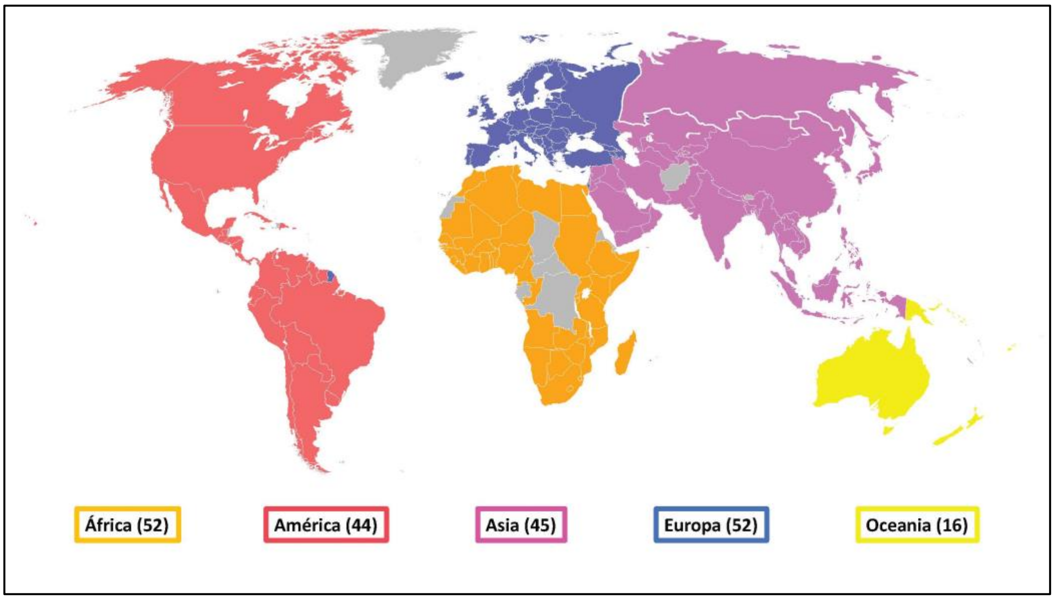


Figura 1. Mapa de los miembros nacionales de la FINA en relación a su confederación.

Por último, cabe destacar que durante esta etapa histórica también se extendió la noción del rendimiento deportivo en el deporte, entendido como la optimización de las capacidades físicas de una persona para maximizar el gesto deportivo. De hecho, el concepto de récord *per se* es relativamente moderno, ya que hasta 1870 solo se tenía en cuenta la clasificación; poco importaba el tiempo empleado en recorrer una determinada distancia, por lo que las marcas eran ignoradas. La palabra *récord* aparece por primera vez en el diccionario Oxford English Dictionary en 1880: "*a record is a performance or occurrence remarkable among, or going beyond, others of the same kind: especially, the best recorded achievement in any competitive sport*". La primera utilización de la palabra *récord* aparece precisamente en una obra sobre natación en 1883 [7].

1.1.2 *Características del medio acuático*

Desde un punto de vista evolutivo, las características específicas del agua no permiten al ser humano desplazarse de forma eficiente en el medio acuoso [5]. Mientras que la carrera a pie es un tipo de locomoción de naturaleza filogenética (i.e., medio en el que ha evolucionado), la natación es de naturaleza ontogenética (i.e., depende del aprendizaje del individuo) [8]. Este importante matiz explica las diferentes progresiones de los records del mundo entre la carrera y la natación a mediados del s. XX (**Figura 2**). Como sugiere Miyashita apoyándose en esta figura [9], mientras que las mejoras en la carrera a pie se debían fundamentalmente a la mejora de la condición física, las mejoras en los records de natación se debieron a los continuos perfeccionamientos y modificaciones de la técnica de nado durante el último siglo, con el estilo de crol consolidándose como estilo libre más rápido en la década de los 20 y 30 del s. XX [5].

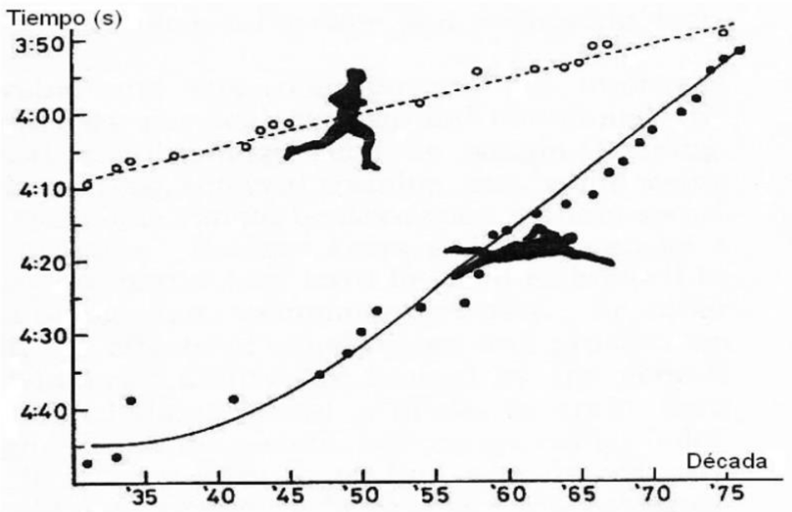


Figura 2. Evolución de los records mundiales en la milla (carrera a pie) y en los 400 m libres de natación (Miyashita y col., 1981).

La natación competitiva, al igual que otros deportes como el atletismo, el ciclismo o el patinaje de velocidad, se caracteriza por la capacidad del deportista de completar una distancia determinada en el menor tiempo posible. Sin embargo, la peculiaridad de que sea una práctica desarrollada en el medio acuático, dota a este deporte de unas características únicas [10]. En primer lugar, el hecho de que el agua sea ~ 800 veces más densa que el aire incrementa considerablemente el gasto energético para desplazarse a través de ella [11]. En segundo lugar, el nadador se encuentra inmerso en un medio inestable que provoca que solo una parte de la fuerza aplicada se traduzca en fuerza propulsiva [11], que es la fuerza que posibilita el avance del nadador en el agua. Mikel Izquierdo destaca la existencia de cuatro fuerzas principales que gobiernan el nado del ser humano [12] (**Figura 3**):

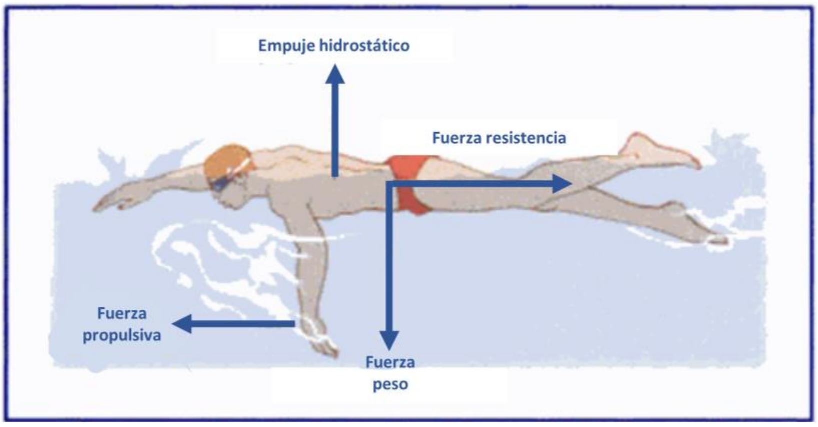


Figura 3. Fuerzas que intervienen durante el nado (Izquierdo, 2008).

- *Fuerza peso*. Se trata de la fuerza vertical y descendente debida al peso del individuo. Esta fuerza junto con el empuje hidrostático determinan la flotabilidad.

- *Empuje hidrostático*. Esta fuerza se basa en el principio de Arquímedes, según el cual "todo cuerpo sumergido en un fluido experimenta un empuje vertical (dirección) y ascendente (sentido) igual al peso del volumen de fluido desalojado". Considerando que la densidad del agua es ~ 1000 $kg{\cdot}m^{-3}$, y que la densidad de los tejidos corporales, es mayor (hueso= ~ 1400-1800 $kg{\cdot}m^{-3}$; músculo, ligamentos y tendones= ~ 1020-1050 $kg{\cdot}m^{-3}$), el cuerpo humano debería hundirse siempre [12]. Sin embargo, la baja densidad del aire en pulmones y vías respiratorias (~ 1.2 $kg{\cdot}m^{-3}$) permiten la flotación del cuerpo en el momento de la inspiración, por lo que la habilidad de flotación pasiva del individuo depende de su capacidad para expandir la caja torácica [12].

- *Fuerza propulsiva*. La propulsión humana en el medio acuático durante el estilo libre (estilo de crol) proviene fundamentalmente de las fuerzas propulsivas de las extremidades superiores [13]. La fuerza propulsiva que realiza el nadador con sus extremidades superiores es la suma vectorial de dos fuerzas cuya correcta interacción resultará en un eficiente desplazamiento hacia delante. Estas dos fuerzas responden a dos principios físicos fundamentales: la fuerza de arrastre y la fuerza de sustentación. La fuerza de arrastre se explica principalmente por el Principio de Acción y Reacción. La acción de empuje que realiza la mano a través del agua hacia atrás acelera y mueve el agua en dirección opuesta a la que uno desea moverse. Esta fuerza estará determinada por la resistencia total de la mano y el brazo contra el agua [2]. Por otro lado, la fuerza de sustentación, explicada por el Principio de Bernoulli, es aquella que utiliza una hélice para propulsarse, cuyas palas no empujan agua hacia atrás sino que giran en un plano perpendicular a la dirección del movimiento, encontrando continuamente agua en reposo [14]. En natación, esta fuerza se ve reflejada cuando la mano del nadador corta el agua generando una zona de altas presiones en la palma y otra zona de bajas presiones en el dorso de la mano. Esta diferencia de presiones genera una mayor velocidad en el flujo de agua que se desliza por el dorso de la mano resultando en una mayor fuerza propulsiva.

- *Fuerza resistencia*. Durante la locomoción en el medio acuático, el nadador desplaza el agua que se encuentra en su camino, sufriendo una fuerza que se opone a su avance llamada fuerza resistencia o fuerza hidrostática. El nadador se enfrenta a tres tipos de fuerzas: la resistencia por fricción, la resistencia de presión y la resistencia por olas. La resistencia por fricción es la menos importante de las tres y depende de la cantidad de superficie en contacto con el agua, la viscosidad del agua, la fricción con la piel, pelo y bañador, y de la velocidad de nado. La resistencia de presión es la más influyente de las tres y se debe a que, durante el nado, se genera una zona de altas presiones frente al nadador y una zona de bajas presiones detrás del mismo. Este gradiente de presiones genera unos flujos turbulentos que frenan el avance del nadador [15]. Por último, la resistencia por olas es un tipo de fuerza que solo se produce cuando el cuerpo se mueve sobre la superficie del agua (entre el agua y el aire). A altas velocidades puede llegar a ser la resistencia más importante, ya que el choque del nadador con la masa de agua que generan las olas es proporcional a la velocidad de nado [16].

Teniendo en cuenta las fuerzas externas a las que se enfrenta el nadador en este singular entorno, el rendimiento en competición estará influenciado por una compleja interacción de factores fisiológicos, morfológicos, neuromusculares, biomecánicos y técnicos en el nadador [17]. Sin embargo, este apartado está focalizado en aquellos factores más determinantes para el rendimiento en pruebas de natación relacionadas con la fuerza, así como las características principales del entrenamiento vibratorio. De esta manera, se contextualizará de una forma más ajustada a los objetivos y contenidos de la presente Tesis Doctoral.

1.2. Bases del entrenamiento de fuerza en el deporte

1.2.1 Fundamentos biológicos

Una de las características básicas de los animales es que pueden moverse, y para generar movimiento es necesaria la producción de fuerza muscular. Los músculos se definen como máquinas moleculares capaces de convertir energía química en energía mecánica [18]. Los mecanismos a partir de los cuales tiene lugar esta conversión son fruto de un complejo sistema cuyo funcionamiento sigue siendo una de las mayores cuestiones sin resolver en el área de la biología [18].

El cuerpo humano dispone de más de 400 músculos esqueléticos voluntarios (i.e., utilizables voluntariamente) y, entre otras funciones, éstos se ocupan de generar fuerza sobre las extremidades para provocar movimiento [19]. El tipo, la amplitud y la potencia de este movimiento depende de la dimensión y disposición de los músculos que actúan sobre las palancas óseas. El proceso anatómico de la contracción muscular se explica a partir de la teoría de los filamentos deslizantes en el sarcómero. Esta teoría establece que la contracción muscular resulta del deslizamiento de los filamentos delgados (moléculas de actina) sobre los filamentos gruesos (cabezas de miosina). La tensión producida por cada sarcómero depende del número de interacciones actina-miosina que acontecen en un momento dado, por lo que el sarcómero se acortará desarrollando la máxima tensión cuando el número de puentes cruzados sea máximo [20] (**Figura 4**). Cuando el músculo está completamente estirado o contraído (**Figura 4-A** y **4-C,** respectivamente), la tensión máxima que puede producir el sarcómero es menor debido a la disminución en el alineamiento entre los puentes cruzados de actina y miosina [21]. Sin embargo, cuando el músculo se encuentra parcialmente contraído, la fuerza máxima potencial es superior debido al óptimo alineamiento de los puentes cruzados de actina y miosina [21]. El proceso de la contracción muscular comienza con la llegada del impulso nervioso desde la motoneurona al espacio sináptico de la unión neuromuscular, lo que conlleva la liberación de acetilcolina, que es una sustancia química que actúa como neurotransmisor. La acetilcolina se une a los receptores de la placa motora, produciendo el potencial de placa, que supera el umbral de excitabilidad de la fibra muscular y conlleva la despolarización de la misma [22]. Dicha despolarización es conducida al retículo sarcoplásmico a través de los

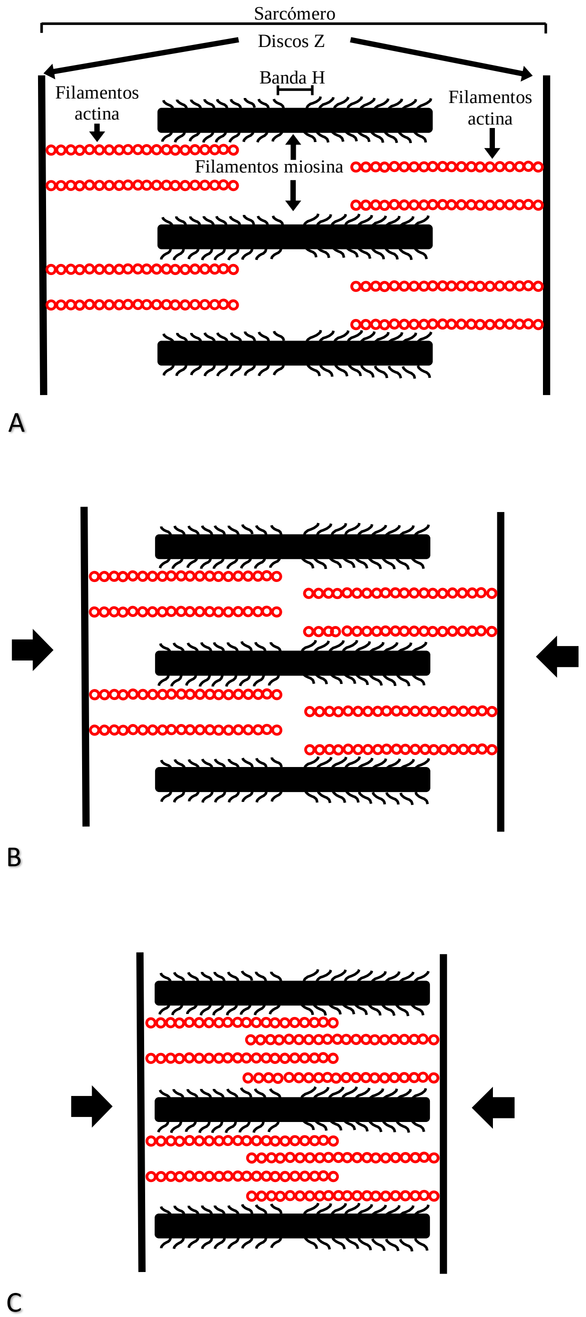


Figura 4. Contracción de una miofibrilla cuando el músculo está estirado (A), contraído parcialmente (B) o completamente contraído (C). (Adaptada de Baechle y Earle, 2007)

túbulos transversos, liberando calcio al interior del músculo. Los iones de calcio se unen a la troponina y provocan un cambio de posición de la tropomiosina (proteínas unidas a los filamentos de actina). Este proceso permitirá que las cabezas de miosina encuentren su espacio en los filamentos de actina para conducir el ATP, rompiéndose por la acción de su enzima ATPasa [19] y desencadenando finalmente la contracción muscular.

1.2.2 Concepto de fuerza

Una vez contextualizados los mecanismos fisiológicos principales que desencadenan la contracción muscular, conviene revisar el concepto de fuerza. Desde el punto de vista de la mecánica, la fuerza se define como toda causa capaz de modificar el estado de reposo de un cuerpo, definida como el producto de una masa por una aceleración ($F= m·a$) y expresada en Newtons (N). Carmelo Bosco definió el término de "fuerza" en su libro [23] como "lo que empuja o tira por medio de un contacto mecánico directo o por la acción de la gravedad y que altera o varía el movimiento de un objeto". Más concretamente, la fuerza muscular se define como "la capacidad de la musculatura para deformar un cuerpo o para modificar la aceleración del mismo" [23]. Desde el punto de vista fisiológico, la fuerza se entiende como la capacidad que tiene el músculo para producir tensión al activarse. Esta tensión depende de numerosos factores, como son el número de puentes cruzados de miosina que pueden interactuar con los filamentos de actina [24], el número de sarcómeros en paralelo, la longitud de la fibra y del músculo, la tensión específica que una fibra es capaz de ejercer por unidad de sección transversal ($N·m^{-2}$) o el tipo de fibra muscular. Además, otros factores como el ángulo de la palanca articular donde se genera la tensión y la velocidad del movimiento también son determinantes en la producción de tensión en el músculo [23].

1.2.3 Manifestaciones de la fuerza

La clasificación de las diferentes manifestaciones de la fuerza requiere el conocimiento de los efectos provocados por la tensión muscular, es decir, la capacidad del músculo de transformar su propia tensión en fuerza aplicada [25]. Badillo y Gorostiaga definieron 4 tipos diferentes de tensión muscular [25]:

- *Tónica.* Se produce cuando se trata de vencer una gran resistencia cercana al 100% de la capacidad del sujeto y la velocidad de ejecución es lenta o nula (e.g., la fuerza isométrica que realiza un gimnasta haciendo el cristo en las anillas).

- *Tónico-explosiva.* Se trata de superar una resistencia inferior a la mencionada en el punto anterior (50 - 80% de la capacidad máxima). La contracción es concéntrica, con un importante componente isométrico durante el inicio de la ejecución, según sea la resistencia. Se consigue un elevado pico de fuerza, aunque en algunos casos se pierde el contacto con la resistencia en la fase final del movimiento, lo que disminuiría la fuerza aplicada (e.g., en un lanzamiento de un objeto pesado).

- *Elástico-explosiva:* Sucede al vencer una resistencia relativamente liviana (inferior al 50% de la capacidad máxima), alcanzándose un pico de fuerza hacia el principio del desarrollo de la tensión. La fase concéntrica del movimiento está precedida por un estiramiento previo (e.g., golpeo de balón, salto con contramovimiento o saque de tenis).

- *Elástico-explosivo-refleja:* Tiene las mismas características que la anterior, con la peculiaridad de que el estiramiento previo a la fase concéntrica es muy intenso. Esto produce un mayor pico de fuerza que en el caso anterior, alcanzándose antes y teniendo lugar durante menos tiempo (e.g., un salto desde una altura determinada seguida de una rápida reacción para elevarse lo máximo posible; "*drop jump*" en inglés).

En acciones más complejas, como en una carrera de velocidad, se produce una combinación de diferentes tipos de tensión, siendo en este caso de tipo explosivo, elástico y reflejo durante toda la carrera [25]. Teniendo en cuenta los tipos de tensión muscular explicados, Badillo y Gorostiaga identifican 5 manifestaciones de la fuerza, aunque nos centraremos en la definición de 4 de ellas debido a su posterior aplicación en la presente Tesis Doctoral.

- *Fuerza isométrica máxima*. Se trata del pico máximo de fuerza cuando no hay movimiento. En otras palabras, se trata de la máxima fuerza voluntaria cuando la resistencia es insuperable.

- *Fuerza dinámica máxima*. Esta manifestación se corresponde con la resistencia que puede superarse una sola vez. Este valor se corresponde con el de la 1RM. Podemos identificar igualmente la fuerza dinámica máxima relativa, definida como la máxima fuerza que puede aplicarse al desplazar resistencias inferiores a la correspondiente a la 1RM. Esta fuerza puede describirse también como la máxima velocidad a la que puede desplazarse una carga submáxima [25].

- *Fuerza explosiva*. La fuerza explosiva de un sujeto corresponde con una fase muy concreta de la curva fuerza-tiempo, siendo la parte de la curva con una mayor pendiente. En este momento el sujeto estaría produciendo el mayor incremento de la tensión muscular por la unidad de tiempo (más conocido como RFD, en la literatura científica).

- *Fuerza elástico-explosiva.* Como se definía previamente en el tipo de tensión que desencadena esta manifestación de la fuerza, existe un componente elástico creado por un estiramiento previo a la fase concéntrica del movimiento. Cuando la transición entre la fase excéntrica y concéntrica se realiza de forma muy rápida, existe una importante facilitación neural debido al efecto del reflejo miotático, que interviene por la activación del CEA [25]. En este caso la manifestación de la fuerza pasaría a ser elástico-explosivo-refleja.

1.2.4 Evaluación de la fuerza

La evaluación de la fuerza forma parte del control del entrenamiento de casi cualquier deportista. A través de ella, se racionaliza el proceso de entrenamiento, pudiendo evaluar los resultados tras un periodo de entrenamiento, ajustar cargas o determinar estados de fatiga en el deportista. El control de la velocidad de ejecución en el entrenamiento de la fuerza ha demostrado tener una importancia crucial para la mejora del rendimiento en cualquier especialidad deportiva. Como describía JJ González-Badillo, cuanto mayor sea la velocidad conseguida ante una misma resistencia, mayor será la intensidad; esto influirá en el efecto del entrenamiento y, por tanto, en el rendimiento deportivo [25].

El interés por controlar la velocidad de ejecución en ejercicios de fuerza tiene una gran trayectoria en el tiempo, desde que a principios de los años 70 Verjovskiy y Trofimov diseñaron un ingenioso aparato electromecánico para medir el tiempo, el desplazamiento y la aceleración durante el recorrido de la barra en ejercicios de halterofilia [26]. Hoy en día podemos identificar numerosos aparatos para determinar la fuerza aplicada durante un ejercicio determinado, tales como las plataformas de fuerza, dinamómetros, galgas extensiométricas o transductores de posición lineal. Estos últimos, también conocidos como "encoders", son probablemente los más populares para medir, de forma indirecta, la velocidad de ejecución durante diferentes ejercicios de fuerza. Cuando nos proponemos realizar una medición, sea con el aparato que sea, debemos considerar su validez, entendiendo esta como el grado en que una prueba mide lo que pretende medir. Además, debemos considerar la fiabilidad de la medida, es decir, el grado de consistencia o repetibilidad de dicha medida [27]. Diferentes estudios han demostrado la validez y fiabilidad de algunos de los aparatos de medida que existen actualmente en el mercado para la evaluación de la fuerza [28–33]. Sin embargo, algunos de estos aparatos cuentan con ciertas limitaciones que pueden dificultar su adquisición, utilidad o fiabilidad (e.g., un precio demasiado elevado para su adquisición, procedimientos estadísticos no idóneos en su validación, o el inconveniente de ser aparatos con un cable que puede limitar el número de ejercicios o incluso ser dañado por pequeños golpes). Estas consideraciones demandan el desarrollo de estudios de validación rigurosos y robustos de alta calidad que pruebe la validez y fiabilidad de determinados aparatos accesibles y económicos para así poder diferenciar de una forma meticulosa aquellos más precisos para medir la velocidad de ejecución.

1.3. La importancia de la fuerza en natación

Los beneficios del entrenamiento de fuerza en natación han sido estudiados previamente [34,35], siendo cuestionados por entrenadores debido a la creencia de que una mayor masa muscular y una menor flexibilidad podría conllevar un aumento en la fuerza resistencia a vencer en el medio acuático (fuerza previamente explicada en el apartado 1.1.2), causando un efecto negativo en el rendimiento [17]. No obstante, los beneficios fisiológicos derivados del entrenamiento de fuerza son indiscutibles, incluyendo aumentos en los depósitos de fosfocreatina (PCr), aumento de proteínas contráctiles, mejora de la potencia anaeróbica, mejora de la arquitectura muscular, optimización de los ángulos de penación de las fibras musculares, aumento de la síntesis proteica o aumento de una hipertrofia de las fibras rápidas [36–38].

El tipo de entrenamiento de fuerza aplicado para mejorar el rendimiento en natación es de muy diversa índole, aunque esta Tesis Doctoral se centra en aquellos tests o rutinas de entrenamiento de fuerza desarrollados "en seco", o más conocidos en la literatura científica como "dry-land tests" o "dry-land training". Aunque en los capítulos 4.1 y 4.2 se discute con mayor profundidad la literatura científica existente en relación a los tipos de tests de fuerza, así como los diferentes entrenamientos de fuerza en natación, a continuación se muestra una breve introducción y justificación de la necesidad de la presente Tesis Doctoral. Además, debido a que la fuerza de las extremidades superiores e inferiores tiene un rol desigual en el rendimiento en natación, esta parte introductoria se realizará acorde a estas dos categorías.

1.3.1 Fuerza de las extremidades superiores y rendimiento en natación

La fuerza desarrollada por los miembros superiores ha demostrado tener una gran asociación con la fuerza propulsiva en el agua [39] y, por lo tanto, con la velocidad de nado [40]. En relación a esto, algunos autores han revelado que la fuerza ejercida por las extremidades superiores contribuye en un ~ 70% de la fuerza propulsiva total [13]. En referencia a los tipos de tests más apropiados para relacionar la fuerza de las extremidades superiores con el rendimiento en natación, existe una amplia variedad en la literatura científica, tanto de naturaleza isométrica, dinámica o isocinética [41–43]. Esta amplia variedad y la falta de una revisión de la literatura que aúne los diferentes tipos de tests y especifique aquellos que podrían ser más adecuados, dificulta la aplicación práctica de tests “en seco” por parte de entrenadores o preparadores físicos en la natación. Por otro lado, aunque la fuerza de las extremidades superiores ha demostrado contribuir notablemente en el rendimiento, no existe ningún consenso sobre el tipo de entrenamiento implicando la musculatura de las extremidades superiores (e.g., pliométrico, vibratorio, pesos libres, inercial, etc.) más adecuado para mejorar la fuerza y el rendimiento en nadadores. Por esta razón, una profunda revisión de la literatura podría clarificar o ayudar a seleccionar aquellas prácticas que potencialmente podrían mejorar la fuerza y el rendimiento en mayor medida.

1.3.2 Fuerza de las extremidades inferiores y rendimiento en natación

La fuerza desarrollada por las extremidades inferiores también ha demostrado tener un papel fundamental durante las fases en las que el nadador tiene contacto con la pared o el suelo/poyete (i.e., durante virajes o en la salida), principalmente en el rendimiento en pruebas cortas de natación (25 m a 100 m). Por ejemplo, Cossor y Masson observaron que el rendimiento durante la fase de la salida desde el poyete contribuye en un ~ 26% en el tiempo de 50 m en estilo libre [44]. La habilidad del nadador para desarrollar fuerza contra el poyete o contra la pared está relacionada con la fuerza y la potencia de las extremidades inferiores, que podría ser evaluada con numerosos tests [45–48]. En este sentido, los saltos verticales han sido los tests más estudiados, revelando fuertes correlaciones con el rendimiento en la fase de la salida (típicamente el tiempo hasta alcanzar los 15 m) [49]. A pesar de la estrecha relación entre la potencia de las extremidades inferiores con el rendimiento durante la salida, la relación con pruebas de natación cortas (i.e., 25, 50 o 100 m) ha sido estudiada en menor medida, con resultados controvertidos [50,51]. Por otro lado, podemos distinguir diferentes programas de entrenamiento involucrando a la musculatura de las extremidades inferiores (e.g., pliometría, entrenamiento inercial, pesos libres con cargas altas, pliometría con cargas, etc.) aunque, al igual que lo expuesto con las extremidades superiores, no existe un consenso en cuanto al tipo de entrenamiento de fuerza más apropiado para maximizar el rendimiento en natación. Esta falta de claridad demanda de un profundo análisis de la literatura, así como examinar con mayor atención el papel de la fuerza y la potencia de las extremidades inferiores en el rendimiento en natación. Además, existe la urgente necesidad de desarrollar estudios de intervención que prueben la eficacia de diferentes métodos de entrenamiento para proporcionar a entrenadores y especialistas con protocolos útiles y válidos que puedan mejorar el rendimiento. Por ejemplo, el efecto del entrenamiento vibratorio en la natación se desconoce, por lo que sería de gran interés comprobar la eficacia de éste método en el rendimiento y en el desarrollo de la fuerza en nadadores. Por último, destacar que la presente Tesis Doctoral se centrará en el papel de la fuerza y potencia de las extremidades inferiores en el rendimiento en natación.

1.4 Entrenamiento vibratorio en el ámbito deportivo

El estímulo vibratorio, entendido como una oscilación mecánica aplicada al cuerpo de un determinado sujeto (*whole-body vibration* o *WBV* en inglés), ha sido implementado como método de entrenamiento deportivo desde hace unas tres décadas [52,53]. El aparato utilizado para el entrenamiento WBV es la plataforma vibratoria, cuyo motor genera movimientos oscilantes, estimulando contracciones musculares involuntarias [54]. En la actualidad, una visita a casi cualquier centro deportivo o gimnasio nos demostrará cuan populares son las plataformas vibratorias, a pesar de su elevado precio. Entre las diferentes plataformas existentes, podemos distinguir dos modos diferentes de transferir la energía vibratoria al cuerpo [55] (**Figura 5**):

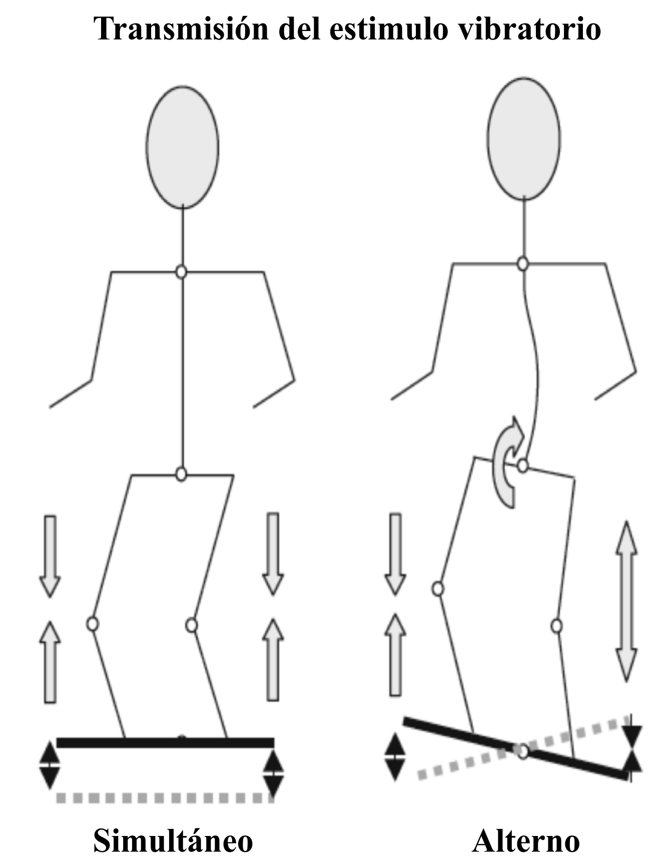


Figura 5. Diseños de vibración en plataformas vibratorias (Cardinale y Wakeling, 2005).

Modo simultáneo o sincrónico. El estímulo vibratorio se transfiere a ambos pies al mismo tiempo (i.e., el movimiento vertical de los pies se produce de forma simultánea) y una aceleración lineal se transfiere al tronco.

Modo alterno. El estimulo se produce con una verticalidad opuesta de un lado al otro, es decir, mientras el pie derecho está en su punto mas bajo, el pie izquierdo está en su punto más alto. Este modo de vibración introduce un movimiento rotacional de la zona lumbar, lo que favorece una menor transmisión del estimulo vibratorio al tronco. En relación a esto, la evidencia científica sugiere que un sujeto puede tolerar aceleraciones más altas a través de este tipo de vibración [56].

Numerosos estudios han examinando la efectividad (tanto crónica como aguda) de este método de entrenamiento en el desarrollo de la fuerza y el rendimiento deportivo. Sin embargo, existe una gran discrepancia en los resultados que a menudo se atribuye a la gran variedad en los protocolos de vibración aplicados. La intensidad del estímulo es una variable fundamental, y varía en función de la amplitud (*A*) y la frecuencia (*f*) utilizada durante el entrenamiento vibratorio [57]. La amplitud depende de la magnitud del movimiento oscilatorio (desplazamiento "peak-to-peak", en mm), mientras que la frecuencia está determinada por el número de ciclos de oscilación (expresada en Hz). A continuación se contextualizará el estado actual del conocimiento en referencia al efecto de tipo crónico o adaptativo del entrenamiento vibratorio, y no de tipo agudo, ya que será el tipo de intervención desarrollado en la presente Tesis Doctoral.

Una revisión sistemática y meta-análisis publicada en 2015 ha examinado los efectos del entrenamiento vibratorio en el desarrollo de la fuerza y en el rendimiento en diferentes deportes (carrera de larga distancia, carrera de velocidad, baloncesto o rugby) [58]. Los resultados de este estudio revelaron efectos reducidos en la fuerza (tamaño del efecto [TE]=0.44), potencia (TE=0.42) y rendimiento deportivo (TE= 0.45). No obstante, otro meta-análisis publicado previamente reportó mayores efectos del entrenamiento vibratorio en la potencia de las extremidades inferiores (altura de vuelo en el salto con contramovimiento; TE=0.77). Considerando este posible efecto positivo del entrenamiento vibratorio en las extremidades inferiores, y la gran relación entre la potencia de las piernas y el rendimiento durante la salida y virajes, es posible que el entrenamiento vibratorio favorezca un incremento en el rendimiento en pruebas cortas de natación.

Capítulo 2

Hipótesis y Objetivos

Hipótesis

La fuerza y la potencia desarrollada por las extremidades inferiores mostrará una relación positiva con el rendimiento en pruebas de natación en nadadores adolescentes.

Los nadadores que realicen un programa de entrenamiento de 6 meses en plataformas vibratorias presentarán mayores incrementos en variables de fuerza, potencia y rendimiento deportivo en pruebas de velocidad que aquellos que no realicen la intervención.

Un aparato optoelectrónico es un sistema válido y fiable para medir la velocidad de ejecución durante ejercicios de fuerza.

Hypothesis

The lower-body strength and power capabilities show a positive relationship with swimming performance in adolescent swimmers.

Swimmers involved in a 6-month whole body vibration training will show greater improvements in strength, power and swimming performance than those swimmers who do not perform the intervention program.

An optoelectronic device is a valid and reliable system to measure movement velocity during resistance exercises.

Objetivos

Los *objetivos generales* de la presente Tesis Doctoral son analizar la importancia de la fuerza muscular en el rendimiento en natación, así como detectar variables determinantes de la fuerza para el rendimiento en natación y examinar los efectos del entrenamiento vibratorio sobre la fuerza, potencia y rendimiento en nadadores adolescentes.

Los *objetivos específicos* que componen esta Tesis Doctoral son:

I. Resumir la literatura científica actual en relación a las variables o tipos de entrenamiento no específicos de la natación para mejorar la fuerza y el rendimiento en nadadores adolescentes.

II. Examinar la literatura científica actual que describa las variables o tipos de entrenamiento específicos de la natación para mejorar la fuerza y el rendimiento en nadadores adolescentes.

III. Determinar las variables de fuerza y potencia que mejor explican el rendimiento en nadadores adolescentes.

IV. Examinar los efectos crónicos del entrenamiento vibratorio en el desarrollo de la fuerza, potencia y rendimiento en nadadores adolescentes.

V. Validar un instrumento económico y accesible para valorar la fuerza y la potencia durante ejercicios de extremidades superiores e inferiores.

Aims

The *general aims* of the present Doctoral Thesis are to analyze the importance of strength and power capabilities in swimming performance, as well as to determine the effects of a 6-month whole-body vibration training period on strength, power and swimming performance in adolescent swimmers.

The *specific aims* included in this Doctoral Thesis are:

- **I.** To summarize the current literature regarding the non-specific strength- and power-related variables and most appropriate training practices to improve strength, power and swimming performance in adolescent swimmers.
- **II.** To examine the current literature studying the most effective swim-specific strength- and power-related variables and training practices to improve strength, power and swimming performance in adolescent swimmers.
- **III.** To determine the strength and power-related tests that are more suitable to predict swimming performance in adolescent swimmers.
- **IV.** To determine the effects of a 6-month whole body vibration training period on strength, power and swimming performance in adolescent swimmers.
- **V.** To validate an accessible and affordable device to measure movement velocity during upper and lower body resistance training.

Capítulo 3

Material y Métodos

A continuación, se detalla la metodología general del proyecto de investigación "*Swimming repercussion on metabolic and structural bone development; benefits of the incorporation of whole body vibration or plyometric training: the RENACIMIENTO project*" (DEP 2012-32724) al cual está adscrita la presente Tesis Doctoral (la metodología completa del proyecto puede consultarse en el estudio metodológico correspondiente [59]). Sin embargo, dentro del capítulo 4 (resultados y discusión) aparece una descripción específica de la metodología utilizada en el desarrollo de cada objetivo.

3.1 Comité de ética

El estudio se llevó a cabo siguiendo las Principios Éticos para las Investigaciones Médicas en Seres Humanos reconocidas por la Declaración de Helsinki de 1975 (revisado en las 64º Asamblea General en Fortaleza 2013, Brasil), y cumpliendo la legislación y la normativa legal Española (ley 14/2007, de 3 de Julio, de Investigación Biomédica). El proyecto fue aprobado por el Comité de Ética de Investigación Clínica de Aragón (**Anexo I**; CEICA ref. CP08/2012). Además, previo a la participación en el proyecto se organizaron reuniones donde se explicaron los objetivos y procedimientos a llevar a cabo en el mismo. Finalmente, todos los padres tuvieron que firmar un consentimiento informado para que sus hijos pudieran participar en el estudio (**Anexo II**). Los nadadores comunicaron verbalmente su conformidad para participar en este proyecto. El proyecto se registro en la base de datos pública (ClinicalTrials.gov número de identificación [NCT02380664]).

3.2 Características de la muestra y diseño del proyecto

Aunque la muestra inicial del proyecto fue de 98 niños y adolescentes nadadores y 75 controles, se seleccionaron únicamente los nadadores para el desarrollo de la presente Tesis Doctoral. Algunos nadadores incluidos en los estudios correspondientes a los capítulos 4.3 y 4.4 no cumplieron con los siguientes criterios de inclusión: 1) tener una edad comprendida entre 12.5 y 17.5 años, 2) no padecer ninguna enfermedad, 3) no padecer ningún tipo de lesión en el periodo de mediciones o durante la intervención, 4) Caucásicos, 5) no estar tomando medicación que afecte al hueso en el momento de comenzar el proyecto ni durante los 3 meses previos (debido a que el objetivo principal del proyecto estaba relacionado con el estudio de la masa ósea, este criterio se aplicó inicialmente a pesar de no tener una influencia directa en la metodología de la presente Tesis Doctoral), 6) no practicar un segundo deporte, además de la natación, y 7) haber estado involucrados en competiciones oficiales dentro de los 15 días cercanos al periodo de mediciones. Además, los nadadores tenían que entrenar un mínimo de 6 horas a la semana, y tener una experiencia mínima de 3 años entrenando natación. A continuación se resume con mayor detalle las muestras finalmente incluidas en cada estudio.

Los **capítulos 4.1 y 4.2**, al tratarse de revisiones sistemáticas, tienen una metodología propia y diferente a los estudios experimentales. Esta metodología se explica en profundidad en dichos capítulos.

El **capítulo 4.3** contiene un diseño transversal y cuenta con la muestra total de 44 nadadores (27 chicos y 17 chicas).

El **capítulo 4.4** contiene datos longitudinales, y fue realizado con una muestra de 37 nadadores (23 chicos y 14 chicas).

El **capítulo 4.5** es un estudio transversal y de validación, y cuenta con los datos extraídos durante un experimento independiente al proyecto RENACIMIENTO. La muestra de este estudio estuvo compuesta por 22 sujetos sanos con experiencia en ejercicios de fuerza, ya que no necesitaban ser nadadores para estudiar la validación de un aparato para medir la velocidad de ejecución en ejercicios de fuerza.

3.3 Pruebas y valoraciones

A continuación se muestran las pruebas de valoración funcional desarrolladas en la presente Tesis Doctoral, y cuyo tratamiento estadístico aparece reflejado en el capítulo 4.

3.3.1 Valoración de la fuerza y potencia "en seco"

- **Media sentadilla isométrica**. La fuerza isométrica máxima partiendo de la posición de media sentadilla fue evaluada en una maquina Smith. Cada nadador se colocó de pie sobre una plataforma de fuerzas KISTLER (Kistler instruments Ltd., Hampshire, Reino Unido) centrada en la maquina Smith, flexionando rodillas a 90º. La barra se ajustó a la altura conveniente para el sujeto en esta posición, y fue anclada con cadenas al suelo para evitar cualquier tipo de movimiento. A la señal del investigador, el nadador debía empujar la barra con la máxima fuerza y tan rápido como fuera posible, registrando el pico de fuerza en N. Cada participante realizó 2 intentos, registrando únicamente el mejor.

- **Media sentadilla dinámica**. En este caso, cada sujeto debía iniciar el movimiento de pie y, a la señal del investigador, realizaba 3 medias sentadillas a la máxima velocidad ascendente posible. Las cargas utilizadas para realizar este test fueron del 20%, 30% y 40% de la fuerza isométrica máxima previamente registrada. La velocidad media propulsiva de la mejor repetición fue registrada para el posterior análisis.

- **Extensión isométrica de rodilla**. La fuerza isométrica máxima de los músculos extensores de cada rodilla fue evaluada usando una galga extensiométrica (MuscleLab, Force Sensor, Norway). Cada nadador adoptaba una posición de sentado con la rodilla a 90º, la espalda recta y los brazos cruzados en el pecho. A la señal del investigador, el nadador extendía la rodilla a la máxima velocidad y con la máxima fuerza posible, registrando el pico máximo de fuerza (N). Se les permitieron dos intentos a cada nadador, registrando únicamente el mejor.

- **Saltos verticales**. Cada nadador realizó 3 tipos de saltos verticales diferentes sobre una plataforma de fuerzas. En primer lugar, realizaron un salto sin contramovimiento (squat jump [**SJ]**) partiendo desde una posición de 90º de flexión de rodilla y los brazos "en jarra" con las manos en la cintura. En segundo lugar, realizaron un salto con contramovimiento (countermovement jump [**CMJ]**) partiendo desde una posición de pie con los brazos en la misma posición que en el SJ. El nadador saltaba realizando un contramovimiento previo lo más rápido posible. El último salto era igual al CMJ, pero incorporando el movimiento de los brazos de forma coordinada para maximizar el rendimiento del salto (salto

Abalakov). Tres intentos fueron permitidos para cada salto con una recuperación de ~ 3 min, registrándose únicamente el mejor.

- **Salto horizontal**. Cada nadador se posicionaba con los pies en paralelo tras una línea, saltando lo más lejos posible permitiendo aprovecharse de la acción de brazos para maximizar el salto. Como los otros saltos, el mejor de los 3 intentos fue registrado.

- **Sprint de carrera de 30 metros**. Finalmente, cada nadador realizó 2 sprints corriendo 30 m a la máxima velocidad (con una recuperación de ~ 3 min), con el mejor intento siendo registrado. Un set de células fotoeléctricas (Byomedic photoelectric cells, Barcelona, España) fue colocado a cada extremo para medir el tiempo necesario para recorrer los 30 m.

3.3.2 Valoración del rendimiento en natación

Las marcas en competiciones oficiales de 50 y 100 m fueron registradas para cada nadador. Como requisitos, los nadadores debían haber competido dentro de un margen de 15 días cercanos a las sesiones de los tests de laboratorio.

3.3.3 Otros tests

La maduración sexual se evaluó facilitando a todos los participantes una planilla con distintas imágenes de maduración sexual para que se auto-evaluasen siguiendo los 5 estadios propuestos por Tanner y Whitehouse (**Anexo III**). Además, la técnica en el estilo de crol de cada nadador fue evaluada subjetivamente por un entrenador con más de 10 años de experiencia utilizando una escala de 10 puntos, con 1 siendo una técnica muy pobre y 10 una técnica perfecta.

3.4 Programa de entrenamiento vibratorio

Aunque el diseño y la metodología empleada en el desarrollo de este programa de entrenamiento se describe más exhaustivamente en el capítulo 4.4, a continuación se resumen las características principales sobre el equipamiento empleado y sobre el diseño del programa de entrenamiento.

3.4.1 Equipamiento

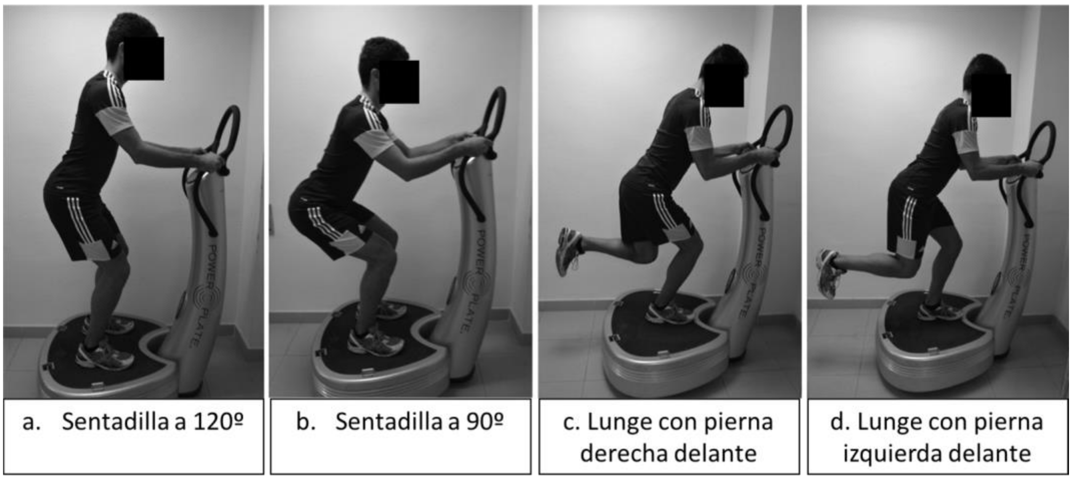
Para el desarrollo de esta intervención, se utilizaron plataformas vibratorias Power Plate® Pro5 (PowerPlate; Amsterdam, Holanda). Esta plataforma es de tipo vertical o sincrónico, lo que significa que las vibraciones tienen lugar verticalmente y no oscilantes). Se colocó una plataforma en el centro deportivo de cada club de natación para que los nadadores no tuvieran que desplazarse al laboratorio para realizar el entrenamiento. En el club de natación con mayor muestra se colocaron dos plataformas vibratorias.

3.4.2 Diseño del estudio

Después de una evaluación inicial, los nadadores fueron asignados aleatoriamente al grupo control o intervención, quedando una muestra final para este estudio de 37 nadadores (20 nadadores en el grupo intervención y 17 nadadores en el grupo control). Estos nadadores participaron en un programa de entrenamiento de WBV durante 6 meses y con una frecuencia de tres sesiones por semana.

Los ejercicios incluidos en esta intervención se muestran gráficamente en la **Figura 6** y constan de: 1) Sentadilla a 120º, 2) Sentadilla a 90º, 3) Desplazamiento de 120º a 90º a una velocidad de 2 segundos para subir y 2 para bajar, 4) Lunge con pierna derecha delante, y 5) Lunge con pierna izquierda delante. El entrenamiento fue siempre supervisado por un investigador para garantizar la seguridad del nadador, anotando también asistencias, faltas e incidencias. Los nadadores realizaban el protocolo en parejas y de forma alterna, (i.e., mientras uno entrenaba, su compañero descansaba). Debido a que las plataformas vibratorias estaban emplazadas en los centros de los clubes de natación, los nadadores empleaban muy poco tiempo en completar el entrenamiento (~ 15 min). En el caso de que un nadador no pudiera asistir a una sesión de entrenamiento, se ofrecía la posibilidad de recuperarla en otro momento.

Figura 6. Ejercicios realizados durante el protocolo de vibración (Gómez-Bruton y col., 2017)



El protocolo de WBV se muestra en la **Tabla 1.** Debido a una falta de evidencia científica sobre las características de un protocolo vibratorio óptimo y a que el objetivo inicial de este proyecto fue mejorar la masa ósea, se utilizó un protocolo vibratorio que mostró previamente mejoras en la masa ósea de adolescentes normoactivos [60]. Este protocolo fue de carácter progresivo y de características similares a las reportadas por una revisión sistemática previa examinando los efectos del WBV en la fuerza y el rendimiento en otros deportes [58]. Los artículos incluidos en esta revisión utilizaron intensidades similares a las aplicadas en la presente Tesis Doctoral, con frecuencias entre 25 y 40 Hz, desplazamientos entre 1.5 to 6 mm y aceleraciones entre 5.4 y 29.6 g.

Tabla 1. Protocolo de vibración de cuerpo entero

Mes	Nº Ses	Frec. (Hz)	Despl. (mm)	Duración (s)	Descanso (s)	Rep.	Vibración total (min)	Entreno total (min)	Acel. Pico (g)
Mes 1	12	30	2	45	45	2	7.5	15	3.6
Mes 2	12	30	4	45	45	2	7.5	15	7.2
Mes 3	12	32	4	45	45	2	7.5	15	8.2
Mes 4	12	34	4	60	60	2*	8	16	9.3
Mes 5	12	36	4	60	60	2*	8	16	10.4
Mes 6	12	38	4	60	60	2*	8	16	11.6

NºSes=Número de sesiones al mes; Frec=Frecuencia; Despl.=Desplazamiento (De pico a pico); Rep=Repeticiones realizadas; Acel. Pico= Aceleración pico.
*Sentadilla 120, 90º y dinámica se realizaron dos veces mientras que el lunge con cada pierna se realizó una vez.

3.5 Análisis estadísticos

A continuación, se resumen brevemente las pruebas estadísticas que se efectuaron para obtener los resultados de esta Tesis Doctoral; no obstante, en el capítulo 4 aparece una descripción más detallada de todos los análisis estadísticos realizados. Dependiendo del estudio, los análisis se realizaron con el paquete informático SPSS (versión 22.0 para Mac OS X, SPSS Inc., Chicago, IL, EEUU), con el paquete estadístico R (versión 3.5.1) o utilizando las hojas proporcionadas por Hopkins [61] para realizar inferencia basada en la magnitud (o "*magnitude-based inference*", en la literatura científica). En general, los datos se presentan como media ± desviación estándar, a menos que se indiquen otros estadísticos. En primer lugar, se estudió la normalidad en la distribución de las variables continuas mediante el test de *Kolmogorov-Smirnov*. Si la distribución de una variable era normal, las diferencias entre grupos se establecían mediante el test para muestras independientes (test *t* de Student) o con el test de análisis de la varianza (ANOVA). En algunas pruebas estadísticas se utilizaron covariables para ajustar variables que podían estar influenciadas por otras. En esos casos se efectuó el test de análisis de la covarianza (ANCOVA) junto con el test post hoc de Bonferroni. Las asociaciones entre variables se estudiaron mediante correlaciones bivariadas de Pearson y regresiones lineales. Las variables nominales como los estadios de maduración sexual de Tanner, se analizaron con tablas de contingencia aplicando el test de Chi-cuadrado. El nivel de significación estadístico fue tomado, como norma general como $p < 0,05$.

Para analizar el efecto del entrenamiento vibratorio en la fuerza, potencia y rendimiento, se utilizaron las hojas de Hopkins para determinar el tamaño del efecto por medio del mínimo cambio apreciable (MCA). Se usaron los puntos de corte establecidos por Hopkins y col. [62]: el tamaño del efecto de la *d* de Cohen puede ser trivial (0,0 – 0,2), pequeño (0,2 – 0,6), moderado (0,6 – 1,2), o grande (> 1,2 – 2,0). Para la comparación intra- e inter-grupos, se determinaron las posibilidades de que el efecto de la intervención fuera beneficioso o perjudicial cuantitativa y cualitativamente. De esta manera, la valoración seguía la relación que se muestra en la **Tabla 2**:

Tabla 2. Relación entre el porcentaje de la probabilidad de acontecimiento y su valoración cualitativa (Hopkins, 2009)

Valoración cuantitativa	Valoración cualitativa
< 1%	Casi seguro que no
1% to 5%	Muy improbable
>5% to 25%	Improbable
>25% to 75%	Posiblemente
>75% to 95%	Probable
>95% to 99%	Muy probable
>99%	Casi seguro

* En el caso de que las posibilidades de tener un efecto beneficioso o perjudicial fueran ambos >5%, el efecto se determinaría como “confuso”.

Por último, para el estudio de validación, se utilizó el paquete estadístico R ya que el SPSS no permitía la realización de las regresiones propuestas por Ludbrook (llamadas "OLP regression") [63]. Este modelo de regresión fue utilizado en lugar de regresiones lineales simples para estimar el error sistemático y el error proporcional, ya que es el más apropiado cuando ninguno de los aparatos es el verdadero "gold standard". El error sistemático tenía lugar cuando el intervalo de confianza del intercepto incluía el valor 0, mientras que existía un error proporcional cuando el intervalo de confianza de la pendiente incluía el valor 1.

Chapter 4

Results and Discussion

A continuación, se presentan los resultados y la discusión de la presente Tesis Doctoral. En primer lugar, los capítulos 4.1 y 4.2 mostrarán los principales hallazgos en referencia al conocimiento científico sobre los ejercicios de la fuerza más determinantes para el rendimiento en natación, así como los tipos de entrenamiento estudiados para mejorar la fuerza y el rendimiento en nadadores. Aunque parece clara la influencia de la fuerza de las extremidades inferiores en el rendimiento durante la salida, no está claro el tipo de ejercicios que mejor expliquen el rendimiento en pruebas de natación, así como el tipo de entrenamiento más apropiado para su mejora. Los resultados que se muestran a continuación destacan la gran relación que guarda la potencia de extremidades inferiores en chicos adolescentes, los efectos triviales de nuestro protocolo de vibración en la fuerza y rendimiento de nadadores adolescentes, y la gran validez y fiabilidad de un aparato optoelectrónico para medir la velocidad de ejecución durante diferentes ejercicios.

The results and discussion of the present Doctoral Thesis are presented in the following 5 sub-chapters. The chapters 4.1 and 4.2 will show the current state of knowledge regarding the most appropriate exercises to explain swimming performance, as well as the best training practices to improve strength, power and swimming performance in adolescents. Although the association between lower-body power and block start performance seems evident, its influence in overall swimming performance and the best training practices to improve strength, power and swimming performance are still under debate. The following results highlight the strong relationship between lower-body power and overall swimming performance in male adolescents, the lack of effect of a whole-body vibration protocol on strength, power and swimming performance in adolescent swimmers, and the great validity and reliability of an optoelectronic device to measure movement velocity during resistance exercises

Chapter 4.1

Non-specific resistance training and swimming performance

Muniz-Pardos, B, Gómez-Bruton, A, Matute-Llorente, A, Gonzalez-Aguero, A, Gomez-Cabello, A, Gonzalo-Skok, O, José A. Casajús, Vicente-Rodríguez G. Non-specific resistance training and swimming performance: Strength or Power? A systematic review. **J Strength Cond Res**. *Accepted for publication*

ABSTRACT

The purpose of this systematic review was to determine which type of non-specific resistance intervention is more effective to enhance swimming performance, and to determine which non-specific strength- or power-related variable better predicts swimming performance. A search was conducted on PubMed, Cochrane Plus and SportDiscus up to June 2018. Studies were distributed into 4 categories: dry-land strength (DLS), dry-land power (DLP), combination of training methods and strength and power in start performance. From 1844 citations, 33 met the inclusion criteria. Cross-sectional DLS studies showed positive associations between swimming performance and DLS development (especially through upper-body isometric assessments), although the efficacy of DLS training interventions remains unclear. DLP training (principally through plyometrics) was a proficient, non-specific method to enhance swimming block start performance (SBS; the start phase off the block and during the first 5-15 m) and jump assessment was the best predictor of SBS. Some pioneering non-specific practices such as the acute exposure to high altitude or the maintenance of a high core temperature during the transition phase before competition appear to improve performance, although more research is required to confirm their efficacy. Further high-quality intervention studies are required to clarify the effect of DLP training on sprint swimming performance.

INTRODUCTION

Swimming performance is influenced by a multitude of factors such as flexibility, body composition or technique [41]. Notably, most of the literature evaluating swimming performance is focused on swimmers' strength and power development with the majority of studies presenting positive associations between strength and swimming success [41,51]. Given this apparent association, a wide variety of strength training protocols have been examined to maximize swimming performance. These include free-weight training, swimming resistance training or plyometric training, amongst others. However, due to the large heterogeneity among these studies (i.e., different assessment tools, protocols, outcomes and conditions), making comparisons between studies remains difficult.

Previous studies have shown that non-specific resistance training (NSRT) provides a foundation of fitness for all sports, allowing the development of a balanced neuromuscular system and serves as a base from which to train more specifically at later stages [64]. Since NSRT requires limited equipment (e.g., bench press, squats or pull ups), and specific dry-land training demands exclusive well-maintained equipment only affordable for a few well-funded laboratories or elite swimming clubs (such as biokinetic benches or specific ergometers), NSRT often remains as the strength training method of choice.

The American College of Sports Medicine (ACSM) 2009 Position Stand defines the term "progression" in resistance training as the pursuit of a specific target over time until the established goal is reached [65]. NSRT would correspond to the first stage of this progression in resistance training. Improvements in non-specific parameters such as motor performance, vertical jump, sprint speed or agility are associated with athletic performance improvements in sport-specific activities [65] and consequently, these practices have gained prominence in the athlete's preparation phase. Despite its popularity, the effectiveness of this modality as a training stimulus is yet to be evaluated and optimized.

Regarding the effects of resistance interventions on swimming performance, the present systematic review considered 2 previous systematic reviews of similar characteristics [17,34]. Although the current review holds some alignments with Crowley et al.'s review [17], there are key differences that make this systematic review necessary and useful for coaches seeking the most recent non-specific strength training strategies. Crowley et al. limited their search to participants aged 16 and over, evaluating only the chronic effects of resistance training while failing to include cross-sectional studies, studies evaluating start performance and studies with acute effect interventions. Subsequently, a review providing up to date quantitative data on NSRT as a means to improve swimming performance, will be a valuable addition to an already established coaching strategy. Thus, the aims of this systematic review were to determine which type of NSRT are more suitable for the enhancement of swimming performance and to determine the non-specific strength and power variables that are better associated with swimming performance in adolescent and young adult swimmers.

METHODS

Literature search

This study was performed following the systematic review methodology proposed in the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [66]. Studies were identified by searching within electronic databases (PubMed, SPORTDiscus and Cochrane Plus), reference lists and consultation with experts in the field. The search was conducted up to and including the 1st of June 2018. The key words used in the search were “swimming”, “muscle strength” and “athletic performance”. The specific search strategy for PubMed was: ("Muscle Strength"[Mesh]) OR "Athletic Performance"[Mesh]) AND "Swimming"[Mesh]) with the additional filter of “Humans”. For SPORTDiscus the search was ((DE "MUSCLE strength") OR (DE "PERFORMANCE")) AND (DE "SWIMMING") and, finally, the search strategy for Cochrane Plus was ((Muscle Strength) OR (Athletic Performance)) AND (Swimming).

Eligibility criteria

For inclusion, studies included in this analyses were longitudinal, randomized or non-randomized controlled trials, studying the effects of NSRT programs on swimming performance. Cross-sectional studies evaluating the relationship between non-specific strength/power variables and swimming performance were also included. All participants were competitive swimmers between 13 and 19 years old (following PubMed criteria).

Studies in languages other than English, unpublished data, and studies involving other athletes excluding competitive swimmers were excluded from the present systematic review. Studies focusing on variables other than strength- or power-related interventions/assessments (e.g., swimming technique, rehabilitation, physiological parameters or respiratory muscle training) and studies in which the assessments/interventions used specific exercises (e.g., biokinetic swim benches or resistance training from swim-specific positions) were also excluded. Additionally, studies only evaluating strength-related variables without including a measure of swimming performance were also excluded.

Quality assessment

The methodological quality of the manuscripts included in this systematic review was assessed using 2 different tools. For cross-sectional studies, the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies proposed by the National Heart, Lung and Blood Institute [67] was used, grading articles on a scale of 14 points. For experimental studies, the Physiotherapy Evidence Database (PEDro) scale [68] was used, classifying articles on a checklist composed of 11 items. Two separate researchers evaluated the quality of the studies independently.

Type of studies

The articles selected for this review were distributed into 4 categories: dry-land strength, dry-land power, combination of training methods and strength and power in start performance.

1. Dry-land strength (DLS). The articles included were those of which assessments/training programs comprise of non-specific dynamic, isometric or isokinetic strength exercises in addition to strength-related NSRT methods such as vibration interventions, electrical stimulation training or core training.
2. Dry-land power (DLP). The studies included in this category were those including jumps or ball throwing exercises.
3. Combination of training methods. This category comprised training interventions which include exercises typical of 2 or more of the previous categories (e.g., intervention training with jumps and weights training).
4. Dry-land strength and power in start performance. Since start performance strongly influences overall swim performance and some studies only examined

the potential effects of NSRT on the start phase performance (block start only or including the subaquatic phase), these articles were classified into an independent sub-section.

RESULTS

Included studies

Searches identified 1844 potentially relevant articles. Following review of titles, abstracts and excluding the duplicates, the total was reduced to 91 relevant manuscripts for inclusion. Of these articles, 33 met the selection criteria and were included in this review (**Figure 7**).

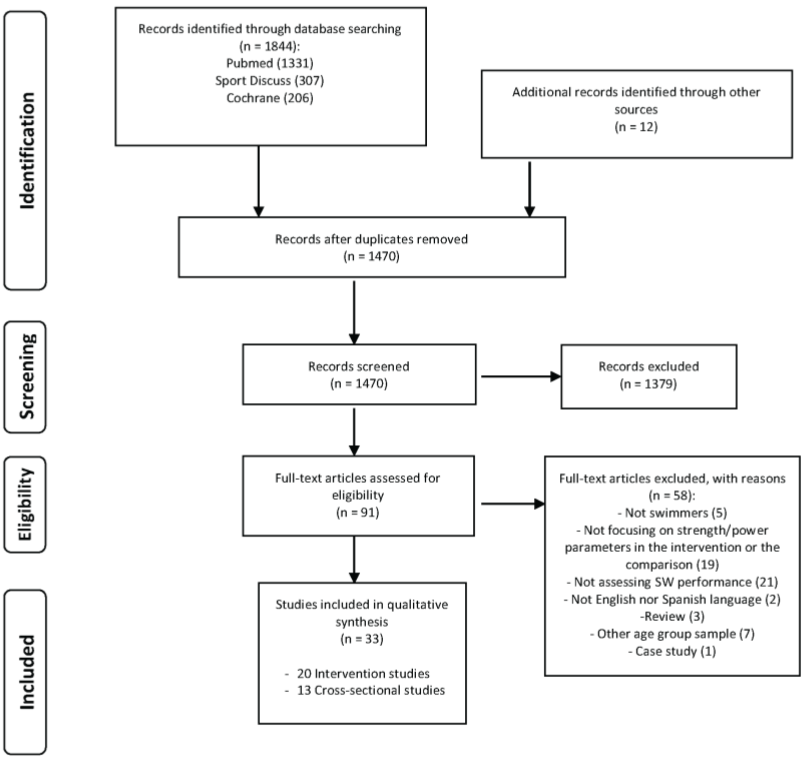


Figure 7. Flow chart of the studies including non-specific tests or protocols

Thirteen out of the 33 included manuscripts were cross-sectional studies. These studies focused on the relationship between swimming performance and DLS (isometric, dynamic, isokinetic) and DLP (jumps, throws) variables (**Table 3**). Some of the cross-sectional studies assessed variables typical of more than 1 category (DLS or DLP), and therefore were included in both sections.

A total of 20 out of the 33 included articles were intervention studies assessing the effect (acute or chronic) of different protocols on swimming performance (**Table 4**), such as postactivation potentiation (PAP), weights training, core training or electrical stimulation. One of these 20 intervention studies [69] also reported associations between performance and DLP and was therefore included in both **Table 3** and **Table 4**.

Table 3. Cross-sectional studies included in the systematic review (n=13)

Article	Age (years)	Level	N (Males)	Variables	Outcomes
Gomez-Bruton et al., 2016 (47)	14.3±2.2	Regional	67(38)	*S(50),* DLS (ISOM KE, GS), DLP (horizontal jump)	Positive relationship between DLP (horizontal jump) and *S(50).*
García-Ramos et al., 2016a (69)	17.1±0.8	International	15(15)	*S(5),S(10),S(15), DLP (*SJ, loaded SJ).	Positive relationship between all distances and SJ and loaded SJ.
Gracía-Ramos et al., 2016b (49)	15.3±1.6	International	20(0)	*S(5),S(10),S(15), DLP (*SJ, CMJ, loaded SJ), DLS (ISOM KF, KE muscle torque).	Positive relationship between SJ and CMJ and *S(5).* Positive relationship between Loaded SJ and *S(5),S(10),S(15),* although no correlation found with DLS.
Loturco et al., 2016 (84)	17.0±0.7	National	10(10)	*S(50), S(100), S(200),* DLS (ISOM: bench press, quarter squat), DLS (bench press) and DLP (SJ, CMJ).	Positive relationship between Jump squat and *S(50).* Positive relationship between tethered SW and CMJ, SJ.
Gola et al., 2014 (46)	23.0±1.2	PE University students	16(16)	*S(25), S(50),* DLS (ISOM shoulder, elbow, knee and hip FLX and EXT).	Positive relationship between the relative sum of the upper extremity muscle torque values and *S(25), S(50).*
Beretić et al., 2013 (45)	21.1±4.3	International	27(27)	*S(10),* DLS (ISOM leg EXT).	Positive relationship between *S(10)* and F_{max}, F rel, $RFD_{50\%}$, RFD $_{50\%rel}$ of the leg EXT.

Garrido et al., 2012 (71)	12.5-18.6	National	78(39)	*S(100)*, *S(200)*, DLS (GS).	Positive relationship between *S(100)* and grip strength in both males and females.
Morouço et al., 2011 (50)	14.9±0.7	National	10(10)	*S(50)*, DLS (bench press, Squat and lat pull-down back), DLP (CMJ).	Positive relationship between CMJ and squat. Positive relationship between bench press and lat pull down back. Positive relationship between *S(50)* and lat pull down back.
West et al., 2011 (48)	21.3±1.7	International	11(11)	*S(15)*, DLS (3RM squat), DLP (CMJ).	*S(15)* correlated with DLS and DLP. Positive relationship between DLS and DLP.
Geladas et al., 2005 (41)	12-14	Young sprinters	263(178)	*S(100)*, DLP (Horizontal jump), DLS (GS).	In boys: Positive relationship between *S(100)*, GS and horizontal jump. In girls: Positive relationship between horizontal jump and *S(100)*.
Arellano et al., 2005 (70)	21.4±2.2	National	11(6)	*S(5)*, DLP (CMJ and simulated jump off the block).	Positive relationship between horizontal force off the block and *S(5)*.
Dopsaj et al., 1999 (51)	NR	Collegiate	16(16)	*S(25)*, DLS (ISOM KE,TF,TE,SF and GS).	Positive relationship between ISOM SF, TF and *S(25)*.
Miyashita, 1979 (72)	Ms(16.7±2.5) Fs(14.6±1.3)	Young swimmers	35(19)	*S(100)*, DLS (ISOK peak torque of KE and arm pull exercise).	Positive relationship between peak torque of arm-pull muscles and *S(100)*

CMJ= countermovement jump; **DLP**= dry-land power; **DLS**= dry-land strength; **EF**: elbow flexion; **EXT**=extension; **F**=force; **FLX**=flexion; **Fs**=females; **GS**= grip strength; **HT**= height; **ISOK**=isokinetic; **ISOM**= isometric; **KE**=knee extension; **KF**=knee flexion; **max**=maximum; **Ms**=males; **NR**=not reported; **PE**= physical education; **RFD**=rate of force development; **RM**=repetition maximum; ***S("number")***= sprint (meters); **SF**=shoulder flexion; **SJ**= squat jump; **SW**=swimmers or swimming; **TE**=trunk extension; **TF**=trunk flexion.

Table 4. Intervention studies included in the systematic review (n=20).

Article	Age (years)	Level	N (Males)	CG [N]	EG [N]	Measurements	Outcomes	Effect
McGowan et al., 2017 (89)	20.0±3.0	International	25(12)	SW remained seated throughout the 30-min transition	30-min combo transition (5-min dry-land circuit + heated jacket).	*S(100), S(15).*	Positive effect of combo transition on both *S(100)* and *S(15).*	Acute
Rejman et al., 2016 (92)	21.9±3.4	National	9(9)	NA	6w, 2 sess/w. UB and LB PT.	Time to water contact during the start phase.	Positive effects of PT on start performance.	Chronic
Iizuka et al., 2016 (95)	20.2±1.0	National	9(9)	NA	PAP (Trunk stabilization exercises)	*S(5).*	Positive effects of PAP on *S(5).*	Acute
McGowan et al., 2016 (87)	16.0±1.0	National	16(11)	SW remained seated throughout the 30-min transition	- 30-min passive transition (wearing a heated jacket while seated) - DLS transition (5-min DLS circuit) - 30-min combo transition (5-min dry-land circuit + heated jacket).	*S(100), S(15).*	Positive effects of DLS and combo transitions on *S(100).* Positive effects of Combo transition on *S(15).*	Acute
García-Ramos et al., 2016a (69)	17.1±0.8	National	15(15)	NA	17 days DLS T (25 SW sess +10 sess of half squat and lunge) at moderate altitude (2,320 m).	*S(5), S(10), S(15),* DLP (loaded SJ with 0, 25, 50, 75, 100% of the SW's body mass).	Positive effect on SJ height and SW performance (higher increment in jump height=greater reduction in start time).	Chronic
Sarramian et al., 2015 (79)	16.0±1.62	National	18(10)	Traditional SW WU	- UB PAP (3 RM pull-ups). - LB PAP (5 jumps to box).	*S(50).* Individual r time.	No effects found on S(50) after any PAP protocol. Traditional WU were	Acute

					- Combined PAP (UB PAP+LB PAP).		significantly faster than those followed by an UB PAP.	
Cuenca-Fernandez et al., 2015 (94)	17-23	National	14(10)	Traditional SW WU	- 3RM lunge PAP WU. - 4 reps YoYo squat WU (position used in the block in a SW start).	*S(15)* and *S*(5). r = 8 min.	Positive effects of both PAP on *S(5)* and *S(15)*, only for the YoYo squat PAP.	Acute
Sawdon-Bea et al., 2015 (78)	14-17	Regional-National	32(16)	[16] SW T only	[16] 6w, 3sess/w. dry-land T (6 strength exercises focused on core and shoulder stabilizers).	*S(50)*, DLS (McGill Trunk Flexor test, GS).	No effects on *S(50)* or UB strength. Positive effects on Core strength.	Chronic
Weston et al., 2015 (73)	16.0±1.0	National	20(10)	[10] SW T only	[10] 12w, 3sess/w. core-T program in addition to their normal SW routine.	*S(50)*. Prone-bridge and straight-arm pull-down test.	Positive effect of core-T on *S(50)*, prone-bridge and straight-arm pull-down test.	Chronic
Girold et al., 2012 (80)	21.8±3.9	National	24(12)	[8] SW T only	- [8] 4w, 3sess/w. dry land T group (pull-ups and draws). - [8] 4w, 3sess/w. ES group (*latissimi dorsi* muscles).	*S(50)* (at w0,w4,w8), EXT peak torque of shoulder (ECC, CON and ISOM).	Positive effects of both ES and Dry-land T programs on *S(50)* and peak torque. No differences between programs.	Chronic
Kilduff et al., 2011 (93)	22.0±2.0	International	9(7)	SW T only	PAP stimulus (1x3 reps at 87%RM squat).	*S(15)*. r = 8 min. DLP (CMJ, PVF and PHF from the block)	Positive effects of PAP on PVF, PHF and CMJ. No effects on *S(15)*.	Acute
Potdevin et al., 2011 (83)	EG (14.3±0.2) CG (14.1±0.2)	Regional	23(10)	[11] SW T only	[12] 6w, 2sess/w. PT before SW T.	*S(50)*, *S(400)*, DLP (CMJ and SJ).	Positive effects of PT on CMJ, SJ, *S(50)* and *S(400)*.	Chronic

Bishop et al., 2009 (91)	EG (13.1±1.4) CG (12.6±1.9)	Regional	22(NS)	[11] SW T only	[11] 8w, 2 extra sess/week of PT	*S*(5.5), V of take-off, time to contact the water.	Positive effects of PT on *S*(5.5): Greater V of the take off to contact, and time to head contact.	Chronic
Aspenes et al., 2009 (74)	EG (17.5±2.9) CG (15.9±1.1)	Regional	20(8)	[9] SW T only	[11] 11w, 2 sess/w. Combined strength and endurance T: 4x4-min high intensity intervals + 3x5 RM (butterfly stroke movement)	*S(50)*, *S(100)*, *S(400)*, DLS (Maximal shoulder strength).	Positive effects of combined strength and endurance T on *S(400)* and maximal strength in bilateral shoulder EXT.	Chronic
Girold et al., 2007 (75)	16.5±3.5	Regional to National	21(10)	[7] 6 sess/w of SW T only + 1.5 h of cycling	- [7] 12w, 6sess/w. Dry-land G: 1.5h/w extra of whole-body free weights T. - [7] 12w, 6sess/w. RAS G: 1.5h/w extra of swim-specific T.	*S(50)* and DLS (EF, EE ISOK peak torque	Positive effects of dry-land and RAS T on *S(50)*. Positive effects of both interventions on ISOK peak torque.	Chronic
Pichon et al., 1995 (81)	23.0±2.1	Regional to national	14(14)	[7] SW T only	[7] 3w, 12 min/sess, 3sess/w. ES (80-Hz) in *latissimi dorsi* muscles.	*S(25)* arms-only, *S(50)* and DLS (Shoulder FLX and EXT peak torque).	Positive effects of ES on muscular strength, *S(25)* arms-only and *S(50)*.	Chronic
Trappe et al., 1994 (43)	20.1±1.2	Regional	10(10)	NA	[5] 6w, 2sess/w. Traditional free-weight T of *latissimus dorsi* and triceps. [5] 6w, 2sess/w. Weight assisted (WAT group) pull-ups and dips (dip and pull T device).	*S(22.9)*[a], *S(365.8)*[a], DLP (Biokinetic SW bench), SWP (Tethered SW).	No differences in the effects of Traditional and WAT groups.	Chronic

Romney et al., 1993 (86)	M(20.8±0.6) F(20.9±0.5)	Regional	12(4)	SW WU (10x25m sprints)	- Dry-land WU (push-ups, sit-ups, lunge jumps, back hyper EXT, butterfly pulls). - No WU. SW seated for 15 min.	*S(91.44)*[a]. r = 3 min.	Positive effects of SW WU on *S(91.44)*[a], when compared to no WU. Dry-land WU presented a trend ($p=0.054$).	Acute
Tanaka et al., 1993 (77)	EG(19.5±0.3) CG(19.2±0.3)	Regional	24(24)	[12] SW T only	[12] 8w, 3sess/w. DLS T (dips, chin-ups, lat pull-downs, elbow EXT and bent arm flies).	*S(22.86)*[a], *S(365.76)*[a].	No effects on *S(22.86)*m[a], *S(365.76)*[a].	Chronic
Strass, 1988 (76)	EG(16.6±1.2) CG(19.2±0.3)	Regional to national	19(17)	[9] SW T only	[10] 6w, 4sess/w. Arm extensor muscles T using barbells.	*S*(25). *S*(50). DLS (ISOM elbow EXT strength).	Positive effects of DLS intervention on DLS, *S*(25) and *S*(50).	Chronic

CG=control group; **CMJ**=counter movement jump; **CON**=concentric; **DLP**=dry-land power; **DLS**=dry-land strength; **ECC**=eccentric; **EG**=experimental group; **ES**=electrical-stimulation; **EXT**=extension; **FLX**=flexion; **GS**=grip strength; **ISOM**=isometric; **LB**=lower Body; **NA**=not applicable; **NS=**not specified; **PAP**=post-activation potentiation; **PHF**=peak horizontal force; **PPO**=peak power output; **PT**=plyometric training; **PVF**=peak vertical force; **r**=recovery; **reps**=repetitions; **RAS**=resisted and assisted sprint; ***S*(“number”)**=sprint (meters); ***S*(“number”)[a]**=yards converted to meters; **Sess=**sessions; **SJ**=squat jump; **SW**=swimming or swimmers; **T**=training; **UB**=upper body; **V**=velocity; **w**=week; **WAT**=weight-assisted training; **WU**=warm up.

Quality Assessment results

Scores of the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies ranged from 3 to 6 out of a maximum 14 points (**Supplementary Table 1**), except 1 study that only reached 1 point [70]. Some of the criteria assessed were not applicable due to the type of variables measured (exposures that cannot vary in amount or level, exposures measured only once over time or blinding assessors). Furthermore, some vital information was not reported in many of the studies such as the participation rate of eligible persons or participant drop-out after baseline.

Scores of the PEDro scale ranged from 4 to 7 out of a maximum 11 points (**Supplementary Table 2**). These scores are relatively good considering that some exercise protocols (e.g., core training, plyometric training or traditional weights training) do not allow for blinding participants or blinding therapists. Furthermore, the extent to which the assessors were blinded and treatment allocation concealed from participants was poorly reported in most of the selected studies.

Supplementary Table 1. Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (n=13).

References	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**TOTAL**
Gomez-Bruton et al., 2016 (47)	Yes	Yes	No	Yes	No	NA	NA	NA	Yes	NA	Yes	No	NA	Yes	6
García-Ramos et al., 2016a (69)	Yes	Yes	No	Yes	No	NA	NA	No	Yes	Yes	Yes	No	NR	No	6
Gracía-Ramos et al., 2016b (49)	Yes	Yes	No	No	No	NA	NA	NA	Yes	NA	Yes	No	NA	No	4
Loturco et al., 2016 (84)	Yes	No	NR	No	No	NA	NA	NA	Yes	NA	Yes	No	NA	No	3
Gola et al., 2014 (46)	Yes	Yes	No	Yes	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	6
Beretić et al., 2013 (45)	Yes	Yes	No	No	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	4
Garrido et al., 2012 (71)	Yes	Yes	Yes	No	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	6
Morouço et al., 2011 (50)	Yes	No	No	No	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	4
West et al., 2011 (48)	Yes	Yes	No	No	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	4
Geladas et al., 2005 (41)	Yes	Yes	Yes	No	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	6
Arellano et al., 2005 (70)	Yes	No	No	No	No	NA	NA	No	No	NA	No	No	NA	NA	1
Dopsaj et al., 1999 (51)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Miyashita, 1979 (72)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	4

1. Was the research question or objective in this paper clearly stated?
2. Was the study population clearly specified and defined?
3. Was the participation rate of eligible persons at least 50%?
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?

5. Was a sample size justification, power description, or variance and effect estimates provided?
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
10. Was the exposure(s) assessed more than once over time?
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
12. Were the outcome assessors blinded to the exposure status of participants?
13. Was loss to follow-up after baseline 20% or less?
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?

Supplementary Table 2. PEDro Scale (n=20)

References	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**TOTAL**
McGowan et al., 2017 (89)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7
Rejman et al., 2016 (92)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Iizuka et al., 2016 (95)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
McGowan et al., 2016 (87)	No	NA	No	Yes	No	No	No	No	Yes	Yes	Yes	4
García-Ramos et al., 2016a (69)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Sarramian et al., 2015 (79)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Cuenca-Fernandez et al., 2015 (94)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Sawdon-Bea et al., 2015 (78)	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Weston et al., 2015 (73)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Girold et al., 2012 (80)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Kilduff et al., 2011 (93)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6
Potdevin et al., 2011 (83)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6
Bishop et al., 2009 (91)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6
Aspenes et al., 2009 (74)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Girold et al., 2007 (75)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5

Pichon et al., 1995 (81)	No	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Trappe et al., 1994 (43)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Romney et al., 1993 (86)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Tanaka et al., 1993 (77)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Strass, 1988 (76)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4

1. Eligibility criteria were specified.
2. Subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received).
3. Allocation was concealed.
4. The groups were similar at baseline regarding the most important prognostic indicators.
5. There was blinding of all subjects.
6. There was blinding of all therapists who administered the therapy.
7. There was blinding of all assessors who measured at least one key outcome.
8. Measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups.
9. All subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat".
10. The results of between-group statistical comparisons are reported for at least one key outcome.
11. The study provides both point measures and measures of variability for at least one key outcome.

DISCUSSION

Non-specific dry-land strength and swimming performance

Over the last 40 years, many investigations have shown positive correlations between swimming velocity and DLS [45,46,51,71–73]. Gola et al. showed that this correlation seems to vary with swimming distance, with the relative importance of strength increasing as the distance decreases [46]. Accordingly, several DLS interventions have shown positive effects on sprint swimming performance [73–75]. However, the wide variety of the protocols and the diversity of results make it necessary to examine the existing evidence in an attempt to reach a consensus of the most effective DLS practices.

One of the pioneering studies investigating the chronic effects of a DLS training on swimming performance was performed by Strass et al. [76]. These authors assessed the effects of a 6-week maximal strength intervention on 25 m and 50 m swimming performance in 10 male adolescent competitive swimmers (9 participants in the control group). Strength training was focused on the arm extensor muscles using barbells, with an intensity between 90% and 100% of 1 maximum repetition (1RM). While the control group failed to illustrate any positive effects, the intervention group displayed an improvement of 4.4% and 2.1% in 25 m and 50 m, respectively.

Conversely, Tanaka et al. [77] evaluated the effects of an 8-week upper-body DLS training on 25 and 400 yards performance (22.9 m and 365.8 m, respectively) in 24 male collegiate swimmers. The training program was intended to simulate the actions employed during freestyle swimming through weight-stacks machines and free weights. Despite a 30% improvement in land strength, there were no significant differences on swimming velocity between the control and the intervention group. The authors stated that the strength gained on land did not transfer to the propulsive forces used in the water.

However, caution must be taken when evaluating these results since this intervention was applied during the competitive phase of the season, including 7 competitions and a high volume of training. As reported by the authors, it is possible that the high physical demand of the training may have masked any minor performance improvements following the strength training intervention [77]. Coaches and sports specialists should therefore consider that the ideal moment to implement NSRT and benefit from its effects may be out of the competitive phase of the season.

Following the study by Tanaka et al. (42), Trappe and Pearson [43] showed similar results after a 12-week training intervention (6-week DLS training and 6-week swim-only training). Ten highly-trained male collegiate swimmers were divided into 2 intervention groups. During the first 6 weeks, 1 group used a weight-assisted dip and pull-up training device whereas the other group engaged in free-weight training (dips and pull-ups exercises). Despite a significant reduction in time observed in the weight-assisted group, no differences were observed between groups in 25 and 300 yards time (22.9 m and 265.8 m, respectively) or in the biokinetic swim bench variables. These results suggested that weight-assisted training might be as beneficial as free-weight training, although the lack of a control group make it difficult to draw meaningful conclusions.

Similarly, Sawdon-Bea and Benson [78] observed positive improvements in core strength in the intervention group after a 6-week core training program in comparison to a control group. However, this enhancement did not result in an improvement in swimming times. This is consistent with Girold et al., who reported positive effects of a 6-week upper-body strength training on strength development, with no changes in swimming performance [75]. These authors suggest that 12 weeks of strength training might be the minimum duration of training to improve swimming times [75].

Only 1 study examined the acute effect of DLS training on swimming performance through the analysis of a PAP stimulus. The protocol of Sarramian et al. [79] incorporated an upper-body (3RM pull-ups), lower-body (5 loaded jumps to box) or a combined (both upper- and lower-body stimulus) PAP, 8 min before 50 m freestyle swimming. The PAP stimulus did not affect performance and therefore the authors concluded that a combined PAP was not more effective than a traditional swimming warm-up. Notably, an isolated upper-body PAP stimulus produced negative effects on swimming performance, most likely due to the pull-up exercise differing from the actual kinematic characteristics of the front crawl stroke.

After several studies reporting no effects [43,75,77–79], 3 experiments have emphasized the importance of DLS training on swimming velocity, supporting the positive effects of DLS found by the pioneering study of Strass [76]. Girold et al. [80] performed a 4-week DLS training, dividing the participants into either an upper-body DLS group (pull-ups and draws) or an upper-body electrical stimulation training group (applied on both *latissimi dorsi*). Both training protocols enhanced 50 m swimming performance by 1.7% and 2%, respectively. Accordingly, Pichon et al. [81] implemented a 3-week electrical stimulation training similar to that implemented by Girold et al. [80], resulting in comparable improvements in 50 m performance (1.4%). Finally, a 2% improvement in 50 m swimming performance was found by Weston et al. [73] after a 12-week isolated core-training program.

Numerous cross-sectional studies support these positive results, finding significant associations between swimming velocity and isometric [41,45,46,51,71], dynamic [50] and isokinetic strength [72]. Interestingly, most of the significant associations found in these studies involve upper-body strength assessments [41,46,50,51,71,72], whereas only 1 study found a significant correlation between swimming velocity and lower-body strength [45]. This finding can be explained due to the greater role that upper-body strength plays in the application of force in water, considering that the majority of the investigations studying strength and swimming velocity only analyze performance in freestyle swimming. This is supported by the findings of Czabański et al. [13], who reported that 70% of the propulsive force in freestyle swimming comes from the upper-body muscles.

The results from the existing non-specific DLS training intervention studies are unclear (4 out of 9 studies reported positive effects on swimming performance), with upper-body electrical stimulation training being potentially more effective than other methods aiming to improve swimming performance [80,81]. Consequently, it would be reasonable to suggest that there is no up-to-date evidence supporting the use of DLS interventions to enhance swimming performance. However, DLS assessments have shown to provide valid indicators to test the swimmers' level of strength, with upper-body isometric evaluations being the most widely used.

Non-specific dry-land power and swimming performance

A wide variety of training and assessment methods can be used to determine non-specific DLP. Plyometric exercises (e.g., jumping and throwing) are among the most common methods and have shown to increase explosive-reactive power maximizing the stretch-shortening cycle, improving power through increased neural drive, changes in muscle coordination, muscle-tendon complex and both muscle size and architecture [82].

To the best of our knowledge, there is only 1 study examining the chronic effect of plyometric training on swimming performance. Potdevin et al. [83] implemented a 6-week lower-body plyometric training program in adolescent swimmers, finding positive effects on 50 m and 400 m times (3.2% and 4.4% enhancements, respectively).

Sarramian et al. [79] studied whether a PAP stimulus (5 loaded jumps to box) yielded to an improvement in 50 m swimming performance in 18 national swimmers. No differences were found between traditional swimming warm-up and jumping PAP with the authors concluding that this may be due to a learning effect and the simplicity of the study design (i.e., experimental protocol in a fixed order, without randomization).

Additionally, several cross-sectional studies showed positive relationships between horizontal jump [41,47], squat jump [84] and swimming performance. Positive associations have also been reported between upper-body power (3 kg ball throwing test) and swimming performance in pre-pubescent swimmers [85], although there is no evidence in adolescents nor in young adults.

Although positive associations between jumping and swimming performance are well documented [41,47,84], there is limited evidence to support the use of plyometric training to enhance swimming performance. Further research in this area is required considering there are only 2 studies investigating the use of plyometrics, with contrasting results.

Combination of training methods

One of the first researchers to apply a combined training (DLS and DLP) was Romney et al. [86], who assessed the acute effect of 3 different warm-ups on 100 yards (91.44 m) performance. These authors hypothesized that dry-land warm-up using free weights and jumps would be less effective than a swimming-only warm up, but more effective than no warm-up. The results were in accordance with the hierarchy of warm-up theorized by the authors, observing a deterioration in swimming performance of 0.17% after dry-land warm-up ($p = 0.054$) and 1.24% after no warm-up, in comparison to the swimming warm-up. However, the short recovery duration used in this study (3 min) would fail to allow for an adequate return to homeostasis negating any ergogenic effect of the dry-land PAP. Sarramian et al. [79] investigated the optimum rest time needed to maximize the efficacy of PAP, studying different recovery times to observe increased muscle performance after a PAP stimulus (combined DLS-DLP: pull-ups and jumps). The authors concluded that an 8-min recovery was the adequate time to alleviate fatigue and to obtain an optimal potentiation. This study also showed that the combined stimulus (pull-ups and jumps) was more effective than DLS or DLP warm-up alone (pull-ups or jumps, respectively) in enhancing 50 m swimming performance. However, there were no significant differences between combined PAP stimulus and traditional swimming warm-up.

Recently, McGowan et al. [87] studied the acute effect of 3 different warm-ups on swimming performance. Sixteen national level swimmers warmed up for 25 min, followed by a 30-min transition phase and a 100 m maximal bout. The same 16 swimmers carried out this regimen in 4 different testing days (over a 2-week period), varying the transition phase. During the first experimental trial, swimmers remained seated throughout the transition phase (control condition). The second experimental trial included the same protocol as the control condition, but swimmers had to wear an additional heated jacket to increase the temperature of the core muscles. During the third experimental day, the swimmers performed a combined DLS-DLP circuit and, finally, during the fourth experimental day, swimmers performed the combined DLS-DLP circuit while wearing a heated jacket. Compared to the control condition, 100 m performance was significantly faster for both combined DLS-DLP circuit conditions, especially with the additional heated jacket (0.68% and 1.5% improvements, respectively). A maintenance of core temperature during the transition phase could improve swim performance, probably through an increased muscle fiber velocity conduction [88]. The same authors have recently replicated this experimental protocol by recruiting 25 elite level swimmers [89], observing an improvement of 0.8% in 100 m performance. While only a small improvement, an additional ~ 0.3 - 0.4% improvement is relevant to increase the swimmer' s chances of winning a medal at the elite level [89].

Girold et al. [75] designed a 12-week combined DLS (press, pull-up, drawn and squat) and DLP (jumps) program in 21 competitive adolescent swimmers. The control group performed an additional running and cycling session to counterbalance the extra training volume. The intervention group significantly improved 50 m swimming velocity by 2.8%, whereas the control group only improved by 0.9%.

In conclusion, the effects (especially acute) of a combined DLS-DLP training remain unclear, probably due to the low number of studies and the small sample sizes used. Among the 4 articles studying acute effects, only those using a heated jacket to maintain a high core temperature showed positive results on swimming performance [87,89]. We therefore hypothesize that the PAP effect might be ineffective when the core temperature gained during the PAP stimulus is not maintained in well trained swimmers. Lastly, further evidence to support combined training is required since there is only 1 chronic intervention studying the effect of this practice on swimming performance (with positive effects on swimming performance) [75].

Strength and power in start performance

Cossor and Mason [44] demonstrated that the swimming start is an important component of the swimming race, having a higher contribution to the success in sprinting events compared to longer distance events. As previously stated [90], the starting phase accounts for 7.7% to 15% of total race time in elite men 50 m freestyle races, highlighting the importance of the force exerted from lower extremities during the swimming block start (SBS) phase. Consequently, over the last decade, several studies have focused on the influence of the lower extremities strength on start performance (distances ranging from 5 m to 15 m).

Bishop et al. [91] studied the chronic effect of an 8-week lower-body plyometric training on 5.5 m SBS performance in 11 adolescent swimmers. The participants assigned to the intervention group followed the same aquatic training as the control group but with an additional 2-h plyometric training per week. SBS assessments revealed a greater change after the 8-week training for the plyometric training group (15%) compared with the control group (3%), concluding that an exposure to 2 h of supplementary plyometric training per week had a significant impact on SBS performance. Eight years later, Rejman et al. [92] found beneficial effects of a 6-week plyometric training on SBS performance (flight time to water contact) in 9 national-level male swimmers. This research reported a 7.5% improvement in SBS performance, although methodological limitations (i.e., reaction times to the starting signal were not taken under consideration and the lack of a control group) could distort these results.

After these long-term training interventions, other authors have studied the acute effect of a PAP stimulus on SBS performance. Kilduff et al. [93] compared a traditional swimming warm-up (volume of 1,500 m) to a PAP stimulus (1 set of 3 squats at 87% 1RM) 8 min before SBS, observing no differences between warm-ups. Despite not detecting an improvement after PAP, it is interesting to note that a lower volume warm-up (i.e., PAP) produced similar effects than a longer traditional swimming warm-up on SBS performance. In contrast, Cuenca-Fernandez et al. [94] found positive effects of 2 different PAP protocols (3 repetitions of lunge exercises and 3 repetitions in a Yo-Yo squat flywheel device, modelling the starting position on the block) on time to 5 m SBS. The Yo-Yo squat stimulus also produced an enhancement on 15 m SBS, agreeing with the initial hypothesis that the Yo-Yo squat protocol would be the most appropriate warm-up to enhance SBS performance due to comparable movement patterns. Similarly, a recent study [95] has examined the acute effect of a trunk stabilization exercise on SBS performance in 9 national-level swimmers, finding a 2.3% decrease in time to 5 m. However, the lack of a control group limits the applicability of these results.

García-Ramos et al. [69] implemented a 17-day DLS training (half squat and lunge exercises) at a moderate altitude of 2,320 m above sea level to find whether any acute changes occur in both SBS performance (time to 5 m, 10 m or 15 m) and vertical jump ability. The results revealed significant improvements in both assessments after the training period. This is in agreement with previous research [96], which also found muscle power improvements after an acute exposure to high altitude, despite the deterioration of the aerobic capacity. In spite of these potential benefits, there are no longitudinal studies to support these results.

When examining cross-sectional studies, DLP assessments (horizontal and vertical jump tests) have been positively associated with SBS performance [47–49,69,70,73]. In addition, Beretic et al. [45] found a positive relationship between DLS measurements (lower-body isometric strength) and 10 m SBS performance.

In conclusion, DLP interventions (especially lower-body plyometrics) seem to enhance SBS and therefore sprint swimming performance. However, the number of training interventions is scarce (2 studies showing chronic effects and 4 studies showing acute effects). It should be noted that the longest and most important part of the start is the underwater phase which should be a focus for future research.

Even though the present systematic review focused on analyzing freestyle swimming performance, the literature search identified an important lack of studies using breaststrokers, backstrokers and butterfly swimmers. Finally, in light of several poor quality of the studies identified in the quality assessments, further researchers should follow the guidelines proposed by CONSORT (for randomized trials) or STROBE (for observational studies) in order to develop high quality research.

PRACTICAL APPLICATIONS

Although it is not clear which evidence-based NSRT is more effective to improve swimming performance, coaches and sports specialists should consider a few strategies resulting from a systematic analysis of the literature. The inclusion of upper-body strength training into the training regimens appears crucial to enhance the propelling forces used in water. Additionally, a period of 12 weeks of NSRT (especially through DLP regimens) has shown to elicit positive effects on swimming performance. Furthermore, the assessment of jumping performance (mainly through horizontal jump) seems a reliable predictor of sprint swimming performance. Non-specific PAP stimulus seems an effective practice to generate a positive acute impact on swimming performance. However, if this stimulus is not applied 8 min before the swimming trial, and if the core temperature gained during the stimulus itself is not maintained, the effectiveness of PAP may deteriorate. Finally, DLS training at moderate altitude seems to enhance DLP and SBS, although further research is required to clarify the effect of this method.

Chapter 4.2

Swim-specific resistance training and swimming performance

Muniz-Pardos, B, Gómez-Bruton, A, Matute-Llorente, A, Gonzalez-Aguero, A, Gomez-Cabello, A, Gonzalo-Skok, O, José A. Casajús, Vicente-Rodríguez G. Swim-specific resistance training and swimming performance: A systematic review. **J Strength Cond Res**. *Accepted for publication.*

ABSTRACT

The purpose of this systematic review was to determine which type of swim-specific training is most beneficial to enhance swimming performance and to determine which specific strength- or power- related tests better predict swimming performance. A search was conducted on PubMed, Cochrane Plus and SportDiscus up to June 2018. Studies were distributed into two main categories: swim-specific dry-land resistance training (SDLRT) and specific in-water swimming power training (SSWPT). From 1844 citations, 25 met the inclusion criteria. It was determined that SSWPT was the most appropriate method to improve swimming performance, with tethered swimming protocols being the most studied and effective. Additionally, SDLRT was a competent method to enhance swimming performance and, specifically, the inclusion of inertial training might evoke greater improvements in both strength/power capacities and swimming performance, than traditional resistance training. In conclusion, tether forces showed the greatest associations with swimming performance, although the efficacy of tethered swimming as a SSWPT method is yet to be confirmed. Further research should focus on the effects of SDLRT to verify the greater transfer of dry-land resistance practices to swimming performance, with inertial training being potentially more beneficial than traditional resistance training.

INTRODUCTION

Swimming is a popular sport in Europe and across other continents. The National Institute of Statistics and Economic Studies in France reported that swimming was ranked as the 11th most practiced sport with 300,900 federative licenses [97]. Statistics from Denmark reported that swimming was the 2nd most practiced sport among children [98] and similar patterns have been seen in children from Australia [99]. Following this increasing success, the number of publications concerning "swimming" and "training" has considerably risen in the last decade (105 studies were published in the year 2008 and 211 were published in 2018, as reported by PubMed). For this reason, it is relevant to provide coaches and swimming specialists with an up-to-date review related to optimal training practices to improve swimming performance.

A recent review identified inconsistencies among studies focusing on non-specific resistance training interventions in swimmers [100], as some studies demonstrated positive effects, while others found that gains in strength were not transferred to the propulsive forces used during swimming. A positive transfer occurs when the resistance training improves the muscle activation patterns required in the execution of the sport skill [101]. Consequently, the inclusion of sports-specific resistance practices in the swimmer's periodization is crucial. It is worth noting that all training adaptations are "specific" to the stimulus applied, and these adaptations are determined by different elements such as the muscle group trained, the range of motion or the speed of movement [65]. In swimming, the muscle strength from the upper limbs provides approximately 75% of the energy required for an efficient propulsive force during front crawl [102]. The muscle strength from the lower body has been shown to contribute only modestly to the propulsive forces, with a greater influence during the start and turn phases [103].

There are previous systematic reviews [17,34,100] investigating different strength/power interventions on swimming performance, but none of them have focused on the effects of swim-specific resistance training (performed on either dry-land or in-water) [104]. These systematic reviews demonstrated the role of muscle strength in swimming, finding a wide variety of strength training protocols to maximize swimming performance (e.g., free-weight training, swimming resistance training or plyometric training). Nevertheless, 2 out of these 3 reviews [34,100] highlighted that studies with high-quality methodologies are lacking, making comparisons between them difficult. For the present systematic review, we perform a comprehensive study of the existing literature focusing on swim-specific resistance training methods. This would provide coaches with an accurate set of practical guidelines to enhance their strength coaching regimes. Thus, the aims of this systematic review were to determine which type of swim-specific interventions are more suitable for the enhancement of swimming performance, and to define the swim-specific strength/power parameters that are better associated with swimming performance in adolescent and young adult swimmers.

METHODS

Literature search

This study was performed following the systematic review methodology proposed in the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [66]. Studies were identified by searching within the electronic databases (PubMed, SPORTDiscus and Cochrane Plus), reference lists and consultation with experts in the field. The search was conducted up to and including the 1st of June 2018. The key words used in the search were “swimming”, “muscle strength” and “athletic performance”. The specific search strategy for PubMed was: ("Muscle Strength"[Mesh])

OR "Athletic Performance"[Mesh]) AND "Swimming"[Mesh]) with the additional filter of “Humans”. For SPORTDiscus the search was ((DE "MUSCLE strength") OR (DE "PERFORMANCE")) AND (DE "SWIMMING") and, finally, the search strategy for Cochrane Plus was ((Muscle Strength) OR (Athletic Performance)) AND (Swimming).

Inclusion criteria

The types of studies included in the present systematic review were longitudinal, randomized or non-randomized controlled trials, studying the effects of swim-specific resistance training programs on swimming performance. Cross-sectional studies evaluating the relationship between swim-specific strength/power parameters and swimming performance were also included. Additionally, the type of subjects (following PubMed criteria) recruited were adolescents or young adults, all of which were competitive swimmers.

Exclusion criteria

Studies in languages other than English, unpublished data, or studies involving triathletes, divers or other that are not competitive swimmers were excluded from the present systematic review. Studies focusing on parameters other than swim-specific strength/power-related interventions or assessments (swimming technique, rehabilitation, physiological parameters or respiratory muscle training) and studies of which power assessments or interventions used non-specific ergometers (e.g., Wingate test) were also excluded. Cross-sectional studies evaluating strength values without considering any kind of swimming performance or vice versa, and training interventions not related to either strength or power training were not included. Finally, training programs only assessing strength changes, without considering swimming performance enhancements, or vice versa, were excluded.

Quality assessment

The manuscripts included in this systematic review were assessed using 2 different tools. For cross-sectional studies, the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies proposed by the National Heart, lung and blood Institute [67] was used, grading articles on a scale of 14 points. For experimental studies, the Physiotherapy Evidence Database (PEDro) scale [68] was used, classifying articles on a checklist composed of 11 items. Two separate researchers evaluated the quality of the studies independently.

Type of studies

The articles selected for this review were distributed into 2 categories: swim-specific dry-land resistance training and specific in-water swimming power training.

1. Swim-specific dry-land resistance training (SDLRT). The studies included in this category were those including SDLRT through specific exercises, similar to the movement pattern used during swimming actions (e.g., training on the biokinetic swim bench or weights training from a swim-specific position).

2. Specific in-water swimming power training (SSWPT). The articles included in this category utilized either tethered swimming, active drag swimming, or velocity through a perturbation method to improve swimming performance.

RESULTS

Included studies

Searches identified 1844 potentially relevant articles. Following the review of titles and abstracts and excluding the duplicates, the total was reduced to 77 relevant manuscripts. Of these articles, 25 met the selection criteria and were included in this systematic review (**Figure 8**).

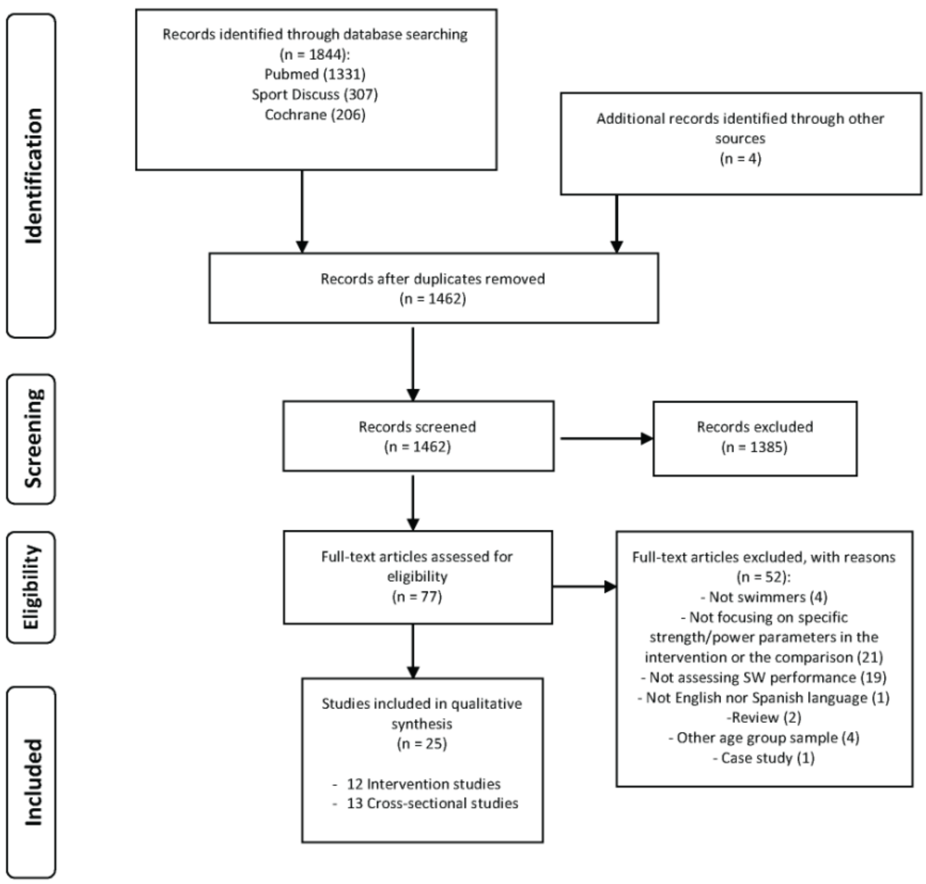


Figure 8. Flow chart of the studies including swim-specific tests or protocols

Regarding the 25 manuscripts that met the inclusion criteria, 13 were cross-sectional studies evaluating the relationship between swimming performance and swim-specific dry-land variables (strength/power during these actions) and SSWPT (tethered swimming, active drag, passive drag) variables (**Table 5**). Twelve out of the 25 included articles were intervention studies assessing the effect (acute or chronic) of different swim-specific protocols on swimming performance (**Table 6**), such as swim-specific postactivation potentiation (PAP), training on the biokinetic bench or swim-specific inertial training.

Table 5. Cross-sectional studies included in the systematic review (n=13)

Article	Age (years)	Level	N (Males)	Variables	Outcomes
Kalva-Filho et al., 2017 (126)	18.0±2.0	Regional to National	9(5)	*S(50), S(100), S(200),* SWP (3 min all-out tethered SW)	Significant correlation between mean tether F and all distances' performance. Higher correlations with longer distances.
Santos et al., 2016 (125)	21.6±4.8	Competitive SW	21(NS)	*S(200), SWP (*Tethered SW).	Positive relationship between PPO (tethered SW) and *S(200).*
Loturco et al., 2016 (84)	17.0±0.7	National	10(10)	*S(50), S(100), S(200),* SWP (tethered SW).	Positive relationship between tether F and *S(50), S(100).*
Morouço et al., 2014 (123)	17.2±2.7	National and International	34(34)	*S(50),* SWP (Tethered SW).	Positive relationship between SWP and *S(50).*
Papoti et al., 2013 (124)	Ms(12.5±0.8) Fs(16.0±1.0)	Trained SW	12(9)	*S(100), S(200), S(400).* SWP (Tethered SW).	Positive relationship between tether F and *S(100), S(200), S(400)* (decreasing with distance).
Dominguez-Castells et al., 2013 (127)	22.1±4.3	National	18(18)	*S(25),* SWP (Tethered SW).	Positive relationship between tether F and *S(25).*
Morouço et al., 2011a (122)	Ms(19.0±2.8) Fs(15.3±1.7)	International	32(20)	*S(50), S(100), S(200)* in all four strokes. SWP (tethered SW).	Positive relationship between absolute values of tether F and *S(50),S(100),S(200)* in all strokes except for the breaststroke *S(200).*

Morouço et al., 2011b (50)	14.9±0.7	National	10(10)	*S(50)*, SWP (Tethered SW: whole body, Arms only, legs only).	Positive relationship between *S(50)* and F production (arms only).
Arellano et al., 2005 (70)	21.4±2.2	National	11(6)	*S(5)*, DLP (CMJ and simulated jump off the block).	Positive relationship between horizontal F off the block, *S(5)* time and *S(5)* mean velocity.
Shimonagata et al., 2003 (111)	21.5±1.0	Competitive SW	11(5)	*S(100)*, *S(25)*, SWP (semi-tethered SW), DLP (biokinetic SW bench).	Positive relationship between both distance performance and both SWP and DLP.
Bradshaw and Hoyle, 1993 (110)	NS	University students	7(7)	*S(25)* full stroke, arms only, legs only. DLP (biokinetic SW bench).	Positive relationship between arm power and *S(25)* (full stroke and arms only SW).
Johnson et al. 1993 (108)	18.0±2.0	Collegiate and high school SW	29(29)	*S(22.86)*, SWP (Tethered SW), DLP (biokinetic SW bench).	Positive relationship between S(22.86) and PPO (Tethered SW) and DLP (SW bench).
Sharp et al. 1982 (102)	15.2±0.3	Competitive SW	40(18)	*S(22.86)*[a], DLP (biokinetic SW bench).	Positive relationship between DLP and *S(22.86)*[a]

CMJ= countermovement jump; **DLP**= dry-land power; **F**=force; **FLX**=flexion; **Fs**=females; **Ms**=males; **NS**= not specified; **PPO**= peak power output; **RM**=Repetitions Maximum; ***S("number")***= sprint (meters); ***S("number")***[a]= yards converted to meters; **sess**=training sessions; **SJ**=squat jump; **SW**=swimmers or swimming; **SWP**= swimming power **WU**= warm up.

Table 6. Intervention studies included in the systematic review (n=12)

Article	Age (years)	Level	N (Males)	CG [N]	EG [N]	Measurements	Outcomes	Effect
Kojima et al., 2017 (116)	13.6±1.1	Regional	24(12)	[12] SW T only (10x15 sprints)	[12] 10w, 2sess/w. SWP program (tethered 10x10 sprints).	*S(50), SWP* (tethered SW*).*	No differences between groups in the effects on *S(50)* nor tethered SWP.	Chronic
Papoti et al., 2017 (115)	16.0±1.5	National	21(12)	[11] SW T only	[10] 7w, 5sess/w. SWP program (50% of the sets during each sess using tethered SW).	*S(50), S(100), S(400),* SWP (tethered SW).	No effects of the SWP program neither on SW times nor tethered SWP.	Chronic
Naczk et al., 2017 (112)	15.8±0.4	National	14(10)	[7] SW T only	[7] 4w, 3sess/w. DLS program (Inertial T employing: 4 sets of 15 s)	*S(50), S(100-butterfly), DLP* (Inertial training device: max power in a 10-s maximal test)	Positive effects on *S(50), S(100-butterfly)* and DLP test.	Chronic
Cuenca-Fernandez et al., 2015 (94)	17-23	National	14(10)	Traditional SW WU	- 3RM lunge PAP WU. - 4 reps Yo-Yo squat WU (position used in the block in a SW start).	*S(15)* and *S*(5) 8 min after each WU/PAP.	Positive effects of PAP on *S(5)* (for both PAP protocols) and *S(15)* (only for the Yo-Yo squat PAP).	Acute

Hancock et al., 2015 (119)	19-22	Collegiate SW	30(15)	[30] Traditional SW WU	[30] PAP (4x10m tethered SW).	*S(100)* 6-min after WU/PAP.	Positive effects of PAP on *S(100)*.	Acute
Sadowski et al., 2012 (106)	EG (14.0±0.5) CG (14.1±0.5)	Young SW	26(26)	[12] SW T only	[14] 6w, 3sess/w: DLP T (simulated SW on an ergometer; 6x50´´) before SW T.	DLS (ISOM shoulder flexion), *S(25)* driven by upper extremities, F during tethered SW.	Positive effect of DLP T on tethered SW F.	Chronic
Dragunas et al., 2012 (117)	EG (19.3±0.9) CG (19.0±1.8)	Regional-National	18(10)	[9] 5w, 3sess/w. Interval T: 3x45.72m[a] + 4x (4x 22.86m[a] + 16x22.86m[a]	[9] 5w, 3sess/w. Same T than CG but wearing a drag suit.	*S(50)*, 6x50 m all-out times with and without drag suit on 2 separate days (r= 10 min).	No differences between groups in *S(50)* after the T period.	Chronic
Aspenes et al., 2009 (74)	EG (17.5±2.9) CG (15.9±1.1)	Collegiate	20(8)	[9] SW T only	[11] 11w, 2sess/w. 4x4 min SW intervals + 3x5RM (cable cross-over device)	*S(50)*, *S(100)*, *S(400)*, SWP (tethered SW).	Positive effects of combined strength and interval SW T on *S(400)* and tethered SW F.	Chronic
Girold et al., 2007 (75)	16.5±3.5	National	21(10)	[7] 12w, 6 sess/w. SW T only	12w, 6sess/w. - [7] Dry-land T with barbells. 1.5h/w extra.	*S(50)* before, at w6 and after intervention.	Positive effects of both dry-land and RAS T on *S(50)* only at w12.	Chronic

					- [7] RAS T with elastic tubes. 1.5h/w extra.			
Girold et al., 2006 (114)	16.5±3.0	Regional to national	37(16)	[11] SW T only + 6x50m sprints.	3w, 3sess/w. - [11] Assisted T with elastic tubes. - [15] Resisted T with elastic tubes.	*S(100)*.	Positive effects of both RAS T methods on *S(100)* (Greater in Resisted G).	Chronic
Roberts et al., 1991 (105)	19.1±2.1	National	16(16)	[NS] SW T only	[NS] 10w, 3 sess/w. Biokinetic resistance T on SW bench.	*S(91.44)*[a] , PPO and fatigue test (biokinetic SW bench).	No positive effects of biokinetic resistance T on *S(91.44)* [a] nor PPO on the biokinetic swim bench.	Chronic
Toussaint et al., 1990 (39)	NS	National	22(16)	[11] SW T only (8sess/w; 4500m/sess)	[11] 10w, 3sess/w of sprints using POP system (16 POP, mounted below the water surface).	*S*(50), *S*(100), *S*(200). Max force, V and power from the POP system.	Positive effect of intervention on max power and velocity in the POP system, *S*(50), *S*(100) and *S*(200).	Chronic

CG=control group; **DLP**=dry-land power; **EG**=experimental Group; **F**=force; **G**=group; **ISOM**=isometric; **NS=**not specified; **PAP**=post-activation potentiation; **POP**=push off points; **r**=recovery; **RAS**=resisted and assisted sprint; **RM**=repetition maximum; ***S*****("number")**=sprint (meters); ***S*****("number")**[a]=yards converted to meters; **Sess=**sessions; **SW**=swimming or swimmers; **SWP**=swimming power; **T**=Training; **V**=velocity; **w**=week; **WU**=warm up.

Quality Assessment

Scores of the Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies ranged from 3 to 5 of a maximum of 14 points (**Supplementary Table 3**), except 1 study that only reached 1 point [70]. Some of the criteria assessed were not applicable due to the type of variables measured (exposures that cannot vary in amount or level, exposures measured only once over time or blinding participants, therapists or assessors). Furthermore, some points were not reported in most of the studies, such as the participation rate of eligible persons or loss to follow-up after baseline.

Scores of the PEDro scale ranged from 4 to 6 of a maximum of 11 points (**Supplementary Table 4**). These scores are relatively good, taking into account that some exercise protocols such as tethered swimming or biokinetic power training do not allow for blinding participants or blinding therapists. Furthermore, blinding of the assessors and concealed allocation were 2 variables that were poorly reported in most of the selected studies.

Supplementary Table 3. Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (n=13).

References	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**TOTAL**
Kalva-Filho et al., 2017 (126)	Yes	Yes	NR	Yes	No	NA	NA	No	Yes	NA	Yes	No	NA	No	5
Santos et al., 2016 (125)	Yes	Yes	No	No	Yes	NA	NA	NA	Yes	NA	Yes	No	NA	No	5
Loturco et al., 2016 (84)	Yes	No	NR	No	No	NA	NA	NA	Yes	NA	Yes	No	NA	No	3
Morouço et al., 2014 (123)	Yes	No	NR	Yes	Yes	NA	NA	NA	Yes	NA	Yes	No	NA	No	5
Papoti et al., 2013 (124)	Yes	No	No	No	No	NA	NA	NA	Yes	NA	Yes	No	NA	No	3
Dominguez-Castells et al., 2013 (127)	Yes	No	No	No	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Morouço et al., 2011a (122)	Yes	No	No	No	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	4
Morouço et al., 2011b (50)	Yes	No	No	No	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Arellano et al., 2005 (70)	Yes	No	No	No	No	NA	NA	No	No	NA	No	No	NA	NA	1
Shimonagata et al., 2003 (111)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Bradshaw and Hoyle, 1993 (110)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Johnson et al. 1993 (108)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	No	NA	NA	3
Sharp et al. 1982 (102)	Yes	No	No	NA	No	NA	NA	No	Yes	NA	Yes	Yes	NA	NA	4

1. Was the research question or objective in this paper clearly stated?
2. Was the study population clearly specified and defined?
3. Was the participation rate of eligible persons at least 50%?
4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?

5. Was a sample size justification, power description, or variance and effect estimates provided?
6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?
7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?
8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?
9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
10. Was the exposure(s) assessed more than once over time?
11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?
12. Were the outcome assessors blinded to the exposure status of participants?
13. Was loss to follow-up after baseline 20% or less?
14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?

Supplementary Table 4. PEDro Scale (n=12).

References	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**TOTAL**
Kojima et al., 2017 (116)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Papoti et al., 2017 (115)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Naczk et al., 2017 (112)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6
Cuenca-Fernandez et al., 2015 (94)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Hancock et al., 2015 (119)	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Sadowski et al., 2012 (106)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Dragunas et al., 2012 (117)	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	4
Aspenes et al., 2009 (74)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Girold et al., 2007 (75)	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	5
Girold et al., 2006 (114)	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Roberts et al., 1991 (105)	No	Yes	No	No	No	No	No	No	Yes	Yes	Yes	4
Toussaint et al., 1990 (39)	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6

1. Eligibility criteria were specified.
2. Subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received).
3. Allocation was concealed.
4. The groups were similar at baseline regarding the most important prognostic indicators.
5. There was blinding of all subjects.
6. There was blinding of all therapists who administered the therapy.
7. There was blinding of all assessors who measured at least one key outcome.

8. Measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups.
9. All subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat".
10. The results of between-group statistical comparisons are reported for at least one key outcome.
11. The study provides both point measures and measures of variability for at least one key outcome.

DISCUSSION

Swim-specific dry-land resistance training

The studies examining the association between SDLRT and swimming performance have changed their research orientations over time, with varying outcomes of interest and protocols across the last 30 years. Up to 2005 most of the studies approached the assessment of dry-land power mainly through biokinetic ergometers, whereas SDLRT through swim-specific movement patterns has been a category of special interest in the last decade.

Concerning the training on biokinetic ergometers, the swimmer lies on a sliding bench with a small incline, arms extended over his/her head and hands secured in hand-paddles [17]. This device was conceived to isolate and mimic the specific arm-movement used during swimming [102]. Roberts et al. [105] developed the first experiment using this device with male swimmers, finding no effects of 10 weeks of biokinetic resistance training on the swimming bench on 100 yards performance (91.44 m). This may be because the biokinetic training was applied during the competitive phase of the season, where the training intensity is notably increased. It is likely that this higher intensity would have attenuated the response to the additional biokinetic stimulus [105]. Similarly, Sadowski et al. [106] found no effects of training with a similar ergometer on 25 m swimming performance. In this case, the lack of positive results might be related to the different stroke frequencies observed during swimming when compared to the frequencies on the ergometer [107].

These results are in agreement with previous cross-sectional findings [108], reporting that dry-land power as measured on the swim bench was not associated with 25 yards swimming performance (22.86 m). Notably, the swimmers in this study were highly trained (with a power output above 400 W) which may account for some of the lack of association. As previously observed [109], the relationship between dry-land power and swimming performance is not linear when a power output is very high (~ 500 W). In conclusion, factors other than power are more important in strong swimmers, such as more efficient biomechanics or a reduction of body drag. Although the swim bench can adopt similar movements to those performed while swimming, it might not reproduce the biomechanical requirements in the water (e.g., propulsive phase). Nevertheless, there are several researchers who have found a positive relationship between dry-land power on the swim bench and swimming performance in cross-sectional studies [102,110,111]. However, these studies were not prospective; they only describe an association and not a cause-effect relationship [34]. Therefore, it can be concluded that swim bench training is an ineffective method to improve swimming performance, given that none of the 2 interventions presented positive effects.

After this period of interest in the effects of biokinetic bench training, recent research has focused on the effects of dry-land strength training using swim-specific resistance exercises. Aspenes et al. [74] observed that an 11-week upper-body strength training on a specific apparatus simulating the butterfly movement resulted in a 1.4% improvement in 400 m performance. This improvement was accompanied by a 6.9% enhancement in maximal swimming force (tethered swimming) and a 20.3% improvement in maximum dry-land strength (bilateral shoulder extension in a cable cross-over apparatus), concluding there was a positive impact of this SDLRT in performance, swimming force and dry-land strength.

Cuenca-Fernandez et al. [94] were the first to compare the effects of a traditional strength PAP protocol (3 repetitions of lunge exercise) to a swim-specific PAP stimulus (3 repetition in a Yo-Yo squat flywheel device, modelling the starting position on the block) on swimming block start performance, in comparison to a control condition (swimming block start after traditional swimming warm-up). The Yo-Yo squat flywheel device uses a wheel to generate a moment of inertia at the end of the concentric phase of the movement. When this point is reached, there is a strong eccentric contraction, which has been demonstrated to evoke greater improvements in muscle peak power than traditional weight training [112]. The authors stated that the Yo-Yo squat protocol was the most effective PAP stimulus to enhance both 5 m and 15 m swimming block start performance (5.7% and 2.4%, respectively) due to the similarity in the movement pattern.

Similarly, a recent study [112] examined the efficacy of an inertial training method in 14 national-level swimmers. The authors carried out a 4-week upper-body inertial training using the Inertial Training Measurement System (ITMS; a novel device which allows the performance of specific movements [112]). Both muscle force and power were determined using the ITMS. The authors reported positive effects in muscle force, power and 100 m swimming performance (improvements of 12.8%, 14.2% and 1.8%, respectively), in comparison to the control group (traditional swimming training). Subsequently, these authors concluded that specific inertial training may provide greater benefits than traditional strength training.

Specific in-water swimming power and swimming performance

Toussaint and Vervoorn [39] were the first researchers to study the effects of a SSWPT on freestyle swimming performance. They implemented a new training device derived from the MAD-system (system to Measure Active Drag; [113]), providing the swimmer with 16 submerged fixed push-off points along the length of a swimming pool. The force applied on these fixed points was measured through a force transducer placed at one end of the swimming pool, measuring maximal force, velocity and power output. The authors evaluated the effects of a 10-week training program with this device on 50 m, 100 m and 200 m swimming performance, in 30 competitive swimmers. The intervention group performed sprints using the aforementioned apparatus, with the control group performing traditional sprints. The results demonstrated a positive effect on force, power and swimming velocity on the MAD-system, with additional improvements in 50 m and 200 m performance in the intervention group. The high specificity of this method and the greater force applied on every push-off point in comparison to normal swimming seemed to favour a positive transfer to swimming performance [39].

After this pioneering study exploring the active drag training paradigm, others studied different active drag training techniques. Girold et al. [114] analyzed the effects of a 3-week tethered swimming intervention (swimming while being held by a flexible restraining device; e.g., tubes or ropes) on 100 m swimming performance in 37 competitive swimmers. They compared 3 different interventions: resisted tethered swimming with elastic bands (resistance against direction of motion; 6 x 30 s sprints), assisted tethered swimming with elastic bands (pull force in the direction of motion; 12 x 25 m sprints), and traditional swimming (control group: 6 x 50 m sprints without elastic bands). Although the authors witnessed swimming improvements in the resisted group, this improvement was not accompanied with strength enhancements but a higher stroke rate. These authors carried out a longer and more rigorous research [75], examining the effects of a 12-week resisted- and assisted- sprint (RAS) training on 50 m performance in 21 adolescent swimmers. The participants involved in the RAS group showed an improvement of 2.3% in swimming performance whereas the control group only showed minimal changes (0.9%). This study showed that the stroke depth and the stroke rate were the best predictors of the 50 m performance in the RAS group, confirming their previous findings.

In contrast, a recent investigation [115] showed no effects of a 7-week tethered swimming program in 21 adolescent swimmers. The differences between the control and intervention group in 100 m, 200 m, 400 m times, and tethered swimming force did not differ after the training period. However, the intervention group increased their lactate production capacity, speculating that the inclusion of tethered swimming in the training routine may increase the anaerobic glycolysis contribution during exercise, despite the lack of improvement observed in swimming force. Kojima et al. [116] showed no significant differences between the intervention and the control group after a 10-week resisted training intervention on 50 m swimming performances in adolescent swimmers. These authors suggested that the level of maturation of the athletes might be a determinant confounding factor in the ability of an adolescent swimmer to respond to any specific training load.

Dragunas et al. [117] studied the effects of training with a drag suit on 50 m performance. Eighteen regional and national level young swimmers were equally divided into the control group and drag suit-trained (DST) group. For 5 weeks, the swimmers involved in the DST group performed the same training as the control group, but while wearing the drag suit (a total training volume of 950 m/week). The authors showed no significant changes in swimming performance, although the DST group was more effective at maintaining technique than the traditional training method. The limitations of this study however, make it difficult to interpret these results. For example, 30 swimmers were initially recruited, but the high dropout (n=18) reduced the statistical power. Furthermore, the use of manual timing [118] and the lack of control over the training regimen may have biased the final results [117].

After these studies focusing on the chronic effect of different SSWPT interventions, Hancock et al. [119] investigated the acute effect of a PAP protocol on swimming performance, when compared to the control condition in 30 young swimmers. Their protocol consisted of 4 repetitions of 10 m all-out tethered swimming 6 minutes before a 100 m maximal effort. The PAP load was individually prescribed, taking into account the swimmers' best time in 100 m (t) and their lean body mass (LBM), using the formula: Load= $0.2 \cdot LBM/(100 \cdot t^{-1})$. The results showed a significant improvement in 100 m performance for the PAP condition, compared to the control condition (0.86% enhancement). Although it is well known that PAP increases the rate of force development [120,121], further analyses through muscle biopsies would confirm the true effect of PAP on lower-body explosive power (i.e., confirming an increased phosphorylation of regulatory myosin light chains [119]).

Additional cross-sectional studies support the use of swimming power assessments through tethered swimming [50,84,108,122–127], semi-tethered swimming [111] and active drag (towing a perturbation buoy) [128] to predict swimming performance in distances ranging from 25 yards (22.86 m) to 400 m.

The association between swimming power and swimming performance seems evident since the 11 existing cross-sectional studies reported positive associations. However, further interventions would be necessary to confirm the effectiveness of this specific training, as 4 interventions improved swimming performance [39,75,114,119] whereas 3 studies reported no effects [115–117]. Despite the effective MAD-system tested by Toussaint et al. [39], no other studies have used this methodology neither in intervention nor in cross-sectional studies, probably due to the high cost of this specific equipment.

In conclusion, the inertial training method seems more beneficial than traditional resistance training to improve swimming performance, although more research is needed to verify this. Although several studies showed cross-sectional associations between the biokinetic bench values and swimming performance, no training interventions have found improvements in swimming performance following biokinetic bench training. However, training on the MAD-system appear to be the most effective method to improve the propulsive forces used in water as well as swimming performance. However, only 1 study investigated this system. Finally, tethered swimming as an effective SSWPT method to improve performance remains under debate due to the contrasting results.

The present systematic review has identified limited research utilizing female swimmers, as well as elite level swimmers, finding important methodological limitations in the training protocols susceptible to bias the results (analyzing males and females as a whole, not adjusting by maturity status or level of performance, or the lack of a control group). Finally, the literature search performed in the present systematic review identified an important lack of studies using breaststrokers, backstrokers and butterfly swimmers.

PRACTICAL APPLICATIONS

Research indicates that swim-specific resistance training is an effective method to improve specific muscle strength and swimming performance. Since this practice allows direct transfer to sports performance, coaches should design training protocols as specific as possible, especially with regard to movement pattern. Based on a critical evaluation of the existing evidence, coaches and practitioners should consider inertial training as a method that potentially offers greater benefits on both strength development and swimming performance, than traditional free weight training. Regarding the different SSWPT methods examined, further high-quality studies are needed to confirm the efficacy of tethered swimming as a method to improve swimming performance. Tethered swimming forces have shown to elicit the greatest relationship with swimming performance. Lastly, training on the MAD-system seems highly effective, although the high cost of this equipment may reduce its availability to most swimmers.

Chapter 4.3

Relationship between strength, power and swimming performance

<u>Muniz-Pardos B</u>, Gómez-Bruton A, Matute-Llorente A, González-Agüero A, Olmedillas H, Gómez-Cabello A, Sutehall S, Pitsiladis Y, Casajús JA, Vicente-Rodríguez G. Lower-body strength and power contribution in sprint swimming performance in trained adolescent swimmers. **Int J Perf Anal Spor**. *Submitted*.

ABSTRACT

The purpose of this study was to determine the association between lower-body strength (LBS) and lower-body power (LBP) capacities with sprint swimming performance in adolescent competitive swimmers. A total of 44 competitive swimmers (27 males and 17 females) performed LBS tests (maximal isometric strength [MIS] half squat, dynamic half squat with 20%, 30% and 40% of the MIS, and MIS knee extension) and LBP tests (squat jump [SJ], countermovement jump [CMJ] and Abalakov jump [ABA]). Further swimming best times in 50 and 100 m races were recorded from official swimming competitions. Swimming performance was correlated with LBP variables (SJ_{PEAK}, CMJ_{RFD}, ABA_{PEAK} ABA_{RFD}; $P \leq 0.05$) and LBS (MIS half squat; $P \leq 0.05$) for both 50 and 100 m performance in males but not in females. Additional age, maturity and freestyle technique-adjusted linear regression models showed that LBP capacity partly predicted both 50 m (ABA_{RFD}; $r^2 = 0.58$; change in $r^2 = 0.18$) and 100 m (SJ_{PEAK}; $r^2 = 0.66$; change in $r^2 = 0.15$) performance in trained male swimmers. This study emphasizes the greater importance of LBP on sprint swimming performance in adolescent males compared to females, suggesting that adolescent male swimmers have a higher ability to transfer LBP to swimming performance than females.

INTRODUCTION

A higher physical fitness is associated with improved health and performance in a wide range of sports [129]. In particular, increases in muscular strength, power, speed, endurance, balance, and coordination have all been linked to improvements in athletic performance [130–132]. A significant amount of research has reported significant associations between sprint performance and measurements of strength [133] and power [134] in numerous sports, suggesting that muscle function has some association with sprint performance [104]. Swimming is characterized by unique demands on muscle function, taking place in a singular environment which results in the application of force under unusual conditions. Although previous research has demonstrated that the upper body represents about 70% of the propulsive forces used in-water in freestyle swimming [13], the role of the lower extremities should not be underestimated considering its importance in the drag force and in the start and turn phases. Previous results have shown that the block start phase accounts for approximately 26.1% of the total 50 m time [44], highlighting the importance of lower-body strength (LBS) and lower-body power (LBP) in sprint swimming performance. These results are in line with a meta-analysis [135] that reported large improvements (3.1%) in sprint performance resulting from LBS and LBP enhancements, emphasizing the need to include lower-body exercises in the training regimen of sprinters.

The need to optimize every relevant aspect in training is evident when considering the very small winning margins. For example, a time difference of 0.01 s separated the gold medal performance of U.S. swimmer Michael Phelps from silver (and an Olympic record of 50.58 s) during the 100-m butterfly in the 2008 Beijing Olympics. Therefore, significant improvements in LBS and LBP could translate in worthwhile gains in swimming performance.

The contribution of LBS and LBP in block start performance (from 5 to 15 m) has been extensively studied [48,49,70]. However, there is a paucity of literature examining the importance of LBS and LBP in short distances (from 25 to 100 m), with unclear conclusions regarding the best indicator to predict overall swimming performance [100]. While Garrido et al. [136] reported higher contributions of LBS (knee extension) to 25 and 50 m swimming performance, in comparison to LBP (countermovement jump; CMJ), previous research [41,47] has suggested that LBP is a better predictor of swimming performance than LBS. Therefore, the aim of this study was to assess and contrast the contribution of LBS and LBP to sprint swimming performance in adolescent competitive swimmers.

METHODS

Participants

Forty-four regional to national level swimmers (27 males and 17 females; 14.6±1.3 y, 166.7±10.3 cm, 56.3±10.9 kg, Tanner Stages 2 to 5) took part in the present study. Participants were included if they met the following inclusion criteria: swimmers between the ages of 12.5 and 17.5 y, Caucasian, healthy and free of injuries. All participants had swum more than 6 hours a week for at least 3 years, competing in regional and national events with a mean performance of 30.0±2.4 s in 50 m and 64.9±4.8 s in 100 m freestyle events, corresponding to an 84% of the Spanish record for the same age-group swimmers.

All procedures were approved by the Ethics Committee of Clinical Research from the Government of Aragón (C.I.PI11/0034; CEICA; SPAIN), and followed the international rules for research with humans, following the declaration of Helsinki (1964) as revised in 2013 in Fortaleza [137]. Parents or tutors provided written consent. This study is part of a randomized controlled trial [59] which is registered in a public database (www.clinicaltrials.gov) with the following register number: NCT02380664.

Testing procedure

Participants attended our laboratory and performed the laboratory strength and power tests (jumps on the force platform, isometric and dynamic half squat and knee extensors strength), anthropometric assessments and questionnaires were completed within 2 hours, with the performance times data recorded on a separate day. Prior to commencement, participants warmed up cycling at 60 W during 10 min. A detailed explanation of these tests is developed in the following sections.

Anthropometric measurements and general information

All participants had basic anthropometric measurements taken (body mass, weight, height). Participants were measured while wearing minimal clothing and without shoes to the nearest 0.1 cm (SECA 225, SECA, Hamburg, Germany) and weighted to the nearest 0.1 kg (SECA 861, SECA). Body mass index (BMI) was then calculated by dividing weight (in kilograms) by squared height (in meters). An ad-hoc structured questionnaire was completed by all participants which included information related to swimming experience, swimming volume, other sports practiced, in addition to medical history, previous injuries and the evaluation of sex maturity proposed by Tanner [138].

Swimming performance times and freestyle technique assessment

The most recent performance in both 50 m and 100 m freestyle swimming (performed up to 15 days near to the testing sessions) were collected from official competitions, reported by the regional swimming federation. These competitions were performed in a 25-m pool. Additionally, the freestyle swimming technique of each swimmer was subjectively graded by an experienced swimming coach with over 10 years of experience. A 10-points scale was used with 1 being a very poor technique and 10 a near perfect technique.

Dry-land strength and power assessments

A strength test has been defined as a procedure to determine the ability to generate high forces against large resistances, whereas a power test has been understood as the assessments to determine the ability to produce a high work rate [104]. Hence, for the present study, those tests which aim to obtain maximum strength would be considered as strength tests, whereas those tests aiming to obtain the maximum strength at a maximum rate or speed, paying special attention to the stretch-shortening cycle performance (jumps or short sprints), would be considered as power tests.

Dry-land strength assessments

Isometric half squat. Maximum isometric strength (MIS) from the half squat position was measured using a KISTLER platform type 9260AA (Kistler instruments Ltd., Hampshire, UK). Participants were placed in a 90º half-squat position standing on the platform, performing 2 repetitions at MIS against a fixed bar with a rest of ~ 3 min in between. The researcher encouraged the participant to push the bar as strong and quick as possible, always maintaining an adequate technique, with the best attempt was recorded.

Dynamic half squat. LBS was measured from the dynamic half-squat exercise performed on a Smith machine (Impulse IT Smith Machine, Midlothian, Scotland) with the 20, 30 and 40% of the participants' MIS loaded in the bar. Participants started the exercise from a standing position and then they were asked to perform three maximum repetitions, with ~ 1 s stop between them in order to avoid technique errors, assessing the maximum propulsive velocity during the concentric phase. A rotator encoder attached to the bar (T-Force dynamic measurement system, model TF-100, Ergotech consulting S.L. Murcia, Spain) was used to register mean propulsive velocity (MPV).

Isometric knee extension. Maximum isometric peak torque through knee extension (MIS KE) was measured using a strain gauge (MuscleLab, Force Sensor, Norway). The participant was sited with an anchorage placed on the distal third of the tibia. This anchorage was connected to the strain gauge, registering force data during the six seconds that the participant performed the maximum knee extension. Two attempts were permitted for each leg, with the best performance recorded.

Dry-land power assessments

Participants completed the squat jump (SJ), countermovement jump (CMJ) and the Abalakov jump (ABA) tests on a portable force platform (Kistler instruments Ltd., Hampshire, UK). For the SJ test, participants were instructed to start from a semi-squatted position (90º knee flexion), with both arms on the hip to isolate the lower limbs action and jumped with no countermovement. For the CMJ performance, participants stood with both hands on their hips, and performed a vertical jump with an earlier fast countermovement. Finally, the ABA test incorporated the assessment of the intermuscular coordination capacity, the participant performed a CMJ but was allowed to freely coordinate the arms and trunk movements to reach the maximum height. Three attempts with a rest of ~ 3 min were permitted for each jump and the best performance was selected for further analysis. Peak force and rate of force development (RFD) were computed for each jump through the BioWare® Software (Kistler Group, Winterthur, Switzerland).

Statistical analysis

Mean and standard deviation (SD) were calculated for each variable. The Kolmogorov-Smirnov test was applied, showing a normal distribution for most of the variables. For non-normal variables, normality was checked with histograms and data were transformed to obtain normalized variables with mean 0 and SD 1 through the Blom's test. Mean and SDs are presented for the whole sample and stratified by sex. One-way ANOVA (sex effect) and ANCOVA (sex effect controlling the age and maturity effect) were used to examine the differences in the data, including the estimation of the 95% CI of the differences between sexes ($p \leq 0.05$). Partial eta square (ηp^2) showed the effect size index interpreted as: (a) no effect if $0 < \eta p^2 \leq 0.04$, (b) minimum if $0.04 < \eta p^2 \leq 0.25$, (c) moderate if $0.25 < \eta p^2 \leq 0.64$, and (d) strong if $\eta p^2 > 0.64$ [139]. Bivariate Pearson correlations were used to assess the relationship between swimming times and fitness variables, analysing males and females separately. Those variables showing significant correlations were included in different linear regression models, for which the 50- and 100-m times were the two dependent variables. Firstly, Model 1 was used to examine the relative influence of age, maturity Status and freestyle technique in swimming performance, so these 3 variables were introduced in the regression model (Enter method). The next model (Model 2) incorporated the LBP variables that had previously shown a correlation with swimming performance (step-wise method). Data did not present multicollinearity (as assessed with the variance inflation factor and the tolerance statistic). In order to assess the reliability of the fitness-related tests with this specific sample, intraclass correlation coefficient (ICC; one-way random) was calculated for each fitness test. Power calculation and sample size estimations were computed based on the primary outcome which is reported in the corresponding methodological article published elsewhere [59]. The present study is based on a secondary analysis and therefore a specific power calculation was not developed for the present calculations. The Statistical Package for the Social Science 24.0 software (SPSS) was used for all analyses and *p* value was set at $p \leq 0.05$.

RESULTS

Sex differences

Personal data and anthropometric characteristics are presented in **Table 7**. The variables for both LBS and LBP tests, as well as 50 m and 100 m freestyle swimming performances are shown in **Table 8**. Males presented higher values for maturity, height and weight (**Table 7**) and also for MIS half squat, MIS KE, MPV of 20 and 30% of the MIS Squat, SJ_{PEAK}, CMJ_{PEAK} and ABA_{PEAK} (**Table 8**), than females for both unadjusted and age- and maturity-adjusted data ($p \leq 0.05$). In addition, males presented better performance times in both 50 m and 100 m when compared to females. No differences were found in age, swimming experience (y), training volume (hours/week), MPV of 40% of the MIS Squat, SJ_{RFD}, CMJ_{RFD}, and ABA_{RFD}, between sexes ($p > 0.05$).

Table 7. Descriptive analysis of anthropometrics and personal data.

	ALL (M±SD)	BOYS (M±SD)	GIRLS (M±SD)	CI (95%)		ANOVA[a]		
	N= 44	N= 27	N= 17	Lower	Higher	*F*	*p*	ηp^2
Age (y)	14.6±1.3	14.75±1.26	14.4±1.4	14.2	15.0	0.668	0.418	0.016
Tanner Stage (I/II/III/IV/V)	0/3/14/22/5	0/1/7/14/5*	0/2/7/8/0	3.4	3.9	4.505	0.041	0.114
Height (cm)	166.5±10.5	172.10±8.41*	157.6±6.5	163.3	169.7	36.78	<0.001	0.467
Weight (kg)	56.0±11.1	61.34±10.12*	47.5±6.4	52.6	59.4	25.295	<0.001	0.376
BMI ($kg \cdot m^{-2}$)	20.0±2.4	20.63±2.58*	19.1±1.6	19.3	20.8	4.962	0.031	0.106
Freestyle T (0-10)	6.3±1.7	6.3±1.8	6.3±1.5	5.8	6.8	0.008	0.930	0.000
SW Exp (y)	8.2±2.6	7.9±2.9	8.6±2.1	7.4	9.0	0.770	0.385	0.018
Tr Vol (h/wk)	10.2±2.0	10.3±1.9	10.2±2.2	9.6	10.8	0.012	0.913	0.000

* = Significant differences between sexes ($p \leq 0.05$).
[a] = Sex differences

ηp2=partial eta squared; CI=confidence interval; BMI=body mass index; SW Exp=swimming experience; Tr Vol=training volume; Freestyle T=freestyle technique;

Table 8. Descriptive analysis the freestyle swimming times, LBS and LBP variables.

	ALL (M±SD)	BOYS (M±SD)	GIRLS (M±SD)	CI (95%)		ANOVA[a]			ANCOVA[b]		
	N= 44	N= 27	N= 17	Lower	Higher	*F*	*p*	ηp^2	*F*	*p*	ηp^2
SW Performance											
T-50 (s)	30.18±2.38	28.89±1.63*	32.22±1.93	29.45	30.90	37.628	<0.001	0.473	26.495	<0.001	0.665
T-100 (s)	65.26±4.77	62.80±3.24*	69.16±4.19	63.81	66.71	31.994	<0.001	0.432	26.537	<0.001	0.666
LBS Variables											
MIS Squat (N)	1280.3±400.5	1460.4±405.35*	994.1±149.4	1158.5	1402.0	20.587	<0.001	0.329	19.108	<0.001	0.589
MIS KE (N)	913.4±195.8	1005.3±182.86*	767.5±108.6	853.9	973.0	23.416	<0.001	0.358	13.034	<0.001	0.494
MPV_{20} ($m\cdot s^{-1}$)	0.63±0.08	0.66±0.08*	0.58±0.05	0.61	0.66	12.934	0.001	0.235	5.854	0.002	0.305
MPV_{30} ($m\cdot s^{-1}$)	0.54±0.08	0.57±0.09*	0.50±0.05	0.52	0.57	6.642	0.014	0.137	4.411	0.009	0.249
MPV_{40} ($m\cdot s^{-1}$)	0.47±0.09	0.46±0.10	0.45±0.08	0.43	0.49	0.174	0.679	0.004	1.013	0.397	0.071
LBP Variables											
SJ_{PEAK} (N) †	1167.1±286.6	1289.4±278.12*	941.3±114.1	1071.5	1262.6	18.475	<0.001	0.345	9.703	<0.001	0.469
SJ_{RFD} ($N\cdot s^{-1}$) †	5156.0±2618.2	5649.0±3055.96	4245.9±1132.2	4283.1	6029	2.524	0.121	0.067	0.970	0.418	0.081
CMJ_{PEAK} (N)	1194.6±273.6	1316.2±250.37*	1001.4±186.0	1111.4	1277.8	19.892	<0.001	0.321	11.989	<0.001	0.473
CMJ_{RFD} ($N\cdot s^{-1}$)	8653.3±5648.4	8787.1±5728.51	8440.6±5686.6	6936.0	10370.5	0.038	0.846	0.001	0.508	0.679	0.037
ABA_{PEAK} (N)	1158.6±287.9	1285.9±260.20*	956.5±204.8	1071.1	1246.1	19.553	<0.001	0.318	13.268	<0.001	0.499
ABA_{RFD} ($N\cdot s^{-1}$)	6893.0±4178.6	7826.6±4677.57	5410.1±2750.3	5622.5	8163.4	3.709	0.061	0.081	1.372	0.265	0.093

* = Significant differences between sexes ($p \leq 0.05$).
[†] = The original sample was reduced to 37 swimmers (24 males and 13 females) due to incorrect jumping execution during the SJ.
[a] = Sex differences.
[b] = Sex differences following age and maturity adjustments.

ηp2=partial eta squared; CI=confidence interval; T-50=best performance time in 50 m; T-100=best performance time in 100 m; LBS=lower-body strength; LBP=lower-body power; MIS squat=maximal isometric strength from half-squat position; MIS KE=maximal isometric strength of the knee extensors; MPV_{20}=mean propulsive velocity in half squat at 20%; MPV_{30}=mean propulsive velocity in half squat at 30%; MPV_{40}=mean propulsive velocity in half squat at 40%; SJ_{PEAK}=squat jump peak force; SJ_{RFD}=squat jump rate of force development; CMJ_{PEAK}=countermovement jump peak force; CMJ_{RFD}=countermovement jump rate of force development;

Bivariate Pearson correlations

For the correlation of the LBP variables, three males and four females had to be excluded due to incorrect jumping execution during SJ (i.e., countermovement prior the concentric phase). Thus, subsequent correlation and linear regression analyses were performed with a sample of 37 swimmers when including SJ (24 males and 13 females). In males, bivariate correlations exhibited significant values between swimming performance and LBP variables (SJ_{PEAK}, CMJ_{PEAK}, ABA_{PEAK} and ABA_{RFD} for both 50 m and 100 m performance; $p \leq 0.05$, **Table 9**). Only one LBS variable correlated with swimming performance in males (MIS Squat; $p \leq 0.05$, **Table 9**). However, in females, bivariate correlations did not find any significant relationship with swimming performance ($p > 0.05$, **Table 9**).

Table 9. Pearson bivariate correlations in males (n=27) and females (n=17) between freestyle swimming times and LBS variables and LBP variables.

	MALES						FEMALES					
LBS variables and swimming performance							LBS variables and swimming performance					
	MIS KE	MIS SQ	MPV_{20}	MPV_{30}	MPV_{40}		MIS KE	MIS SQ	MPV_{20}	MPV_{30}	MPV_{40}	
T-50	-0.142	-0.430*	-0.212	-0.008	-0.037		-0.305	-0.076	-0.246	0.018	-0.298	
T-100	-0.161	-0.443*	-0.313	-0.120	-0.105		-0.358	-0.104	-0.124	-0.045	-0.343	
LBP variables and swimming performance							LBP variables and swimming performance					
	†SJ_{PEAK}	†SJ_{RFD}	CMJ_{PEAK}	CMJ_{RFD}	ABA_{PEAK}	ABA_{RFD}	†SJ_{PEAK}	†SJ_{RFD}	CMJ_{PEAK}	CMJ_{RFD}	ABA_{PEAK}	ABA_{RFD}
T-50	-0.573**	-0.252	-0.497**	-0.262	-0.503**	-0.452**	-0.082	0.037	-0.150	0.099	-0.274	-0.101
T-100	-0.642**	-0.322	-0.544**	-0.296	-0.488**	-0.415*	-0.208	0.063	-0.222	-0.062	-0.308	-0.111

* $p \leq 0.05$; ** $p \leq 0.01$.
† = The sample size was reduced to 24 males and 13 females due to incorrect jumping execution during SJ.

ABA_{PEAK}=ABA peak force; ABA_{RFD}=ABA rate of force development; CMJ_{PEAK}=CMJ peak force; CMJ_{RFD}=CMJ rate of force development; LBS=lower-body strength; LBP=lower-body power; MIS KE=maximal isometric strength of the knee extensors; MIS SQ=maximal isometric strength from half-squat position; MPV_{20}=mean propulsive velocity in half squat at 20%; MPV_{30}=mean propulsive velocity in half squat at 30%; MPV_{40}=mean propulsive velocity in half squat at 40%; SJ_{PEAK}=SJ peak force; SJ_{RFD}=SJ rate of force development; T-50=best performance time in 50 m; T-100=best performance time in 100 m.

Multiple linear regressions

Table 10 displays the results of the linear regression analyses performed between performance times and the variables that had shown a significant correlation in the aforementioned correlation analysis, being solely for male swimmers. For 50 m performance, age, maturity and freestyle technique adjustments were firstly performed, indicating a significant predictive value of r^2=0.40 ($p \leq 0.01$; Model 1, **Table 10**). When LBP variables were introduced in the regression analyses, only ABA_{RFD} significantly increased the predictive value (r^2 = 0.58, change in r^2= 0.18, $p \leq 0.05$; Model 2, **Table 10**). Similarly for 100 m performance, age, maturity and freestyle technique adjustments indicated a significant predictive value of r^2=0.51 ($p \leq 0.01$; Model 1, **Table 10**). When adding the LBP variables that previously showed a significant correlation with 100 m performance, SJ_{PEAK} was the only included in the regression model (Model 2, r^2= 0.66, change in r^2=0.15, $p \leq 0.01$; **Table 10**).

Table 10. Linear Regression models to predict 50 m and 100 m swimming performance in male swimmers (n= 24).

	SEE	r	r^2	Change in r^2	Adjusted r^2	β	Semip corre	*p*
T-50								
Model 1	1.30	0.635	0.404	0.404	0.314			0.014*
Age						-0.491	-0.513	0.015*
Tanner						-0.096	-0.117	0.605
Freestyle T						-0.249	-0.296	0.180
Model 2	1.11	0.764	0.584	0.180	0.496			0.010*
ABA_{RFD}						-0.426	-0.550	0.010*
Age						-0.459	-0.555	0.009*
Tanner						-0.087	-0.126	0.586
Freestyle T						-0.253	-0.354	0.116
T-100								
Model 1	2.34	0.714	0.509	0.509	0.436			0.002*
Age						-0.459	-0.524	0.012*
Tanner						-0.069	-0.093	0.682
Freestyle T						-0.423	-0.504	0.017*
Model 2	2.01	0.811	0.657	0.148	0.585			0.010*
SJ_{PEAK}						-0.431	-0.549	0.010*
Age						-0.280	-0.381	0.088
Tanner						-0.090	-0.144	0.534
Freestyle T						-0.361	-0.507	0.019*

*$p \leq 0.05$

Model 1: Linear regression model introducing Age, Tanner and Freestyle technique assessment (Enter method).
Model 2: Linear regression model introducing Model 1 + all the LBP variables that previously showed significant correlations (step-wise method).

ABA_{RFD}=Abalakov jump rate of force development; β =estimated standardized regression coefficient; B=estimated non-standardized regression coefficient; Freestyle T=freestyle technique; SEE=standard error of estimation of the model; Semip corre=semi-partial correlation; SJ_{PEAK}=squat jump peak force; T-50=best performance time in 50 m; T-100=best performance time in 100 m.

Reliability of the tests

Table 11 displays the ICC results for all the fitness variables. All of them presented excellent ICC (range: 0.912 - 0.977), indicating that the performed tests were highly reliable methods to test strength and power in this group of adolescent swimmers.

Table 11. Intraclass correlation coefficient for the strength and power tests.

	ICC
MIS KE left	0.950
MIS KE right	0.924
SJ	0.954
ABA	0.977
CMJ	0.972
MIS Squat	0.923
MPV_{20}	0.941
MPV_{30}	0.912
MPV_{40}	0.944

ICC=intraclass correlation coefficient; MIS squat=maximal isometric strength from half-squat position; MIS KE=maximal isometric strength of the knee extensors; MPV_{20}=mean propulsive velocity in half squat at 20%; MPV_{30}=mean propulsive velocity in half squat at 30%; MPV_{40}=mean propulsive velocity in half squat at 40%; SJ=squat jump; CMJ=countermovement; ABA=abalakov jump.

DISCUSSION

The main findings of the present study revealed that LBP through vertical jumps has a superior influence in sprint swimming performance than LBS, in adolescent male swimmers. This study also highlights the importance of LBP depending on the distance swam, with arm coordination during the jump being remarkably more important during shorter events. Our findings showed that vertical jumps explained 18% and 15% of the variance for 50 m and 100 m swimming performance, respectively, after age, maturity status and freestyle technique adjustments. None of the LBS variables explained swimming performance in this group of swimmers neither for 50 m nor 100 m performance.

In males, data exhibited a significant relationship between LBP tests and swimming performance and only one LBS test correlated with swimming performance (MIS half squat). When LBS and LBP variables were analysed through linear regression models, no LBS variables were included in any regression model. The importance of LBP showed in the present study is in agreement with Garcia-Ramos et al. [49], who only found associations between LBP (SJ and CMJ) and swimming start performance (time to 5, 10 and 15m), but not with LBS (MIS KE and flexion). Several cross-sectional studies [41,47,84] reinforce the relationship between LBP (jumping ability) and swimming performance although this association appears arguable when the including adolescent females [41].

The difference between sexes observed in the present study agrees with previous longitudinal data which examined the LBP capacity over different maturation stages among males and females [140]. This longitudinal study observed that adolescent males experienced an enhancement in LBP (vertical jumping performance) from prepubescence (Tanner stages 1-3) to postpubescence (Tanner stages 4-5), whereas adolescent girls did not. The authors suggested that the neuromuscular increase that takes place in prepubertal males naturally, may be artificially induced through neuromuscular training in females across puberty. According to this hypothesis, strong evidence supports that lower extremity power can be modified in adolescent females with neuromuscular training [141–143], and this could explain why LBP did not correlate with swimming performance in this group of female swimmers. Other factors are likely to predict swimming performance in female swimmers, such as a reduced energy expenditure for staying afloat because of their higher percentage of fatty tissue [144], or a smaller frontal area in females which has shown to reduce drag values (i.e. lower resistance) [145].

In order to perform a more comprehensive analyses of the LBS and LBP variables correlated with swimming performance shown in males, further linear regression analysis revealed that ABA_{RFD} was the only variable predicting 50 m performance, whereas SJ_{PEAK} was the only variable that predicted 100 m performance. The higher contribution of ABA_{RFD} to predict 50 m performance may be partially explained by the positive transfer of the LBP exerted during the jump as well as a greater influence of the intermuscular coordination using trunk and upper limbs to the specific action [146]. A superior performance in this jump not only reveals those powerful swimmers, but also those swimmers capable to efficiently coordinate both the upper and lower limbs to perform an optimal moment of inertia. This greater moment of inertia and coordination during the early phase of the concentric movement (where the RFD takes place), could be linked to a greater LBP exerted during the take-off phase as well as an optimal rotation during the flight phase. As previously reported, the main aim of the flight phase is not only to go as far as possible, but also to prepare the body for a streamlined entry to favour an efficient under-water phase [147,148]. In order to optimize the flight phase, arm movements seem to play a crucial role since they highly influence the angular momentum needed to enter in the water with the optimal rotation [149]. We therefore suggest that the capacities tested during ABA jump (i.e., LBP and optimal coordination to use the arm movement) would partially explain a high performance during the start phase and thus 50 m performance in male adolescent swimmers.

Regarding the greater influence of SJ_{PEAK} to predict 100 m swimming performance shown in this study, it is worth noting that this test has been designed to isolate the lower-body power, avoiding the influence of other factors that take place during other jumps, such as the elastic energy during CMJ or ABA or the coordination capacity using the trunk and upper limbs during ABA [146]. Therefore, it seems that LBP in isolation may play a greater role in this distance, which could be explained due to a higher number of turns (1 in 50 m races vs. 3 in 100 m races over a 25-m pool) and thus a higher contribution of the freestyle turning performance during a longer event, when compared to a 50 m race [83]. In relation to the turning phase, it is believed that there exists a negligible countermovement of the lower limbs during the push-off phase in order to store elastic energy for a greater push-off [150]. However, as previously reported, to store elastic energy the activation of the stretch-shortening cycle is required, and muscles must be active during the stretch phase in order to store such energy [151]. Nevertheless, since the turn phase has a critical time element and performing a countermovement has shown to risk the swimmer´s valuable time [152], it is common that the swimmer perform little to no active eccentric phase during the push-off phase [153]. We therefore hypothesize that a higher jump performance without countermovement (i.e., SJ performance) might predict a shorter ground contact time during the pushing-off the wall phase, partly predicting 100 m performance. As displayed in **Table 10**, freestyle swimming technique significantly predicted swimming performance only for 100 m, which is in agreement with previous research highlighting that biomechanical factors (e.g., stroke rate, stroke length and stroke index) contribute more to 100 m and 400m performance in adolescent swimmers [154,155], compared with physiological or anthropometrical factors.

It is worth considering that the aforementioned cross-sectional data do not report a cause-effect relationship, being difficult to assess these markers as causative. Nonetheless these results are in agreement with previous intervention studies. Bishop et al. [91] found that 8 weeks of plyometric training improved the start phase (time to 5 m) and also the turning phases (enhancement of 2.9%), in adolescent swimmers. Potdevin et al. [83]

developed a 6-week plyometric training in adolescent swimmers and, besides an improvement in CMJ and SJ height, they observed higher improvements in 400m performance (4.4%), in comparison with 50 m performance (3.2%). Considering that this latter study is the only which investigated the chronic effects of plyometrics on overall swimming performance in adolescent swimmers (34), definitive conclusions cannot be made. Further cross-sectional data [136] revealed positive relationships between LBS (leg extension) and sprint performance (25 and 50 m) but not with LBP (CMJ). Nevertheless, swimmers involved in their study [136] were prepubescents (Tanner stages 1-2) and, as reported by the authors, vertical jump performance in prepubescent swimmers could be highly dependent on skill [156]. We therefore hypothesise that the potential relationship between LBP and swimming performance might not reflect faster swimmers at this maturity stage yet.

Some limitations are important to consider in the interpretation of the present results. Additional muscle composition analysis through biopsies might have revealed whether the higher LBP contribution could have been due to either the characteristics of the LBP tests, or the specific swimmer's physiological profile. However, the development of this analysis was not possible for this study and we assumed that this physiological profile would be representative for this specific sample and level of performance. In order to obtain more precise and reliable data, a wider sample size is recommended for both male and female groups. The incapacity of some adolescent swimmers to adequately perform the SJ technique was another limitation since it partially reduced the sample size, which would require a further familiarization session in future investigations. The method used in this study to assess SJ performance (i.e., jumping from a 90º knee flexion position) is widely used in both testing and research, although the optimal knee starting angle to maximize jumping performance has shown to be widely varied between subjects

[157]. Therefore, this starting angle should be personalized for each individual in further studies. Finally, freestyle technique was not assessed through objective biomechanical data (e.g., stroke index, stroke rate or stroke length) but rather a qualitative assessment from an experienced coach and therefore, this assessment should be carefully interpreted. Considering the strong relationship between LBP and swimming performance and the lack of plyometric training interventions aiming to improve swimming performance, there is an urgent need for scientific validation of plyometric training exercises to improve swimming performance.

CONCLUSIONS

Besides a superior contribution of LBP to sprint swimming performance than LBS in male adolescent swimmers, our study suggests that a vertical jump potentiating both arm coordination and LBP (i.e., ABA jump) is more accurate to predict shorter distances performance. This study will also aid coaches to decide which LBP test would be the most appropriate for sprinters, depending on the distance swam. Consequently, coaches should implement training sessions focused on the improvement of power and also incorporate specific LBP tests through vertical jumps to assess the swimmer´s progression. The arm movement during a jump seems to favour the prediction of 50 m performance, probably due to a positive transfer of both LBP and arm movement to the specific sports action. In the present study, SJ peak power, in part, has shown to predict 100 m swimming performance, hypothesizing that the power exerted during this jump could be related to the power utilized during the push-off the wall phase. Additionally, from the lack of a significant relationship between LBP and swimming performance in female swimmers observed in our study, we encourage coaches and trainers to focus on LBP training practices during adolescence with this specific group.

Chapter 4.4

Long-term effects of whole-body vibration training on strength, power and swimming performance

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Muniz-Pardos B, Gómez-Bruton A, Matute-Llorente A, González-Agüero A, Gómez-Cabello A, Casajús JA, Vicente-Rodríguez G. Long-term effects of whole-body vibration in trained adolescent swimmers. Does it increase strength, power or swimming performance? **Int J Sports Physiol Perf**. *Submitted.*

ABSTRACT

The purpose of this study was to examine the effects of a 6-month whole-body vibration (WBV) training on lower-body strength (LBS), lower-body power (LBP) and swimming performance in adolescent trained swimmers. Thirty-seven swimmers (23 males, 14 females; 14.8 ± 1.3 y) were randomly assigned to the WBV (n= 20) or the control group (n=17). Isometric LBS (knee extension and half-squat) and LBP (vertical and horizontal jumps and 30 m sprint) tests were performed before and after the intervention period. Swimming performance times in 100 m were collected from official competitions. Since time x sex interaction was not found for any variable ($p > 0.05$), males and females were analysed as a whole. Within-group analyses showed a *most likely beneficial* moderate effect of WBV on isometric knee extension [effect size (ES)= 0.63], 30 m sprint test (ES= 0.62) and 100 m performance (ES= 0.25), although these were corresponded with comparable small to moderate effects in the control group (ES= 0.73, 0.71 and 0.20, respectively). The control group obtained a small *possibly beneficial* effect of swimming-only training on vertical jump performance, whereas no effect was observed in the WBV group. *Unclear* effects were observed for the rest of the variables assessed. Between-group analyses revealed *unclear* effects of WBV training when compared to the control condition in all studied variables. There is no current evidence to support the use of WBV training and therefore coaches and sports specialists should select other methods of training when the aim is to increase LBS, LBP or swimming performance.

INTRODUCTION

Whole-body vibration (WBV) is an oscillatory training method widely used in sports centers [158]. This protocol has been described as the sinusoidal oscillations produced by industrial machines which are transmitted to the human body, enhancing the tonic vibration reflex that stimulates reflex muscle contraction [54], which can potentially improve the neuromuscular function [158]. The seminal research into the stress produced by WBV was focused on the health-related risks construction workers were exposed to [159,160]. From the late 90s, the study of this stimulus began to gain popularity in the field of sports science since a number of pioneering publications proposed WBV as an effective training method to increase lower-body strength (LBS) and lower-body explosive power (LBP) and, potentially, athletic performance [161–164].

The influence of LBP in short-distance swimming performance is well documented [45,48,100,165]. The instants when the swimmer has access to ground reaction forces (i.e., dive and turn phases) play a decisive role in overall swimming performance. Lyttle and Benjanuvatra stated that start performance can potentially account for as much as ~15% of the race time over a 100 m competition [103], highlighting the importance of maximizing LBP during the block start performance. A previous meta-analysis revealed positive chronic effects of WBV on LBP through both countermovement jump (CMJ) and squat jump performance, especially when the WBV intervention was longer than 12 weeks, with high frequencies (>30 Hz) and high amplitudes (>3 mm) applied [158]. Delechuse et al. compared the effects of a WBV training protocol with a conventional resistance training routine and, despite witnessing comparable effects on both dynamic and isometric LBS, the authors reported greater effects of the WBV group on LBP (CMJ height) in healthy adults [166]. Previous authors suggested that the physiological mechanisms behind these improvements might be due to neuromuscular adaptations, leading to improvements in motor unit firing and synchronization, synergist muscle contraction, antagonist muscle inhibition and adaptation of the reflex response [162,167].

Hortobagyi et al. [58] performed a further meta-analytical study of the acute and chronic effects of WBV on both LBP and athletic performance in competitive athletes of a wide range of ages representing different sports such as long distance running, rugby or sprinting. However, only one of the included studies examining long-term effects involved adolescent athletes (basketball players), which would be an important novelty of the present study. Presumably, WBV training could increase LBP and it is worth noting that the contribution of this capability varies depending on the sport studied (i.e., different physiological needs) [168]. Consequently, it might be reasonable to argue that the benefit of WBV training on sports performance depends on the LBP demands during specific sports actions. The authors of this meta-analysis reported small chronic effects of WBV training on maximal force [effect size (ES)= 0.44], power (ES= 0.42) and athletic performance (ES= 0.45). However, there is no previous evidence examining the effects of WBV on swimming performance, which could potentially produce a greater transfer to the sports-specific action given the remarkable importance of the LBP capacity in overall short-distance swimming performance. Thus, the main aim of this randomized control trial was to determine the effects of a 6-month WBV training on LBS and LBP development, as well as swimming performance in trained adolescent swimmers. We hypothesized that the WBV group would enhance LBP and swimming performance to a greater extent than the control group.

METHODS

Subjects

Thirty-seven swimmers from four different swimming clubs of Zaragoza (Aragon, Spain) were finally included in the present study, in the framework of the RENACIMIENTO project [59]. The randomized allocation of these swimmers into the control and intervention groups were initially performed in SPSS with the whole sample (n= 98) included in the project. For this study, the following inclusion criteria determined the eligibility of the participants: swimmers between the ages of 12.5 and 17.5 years, Caucasian, healthy and free of injuries. The included athletes had swum more than 6 hours per week for at least 3 years and competed in regional to national level events, without practicing an additional sport simultaneously. Swimmers had to be involved in a 100 m official competition within 15 days near the testing sessions. Swimmers had a mean performance time 68.02±7.8 s in 100 m freestyle events, corresponding to a ~78% of the Spanish record for the same age-group swimmers.

Anthropometric measurements and general information

All participants had basic anthropometric measurements taken (body mass, weight, height). Participants were measured while wearing minimal clothing and without shoes to the nearest 0.1 cm (SECA 225, SECA, Hamburg, Germany) and weighted to the nearest 0.1 kg (SECA 861, SECA). Body mass index (BMI) was then calculated by dividing weight (kg) by squared height (m^2). An ad-hoc structured questionnaire was completed by all participants which included information related to swimming experience, swimming volume, in addition to medical history, previous injuries, evaluation of pubertal stage proposed by Tanner [138] and other personal data.

All procedures were approved by the Ethics Committee of Clinical Research from the Government of Aragón (C.I.PI11/0034; CEICA; SPAIN), and followed the international rules for research with humans, following the declaration of Helsinki (1964) as revised in 2000 in Edinburgh. Parents or a legal guardian provided written consent and verbal assent from the participants was obtained. This study is part of a Randomized Controlled Trial [59] which is registered in a public database (www.clinicaltrials.gov) with the following register number: NCT02380664.

Lower-body strength and power assessments and Swimming performance times

Dry-land assessments and swimming performance records were collected before and after the 6-month intervention period. Participants performed a total of 2 LBS isometric tests (half squat and leg extension) and 3 LBP dynamic tests (30 m sprint test, horizontal jump and CMJ) with special emphasis in the assessment of the stretch and shortening cycle in the lower extremities.

Regarding the LBS isometric tests, maximum isometric strength (MIS) from the half-squat position was measured using a force platform (Kistler type 9260AA, Kistler instruments Ltd., Hampshire, UK). Participants were placed in a 90º half-squat position standing on the platform, performing 2 repetitions at MIS against a fixed bar with only the best repetition recorded. Two repetitions were allowed for this exercise instead of the 3 permitted for other exercises to prevent from any potential back injury during this maximal isometric test. A researcher supervised and encouraged the participant to push the bar as strong and quick as possible, always maintaining an adequate technique. In addition, MIS of the knee extensor muscles was measured using a strain gauge (MuscleLab, Force Sensor, Norway). The participant was sited with an anchorage placed on the distal third of the tibia. This anchorage was connected to the strain gauge, registering force data during the 6 s that the participant had to perform the maximum knee extension. Two attempts were permitted for each leg, with the best performance recorded.

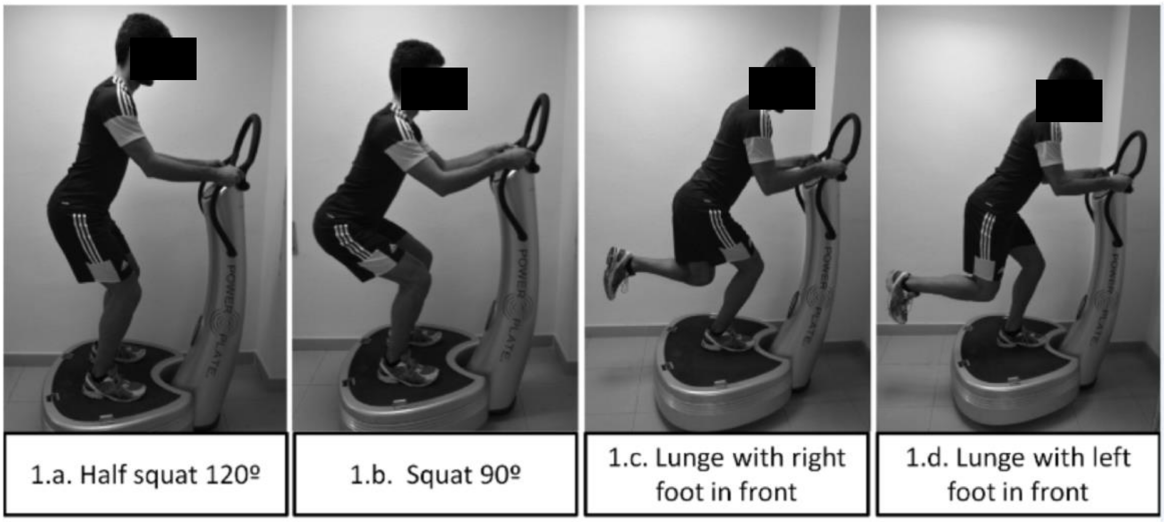
Regarding the LBP dynamic assessments, participants performed a 30 m sprint running test, which consisted of two maximal efforts of 30 m running sprint with a ~3 min rest in between. Timing gates (Byomedic photoelectric cells, Spain, Barcelona) were placed along an indoor sports court separated by 30 m. The best performance was recorded. Although this is a non-specific test for a swimmer, the maximum acceleration during a short sprint has shown to be a reliable method to measure maximum LBP [169]. Additionally, horizontal jump test allowed to further assess explosive leg power. The participant stood behind the starting line with the legs slightly apart, jumping as far as possible allowing to swing his/her arms and bend his/her knees to aid the jump. Three attempts were performed, with the best performance recorded for further analyses. Finally, participants completed the CMJ test on a portable force platform (Kistler type 9260AA, Kistler instruments Ltd., Hampshire, UK). Participants stood with both hands on their hips to isolate the lower limb action, and performed a vertical jump with an earlier fast countermovement. Three attempts were permitted and the best performance was recorded for further analysis. The raw data from each jump was introduced in an Excel macro [170] to determine CMJ height (CMJ_{HT}). Firstly, take-off velocity (TOV) was calculated from the mechanical impulse and the time to reach this mechanical impulse. Then, jump height was calculated as follows:

$$CMJ_{HT} = (TOV^2)/(2 \cdot G)$$, where G is gravity.

The most recent performance times in 100 m freestyle swimming (performed up to 15 days near to the testing sessions, in a 25-m swimming pool) were collected from official competitions (reported by the regional swimming federation) and converted to the well-established International Swimming Federation (FINA) points [6] in order to standardize between swimming strokes and thus allow the comparison.

Whole Body Vibration procedures

The participants included in the WBV group performed both static and dynamic lower-body exercises on a vertical and synchronous vibration platform (Power Plate® Pro5; PowerPlate, Amsterdam, Netherlands) whereas the participants allocated in the control group were asked to maintain their habitual training routine throughout the intervention period. Participants included in the WBV group performed 3 sessions per week during a total of 24 weeks. Each training session was composed of 2 sets of 5 exercises (displayed in **Figure 9**), which were performed in the following order: 1) half squatting (bent knees at 120º) on the platform; 2) squat 90º; 3) dynamic squat from 120º - 90º bent knees at a range of 2 s up 2 s down; 4) static lunge with right foot in front; and 5) static lunge with left foot in front. This protocol was repeated twice during each session, taking around 15 min to complete the whole training session. A researcher supervised all training sessions throughout the 6-month WBV period to ensure the swimmer performed each session in a safe and appropriate manner. The training volume and intensity increased over the training period of 6 months, with the specific amplitudes, frequencies, durations and rests detailed in **Figure 9**.



	Sessions	Frequency (Hz)	Peak-to-peak displacement (mm)	Duration (s)	Rest (s)	Repetitions	Vibration total time (min)	Training total time (min)	Peak acceleration (g)
Month 1	12	30	2	45	45	2	7.5	15	3.6
Month 2	12	30	4	45	45	2	7.5	15	7.2
Month 3	12	32	4	45	45	2	7.5	15	8.2
Month 4	12	34	4	60	60	2*	8	16	9.3
Month 5	12	36	4	60	60	2*	8	16	10.4
Month 6	12	38	4	60	60	2*	8	16	11.6

Squat&120°,&90° and&dynamic&were&performed&twice,&while&unge&with&each&eg&was&only&performed&once

Figure 9. Whole-body vibration exercises and protocol.

Statistical analysis

Mean and standard deviation (SD) were calculated for each variable. Chi-square test was initially performed to identify any potential differences in the maturity status of the swimmers between groups pre-intervention. Males and females were analysed together since time x sex interaction did not reach significance for any DLS, DLP or performance variable ($p > 0.05$). All data was transformed logarithmically to reduce potential bias arising from non-uniformity error. The effect size (ES, 95% confidence interval) for each variable was calculated using the pooled pre-intervention SD. Threshold values for Cohen ES statistics were: > 0.2 (small effect); > 0.6 (moderate effect); > 1.2 (large effect) [62]. For within/between-groups comparisons, the chances that the differences in performance and measures of LBS were better/greater (ie., greater than the smallest worthwhile change [0.2 multiplied by the between-subjects SD, based on the Cohen *d* principle]), similar, or worse/smaller were calculated. Quantitative chances of beneficial/better or detrimental/poorer effect were assessed qualitatively as follows: <1%, almost certainly not; 1% to 5%, very unlikely; >5% to 25%, unlikely; >25% to 75%, possibly; >75% to 95%, likely; >95% to 99%, very likely and >99%, almost certainly [62]. If the chances of having beneficial/better and detrimental/poorer performances were both >5%, the true difference was assessed as unclear. Otherwise, we interpreted that change as the observed chance [62].

RESULTS

Subjects

Although 98 swimmers were initially allocated into the control and intervention group in a randomized fashion, 61 were excluded from the present study for the following reasons: Eight swimmers declined to participate, 22 did not meet the inclusion criteria, 14 were excluded due to discontinued practice or disease over the experimental period, 12 swimmers were excluded for practicing additional sports, and five did not compete within 15 days near the testing sessions. A final sample of 37 adolescent swimmers (13 males and seven females allocated in the intervention group and 10 males and seven females allocated in the control group) was included in the present study, with the main personal and anthropometric data displayed in **Table 12**. Chi-square test showed no differences in the maturity status pre-intervention between groups ($p > 0.05$).

Table 12. Personal and Anthropometric data, Mean ± SD

	All N= 37	Males N= 23	Females N= 14
Age (y)	14.8±1.4	15.0±1.3	14.4±1.4
Height (cm)	167.3±11.2	172.5±8.5	158.7±9.7
Weight (kg)	56.9±11.5	61.6±9.5	49.2±10.4
Tanner Stage (I/II/III/IV/V)	0/2/9/21/5	0/0/7/11/5	0/2/2/10/0
Swimming Experience (y)	7.8±2.9	7.9±3.1	7.7±2.5
Training Volume (h/week)	10.3±1.9	10.1±1.9	10.7±1.9

Whole Body Vibration training effects

Within-group comparisons showed that the WBV group had a *most likely beneficial* small to moderate effect on knee extensors isometric strength, 30 m sprint running test and 100 m swimming performance after the 6-month training period (ES= 0.63, 0.62 and 0.25, respectively; **Table 13**). However, these effects were comparable to the *likely beneficial* small to moderate effect observed in the control group (ES= 0.73, 0.62 and 0.20, respectively; **Table 13**). In addition, the control group exhibited a *possibly beneficial* small effect after the 6-month period (ES= 0.27), whereas the WBV group did not (ES= 0.07). The rest of the strength- and performance-related variables showed no effects after the WBV period. In the between-groups analyses, unclear effects were observed in all variables when comparing the WBV group with the control group (**Figure 10**).

Table 13. Within-group changes in LBS, LBP and swimming performance after the 6-month WBV period

	Pre-test	Post-test	Differences* % (95% CL)	Differences* Standardized (95% CL)†	Chances‡	QA
Pre-Post Intervention Group (N = 20; 13 males and 7 females)						
FINA 100	392.7±63.2	412.2±69.5	5.1 (-1.1; 11.7)	0.25 (-0.05; 0.55)	63/37/0%	Possibly Beneficial
MIS SQ (N)	1420.2±511.8	1346.8±347.2	-2.9 (-11.1; 6.0)	-0.09 (-0.35; 0.17)	2/79/19%	Likely Trivial
MIS KE (N)	947.3±230.6	1101.2±253.0	16.6 (10.5; 23.1)	0.63 (0.41; 0.85)	100/0/0%	Most Likely Beneficial
CMJ (m)	0.29±0.07	0.30±0.06	1.7 (-4.5; 8.4)	0.07 (-0.18; 0.31)	14/85/2%	Unclear
30 m (s)	4.96±0.45	4.68±0.42	5.6 (3.3; 8.0)	0.62 (0.36; 0.89)	100/0/0%	Most Likely Beneficial
Horiz Jump (m)	1.99±0.28	1.94±0.30	-2.8 (-5.6; 0.2)	-0.19 (-0.40; 0.01)	0/52/47%	Possibly Harmful
Pre-Post Control Group (N = 17; 10 males and 7 females)						
FINA 100	360.5±95.8	380.9±105.3	5.6 (-1.0; 12.7)	0.20 (-0.04; 0.44)	51/49/0%	Possibly Beneficial
MIS SQ (N)	1244.9±284.7	1172.7±253.5	-5.5 (-11.1; 0.4)	-0.24 (-0.49; 0.02)	0/38/62%	Possibly Harmful
MIS KE (N)	896.5±203.3	1075.6±308.1	18.7 (11.9; 25.8)	0.73 (0.48; 0.97)	100/0/0%	Most Likely Beneficial
CMJ (m)	0.26±0.04	0.27±0.04	3.9 (-1.0; 9.1)	0.27 (-0.07; 0.60)	66/34/0%	Possibly Beneficial
30 m (s)	5.09±0.31	4.86±0.32	4.5 (1.2; 7.9)	0.71 (0.18; 1.25)	97/3/0%	Very Likely Beneficial
Horiz Jump (m)	1.85±0.23	1.83±0.22	-0.8 (-3.5; 1.9)	-0.06 (-0.26; 0.14)	1/91/8%	Likely Trivial

*All differences are presented as improvements (positive), so that negative and positive differences are in the same direction.
† Effect size.
‡ % of the chances of having better/similar/poorer values.

Abbreviations: CL=confidence limits; QA=quality assessment; 30 m=30 m sprint running test; Horiz Jump= horizontal jump; CMJ=countermovement jump; MIS KE=knee extension maximal isometric strength; MIS SQ=half squat maximal isometric strength; FINA 100= FINA points in 100m.

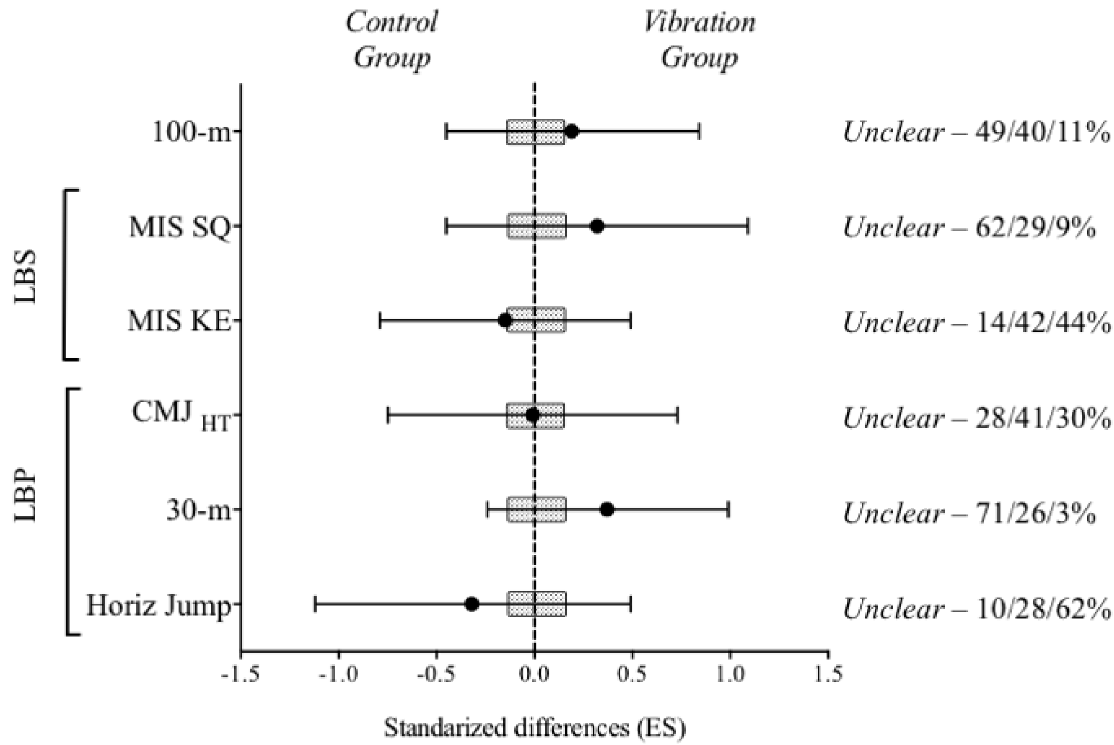


Figure 10. Effectiveness of the 6-month intervention period when compared to the control group to improve LBS, LBP and swimming. A reduction of time in 30 m running sprint test was interpreted as a positive effect. Trivial areas (shaded rectangles) were calculate. from the smallest worthwhile change (further detailed in the methods section). Quality assessment and % of the chances of having better/similar/poorer effect in favour to the vibration group are also reported.

DISCUSSION

Contrary to our initial hypothesis, the main findings of this intervention study showed that a 6-month WBV training period (3 sessions per week with a gradually increased intensity) did not elicit additional improvements in neither LBS, LBP nor swimming performance when compared to the control group, in trained adolescent swimmers.

Regarding the effects of WBV on LBS, our results showed small and wide-ranging effect sizes across the two isometric LBS exercises examined (CIs range= CIs range= -0.35 to 0.85 and -0.49 to 0.97 for the intervention and control group, respectively). Seminal well designed (i.e., controlled and randomized) research into the effects of WBV on isometric LBS reported positive effects of a 12-week WBV training on knee extensors isometric strength (16.6%), with a similar improvement observed in a resistance training group (14.4%) [166]. However, the fact that this study only included untrained adult females makes difficult to compare with the trained swimmers from our study. Hortobagyi et al. performed a meta-analytical study of the effects of WBV on LBS only including trained individuals. One of the studies included in this meta-analysis [171] compared the effects of 4 weeks under three different training conditions (WBV training group, loaded WBV training group, and loaded training group) on the knee extensors isometric strength in elite track and field athletes. There was only a significant time x group interaction for the loaded WBV training group, hypothesizing that combining WBV loaded with a weight corresponding to the 75% of the maximal isometric strength enhances isometric LBS. Nevertheless, when examining the overall effects reported by the meta-analysis of Hortobagyi et al., uncertain chronic effects were found from WBV protocols of similar characteristics (frequency range= 25 to 40 Hz; amplitude range= 1.5 to 6 mm; acceleration range= 5.4 to 29.6 g) on maximal voluntary force from the lower extremities (ES range= -0.19 to 0.87) [58].

When examining the effects of WBV on LBP, unclear effects were also observed. Similar to the effects seen on LBS, the effect sizes found on the 3 LBP variables were small and widely varied (ES range: -0.19 to 0.62 and -0.06 to 0.71 for the intervention and control group, respectively). It is worth noting that the control group showed larger improvements for CMJ performance when compared to the WBV group (ES = 0.27 and

0.07, respectively). However, the higher CMJ initial values of the intervention group at baseline (+ 3 cm on average) might have inhibited any improvement of the WBV training stimulus in CMJ performance due to a potentially reduced capacity for improvement, as previously suggested [158]. These results are in disagreement with Manimmanakorn et al. [158], who found moderate positive effects of WBV on LBP (CMJ performance; mean ES= 0.77). This review and meta-analysis also included studies with non-athletic participants; it is therefore likely that these less trained individuals had superior improvements from WBV training than competitive trained athletes. Manimmanakorn et al. [158] also revealed that the vibration exposure in each training session should be more than 10 min to maximize the benefits from WBV, which is longer than the durations selected for the present study (durations from 7.5 min to 8 min per session). A more recent meta-analysis has examined the chronic effects of WBV on LBP at frequencies ranging from 25 to 40, amplitudes from 4 to 8 mm and accelerations from 10 to 39 g, over training periods from 4 to 15 weeks [58]. Only three out of nine studies included in this meta-analysis showed positive effects of WBV on LBP, highlighting the inconsistencies in the results deduced from a wide range of effect sizes (ES range: -1.01 to 1.32). Although the comparisons between WBV studies should be considered with caution due to the wide variety of protocols, sports and exercise tests used, the present findings do not support the use of WBV as an effective method to enhance either LBS or LBP in trained adolescent swimmers. Concurrently, this lack of effect on muscle function is in concordance with the lack of effect of the same WBV protocol on several bone markers (i.e., bone mineral content and bone mineral density) in this group of swimmers [172].

Finally, although we witnessed small positive effects of WBV on swimming performance (ES= 0.25), this improvement was not different from the observed in the control group (ES= 0.20). We therefore hypothesize that the addition of WBV training does not elicit any LBS, LBP or swimming performance improvements in adolescent swimmers. The traditional swimming training and the maturity changes over the intervention period were the sole reason for the minor improvements obtained after the intervention period. Although previous studies have examined the effects of WBV on athletic performance in other sports such as basketball, track and field sprinting, long distance running or rugby [171,173–176], the present research is the first to examine the chronic effects of WBV on swimming performance. A quantitative analysis of the effects of WBV of these five studies [58] reported small and varying effects on athletic performance (ES range= -035 to 0.93), with only two out of the five showing a significant group by time interaction [171,175]. These results are supported by additional reviews that consider the current WBV paradigm unlikely to produce any additional benefits to the performance of trained competitive athletes [57,177]. A further difficulty in the interpretation of these results lies on the wide variety in the WBV protocol designs (i.e., frequencies, amplitudes and accelerations), which complicates the identification of the optimal dose that would elicit sufficient levels of muscle activation from WBV. In relation to this, a recent study [178] pointed out that the magnitude of the response to the vibration stimulus (as measured through electromyography) to generate acute increases in muscle strength is individualized. These authors concluded that the individualized vibratory stimulus of each athlete should be determined in advance to maximize the benefits from this training method. A final point to consider is the use of the handle bars in the vibration platform during the WBV training. Previous research used hands-free exercises during the vibration routine to prevent from any potential reduction in the vibratory load [179], however, we allowed swimmers to gently handle the bars with their hands just to ensure a sufficient balance to avoid any risk of fall.

PRACTICAL APPLICATIONS

Considering the current state of knowledge and the findings of the present study, we do not recommend coaches and trainers to use this method to improve LBS, LBP or swimming performance given the unclear and inconsistent effects of WBV training. Nevertheless, there are some drawbacks that could affect the results of this study and the reader and further studies should consider. The main limitation of this study is attributed to the small sample size finally included. The reason for this remarkable drop out was mainly because swimmers failed to meet some relevant inclusion criteria, especially in relation to the wide range of swimming experience, weekly training volumes and age. Future studies using wider samples should consider to divide it into subgroups according to different maturity status to examine possible differences in the response to the vibration stimulus. Another important limitation of this study is the lower initial values observed in the control group, which could have given this group a greater potential to improve. Thus, further research including more homogeneous and larger samples would be recommended to confirm these results. In our study, we used progressive loading throughout the 6-month WBV training period to elicit continuous adaptations, however, more frequent follow-up assessments (e.g., at weeks 6, 12 and 18) could have shown more thorough and reliable information about the response to WBV over time. An active control group to counterbalance the extra workload performed by the intervention group was not included and would have been appropriate to determine the true effects of WBV. However, even performing a higher workload, WBV did not elicit any extra improvement. We encourage future research to apply individualized frequencies and longer exposures per session to withdraw final conclusions on the effectiveness of this practice, focusing on the muscle adaptations and the transfer to the sports-specific action.

CONCLUSIONS

The results from this randomized controlled trial revealed that the WBV protocol selected for this study had no additional chronic effects on LBS, LBP and athletic performance, when compared to the control group, in trained adolescent swimmers. In our study, we used similar WBV intensities and volumes than previously reported with other sports, and we obtained comparable inconsistent results also with swimmers. Although the addition of WBV to the swimmer´s training routine seems unnecessary to increase strength or power, less trained individuals appear to benefit from this practice [158].

Chapter 4.5

Validity and reliability of an optoelectronic system to measure movement velocity resistance exercises

Muniz-Pardos B, Lozano-Berges G, Marín-Puyalto J, González-Agüero A, Vicente-Rodríguez G, Casajús JA, Garatachea N. Validity and reliability of an optoelectronic system to measure movement velocity during bench press and half squat in a Smith machine. **Proc Inst Mech Eng P J Sport Eng Technol**. *Submitted*.

ABSTRACT

The purpose of this study was to determine the validity and reliability of a camera-based optoelectronic system to measure movement velocity during bench press (BP) and half squat (HS) at different load intensities. Twenty-two active males (age: 28.2 ± 3.9 y; 1RM BP: 77.9 ± 19.0 kg; 1RM HS: 116.6 ± 22.5 kg) participated in this study. After an initial 1RM testing session, participants performed five repetitions for each load (40, 60 and 80% 1RM) and exercise (BP and HS) on a Smith machine in the second testing session. A third testing session was used for the test-retest reliability study. Time, displacement and mean propulsive velocity (MPV) were simultaneously determined by the reference method (T-Force system; T-F) and the Velowin system (VW). In BP, ordinary least products (OLP) regression analysis revealed low fixed biases for MPV at 40%, time at 60% and displacement at 80% 1RM (intercept= 0.065 $m \cdot s^{-1}$, -28.02 ms and 0.87 cm, respectively). In HS, low fixed biases were also detected for MPV at 40% and 80% 1RM (intercept= -0.040 and 0.023 $m \cdot s^{-1}$, respectively), for time at 40% and 60% 1RM (intercept= -53.05 and -101.85 ms, respectively), and displacement at 60% 1RM (intercept= -1.95 cm). Proportional bias was only observed for MPV at 80% BP. In HS, there was proportional bias for time and MPV at 40% 1RM, and also for time at 60% 1RM. The reliability test showed low and comparable fixed and proportional biases between systems across exercises and intensities. VW confirmed to be a valid and reliable system to measure movement velocity across a wide range of intensities (40-80%1RM) for two basic strength exercises through a robust statistical approach. VW would provide coaches and trainers with a suitable, affordable and easy-to-use equipment capable of measuring movement velocity in different exercises at different load intensities.

INTRODUCTION

The load-velocity relationship assessment has emerged as a method for objectively monitoring and prescribing resistance training velocity [180–183]. Previous studies suggest that movement velocity can be used to accurately predict the relative load of basic resistance exercise commonly included in strength training such as bench press (BP) or half squat (HS), among others [184–186]. Thus, the determination of the movement velocity would eliminate the need for a direct one-repetition maximum (1RM) testing, avoiding the intrinsic risks of a maximal strength test [185,187,188]. Accurate and reliable assessment of movement velocity is fundamental to sports testing, training and rehabilitation. Thus, kinematic systems are becoming increasingly popular as tools for measuring movement velocity during resistance exercise [189–191].

The linear position transducer is one of the mostly used systems for load-velocity testing [185,192]. This system is characterized by the use of a tethered cable (attached to an external load) designed to measure time and displacement (distinguishing both eccentric and concentric phases) and enabling the calculation of movement velocity, which is essential for strength testing and training [185].

There are currently several commercial linear position transducers (e.g., “T-Force (T-F)”, “Tendo Weightlifting Analyzer”, “MuscleLab”, “Smart Coach” or “Chronojump”, among others) helping coaches and researchers to measure movement velocity in resistance training [192–195]. Nevertheless, most of them use a cable-based system which might cause some drawbacks, such as the need to attach a cable to the main body part engaged in the exercise, or the great sensitivity of this cable-based system to be damaged by even small blows. Considering the high cost of the traditional linear transducers that has often been used as the reference method (e.g., the T-F system, with a cost of ~ $3500), its acquisition would also be an important inconvenient for many potential users. This has led to an increasing interest in the development of economical wireless measurement tools and wearables to assess kinematic variables to solve the aforementioned difficulties [28,196] and facilitating its acquisition beyond a few well-funded laboratories or elite sports clubs.

Velowin (VW) was developed as an optoelectronic equipment that measures displacement through an infrared reflector attached to a bar (or any part of the body) captured by an infrared camera (see **Figure 11**). This wireless system would allow the tested participant to perform a greater amount of exercises without bumping a cable that could spoil the measurements. Any exercise employing any range of motion over the frontal plane (potentially both vertical- and horizontal-based movements) could be performed as long as the infrared reflector is positioned in the appropriate plane view for the camera. Additionally, VW software computes displacement and time to calculate several kinematics variables.

VW was launched in 2017, and there are currently three validation studies stating that this device is valid and reliable to assess movement velocity during free-weight HS and countermovement jump (CMJ) [197–199]. However, from a profound examination of these studies we detect some limitations that make the present study necessary. It is crucial to consider that the VW device is a camera-based system only able to assess movement velocity two-dimensionally. This requires the assessed exercise to be strictly executed in the frontal plane, since any movement performed in the sagittal plane would be undetected, biasing the measurement. This limitation adds an important error to the measurement due to the inter-individual variability in the exercise technique, which would be avoided by restricting the movement pattern (i.e., by using a Smith Machine). In addition to this, the validation of VW using further resistance exercises (e.g., BP) would be needed to expand the practical application of this system. Finally, there is an important limitation in the statistical analyses used by two of the three existing studies validating VW [198,199]. While the 'gold standard' method to assess movement velocity is the 3-D capture motion system, and not T-F, Model I linear regression analysis (e.g., least squared regression) should not be used since this statistical method does not assume a potential error in the reference method (T-F in this case). Instead, Model II regression analysis [e.g., Ordinary Least Products (OLP) regression] should be used to allow for a more accurate determination of bias and therefore confirm the real validity of VW [63]. Hence, the main purpose of this study was to evaluate the validity and reliability of the VW system to assess time, displacement and mean propulsive velocity (MPV) in two strength training exercises, BP and HS, over a range of intensities (40, 60 and 80% 1RM) in a Smith machine. It was hypothesized that VW measurements would be valid and reliable, in comparison with T-F, irrespective of the load or the exercise performed.

METHODS

Experimental Approach to the problem

A validation and reliability study was designed to compare time, displacement and MPV as measured by T-F (used as the 'gold standard') and VW during BP and HS exercises executed at three different intensities (40, 60, 80% 1RM) on a Smith machine. Although it is not the gold standard method to assess movement velocity, T-F has been widely used to assess both kinematic and kinetic characteristics in resistance training [185] and has also been used as a reference method in several validation studies [28,200,29]. Different exercises and load intensities were selected to test the validity of VW at different velocities and ranges of displacement. Participants were required to attend the laboratory on three occasions separated by at least 48 h from each other. The first session was used to assess 1RM in both exercises for each participant. Validity test was performed with all 1232 repetitions collected during second and third testing sessions, as every repetition was measured simultaneously with T-F and VW. Finally, the third session was used for the reliability test by comparing the data obtained in sessions two and three.

Subjects

Twenty-two healthy and active males (mean age: 28.2 ± 3.9 y; height: 177.8 ± 7.5 cm; body mass: 74.7 ± 7.9 kg; strength training volume: 151.9 ± 96.7 min/week; 1RM BP: 77.9 ± 19.0 kg; 1RM HS: 116.6 ± 22.5 kg) voluntarily participated in this study. Participants met the following inclusion criteria: men from 20 to 35 years old with at least one year of experience in strength training, specially familiarized with BP and HS exercises. Participants with musculoskeletal injuries or any medical condition that could alter performance were excluded. Participants were not allowed to exercise within the last 48 h prior to data collection. Since meaningful changes in muscle function have been observed in females depending on the menstrual cycle phase (e.g. increase in muscle strength at mid-cycle, when compared with both follicular and luteal phases [201]), we decided to include only males in the present study.

Participants were informed about the protocol of the study, as well as potential risks and benefits. Prior to data collection, each participant completed and signed an informed consent form. This study was performed following the declaration of Helsinki 1964 (revision of Fortaleza 2013) and the protocol was approved by the Ethics Committee of Clinical Research from the Government of Aragon (CEICA, Spain) [C.I. PI17/0126].

Procedures

Each participant completed three testing sessions separated by at least 48 h. The first session was used for personal data compilation, body composition measurements and indirect 1RM test in BP and HS, according to Brzycki equation [202] [1RM = 100 * (Weight (kg) / 102.78 - 2.78 * Number of repetitions)]. Since this equation is valid for estimating 1RM when the number of repetitions is lower than 10, the weights used during all indirect 1RM tests were calculated to reach less than 10 repetitions. In addition, this equation has previously shown to be highly accurate with resistance-trained middle-aged men [203]. Tests were performed with the assistance of two researchers to guarantee the safety of the participants.

During the second testing session, each participant performed five repetitions at maximum velocity for each load (40, 60 and 80% 1RM; following this incremental order) and exercise (BP and HS; in a randomized order) in a Smith machine, with a rest period between sets of at least 3 min. The re-test was performed in the third testing session, replicating the protocol but swapping the exercise order.

Prior to each testing session, participants performed a warm-up that consisted of 5 min of low intensity cycling (Ergoline cycle ergometer, Ergoline GmbH, Bitz, Deutschland), 5 min of upper- and lower-body joints mobilizations and a set of 10 repetitions with the 50% of the load used in the first attempt, for both exercises. BP exercise began with both arms in full extension and the hands grasping the barbell at approximately 5 cm wider apart than shoulder width. During eccentric action, participants took down the barbell at moderate velocity until approximately 5 cm over the chest. Adjustable safety catchers were used to control this distance. From this position, concentric action was performed at maximal voluntary velocity. For HS exercise, eccentric action was performed at moderate velocity from the position with hips and knees in full extension to 90º of knee flexion. A goniometer was used to accurately measure this knee angle, and the displacement of the bar was recorded for each individual to detect potentially incomplete repetitions during all HS tests. From this point, concentric action was also performed at maximal voluntary velocity. A pause of approximately 1.5 s between the concentric and eccentric phases was performed in both BP and HS exercises. The distance covered during eccentric phase in HS was measured prior to the first testing session by T-F system. This distance was the same in the three testing sessions. During all repetitions, participants were encouraged to perform the propulsive phase of the movement as rapidly as possible.

Measurement equipment and data acquisition

A Smith machine (Impulse IT Smith Machine, Midlothian, Scotland) was used for performing all test conditions. Displacement, time and MPV were simultaneously measured with T-F system (T-Force Dynamic Measurement System®, Ergotech, Murcia, Spain) and VW (Velowin, DeporTEC, Murcia, Spain). T-F (sample frequency of 1000 Hz) consists of a linear velocity transducer extension cable; however, VW (sample frequency of 500 Hz) is an optoelectronic linear position transducer system that does not use cable. Both methods automatically calculate the above-mentioned variables and provide instantaneous velocity and displacement feedback. Following VW manufacturer guidelines, "two reflective circles in line" calibration was applied each day prior to start each testing session. This calibration is the most accurate and consists of placing two reflective circles separated by 500 mm beside the barbell at the same plane of the reflective used during testing. In each calibration, inclination angle was approximately 90º being the mean of mm per pixel 1.459 ± 0.032 mm/px. The camera was positioned perpendicularly with respect to the plane of the marker movement, and was set high enough to encompass the tallest participant performing the HS and also the lowest point of the barbell during BP. T-F system has been previously used as a reference method to validate other systems [29] and, in consequence, it was also used for this validity study with the same purpose. Additionally, this system has been widely used among researchers and trainers to assess kinetic and kinematic variables in strength exercises [192,204,205].

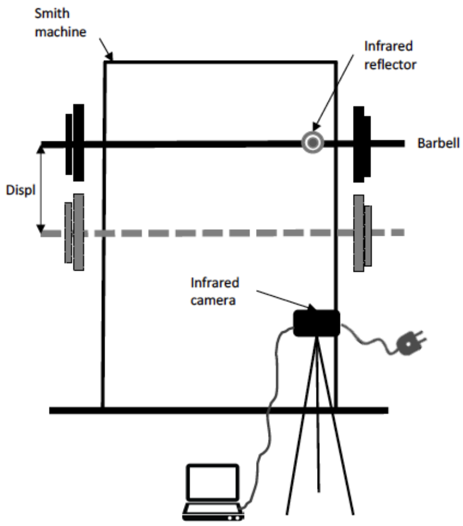


Figure 11. Scheme of the optoelectronic system

Data analysis

The Statistical Package for the Social Science (SPSS; version 24.0 for Mac OS X, SPSS Inc., Chicago, IL, USA) and the statistical software R (version 3.5.1) were used for all statistical analyses. We separated the data analysis by load intensity and exercise since analysis of variance (ANOVA) tests indicated a significant influence of exercise type, intensity and their interaction (η_p^2 = 0.473, 0.043 and 0.022, respectively; all $p<0.01$). Time, displacement and MPV for each load intensity and exercise were computed and statistically analyzed. Bland Altman plots were performed to reveal the agreement between VW and T-

F in BP and HS, since this is the approach typically used to test agreement between methods and helps comparing with previous validity studies [31]. However, because fixed and proportional bias cannot be determined through this analysis, OLP regression analysis was performed by computing the equations provided by Ludbrook in R [206]. Validity was determined following the presence and degree of bias between methods. The degree of fixed bias was deduced from the y-intercept 95% of the confidence intervals (CIs). If the CIs for the intercept include the value of zero, then there is no fixed bias. Proportional biases were assessed from the 95% CIs for the slope. If the CIs for the slope include the value of 1.0, then there is no proportional bias. OLP regression analysis provides with different errors, intercepts and slopes than least squares regression because error is assumed for both VW and T-F. In addition, test-retest reliability for MPV was also determined through OLP regression analysis following the same procedures described above.

RESULTS

Concurrent validity

From a total of 1320 repetitions registered, 88 were excluded due to inappropriate exercise technique or error in the measurement by either T-F or VW. As seen in **Figure 12**, the box plots graphically show that the distribution of the values obtained for all variables, intensities and exercises for both T-F and VW (**Table 14** shows the corresponding numerical values). **Table 14** summarizes the differences observed between both systems. When examining the agreement between devices in measuring MPV in BP and HS, we observed a small mean difference, as depicted in **Figure 13**.

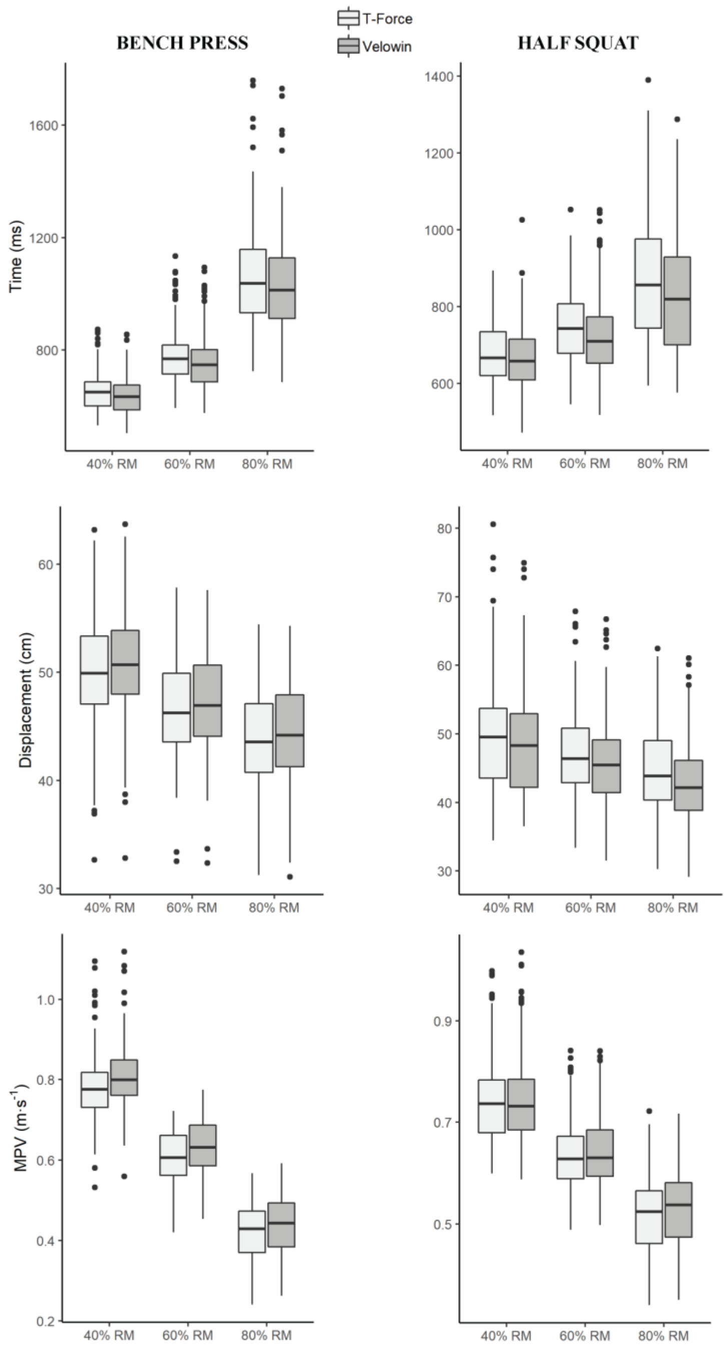


Figure 12. Time, displacement, and MPV obtained in bench press and half squat exercises by T-F and VW systems. The boxes represent the median values with the 25th percentile and 75th percentiles.

Table 14. Concurrent validity of T-Force vs. Velowin. Values of Time (ms), Displ (cm) and MPV ($m \cdot s^{-1}$).

	Mean ± SD		Fixed bias			Proportional bias		
	T-F	VW	Intercept	95% CI	QA[a]	Slope	95% CI	QA[b]
BP 40%								
Time	653.1±65.6	636.5±63.1	8.324	-18.89 to 35.54	No	0.962	0.92 to 1.00	No
Displ	50.12±5.18	50.82±5.11	1.396	-0.06 to 2.85	No	0.986	0.96 to 1.02	No
MPV	0.776±0.08	0.806±0.08	0.065	0.03 to 0.10	Yes	0.954	0.91 to 1.00	No
BP 60%								
Time	780.0±95.2	759.2±96.1	-28.018	-49.68 to -6.36	Yes	1.009	0.98 to 1.04	No
Displ	46.78±4.5	47.29±4.6	-0.497	-1.78 to 0.78	No	1.022	0.99 to 1.05	No
MPV	0.605±0.07	0.629±0.07	0.010	-0.01 to 0.03	No	1.023	0.99 to 1.05	No
BP 80%								
Time	1060.7±175.2	1034.7±173.7	-16.965	-33.96 to 0.03	No	0.991	0.98 to 1.01	No
Displ	43.72±4.6	44.40±4.6	0.873	0.11 to 1.64	Yes	0.996	0.98 to 1.01	No
MPV	0.422±0.07	0.439±0.07	0.005	0.00 to 0.01	No	1.028	1.01 to 1.05	Yes
HS 40%								
Time	679.0±76.5	662.2±80.6	-53.049	-86.06 to -20.04	Yes	1.053	1.01 to 1.10	Yes
Displ	49.90±7.76	48.53±7.59	-0.276	-1.40 to 0.84	No	0.978	0.96 to 1.00	No
MPV	0.737±0.08	0.743±0.09	-0.040	-0.07 to -0.01	Yes	1.062	1.02 to 1.10	Yes
HS 60%								
Time	748.8±91.0	724.5±100.4	-101.854	-144.27 to -59.43	Yes	1.103	1.05 to 1.16	Yes
Displ	47.19±6.4	45.59±6.4	-1.950	-3.63 to -0.27	Yes	1.007	0.97 to 1.04	No
MPV	0.634±0.07	0.642±0.07	-0.013	-0.04 to 0.01	No	1.032	0.99 to 1.07	No
HS 80%								
Time	873.3±159.8	831.1±155.7	-19.664	-49.14 to 9.81	No	0.974	0.94 to 1.01	No
Displ	44.58±6.2	43.15±6.2	-1.126	-2.28 to 0.03	No	0.993	0.97 to 1.02	No
MPV	0.520±0.08	0.533±0.08	0.023	0.01 to 0.04	Yes	0.981	0.95 to 1.01	No

QA[a] = Qualitative assessment for the presence of fixed bias.
QA[b] = Qualitative assessment for the presence of proportional bias.

BP=bench press; 95% CI=95% confidence interval; HS= half squat; T-F=T-Force; VW=Velowin; Displ=displacement; MPV=mean propulsive velocity.

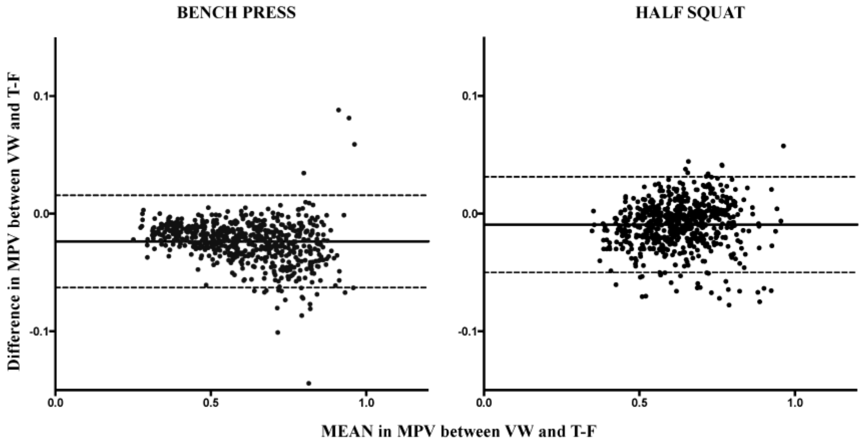


Figura 13. Comparison of MPV between T-F and VW in bench press and half squat. The center line determines the mean difference between systems, whereas the broken lines represent the 95% limits of agreement.

In BP, fixed biases were detected for MPV at 40%, time at 60% and displacement at 80% 1RM (intercept= 0.065 $m \cdot s^{-1}$, -28.02 ms and 0.87 cm, respectively). In HS, fixed bias were also observed for MPV at 40% and 80% 1RM (intercept= -0.040 and 0.023 $m \cdot s^{-1}$, respectively), for time at 40% and 60% 1RM (intercept= -53.05 and -101.85 ms, respectively) and, finally, for displacement at 60% 1RM (intercept= -1.95 cm). Proportional biases were identified for MPV at 80% 1RM in BP (slope= 1.03). In HS, we observed proportional biases for time at 40% and 60% 1RM (slope= 1.05 and 1.10, respectively), and also for MPV at 40% 1RM (slope= 1.06). **Figure 14** shows the OLP regression plots for MPV during both exercises at the different intensities.

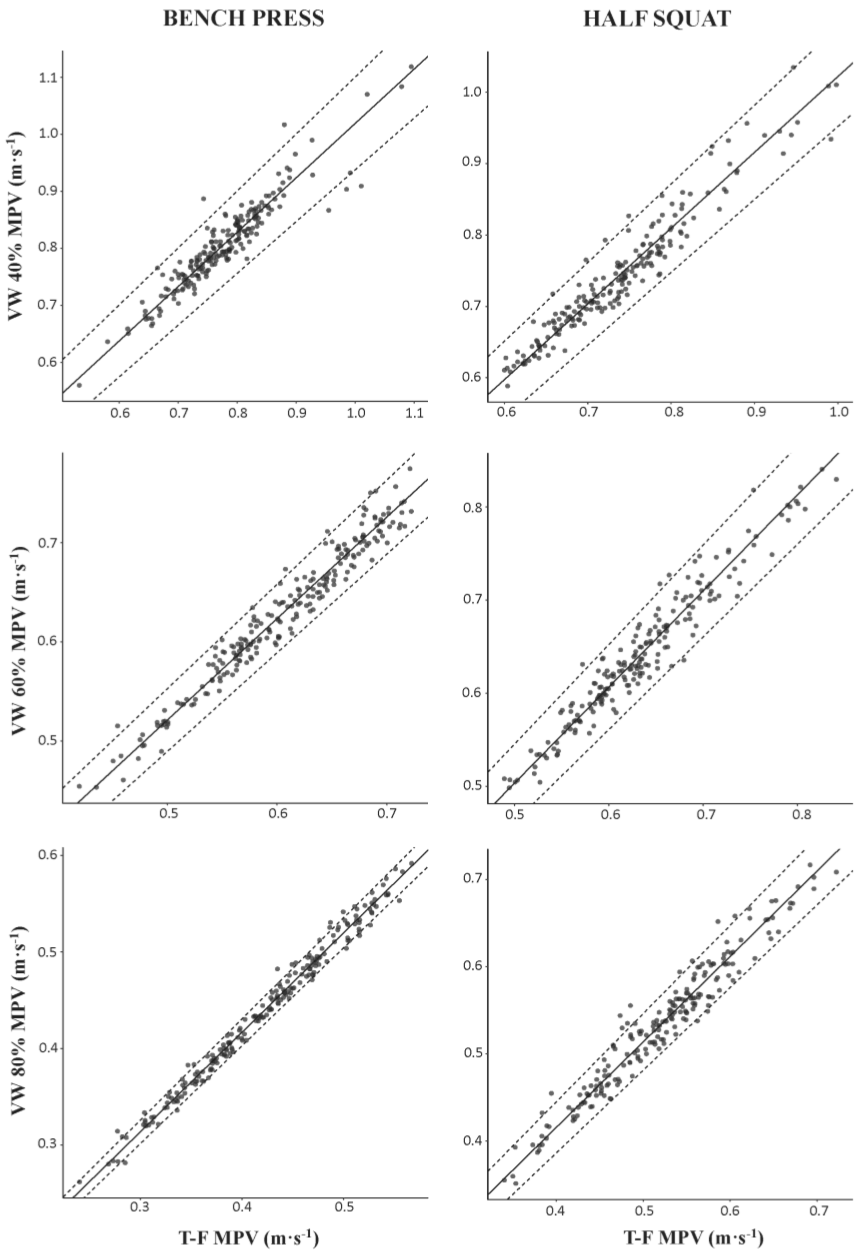


Figure 14. Ordinary Least Products regression plots of the relation between the MPV determined by T-F and VW at different intensities and exercises. Regression and CIs lines are reported.

Test-retest reliability

The test-retest reliability results for MPV in both exercises and across all intensities are provided in **Table 15**. In BP, we observed fixed biases for MPV at 60% and 80% 1RM as measured with T-F (intercept= 0.082 and 0.081 $m \cdot s^{-1}$, respectively), whereas VW only showed fixed bias for MPV at 80% 1RM (intercept= 0.058). In HS, only VW presented fixed bias for MPV at 80% 1RM (intercept= -0.092). In relation to the assessment of heteroscedasticity in the reliability test (**Table 15**), T-F presented proportional biases for MPV at 60% and 80% 1RM in BP (slope= 0.86 and 0.81, respectively), whereas VW presented heteroscedasticity for MPV at 80% 1RM during BP and 80% 1RM during HS (slope= 0.87 and 1.21, respectively).

Table 15. Test-retest reliability of MPV ($m \cdot s^{-1}$) measured by Velowin and T-Force.

	Mean ± SD		Fixed bias			Proportional bias		
	Day 2	Day 3	Intercept	95% CI	QA[a]	Slope	95% CI	QA[b]
BP 40%								
T-F	0.781±0.09	0.772±0.07	0.101	-0.01 to 0.21	No	0.858	0.72 to 1.00	No
VW	0.813±0.08	0.799±0.07	0.063	-0.06 to 0.19	No	0.904	0.75 to 1.06	No
BP 60%								
T-F	0.607±0.07	0.603±0.06	0.082	0.02 to 0.14	Yes	0.859	0.76 to 0.95	Yes
VW	0.629±0.07	0.628±0.07	0.015	-0.06 to 0.09	No	0.976	0.86 to 1.09	No
BP 80%								
T-F	0.421±0.08	0.422±0.06	0.081	0.04 to 0.12	Yes	0.812	0.72 to 0.91	Yes
VW	0.439±0.08	0.439±0.07	0.058	0.02 to 0.10	Yes	0.867	0.77 to 0.96	Yes
HS 40%								
T-F	0.731±0.08	0.744±0.08	-0.011	-0.12 to 0.10	No	1.033	0.88 to 1.18	No
VW	0.733±0.08	0.753±0.09	-0.048	-0.17 to 0.08	No	1.091	0.92 to 1.26	No
HS 60%								
T-F	0.629±0.07	0.639±0.07	0.004	-0.09 to 0.10	No	1.008	0.86 to 1.15	No
VW	0.634±0.07	0.650±0.08	-0.065	-0.17 to 0.04	No	1.128	0.96 to 1.29	No
HS 80%								
T-F	0.514±0.07	0.525±0.08	-0.031	-0.09 to 0.03	No	1.082	0.96 to 1.20	No
VW	0.525±0.07	0.541±0.08	-0.092	-0.17 to -0.02	Yes	1.206	1.07 to 1.35	Yes

QA[a] = Qualitative assessment for the presence of fixed bias.
QA[b] = Qualitative assessment for the presence of proportional bias.

BP=bench press; 95% CI=95% confidence interval; HS= half squat; T-F=T-Force; VW=Velowin; MPV=mean propulsive velocity.

Discussion

The main findings of the present study confirmed that VW is a valid and reliable device to measure movement velocity during HS in a Smith machine across different intensities, and also revealed that VW is also valid and reliable to be used during BP. To the best of our knowledge, this is the first study testing VW using OLP regression analysis over a range of intensities. Most of the previous validity studies not using the true gold standard method employed a combination of both Bland-Altman and least squared linear regression analysis to determine bias and agreement between systems [28,29,207]. However, the use of these methods to determine the magnitude of bias, as determined by the slope of the linear correlation, assign all bias to the dependent variable (VW in this case) [63]. When not using the true gold standard for the comparison, the selection of OLP regression analysis seems more appropriate since it also assumes potential error in the reference method, allowing for a more accurate determination of fixed and proportional bias [63,206,208].

Recent studies examined the validity and reliability of VW during free-weight HS over a range of intensities [197,198]. Similar to our study, García-Ramos et al. [198] used the T-F system as the reference method finding a low fixed bias in MPV between devices during HS (fixed bias= 0.02 by García-Ramos vs. fixed bias range= -0.04 to 0.02 in our study). García-Ramos et al. [198] found a significant proportional bias in the assessment of MPV during HS, observing an underestimation of MPV with increasing MPV, as assessed by VW. In our study, we also found proportional bias in the assessment of MPV during HS, but only at 80% 1RM and in the opposite direction (i.e., VW overestimated MPV with increasing MPV). Notably, García-Ramos et al. [198] determined bias through the Bland-Altman method, which could potentially distort the results of this validity test.

It is worth noting the presence of fixed bias in the displacement during 80% 1RM BP. Since the camera was positioned at the same distance and height for both exercises to encompass the vertical movement developed during each exercise, a slight parallax error might have influenced the measurement in this case. Notably, the presence of proportional bias for MPV was only at 80% 1RM BP and 40% 1RM HS. This might be because participants performing the 80% 1RM BP were sometimes unable to full extend the arms during all repetitions, whereas during the 40% 1RM HS participants easily completed the whole movement, even performing a small countermovement at the end of the concentric phase. It is possible that the two different filters interpreting kinematics might have affected the precise moment of starting and finishing the concentric phase, thus increasing heteroscedasticity between systems in these cases. However, it should be considered that assessments conducted in sports science are commonly characterized by the presence of heteroscedasticity [209].

In addition to this study, Laza-Cagigas et al. [197] recently performed a comprehensive validity study of VW using the gold standard method to assess both movement velocity and force production (3D motion capture system and force platform, respectively) during free-weight HS. Although these authors did not examine MPV, they did not find neither fixed nor proportional bias in mean velocity (intercept= -0.04 and slope=1.01). These authors also reported the presence of fixed bias in the measurement of displacement, but remarkably higher than our study (fixed bias= -10.24 cm by Laza-Cagigas vs. a fixed bias at 60% 1RM HS of -1.95 cm in our study). Although Laza-Cagigas et al. [197] appropriately used the gold standard method to test the validity of VW, not preventing the movement from horizontal oscillations (i.e., using free-weights) when comparing a 3D device and a 2D device (i.e., VW), could alter the accuracy in the evaluation of vertical velocity as measured by VW. This additional bias could potentially explain the greater error in the measurement of displacement observed in their study.

Peña García-Orea et al. [199] also performed a validity study of VW during a loaded CMJ in a Smith Machine over a range of intensities. These authors revealed that VW was a valid and reliable tool to measure CMJ velocity, when compared to T-F. However, these authors reported the absolute values for mean and peak velocity from each device and the concordance correlation coefficient instead of reporting fixed or proportional bias between devices [210]. This makes the comparison with our results challenging.

While we also explored the degree of bias across load intensities between VW and T-F, some of the aforementioned studies did not report the specific error across different loads [197,199]. The study by García-Ramos et al. [198] found no main effects of variable x load interaction across different intensities during free-weight HS. Thus, the comprehensive examination of the bias at different load intensities and exercises reinforce preceding studies and expand the utility of VW since most athletes develop their strength training varying load intensities depending on the periodization plan [30].

Previous research examined the validity of similar instruments of which main function is also the measurement of movement velocity. The PUSH band [28] found larger systematic bias in the assessment of mean velocity during HS (0.11 $m{\cdot}s^{-1}$ by PUSH vs. a range of -0.04 to 0.02 $m{\cdot}s^{-1}$ by VW in our study). Similarly, a previous research [211] carried out a similar investigation studying the validity of a video analysis software (Kinovea) for quantifying movement velocity during the BP exercise at different intensities, also reporting larger systematic bias for MPV than our study (range: -0.43 $m{\cdot}s^{-1}$ to -0.16 $m{\cdot}s^{-1}$ for Kinovea vs. 0.01 $m{\cdot}s^{-1}$ to 0.07 $m{\cdot}s^{-1}$ for VW).

Regarding the test-retest reliability study, both fixed and proportional biases seemed to follow the same pattern (i.e., variables with meaningful fixed biases were accompanied by proportional biases). Although these biases were small, the necessity to perform a manual calibration procedure could also be a source of error in the measurement, potentially decreasing the accuracy from one day or exercise to another. We agree with

Peña García-Orea et al. [199] in that a simpler calibration process would facilitate the usability of VW and could also increase the accuracy between testing sessions.

Our results confirm through a robust statistical analysis that an affordable and comfortable system (VW) can be utilized to measure movement velocity during the BP and HS exercises at different intensities in a Smith Machine. As far as the limitations of a 2D camera-based instrument are concerned, the accuracy of the measurements depends on whether the movement is performed on the frontal plane. Consequently, if the exercises were performed away from the vertical vector, the measurements might be distorted [211]. In the current study, all measurements were performed on a Smith machine to avoid these risks. Sports practitioners and specialists should consider this source of error and, as previously reported, the experience of the lifters could be determinant when the use of the Smith machine is not possible [211]. Another important limitation of this system is that it requires a nearby camera and laptop, which would take up floor space and might difficult simultaneous training practices. This should be considered by the coach or sports specialist to adequately organize the testing procedures in advance.

Importantly, certain limitations should be considered when interpreting the results of the present study. In particular, a wider variety of exercises and intensities are needed to provide further validation of the VW system. For example, the VW system has shown to be valid and reliable over vertical-based movements (squat, countermovement jump and BP), although its efficacy on horizontal-based movements (e.g., ball throwing, running or ball kicking) is still unknown. Finally, as only males were recruited for this study, the results cannot be directly applied to female athletes. This study reinforces the validity and reliability of VW and expands its use to a wider range of intensities (from 40% to 80% 1RM) and exercises (BP and HS) in a Smith Machine.

CONCLUSION

The VW system has proven to be a valid and reliable tool in comparison with the reference method when measuring time, displacement and MPV across different exercises and load intensities. Besides, it seems operational, easy-to-use and comfortable since it does not require a cable to perform strength exercises, as long as they are performed in the vertical plane. Notably, the use of VW could help coaches and trainers in the assessment of the load-velocity relationship, facilitating the testing process in field situations thanks to the easily portable camera. Nevertheless, the coach should also consider that the inherent limitation in a 2D instrument might difficult the accuracy of exercises performed out of the vertical plane. The economical cost of VW in comparison with the reference method (T-F) would allow a wider range of coaches or sports clubs to afford this equipment.

Capítulo 5

Conclusiones y Aportaciones principales

Conclusiones Generales [In Spanish]

I. El trabajo de fuerza de las extremidades superiores parece crucial para la mejora de las fuerzas propulsivas durante el nado. Sin embargo, el entrenamiento de potencia de las extremidades inferiores produce un mayor efecto sobre el rendimiento durante la salida. El tipo de entrenamiento más adecuado para la mejora de la fuerza y potencia de las extremidades inferiores y sobre el rendimiento en competición no está claro.

II. La potencia de las extremidades inferiores tienen una gran importancia en el rendimiento de nadadores chicos adolescentes, con los saltos verticales mostrando mayores valores predictivos del rendimiento.

III. El entrenamiento vibratorio en las dosis suministradas durante 6 meses no parece producir ningún efecto beneficioso para la mejora de la fuerza, potencia o rendimiento deportivo en nadadores adolescentes.

IV. El sistema optoelectrónico parece ser un método válido, fiable y accesible para medir la velocidad de desplazamiento de la barra durante ejercicios de fuerza.

General Conclusions [In English]

I. Upper-body strength training seems crucial to improve the propulsive forces during swimming. However, the development of the lower-body strength and power capabilities produces greater effects on the start performance. The most appropriate type of training to improve strength, power and swimming performance remains unclear.

II. Lower-body power capability shows a great influence in swimming performance, especially in male adolescent swimmers. Vertical jumps seem the most appropriate tests to explain swimming performance.

III. Whole-body vibration training with the designed protocol had no effects on strength, power and swimming performance in adolescent swimmers.

IV. An optoelectronic system is a valid, reliable and affordable method to measure movement velocity during resistance exercises.

Aportaciones principales de la Tesis Doctoral [in Spanish]

- Con las revisiones sistemáticas (capítulos 4.1 y 4.2), se describieron las prácticas de entrenamiento no específicas y específicas de la natación existentes para mejorar la fuerza, potencia y rendimiento en nadadores, apoyadas con estudios transversales revelando asociaciones entre fuerza, potencia y rendimiento. Aunque se deducen diversas conclusiones de estos trabajos, se destaca la gran relación que guarda la potencia de las extremidades inferiores con el rendimiento durante la fase de la salida. Sin embargo, estas revisiones ponen de manifiesto la necesidad de optimizar el entrenamiento de la fuerza y potencia de las extremidades inferiores, dada la escasa evidencia científica con datos longitudinales.

- Con el estudio transversal (capítulo 4.3) se determinó que la potencia de las extremidades inferiores se asocia positivamente al rendimiento en competición en nadadores chicos adolescentes. Además, este estudio sugiere que el salto vertical utilizando la acción de brazos (i.e., salto Abalakov) es el que mejor explica el rendimiento en distancias cortas.

- Mediante el artículo longitudinal (capítulo 4.4), se concluyó que 6 meses de entrenamiento vibratorio de cuerpo entero, en las dosis descritas, no produce efectos significativos en la fuerza, potencia y rendimiento de nadadores adolescentes.

- El artículo de validación (capítulo 4.5) demuestra que un aparato optoelectrónico es válido y fiable y accesible para medir la velocidad de desplazamiento durante ejercicios de fuerza. Una fortaleza de este estudio reside en la utilización de una metodología estadística robusta que permite un test de validación más rigurosa que la utilizada tradicionalmente. Contar con equipos de probada precisión y fiabilidad puede ayudar en la investigación sobre el tipo de entrenamiento más apropiado para la mejora de la fuerza y la potencia de las extremidades inferiores; además, podría ser de gran utilidad para entrenadores por su sencillez de manejo, precisión, y por su precio más asequible.

Main contributions of the Thesis [in English]

- With the systematic reviews (Chapter 4.1 and 4.2), we described the non-specific and swim-specific resistance practices to improve strength, power and swimming performance in adolescent swimmers, including cross-sectional studies to reinforce the longitudinal findings. Although there are diverse practical applications deduced from these systematic reviews, they highlight the strong associations between the lower-body power and the start phase performance. However, there is an urgent need to optimize the strength and power training of the lower extremities given the limited research including longitudinal data.

- From the cross-sectional study (Chapter 4.3), it was determined that those male swimmers able to develop greater levels of lower-body power during dry-land tests were those showing greater swimming performance. In addition, this study suggested that vertical jump test using arm movement (i.e., Abalakov jump) was more accurate in predicting swimming performance in short distance events.

- The longitudinal study (Chapter 4.4) concluded that a 6-month whole-body vibration training, following the volume and intensities described above, does not elicit any significant effects on strength, power and swimming performance in adolescent swimmers.

- The validity study (Chapter 4.5) shows that an optoelectronic device is valid and reliable in measuring the movement velocity during different resistance exercises. A key point of this study is the use of a robust statistical method providing with a rigorous validity test. It is of great value to provide coaches and researches with high quality validity studies to allow them examine the most appropriate training practices to improve lower-body strength and power.

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Sobre el doctorando

Borja Muñiz Pardos, nacido en Zaragoza el 24 de septiembre de 1988, realizó la Licenciatura en Ciencias de la Actividad Física y el Deporte en la Universidad Europea de Madrid en el año 2010, culminando con la doble titulación por la Universidad de Staffordshire (Inglaterra, Reino Unido) al realizar el último año (curso 2009-2010) en ésta universidad británica. Posteriormente, comenzó a trabajar como preparador físico y entrenador de atletismo en 2 clubes aragoneses mientras completaba el Master de Profesorado en Educación Física en Huesca (Universidad de Zaragoza). Tras finalizar este máster, el doctorando realizó varias sustituciones como profesor de educación física en varios colegios concertados, hasta que finalmente se decidió a comenzar la Tesis Doctoral en octubre del 2014, bajo la supervisión de Germán Vicente Rodríguez y José Antonio Casajús en el grupo de investigación GENUD (Universidad de Zaragoza). Desde entonces hasta principios del año 2018, el doctorado ha participando en diversos proyectos nacionales con poblaciones especiales y con fines relacionados con la mejora de la salud (proyecto PREFIT, proyecto ELDER 3.0 o proyecto CALINA), al mismo tiempo que compaginaba ésta labor científica con el entrenamiento de atletas y triatletas, y coordinando la sección de atletismo de un colegio. Además, el doctorando finalizó en el año 2018 el Máster de Alto Rendimiento Deportivo (COE-UCAM). En febrero del año 2018, el doctorando se embarcó en una expedición a Kenia de 1 mes bajo la supervisión del profesor Yannis Pitsiladis con el objetivo de probar la eficacia de diferentes aplicaciones tecnológicas enmarcadas en el proyecto internacional *Sub2hrs maratón Project*. Desde entonces, Borja Muñiz Pardos ha estado trabajando para este proyecto, colaborando en diferentes estudios en la Universidad de Zaragoza y en la Universidad de Stirling (Escocia), habiendo realizado una estancia de 7 meses en esta universidad.

About the PhD student

Borja Muñiz Pardos was born on September 24th, 1988 in Zaragoza (Spain). He completed his Bachelor's degree in Sports and Exercise Sciences at the Universidad Europea de Madrid (Madrid, Spain) in 2010, obtaining the double degree from the University of Staffordshire (England, UK) after completing the final year in this university (2009-2010). Soon after, Borja Muñiz Pardos started working in 2 different track and field clubs as the main coach and strength and conditioning specialist while studying the Physical Education Master's in Huesca (University of Zaragoza). After completing this Master's, Borja worked as PE teacher (replacement) on several occasions, until he finally decided to start a PhD in October 2014 in the GENUD research group (University of Zaragoza, Spain), under the supervision of Dr. Germán Vicente Rodríguez and Prof. José A. Casajús. Since then, Borja has been involved in several national research projects focusing on the study of health determinants in special populations (PREFIT project, ELDER 3.0 project or CALINA project). Concurrently, Borja combined his scientific work with the training of regional and national athletes and triathletes, and also managing the track and field division of an education school. In 2018, Borja completed a Master's in High Performance Sport in the Spanish Olympic Committee, which has also been a valuable complement to his career. In February 2018 Borja signed onto an expedition to Kenya for 1 month under the supervision of Prof. Yannis Pitsiladis. The main aim of this expedition was to test the effectiveness of different technological applications to improve athletic performance in runners. These experiments are within the framework of the Sub2hrs marathon project, and Borja has been working for this project since then, collaborating in different studies in the University of Zaragoza and also in the University of Stirling, where he has spent 7 months during a research stay.

Publications of the PhD student

1. Sutehall, S, **Muniz-Pardos, B**, Bosch, A, Gianfrancesco, A, Pitsiladis, YP. Sports drinks on the edge of a new era. *Curr Sports Med Rep*. 17(4), pp. 112 – 116.

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Apéndice ***[Appendix]***

A continuación, se muestra el factor de impacto y ranking de cada revista en "*ISI Web of Knowledge – Journal Citation Reports*" dentro de sus áreas correspondientes.

[*Impact factor and ranking of each journal in "ISI Web of Knowledge – Journal Citation Reports" within their subject categories.*]

Artículos aceptados o sometidos [A*ccepted or submitted manuscripts*]:

Artículo/Article [*Chapter within the thesis doc*]	***Revista/Journal***	***Factor de impacto/ Impact Factor***
I [*4.1*]	**Journal of Strength and Conditioning Research**[a] *Ranking in 2017 ISI – JCR: 29/81 (Sport Sciences) – Q2*	**2.325**
II [*4.2*]	**Journal of Strength and Conditioning Research**[a] *Ranking in 2017 ISI – JCR: 29/81 (Sport Sciences) – Q2*	**2.325**
III [*4.3*]	**Journal of Strength and Conditioning Research** *Ranking in 2017 ISI – JCR: 29/81 (Sport Sciences) – Q2*	**2.325**
IV [*4.4*]	**International Journal of Sports Physiology and Performance** *Ranking in 2017 ISI – JCR: 10/81 (Sport Sciences) – Q1*	**3.384**
V [*4.5*]	**Proceedings of the Institution of Mechanical Engineers. Part P, Journal of sports engineering and technology.** *Ranking in 2017 ISI – JCR: 93/128 (Mechanical Engineering) – Q3*	**1.070**

[a]: Anexo IV. Carta de aceptación [Acceptance letter].

Agradecimientos **[Acknowledgements]**

Como suele decirse, lo mejor debe dejarse para el final. Durante el último año he leído varias noticias que hablaban de las consecuencias de realizar una tesis doctoral en la salud mental del estudiante, señalando uno de los artículos que "*los estudiantes de doctorado son seis veces más propensos a desarrollar ansiedad o depresión en comparación con la población normal, encontrándose el 39% de ellos en estado de depresión*". Este artículo apuntaba que los sentimientos de infelicidad en los doctorandos se debían a sentirse bajo presión constante, a la pérdida de autoconfianza o a sentimientos de incompetencia. Sin embargo, estoy convencido de que la gestión de estos sentimientos depende en gran medida de las personas de las que te rodeas, y en este sentido me siento inmensamente afortunado. Al finalizar un trabajo de esta magnitud te vienen a la cabeza muchas personas que, de una forma u otra, han contribuido al proceso y culminación de este trabajo. Lamentablemente, muchas veces nos olvidamos de agradecer debidamente este apoyo, por lo que voy a intentar reflejar en este apartado la gratitud que siento por aquellas personas sin las que hubiera sido imposible culminar este proceso.

Mamá, qué no agradecerte a ti. Gran parte del motivo por el que no pertenezco al 39% de doctorandos deprimidos se debe a tu apoyo ☺. Tenerte al llegar a casa a diario, siempre dispuesta a escuchar mis desahogos y a compartir mis alegrías, ha supuesto un pilar fundamental en mi capacidad para esforzarme cada día y persistir a pesar de las dificultades. Por no hablar de tus maravillosos tuppers, envidiados por todo el grupo GENUD. Gracias por forjar la persona que soy, porque sin ti y sin tu resiliencia durante los últimos 15 años no hubiera podido ser el "Borja" que soy hoy. **Papá**, sin ánimo de ponerme demasiado sentimental y complicarle el trabajo al lector, es a tí a quien dedico y he dedicado todo mi trabajo y esfuerzo a lo largo de mi vida, siendo mi fuerza, referencia y motivación

para todo. Te fuiste pronto y te he tenido presente cada día, sientiendo que sigues ahí apoyándome y dándome la fuerza necesaria para relativizar problemas, no quejarme, ser optimista y seguir hacia delante con una sonrisa; gracias, te quiero. **Andrea** ("Barri" o "Billi", en su defecto), las circunstancias que hemos vivido nos han convertido en, probablemente, los hermanos más unidos que conozco. Aunque el camino pre-doctoral no nos haya permitido hacer demasiados planes juntos (nos salvan nuestros encuentros nocturnos viendo capítulos de *Friends* sin parar), has sido sin duda una de las personas que más me ha ayudado a ser mejor cada día. Muchas gracias por estar siempre dispuesta a escucharme y a preocuparte tanto por mis asuntos "frikis", que muchas veces son complicados de entender o un poco aburridos. Gracias.

A mis **tíos Muñiz**, gracias por recoger el testigo de mi padre y ser las personas más generosas que jamás he conocido. Gracias por vuestra preocupación y por permitirnos a mi hermana y a mí hacer lo que hubiéramos querido, sin poner barreras a nada. **Tío Quique**, tu has sido muchas veces el portavoz de un grupo de hermanos preocupados por sus sobrinos adolescentes despistados y, durante unos pocos años, algo "desviados". Siempre voy a recordar unos años de bachillerato complicados, pero que únicamente necesitaron de un verano de trabajo a tiempo completo en el Colegio Mayor Miraflores y un comprometido **Enrique Urbina** para quitarme todas las tonterías; gracias. **Tío Jai**, jamás olvidaré lo que has hecho por nosotros y vuestro hermano. Hay pocas cosas que me emocionen de verdad, y una es veros orgullosos de mi. Sois increíbles y os quiero.

A mi **familia Pardos** (o "parderas"), que siempre me han apoyado en mis decisiones, aunque resultara difícil comprender que con 30 años no quisiera tener un trabajo normal, sino dedicarme a "eso de investigar" ;-). En especial, agradecimientos especiales a mi **tio César**. La vida no es fácil para nadie, ni lo ha sido para ti. Siempre me has mostrado tu cariño y apoyo, y siempre recordaré esa tarde en el Alcampo Utrillas cuando me regalaste mi primer ordenador portátil para que me lo pudiera llevar a Inglaterra a terminar la carrera. Entonces, yo era un chaval de 20 años y no valoré ni agradecí suficientemente el esfuerzo que supuso para ti, ni la enorme bondad para tener este detalle sin ningún otro motivo más que querer lo mejor para mi. Gracias por ser la excelente persona que eres.

Hay familia que no tiene tu misma sangre, y tengo dos hermanos que han hecho que estos casi 5 años de tesis hayan sido mucho más llevaderos de lo que hubieran sido sin ellos: **Diego** y **Sergio**. El periodo pre-doctoral no tiene horarios, apenas días de vacaciones sin estar dándole vueltas a algún “paper”, congreso, o proyecto, y por ello considero vital organizarse y sacar pequeños momentos para irse a correr, tomar un café o dar una vuelta para despejarse. Muchas gracias a los dos por adaptar vuestros horarios/planes a mis necesidades, por estar ahí siempre que lo he necesitado, por las risas y lo bien que lo pasamos y pasaremos. Sois imprescindibles. Y hablando de familia de distinta sangre, imposible olvidarme de la 2ª mejor mamá del mundo, aunque la mejor suegra del planeta, eso sí ;-). Gracias **Blanca** por tu cariño y por las risas que igualmente hacen este camino menos arduo.

En verano del año 2014, me “picó” la curiosidad y comencé a buscar grupos de investigación relacionados con las ciencias del ejercicio en Zaragoza. Yo no conocía a nadie en la Universidad de Zaragoza ya que estudié la licenciatura en Madrid, por lo que andaba bastante perdido. Navegando por internet, localicé un grupo de investigación puntero en la universidad, y un contacto al que poder referirme para que me explicara en qué consistía esto de “hacer la tesis”: *gervicen@unizar.es*. **Germán**, una primera reunión contigo en septiembre del 2014 me convenció y motivó a embarcarme en esta temerosa aventura, y por ello agradezco profundamente tu confianza y apoyo. A pesar de las exigencias de un decanato, siempre has hecho todo lo posible por ayudarme y apoyarme, dándome la oportunidad de realizar mi Tesis Doctoral a partir de los datos del proyecto RENACIMIENTO. Gracias por tu cercanía y apoyo Ger.

José Antonio Casajús o, con un poco de confianza, JAC. Aunque no haya estado vinculado directamente a uno de tus proyectos, siempre has contado conmigo cuando se ha podido y has sido una figura especial en este camino. Primero, me tuviste en cuenta cuando hubo financiación del CIBER para contratar un investigador, lo que me proporcionó sustento económico para poder continuar investigando durante casi un año. En enero del 2018 me pusiste en contacto con el Prof. Yannis Pitsiladis, lo que me permitió vivir experiencias muy enriquecedoras y, posteriormente, disponer de financiación para centrarme en desarrollar mi labor investigadora. Solo de esta manera pude dejar de lado trabajos temporales que lastraban mi avance en el mundo académico. Por supuesto, el trabajo es más llevadero si se alterna con otras vivencias, y tu preocupación por hacer equipo y por disfrutar de experiencias en grupo en Biel o, más a menudo, en el callejón, mitiga el estrés del día a día. Muchísimas gracias por tu apoyo JAC.

Dear ***Yannis****, although it has only been ~ 1 year working for you in Sub2, it feels many more; it has been one of the most intense, fruitful and even crazy periods of my life. I will always appreciate your support and trust on my work during the last year, since this has allowed me to quit my part-time jobs and finally focus on research. I am sure this is only the beginning. Thank you; onwards and upwards.*

También quería agradecer de una forma especial a **Alex (Gómez) Bruton**. Tu has sido mi supervisor de tesis del día a día, preocupándote por mis avances y mis nulos conocimientos en estadística cuando llegué. Gracias por dedicarme tiempo siempre que lo he necesitado, siempre con una sonrisa y una predisposición inmejorable. Durante los 3 primeros años de tesis, el hecho de trabajar simultáneamente hizo que fuera a otro ritmo, siendo "¿cómo va la review?" la frase más oída en la historia. Sin embargo, gracias a tu paciencia y apoyo he aprendido muchísimo y te estoy realmente agradecido. Gracias Brut. **Gabrielini**, no solo eres un gran compañero, sino también un gran amigo y persona. Tu presencia en mi vida pre-doctoral (incluyendo tus chistes lamentables) ha aportado muchas risas y buenas experiencias a mi y al grupo entero, porque bien sabes que el humor tiene cabida en cualquier sitio, por absurdo que sea. Gracias por ser como eres, Gabri. **George,** seguramente la persona más inteligente que conozco. La persona más demandada en el grupo entero cuando hay problemas estadísticos y se nos empiezan a cruzar los cables a las personas terrestres; entonces llega George con una sonrisa y RStudio, y te soluciona la vida. Al margen de ayudas estadísticas, ha sido un auténtico lujo compartir contigo estos 4 años y "pico", con sus torneos de ping-pong, juegos de mesa, partidos de pádel, posteriores cervezas, y muchas otras experiencias. Espero que podamos seguir haciendo esto encel futuro. Gracias por todo.

El grupo GENUD-Zaragoza, como grupo de investigación puntero en España, crece, aumenta su número de investigadores y dificulta la labor de escribir unos agradecimientos completos. Por ello, espero no olvidarme de nadie, y pido disculpas en tal caso. **Alex**, o AGA, eres un referente para todos los "pre-docs" y "post-docs" de GENUD. Muchas gracias por dar ejemplo, por la sensatez de tus consejos y, sobretodo, por tu sentido del humor. **Alba Gómez**, una de las risas más oídas y contagiosas de GENUD (compitiendo con la de Navarret). Gracias por tu transparencia cuando hemos necesitado hablar o pedirte consejo, por tu buena predisposición, profesionalidad y tu buen carácter. **Matu**, gracias por tu predisposición a ayudar siempre que lo he necesitado. Será una buena señal si llega el día en el que volvamos a compartir trabajo, más allá de las clases del módulo de hípica… Muchas gracias **Nuria** por confiar en mi y en mi trabajo, a pesar de los dolores de cabeza que nos ha dado VeloWin. **Navarret** y **Ana**, hemos compartido momentos estupendos, muchas gracias por tener siempre una actitud positiva ante todo y por las risas compartidas. Mucho ánimo y fuerza con lo que os queda de tesis! **Adrián** y **José Luis**, dos fichajes brillantes del año pasado. Un placer compartir oficina vosotros. Estoy seguro de que vais a tener una trayectoria pre-doctoral brillante si seguís currando como lo estáis haciendo hasta ahora. **Jorge Subías**, **Cris Comeras** y **Ángel Iván** (alias "*mi arma*"), acabáis de emprender un complicado camino en el que vais a aprender muchísimo, aunque como ya sabéis no es fácil. Os deseo lo mejor y espero estar ahí para poder veros y apoyaros. Ánimo. **Lade**, aunque no hemos coincidido demasiado tiempo por haber estado de estancia en Escocia, ha sido un placer disfrutar de tu sentido del humor y de ver mejorar tu nivel de español! Acabas de salir del cascarón y estoy seguro de que con esa capacidad de trabajo y actitud harás lo que te propongas. Por último, no me olvido del líder del grupo GENUD y de la persona que le da gran parte del "caché" que tiene el grupo hoy en día. **Luís Moreno**, tu trayectoria, tus esfuerzos por haber creado este grupo y, sobretodo, tu persona, es un modelo a seguir para todos nosotros. Gracias Luís. Muchas gracias igualmente a todos mis compañeros y compañeras de la parte de nutrición por su apoyo y cariño durante estos años.

*Dear **Shaun** (i.e., Shawn, Shun or Sean), during the last year I have probably spent more time with you than with my girlfriend. It has been great experiences living and working together, including the early mornings in Stirling. I am sure there will be many more ahead. Thanks for this!*

Como bien he empezado en la primera línea de este apartado, lo mejor se debe dejar para el final. Muchísimas gracias a mi **Andrea Rejes**, mi compañera de vida y mi mayor apoyo, porque sin ti no podría haber vivido este periodo pre-doctoral con las mismas ganas y motivación. Además de vivir separados por más de 300 km, no ha sido fácil afrontar una

estancia de 7 meses en Escocia, fines de semana de escapada llevándome el ordenador a todas partes para trabajar, incluyendo esos días de trabajo durante nuestras vacaciones en París. A pesar de las dificultades de estos años, siempre has hecho las cosas fáciles y me has apoyado en todas mis decisiones con una sonrisa, y esto para mi no tiene precio. Por todo lo que nos queda por vivir, por los viajes que tenemos planeados y por esta nueva etapa juntos que deseo tanto. Te quiero.

Anexos ***[Annexes]***

Anexo I

GOBIERNO DE ARAGON
Departamento de Sanidad, Bienestar Social y Familia

Informe Dictamen Favorable
Proyecto Investigación Biomédica
C.P. - C.I. PI11/0034
18 de abril de 2012

/CEIC Aragón (CEICA)

Dña. María González Hinjos, Secretaria del CEIC Aragón (CEICA)

CERTIFICA

1º. Que el CEIC Aragón (CEICA) en su reunión del día 18/04/2012, Acta Nº CP08/2012 ha evaluado la propuesta del investigador referida al estudio:

Título: Repercusión del entrenamiento y la práctica de la natación sobre el desarrollo metabólico y estructural del hueso en crecimiento. Beneficios de la incorporación de entrenamiento pliométrico o vibratorio. (RENACIMIENTO).

Versión Protocolo: abril 2012
Versión hoja de información al paciente y consentimiento informado abril/2012

1º. Considera que

- El proyecto se plantea siguiendo los requisitos de la Ley 14/2007, de 3 de julio, de Investigación Biomédica y su realización es pertinente.
- Se cumplen los requisitos necesarios de idoneidad del protocolo en relación con los objetivos del estudio y están justificados los riesgos y molestias previsibles para el sujeto.
- Son adecuados tanto el procedimiento para obtener el consentimiento informado como la compensación prevista para los sujetos por daños que pudieran derivarse de su participación en el estudio.
- El alcance de las compensaciones económicas previstas no interfiere con el respeto a los postulados éticos.
- La capacidad de los Investigadores y los medios disponibles son apropiados para llevar a cabo el estudio.

2º. Por lo que este CEIC emite un **DICTAMEN FAVORABLE.**

3º. Este CEIC acepta que dicho estudio sea realizado en los siguientes Centros por los Investigadores:

Dr. Germán Vicente Rodríguez, Universidad de Zaragoza.

Lo que firmo en Zaragoza, a 18 de abril de 2012

Fdo:

Dña. María González Hinjos
Secretaria del CEIC Aragón (CEICA)

Departamento de Salud y Consumo del Gobierno de Aragón
Avda Gómez Laguna 25 Zaragoza 50009 Zaragoza España
Tel. 976 71 48 57 Fax. 976 71 55 54 Correo electrónico mgonzalezh.ceic@aragob.es

GOBIERNO DE ARAGON
Departamento de Salud y Consumo

COMITÉ ÉTICO DE INVESTIGACIÓN
CLÍNICA DE ARAGÓN (CEICA)
Avda. Gómez Laguna, 25 planta 11
50009 Zaragoza

COMPOSICIÓN DEL COMITÉ ÉTICO DE INVESTIGACIÓN CLÍNICA DE ARAGÓN

Dra. María González Hinjos, Secretaria del Comité Ético de Investigación Clínica de Aragón,

CERTIFICA

1° En la reunión celebrada el día 18 de abril de 2012, correspondiente al Acta n° **CP08/2012**, se cumplieron los requisitos establecidos en la legislación vigente -Real Decreto 223/2004 y Decreto 26/2003 del Gobierno de Aragón, modificado por el Decreto 292/2005– para que la decisión del citado CEIC sea válida.

3° El CEIC de Aragón, tanto en su composición, como en sus PNT, cumple con las normas de BPC.

4° La composición del CEIC de Aragón en la citada fecha, era la siguiente:

- **Presidente:** Cesar Loris Pablo; Médico. Servicio de Pediatría. Hospital Universitario Miguel Servet. Representante de Comisión de Investigación.
- **Vicepresidente:** Carlos Aibar Remón; Médico. Servicio de Medicina Preventiva y Salud Pública. Hospital Clínico Universitario Lozano Blesa. Profesional Sanitario experto en epidemiología clínica.
- **Secretaria:** María González Hinjos; Farmacéutica.
- Pilar Comet Cortés; Enfermera. Unidad Mixta de Investigación. Hospital Clínico Universitario Lozano Blesa.
- Marina Heredia Ríos; Representante de las Organizaciones de Consumidores y Usuarios.
- Gabriel Hernández Delgado; Médico. Servicio de Radiología. Hospital Universitario Miguel Servet. Representante de Comisión de Investigación.
- Angela Idoipe Tomás; Farmacéutica. Servicio de Farmacia. Hospital Universitario Miguel Servet. Farmacéutica de Hospital.
- María Jesús Lallana Álvarez. Farmacéutica de Atención Primaria de Zaragoza Sector III.
- Jesús Magdalena Bello; Médico. Centro de Salud de Azuara. Médico con labor asistencial y representante del Comité de Ética Asistencial del Área de Atención Primaria II y V.
- Mariano Mateo Arrizabalaga; Médico. Servicio de Farmacología Clínica. Hospital Clínico Universitario Lozano Blesa.
- Elisa Moreu Carbonell; Jurista. Profesora de la Facultad de Derecho, Universidad de Zaragoza.
- Javier Perfecto Ejarque; Médico. Centro de Salud Arrabal. Médico con labor asistencial.
- Alexandra Prados Torres; Médico. Instituto Aragonés de Ciencias de la Salud. Representante de Comisión de Investigación.
- José Puzo Foncillas; Médico. Servicio de Bioquímica. Hospital General San Jorge. Representante de Comisión de Investigación.
- Mónica Torrijos Tejada; Médico. Instituto Aragonés de Ciencias de la Salud.

Para que conste donde proceda, y a petición del promotor,

Zaragoza, a 18 de abril de 2012

Firmado: María González Hinjos

DNV

Anexo II

INFORMACIÓN PARA PADRES PARA EL CONSENTIMIENTO INFORMADO CORRESPONDIENTE A LA PARTICIPACIÓN EN EL PROYECTO "RENACIMIENTO"

Proyecto de investigación para el que se solicita el consentimiento informado

La participación que se solicita es para la realización de un proyecto de investigación sobre "***Re****percusión del entrenamiento y la práctica de la* ***na****tacion sobre el desarrollo metabólico y estructural del hueso en cre****cimiento.*** *Beneficios de la incorporación de entrenamiento pliométrico o vibratorio. (acrónimo: RENACIMIENTO)****"*** financiado por el MICIN, en el que participa el Departamento de Fisiatría y Enfermería de la Universidad de Zaragoza, del que es investigador principal el profesor Dr. Germán Vicente-Rodríguez, Profesor Contratado Doctor de la Universidad de Zaragoza (Departamento de Fisiatría y Enfermería C/ Domingo Miral s/n 50008 Zaragoza, teléfono 974238422 (ext 853258), e-mail: gervicen@unizar.es).

Facultativos que intervienen:
Profesor Dr. Germán Vicente-Rodriguez, y personal autorizado.

Intervención para la que se solicita el consentimiento informado

Realización de una valoración médico-deportiva.

Finalidad de la intervención:
Observar el efecto de la práctica y entrenamiento de natación sobre el metabolismo, la geometría y arquitectura del hueso y sus posibles relaciones.

Confidencialidad de los resultados

Se garantiza la absoluta confidencialidad de los resultados, de forma que en ningún caso, sin consentimiento previo del participante, se dará a conocer ningún dato personal ni de los resultados de su colaboración en este proyecto.

Naturaleza del estudio

Realización de una prueba de tomografía cuantitativa computerizada periférica (pQCT) y otra de densitometría dual de rayos X (DXA) para obtener información del estado, geometría y arquitectura del hueso y estimar así factores determinantes de la fortaleza y resistencia del esqueleto. Estas técnicas conllevan una dosis de radiación total de entre 5 y 10 mrem, que es una dosis 20 veces más baja que la de una radiografía de tórax y similar a la radiación solar que conlleva un día de playa.

Se obtendrán muestras de sangre (punción cubital) para determinaciones de marcadores bioquímicos del metabolismo del hueso.

Además se realizarán pruebas de condición física:

Cardiovascular

El consumo máximo de oxígeno (VO2max) se estimará mediante una prueba de campo incluido en la batería Eurofit para escolares (test de 20 m de ida y vuelta).

Test de velocidad de carrera

El tiempo invertido en correr 30 m (T30) se medirá utilizando células fotoeléctricas (Byomedics, Barcelona).

La fuerza isométrica máxima (FIM)

De pierna

Test de máxima contracción voluntaria isométrica (MCVI)

Se registrará la fuerza ejercida por el sujeto durante 10 segundos con un ángulo de flexión de rodilla de 110º.

De brazo

La dinamometría manual se realizará con un dinamómetro y el adolescente de pie, brazos extendidos a lo largo del cuerpo hará la mayor fuerza posible de prensión manual sin apoyar el brazo en el cuerpo.

Fuerza dinámica de las piernas.

Las fuerzas generadas durante el salto vertical se medirán mediante el cálculo de la altura de vuelo durante el salto con una plataforma que registra la fuerza realizada durante el salto.

Potencia muscular de tren inferior al 10%, 20% y al 30% de la MCVI.

El objetivo de dicha evaluación será cuantificar la potencia máxima que será capaz de imprimir el adolescente durante la fase concéntrica del movimiento de extensión de piernas, utilizando una carga equivalente al 10, 20 y 30% de la *MCVI* que hemos medido anteriormente.

Valoración de la dieta

La dieta se valorará a partir de tres recuerdos de 24 h no consecutivos y en días distintos de la semana, realizados con un software informático.

La duración total de la sesión de laboratorio será de 2 horas (una tarde).

Para la extracción sanguínea se citara al participante un sábado por la mañana a elección del participante

Posibles beneficios

- Detección precoz de mineralización débil u otros problemas de microarquitectura ósea.
- Mejora de la mineralización y desarrollo óseo durante el crecimiento.

Riesgos

No se ha descrito ningún efecto adverso grave derivado de estas pruebas o de la participación en un programa de ejercicio físico de estas características.

Contraindicaciones

Patologías graves que contraindiquen la práctica deportiva escolar.

Advertencias

1. El participante es advertido sobre la posibilidad de utilizar los resultados del diagnóstico en un proceso de investigación, que en ningún caso podrá comportar riesgo adicional para su salud y que no tendrá carácter comercial.
2. El participante es advertido de que puede revocar libremente por escrito su consentimiento en cualquier momento.
3. El participante es advertido de su derecho a que se le dé una copia del documento firmado.
4. El participante contará con la cobertura de un seguro para la realización de las pruebas.
5. El participante puede obtener la información complementaria del investigador principal del proyecto, cuya dirección figura en este escrito.
6. El participante puede solicitar por escrito dirigido al investigador principal del proyecto los resultados concretos obtenidos en su muestra donada.

Un saludo

Germán-Vicente Rodríguez

GOBIERNO DE ARAGON

Departamento de Fisiatría y Enfermería
Universidad Zaragoza

CONSENTIMIENTO INFORMADO CORRESPONDIENTE A:

Datos del participante

D./Dª____

DNI: _____________________ Edad___________

Que presta su consentimiento:

- ❑ Por si mismo
- ❑ Por medio del tutor legal:

D./Dª____

DNI: _____________________

Teléfono 1:___________________ Teléfono 2:___________________

En Zaragoza, a .... de .... de 20....

D...……………………………………........

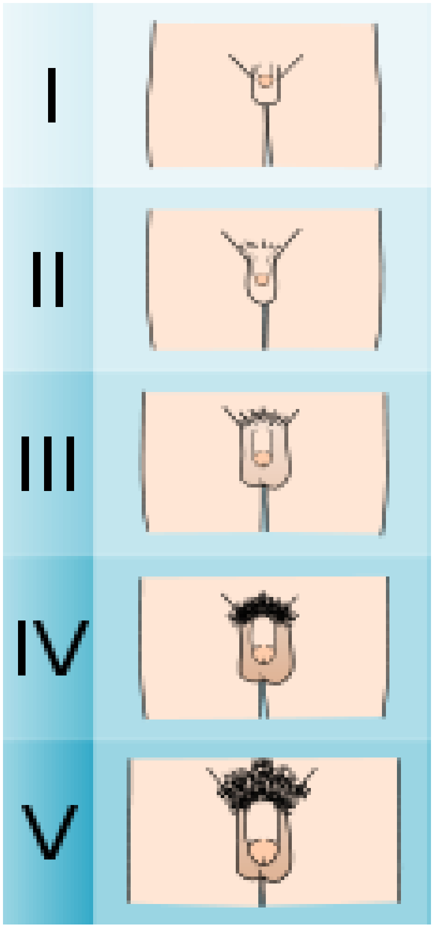
manifiesta que ha recibido información suficiente y en términos comprensibles para tomar la decisión de acuerdo con su propia y libre voluntad y **presta su consentimiento y autorización** a la práctica de la intervención reseñada en el proyecto:
“*Re*_percusión del entrenamiento y la práctica de la_ ***na***_tacion sobre el desarrollo metabólico y estructural del hueso en cre_***cimiento.*** _Beneficios de la incorporación de entrenemiento pliométrico o vibratorio. (acrónimo: RENACIMIENTO)_**”** financiado por el MICIN, en el que participa el Departamento de Fisiatría y Enfermería de la Universidad de Zaragoza, del que es investigador principal el profesor Dr. Germán Vicente-Rodríguez, Profesor Contratado Doctor de la Universidad de Zaragoza (Departamento de Fisiatría y Enfermería C/ Domingo Miral s/n 50008 Zaragoza, teléfono 974238422 (ext 853258), e-mail: gervicen@unizar.es).

Facultativos que intervienen:
Profesor Dr. Germán Vicente-Rodriguez, y personal autorizado.

PARTICIPANTE	DOCTOR
Padre, madre o tutor	Dr. G. Vicente-Rodríguez

Anexo III

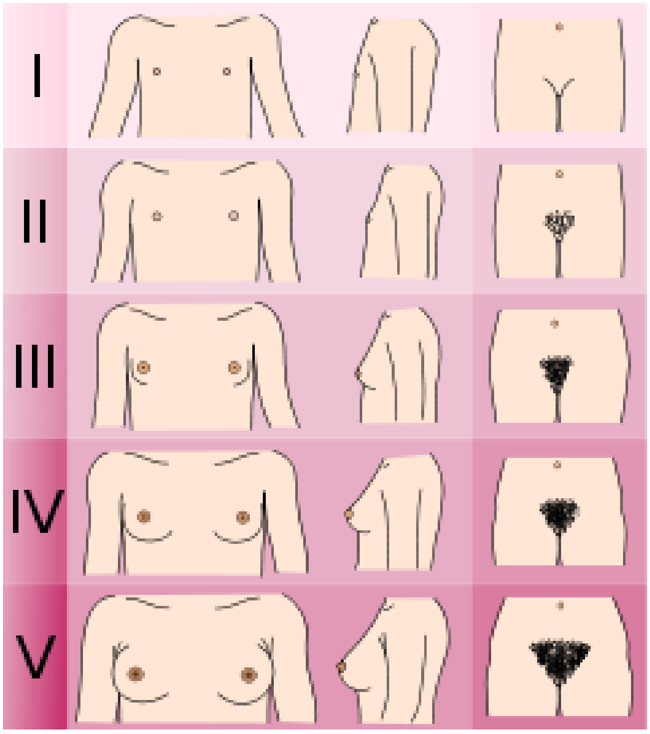
ESTADIO DE TANNER



Considerando las siguientes imágenes, marca la casilla que consideres que más se parece a tu propio cuerpo.

I	II	III	IV	V

ESTADIO DE TANNER



Considerando las siguientes imágenes, marca la casilla que consideres que más se parece a tu propio cuerpo.

I	II	III	IV	V

1. ¿A qué edad tuviste tu primera menstruación? ________________________

   (*Si aun no la has tenido deja de responder*)

2. ¿Tus menstruaciones se producen de manera regular? SI ☐ NO ☐

3. ¿Cuántos periodos tienes a lo largo de un año? Más de 8 ☐ Menos de 8 ☐

   Específicamente tengo ______ periodos al año

Anexo IV

Date: May 12, 2019
To: "German Vicente-Rodriguez" gervicen@unizar.es
cc: ratamess@tcnj.edu
From: "Journal of Strength and Conditioning Research" kraemer.45@osu.edu
Subject: JSCR Decision ACCEPT

May 12, 2019

RE: JSCR-08-10213R6, entitled "Review#1 - "Non-specific resistance training and swimming performance: Strength or Power? A systematic review"

Review#2 - "Swim-specific resistance training: A systematic review""

Dear Dr. Vicente-Rodriguez,

I am pleased to inform you of the official acceptance of your manuscript, JSCR-08-10213R6, entitled "Review#1 - "Non-specific resistance training and swimming performance: Strength or Power? A systematic review"

Review#2 - "Swim-specific resistance training: A systematic review"" for publication in the Journal of Strength and Conditioning Research. Congratulations to you and your co-authors in meeting the very high standard of quality that is required for publication in this Journal.

The production staff at Lippincott, Williams and Wilkins (LWW) will be sending galley proofs and work with you to put your manuscript into proper format for publication.

I want to take this opportunity to remind you to check the page proofs promptly and carefully for accuracy when you eventually receive them. You will receive them via email so please be attentive to such communications.

Non-specific resistance training and swimming performance: Strength or power? A systematic review

Running title: **Non-specific resistance training in swimming**

Borja Muniz-Pardos [a]; Alejandro Gomez-Bruton [a,b,c,d]; Angel Matute-Llorente [a,b,c,d]; Alejandro Gonzalez-Aguero [a,b,c,d]; Alba Gomez-Cabello [a,b,c,d,e]; Oliver Gonzalo-Skok [f]; Jose A. Casajus [a,b,c,g] and German Vicente-Rodriguez [a,b,c,d]

Swim-specific resistance training: A systematic review

Running title: **Swim-specific training and swimming performance**

Borja Muniz-Pardos [a]; Alejandro Gomez-Bruton [a,b,c,d]; Angel Matute-Llorente [a,b,c,d]; Alejandro Gonzalez-Aguero [a,b,c,d]; Alba Gomez-Cabello [a,b,c,d,e]; Oliver Gonzalo-Skok [f]; Jose A. Casajus [a,b,c,g] and German Vicente-Rodriguez [a,b,c,d]