UNIVERSIDAD DE MURCIA

ESCUELA INTERNACIONAL DE DOCTORADO

TESIS DOCTORAL

Effects of resistance training modality on physical performance and muscle structure

Efectos de la libertad de movimiento en el entrenamiento de fuerza sobre el rendimiento físico y la estructura muscular

D. Alejandro Hernández Belmonte

2023

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Autor: D. Alejandro Hernández Belmonte

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UNIVERSIDAD DE MURCIA

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A mi familia, pareja y amigos

No hay manera más oportuna de comenzar este documento que AGRADECIENDO a todos aquellos que han contribuido directa o indirectamente a esta Tesis Doctoral:

A mis padres, por ser ejemplo de lucha diaria, enseñándome el significado de las palabras trabajo, sacrificio y humildad. Por allanarme cada uno de los caminos que he decidido tomar y nunca dejar de confiar en mí.

A mi hermana por ser un pilar fundamental en mi vida. Estoy muy orgulloso de ti y nunca dejaré de apoyarte.

A mis abuelos/as por inculcarme gran parte de los valores que tengo hoy en día. Gracias por ser fuente de serenidad y paz cuando más lo he necesitado. Al resto de mis familiares por el apoyo que me mostráis a diario.

A mi pareja, María, por entender todas las horas que le he robado para pasarlas enfrente de un ordenador. Gracias por comprenderme y acompañarme en este bonito y duro camino.

A mi director, Jesús García Pallarés, por mostrar plena confianza en mi trabajo desde el primer momento en que crucé la puerta del laboratorio. Gracias por todo lo que me has enseñado a lo largo de estos 5 años.

A mis compañeros del grupo Human Performance and Sports Science, por ser piezas clave en el proyecto que hoy culmina. Una gran parte de todo esto es vuestra.

Por último, GRACIAS a todos los participantes que han formado parte de las investigaciones que se incluyen en esta Tesis Doctoral.

Muchas gracias a todos/as

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Grants and funding sources

The following grants have funded this Doctoral Thesis:

1. Ayudas para la formación de profesorado universitario (FPU) otorgadas por el Ministerio de Educación, Cultura y Deporte (Convocatoria 2019, FPU19/03258).

2. Ayudas para estancias predoctorales en el exterior y en España, destinadas a estudiantes de doctorado en las líneas de actuación de la Escuela Internacional de Doctorado y el Campus de Excelencia Internacional Mare Nostrum (Convocatorias R-254/2022 y R-163/2023).

3. Programa Erasmus+ financiado por la Comisión Europea para la realización de prácticas en el extranjero.

Research stays

This Doctoral Thesis included two research stays in the following destinations:

1. Faculty of Sport and Health Sciences of the University of Jyväskylä (from 21/02/2022 to 21/05/2022). Supervised by Taija Juutinen (Department of Biology of Physical Activity).
2. Faculty of Sport Sciences of the University of Granada (from 15/03/2023 to 15/06/2023). Supervised by Javier Courel Ibáñez (Department of Physical and Sports Education).

Certificates of both research stays are presented in Appendix 1.

Main scientific contributions

The current Doctoral Thesis is presented as a compendium of Articles that have been published (except one that is under review) in scientific journals indexed in the Journal Citation Reports (JCR):

Article 1 **Hernández-Belmonte, A.**, Buendía-Romero, Á., Pallarés, J.G., & Martínez-Cava, A. (2023). Velocity-based method in free-weight and machine-based training modalities: The degree of freedom matters. *Journal of Strength and Conditioning Research*. (Online ahead of print). https://doi.org/10.1519/JSC.0000000000004480.

Article 2 **Hernández-Belmonte, A.**, Courel-Ibáñez, J., Conesa-Ros, E., Martínez-Cava, A., & Pallarés, J.G. (2022). Level of effort: A reliable and practical alternative to the velocity-based approach for monitoring resistance training. *Journal of Strength and Conditioning Research*, 36(11), 2992-2999. https://doi.org/10.1519/JSC.0000000000004060 .

Article 3 **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). Pectoralis cross-sectional area can be accurately measured using panoramic ultrasound: A validity and repeatability study. *Ultrasound in Medicine & Biology*,48(3),460-468. https://doi.org/10.1016/j.ultrasmedbio.2021.10.017.

Article 4 **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). Panoramic ultrasound requires a trained operator and specific evaluation sites to maximize its sensitivity: A comprehensive analysis of the measurement errors. *Physiology & Behavior*, 248, 113737. https://doi.org/10.1016/j.physbeh.2022.113737.

Article 5 **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). The 2-point method: A quick, accurate, and repeatable approach to estimate ultrasound-derived quadriceps femoris cross-sectional area. *International Journal of Sports Physiology and Performance*, 17(10), 1480-1488. https://doi.org/10.1123/ijspp.2021-0381.

Article 6 **Hernández-Belmonte, A.**, Buendía-Romero, Á., Franco-López, F., Martínez-Cava, A., & Pallarés, J.G. (2023). Adaptations in athletic performance and muscle architecture are not meaningfully conditioned by training free-weight versus machine-based exercises: Challenging a traditional assumption using the velocity-based method. *Scandinavian Journal of Medicine & Science in Sports.* (Online ahead of print). https://doi.org/10.1111/sms.14433.

Article 7 **Hernández-Belmonte, A.**, Martínez-Cava, A., Buendía-Romero, Á., Franco-López, F., & Pallarés, J.G. (2023). Free-weight and machine-based training are equally effective on strength and hypertrophy: Challenging a traditional myth. (*Under review in Medicine & Science in Sports & Exercise journal*).

Dissemination activities

The results of the aforementioned Articles have also been presented in the following dissemination activities:

Article 1 – Oral communication: Hernández-Belmonte, A., Martínez-Cava, A., Buendía-Romero, Á., Romero-Borrego, E., & Pallarés, J.G. (October 7 - 8th, 2022). *Load-velocity relationship of free-weight and machine-based resistance exercises: A comparison in the bench press, squat, prone bench pull and shoulder press*. I Congreso Internacional sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular. Granada, Spain.

Article 1 – Oral communication: Hernández-Belmonte, A., Romero-Borrego, E., Buendía-Romero, Á., Martínez-Cava, A., & Pallarés, J.G. (October 21st - 22nd, 2022). *Load-velocity relationship of free-weight and machine-based bench press and squat exercises are not influenced by the relative strength level.* III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte. Murcia, Spain.

Article 2 – Oral communication: Hernández-Belmonte, A., Martínez-Cava, A., Conesa-Ros, E., Franco-López, F., Buendía-Romero, Á., Courel-Ibáñez, J., Pallarés, J.G. (September 8 - 10th, 2021). *Level of effort: A reliable and practical alternative to the velocity-based approach for monitoring resistance training*. 26th Annual Congress of the European College of Sport Science. Cologne, Germany.

Article 2 – Plenary presentation: Hernández-Belmonte, A. (September 17 - 18th, 2021). *Uso de variables mecánicas para prescribir el entrenamiento de* *fuerza y evaluar la función neuromuscular.* Jornadas sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular: Últimos Avances en Investigación y Transferencia. A Coruña, Spain.

Article 3 – Oral communication: Hernández-Belmonte, A., Martínez-Cava, A., Buendía-Romero, Á., Pallarés, J.G. (October 21^{st} - 22^{nd}, 2022). *Pectoralis cross-sectional area can be accurately measured using panoramic ultrasound: A comprehensive analysis of the measurement errors.* III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte. Murcia, Spain.

Article 4 – Oral communication: Hernández-Belmonte, A., Martínez-Cava, A., Buendía-Romero, Á., Courel-Ibáñez, J., Franco-López, F., Pallarés, J.G. (September 8 - 10^{th}, 2021). *Repeatability and reproducibility of panoramic ultrasonography are highly dependent on the muscle region: A step-by-step analysis of the measurement errors.* 26^{th} Annual Congress of the European College of Sport Science. Cologne, Germany.

Article 5 – Oral communication: Hernández-Belmonte, A., Martínez-Cava, A., Pallarés, J.G. (October 21^{st} - 22^{nd}, 2022). *Two-point method: A quick, accurate, and repeatable approach to estimate ultrasound-derived quadriceps femoris cross-sectional area*. III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte. Murcia, Spain.

Certificates of these dissemination activities are presented in Appendix 2.

1. Resumen

Tradicionalmente, los profesionales entorno al entrenamiento de fuerza han promulgado una superior eficacia de los ejercicios realizados con peso libre sobre aquellos llevados a cabo con maquinaria guiada con el objetivo de maximizar las adaptaciones sobre el rendimiento físico y la estructura muscular. Este dogma, sustentado principalmente por la mayor actividad muscular aguda registrada durante el entrenamiento con peso libre, se ha visto cuestionado por las intervenciones longitudinales sobre la temática que, en conjunto, no evidencian una manifiesta superioridad de ninguna de estas dos modalidades. Sin embargo, es importante resaltar que una gran parte de los estudios que han comparado el entrenamiento de fuerza con peso libre o con maquinaria guiada presentan algunas importantes limitaciones. En primer lugar, la mayoría de ellos i) ha programado la intensidad relativa y el volumen intraserie utilizando metodologías muy extenuantes y poco precisas (p.ej. número de repeticiones máximas, *n*RM). En segundo lugar, una gran parte de estas investigaciones ii) ha comparado diferentes ejercicios en lugar de diferentes modalidades de entrenamiento, iii) ha basado su rutina en un único ejercicio, iv) ha incluido un solo parámetro de fuerza (generalmente la repetición máxima, 1RM), el cual v) ha sido evaluado mayoritariamente en la modalidad entrenada o incluso únicamente en una de las dos modalidades comparadas. Por otro lado, vi) existe escasa información en torno a si las adaptaciones sobre el tamaño y la arquitectura muscular podrían verse influidas de forma significativa por la utilización de peso libre o maquinaria guiada para la realización de los ejercicios de fuerza. Teniendo en cuenta todo lo anterior, la presente tesis doctoral desarrolló un cuerpo de evidencia científica compuesto por 7 investigaciones con la principal finalidad de comparar los efectos del entrenamiento de fuerza con peso libre o con maquinaria guiada sobre el rendimiento físico y la estructura muscular.

Tal y como se podrá inferir a lo largo del presente resumen, así como en el posterior cuerpo de evidencia, este proyecto de Tesis Doctoral encuentra su fundamento en la amplia y rigurosa metodología de evaluación y programación utilizada. Esta metodología ha sido exhaustivamente examinada en los dos primeros cuerpos de evidencia (Estudios I y II, Artículos 1 - 5) para, posteriormente, ser implementada en los artículos desarrollados para abordar la principal pregunta de investigación que vertebra este proyecto (Estudio III, Artículos 6 y 7).

ESTUDIO I

Los 2 Artículos que conforman el Estudio I examinaron la idoneidad de estrategias derivadas del método basado en la velocidad (en inglés, *Velocity-Based Training*) para programar la intensidad y el volumen intraserie en diferentes modalidades de los ejercicios sentadilla completa (SC), press de banca (PB), remo dorsal (RD) y press de hombros (PH).

En concreto, el **Articulo 1** tuvo como principal objetivo analizar la relación carga-velocidad (C-V) en las modalidades de peso libre y máquina guiada de los ejercicios SC, PB, RD y PH. Además, esta investigación estudió la posible influencia del nivel de fuerza del sujeto sobre estas relaciones C-V. Tras los diferentes análisis realizados, este artículo encontró i) relaciones muy estrechas ($R^2 \geq 0{,}95$) entre la intensidad relativa y ambos parámetros de velocidad (media y media propulsiva) en todos los ejercicios y modalidades examinadas. Sin embargo, se obtuvieron ii) diferencias significativas entre ambas modalidades con respecto a la velocidad alcanzada ante intensidades desde el 30 al 100% de la 1RM. Por otra parte, iii) las diferencias encontradas entre los dos grupos con diferentes niveles de fuerza con respecto a los parámetros de velocidad resultantes de las relaciones C-V fueron reducidas y no significativas ($\leq 0{,}02\ m \cdot s^{-1}$). En conjunto, estos hallazgos sugieren una elevada precisión, estabilidad y especificidad de la relación C-V en las modalidades de peso libre y máquina guiada de los ejercicios examinados. En la práctica, los altos ajustes encontrados en las 8 relaciones C-V analizadas (4 ejercicios x 2 modalidades) apoyarían el uso de la velocidad de ejecución como variable para i) monitorizar y prescribir una intensidad relativa objetivo y ii) cuantificar los cambios en el rendimiento de un sujeto sin necesidad de realizar un test máximo 1RM o nRM.

Por su parte, el **Articulo 2** analizó la idoneidad del Carácter del Esfuerzo como metodología para programar la intensidad y el volumen intraserie en los ejercicios SC, PB, RD y PH. En concreto, el objetivo de este estudio fue triple: i) examinar la variabilidad inter e intrasujeto en el nRM ante 4 intensidades relativas (65, 75, 85 y 95% 1RM), ii) investigar la relación entre el número de repeticiones completadas y la pérdida de velocidad incurrida, y iii) estudiar la influencia del nivel de fuerza del sujeto sobre los dos objetivos previamente mencionados. Los análisis de variabilidad inter e intrasujeto incluyeron el intervalo de confianza del 95% (IC 95%) y el error estándar de la medida (EEM), respectivamente. Para las diferentes intensidades relativas, niveles de fuerza y ejercicios examinados, los principales resultados mostraron: i) una muy reducida variabilidad inter (IC 95% ≤ 4 repeticiones) e intrasujeto (EEM ≤ 2 repeticiones) en el nRM y ii) una relación muy alta ($R^2 \geq 0,97$) entre el número de repeticiones completadas y el porcentaje de pérdida de velocidad generado. Los hallazgos reportados por esta investigación posicionarían al Carácter del Esfuerzo como una alternativa precisa y fiable al método basado en la velocidad para prescribir la intensidad relativa y el volumen intraserie en los 4 ejercicios examinados. Debido a su simplicidad y naturaleza práctica, esta metodología podría ser implementada para la programación de sesiones de entrenamiento de fuerza realizadas simultáneamente por un número elevado de deportistas, permitiendo así prescribir de manera individualizada los principales parámetros que modulan la magnitud y dirección de las adaptaciones.

ESTUDIO II

Los 3 Artículos que conforman el Estudio II tuvieron como principal objetivo cuantificar los errores de medición generados al implementar la ecografía panorámica para evaluar el área de sección transversal anatómica (ASTA) de la musculatura del tren superior e inferior.

En concreto, los **Artículos 3 y 4** realizaron un análisis exhaustivo de la validez y repetibilidad de la ecografía panorámica para evaluar el ASTA del pectoral mayor y del cuádriceps femoral, respectivamente. Para ello, se cuantificaron los errores generados por un ecografista entrenado (>200 h de experiencia) y otro principiante (~10h de experiencia) durante la adquisición y análisis del ASTA del pectoral mayor (Artículo 3) y cuádriceps femoral (Artículo 4). Los errores de adquisición se analizaron comparando 2 imágenes adquiridas con 5 minutos de diferencia, mientras que la primera adquisición se analizó dos veces para cuantificar los errores de análisis. Además, el ASTA de la primera adquisición realizada por cada ecografista se comparó con la obtenida mediante resonancia magnética. Los principales resultados de ambos artículos mostraron que los errores cometidos por el ecografista entrenado fueron menores que los generados por el principiante, especialmente durante la adquisición de las imágenes y la comparación con la resonancia magnética. En lo que respecta específicamente a los músculos que componen el cuádriceps femoral (vasto lateral, medial, intermedio y recto femoral), el Artículo 4 reveló que los errores cometidos fueron inferiores en las regiones centrales del muslo (del 30 al 60% de la longitud del fémur). Estos hallazgos sugieren que la ecografía panorámica es una técnica válida y repetible para medir el ASTA de los músculos pectoral mayor y cuádriceps femoral, especialmente cuando se implementa por parte de un ecografista entrenado.

El **Artículo 5**, por su parte, realizó un triple análisis con el objetivo de examinar la idoneidad del método de 2 puntos para estimar el ASTA del cuádriceps femoral medida mediante ecografía panorámica en diferentes regiones del muslo. En primer lugar, se comparó el ASTA (analizando conjuntamente el vasto lateral, medial, intermedio y recto femoral) obtenido mediante ecografía panorámica y el medido con resonancia magnética al 20, 30, 40, 50, 60 y 70% de la distancia entre el trocánter mayor y la rótula. En segundo lugar, el ASTA obtenido mediante ecografía en las regiones del 30 y 60% (2-point$_{30\text{-}60\%}$) y en las regiones del 20 y 70% (2-point$_{20\text{-}70\%}$) de cada sujeto se utilizó para estimar el ASTA de las regiones restantes. Por último, se examinó la repetibilidad (test-retest) de los enfoques 2-point$_{30\text{-}60\%}$ y 2-point$_{20\text{-}70\%}$ comparando los errores generados por cada uno de ellos en dos estimaciones distintas. Como resultado de los tres análisis planteados, el presente artículo encontró un acuerdo casi perfecto ($r \geq 0{,}968$) y reducidos errores (EEM $\leq 2{,}43$ cm^2) al comparar el ASTA medido mediante ecografía panorámica y resonancia magnética. Por otro lado, se encontraron reducidos errores de estimación y test-retest para el 2-point$_{20\text{-}70\%}$ (EEM $\leq 5{,}67$ cm^2) pero especialmente para el 2-point$_{30\text{-}60\%}$ (EEM $\leq 3{,}62$ cm^2). Por un lado, estos resultados sugieren que la ecografía panorámica podría utilizarse como una alternativa válida y repetible a las técnicas tradicionales para evaluar conjuntamente los músculos que conforman el ASTA del cuádriceps femoral. Además, los reducidos errores de estimación y alta repetibilidad encontrados para el método de 2 puntos, especialmente para el implementado utilizando las regiones del 30 y 60%, posicionan a este método como una estrategia precisa y repetible para agilizar la evaluación del ASTA del cuádriceps a lo largo del muslo. Así, se podría reducir la fatiga y el requerimiento temporal de los evaluadores, aumentando la aplicación práctica de esta técnica.

ESTUDIO III

Los resultados los 5 Artículos previamente descritos sentaron las bases metodológicas de las investigaciones incluidas en el Estudio III. En concreto, los Artículos 6 y 7 tuvieron como objetivo comparar los efectos del entrenamiento de fuerza con peso libre o con maquinaria guiada sobre el rendimiento físico, la estructura muscular y los niveles de molestias articulares.

Para ello, 34 (**Artículo 6**) y 38 (**Artículo 7**) varones experimentados en el entrenamiento de fuerza completaron un programa de intervención de 8 semanas distribuidos en dos grupos: Peso libre o Maquinaria guiada. La frecuencia de entrenamiento (3 sesiones por semana), número de series (3 series por ejercicio), descanso entre series (4 minutos) y entre sesiones (48 horas), volumen intraserie (mitad de las repeticiones posibles) e intensidad relativa (65 al 85% 1RM, programación lineal) fue idéntico para ambos grupos. Por lo tanto, ambas modalidades únicamente difirieron en el uso de barras o máquinas guiadas para ejecutar los ejercicios SC, PB, RD y PH. La velocidad de ejecución fue utilizada para ajustar de manera precisa las diferentes intensidades relativas programadas a lo largo de las 8 semanas. Ambos grupos se compararon utilizando una amplia batería de valoraciones del rendimiento físico que incluyó 5 capacidades atléticas (sprint, cambio de dirección, salto vertical, equilibrio, rendimiento cíclico anaeróbico de miembros superiores e inferiores) y 8 tests (4 ejercicios x 2 modalidades) de evaluación de la fuerza. Para comparar los cambios estructurales producidos por ambas modalidades de entrenamiento, se registró el ASTA de los músculos cuádriceps femoral (regiones proximal y distal), pectoral mayor y recto abdominal, así como la arquitectura muscular del vasto lateral. Complementariamente, se administraron los cuestionarios DASH y WOMAC para evaluar posibles cambios en los niveles de molestias articulares de las extremidades superiores e inferiores, respectivamente. Los principales resultados de ambas investigaciones mostraron que las dos modalidades de entrenamiento i) aumentaron de forma significativa y similar la fuerza, el tamaño muscular, el salto vertical y la capacidad anaeróbica de las extremidades inferiores, además de ii) reducir los niveles de molestias articulares de ambas extremidades. Por su parte, iii) el grupo que entrenó utilizando maquinaria guiada incrementó significativamente la potencia anaeróbica de las extremidades superiores, mientras que el grupo que utilizó peso libre mejoró significativamente el cambio de dirección y 2 de las 6 condiciones de equilibrio examinadas. Por último, iv) los cambios generados por ambas modalidades de entrenamiento sobre la capacidad de sprint y la arquitectura muscular fueron reducidos y no significativos.

Las conclusiones de ambos artículos demuestran que las adaptaciones sobre el rendimiento físico y la estructura muscular no estarían condicionadas significativamente por el uso de peso libre o maquinaria guiada para la realización de los ejercicios de fuerza. Por tanto, en la práctica, los deportistas podrían utilizar cualquiera de estas modalidades en función de sus posibilidades o preferencias, al tiempo que se centran en otras variables de entrenamiento que han demostrado condicionar significativamente las adaptaciones mencionadas (p.ej., la intensidad, la velocidad de ejecución, el volumen intraserie o el rango de movimiento).

2. Abstract

Throughout a rigorous evaluation and programming methodology, the main objective of this Doctoral Thesis was to compare the effects of free-weight and machine-based resistance training on physical performance and muscle structure. This methodology was thoroughly examined in Studies I and II (Articles 1-5) and subsequently implemented in the Articles developed to address the main research question underlying this project (Study III, Articles 6 and 7).

Article 1 aimed to analyze the load-velocity (L-V) relationship of the free-weight and machine-based modalities of squat (SQ), bench press (BP), prone bench pull (PBP) and shoulder press (SP) exercises, as well as to examine the influence of the subject's strength level on these L-V relationships. Analyses showed very close adjustments ($R^2 \geq 0.95$) for the 8 L-V relationships examined, which exhibited not being conditioned by the subject's strength level but by the training modality (velocity attained at each intensity was significantly faster for the free-weight variant). **Article 2** examined the suitability of the level of effort method to program the intensity and intraset volume in SQ, BP, PBP, and SP exercises. Regardless of the subject's strength level, this study found very low inter- (Confidence interval, CI 95% ≤ 4 repetitions) and intra-subject (Standard error of the measurement, SEM ≤ 2 repetitions) variability in nRM, as well as a high relationship ($R^2 \geq 0.97$) between the repetitions completed and velocity loss incurred.

Articles 3 and 4 quantified acquisition and analysis errors made when implementing ultrasound to assess the anatomical cross-sectional area (ACSA) of the pectoralis major (Article 3) and quadriceps (Article 4). Acquisition errors included the comparison of two images acquired 5 min apart, while the first acquisition was analyzed twice to quantify analysis errors. Moreover, the ACSA from the first acquisition was

compared with that obtained by magnetic resonance imaging (MRI). These errors were quantified for a trained and a novice sonographer. Both Articles revealed small errors (especially for the trained sonographer) when acquiring and analyzing ACSA of these muscles, as well as high agreement with MRI. On the other hand, **Article 5** examined the agreement between quadriceps ACSA (considering all the muscles together) measured by ultrasound and MRI, as well as the validity and reliability of two approaches of the 2-point method (using the 30-60% or 20-70% thigh regions) for estimating ultrasound-derived quadriceps femoris ACSA. Besides almost perfect agreement ($r \geq 0.968$) between ultrasound and MRI, this study found small estimation and test-retest errors for the 2-point$_{20\text{-}70\%}$ (SEM ≤ 5.67 cm^2) but especially for the 2-point$_{30\text{-}60\%}$ (SEM ≤ 3.62 cm^2).

All these results laid the methodological basis for Study III. **Articles 6 and 7** compared the effects of free-weight and machine-based resistance training on physical performance, muscle structure, and discomfort levels. For this purpose, 34 (Article 6) and 38 (Article 7) males completed an 8-week velocity-controlled training allocated into free-weight or machine-based groups. All training parameters were identical for both modalities, so they only differed in the use of barbells or machines for performing SQ, BP, PBP, and SP exercises. Changes in physical performance were compared in 5 athletic (sprint, change of direction, vertical jump, balance, upper- and lower-limb anaerobic cycling performance) and 8 strength tests. The ACSA of the quadriceps, pectoralis major and rectus abdominis, as well as the muscle architecture of the vastus lateralis, were measured to examine structural changes. Furthermore, the DASH and WOMAC questionnaires were administered to assess changes in upper- and lower-limb discomfort, respectively. Results of both studies suggest that free-weight and machine-based training modalities would be similarly effective to promote physical performance and structural changes without increasing joint discomfort.

INTRODUCTION

3. Introduction

3.1. Factors influencing resistance training adaptations

Resistance training (RT) can be defined as the repetition of voluntary musculoskeletal contractions against a load heavier than those commonly encountered in daily activities (Lee & Carroll, 2007). This type of training is becoming increasingly practiced by all age spectrums due to its capacity to influence neural, musculoskeletal, metabolic and hormonal systems. Among others, RT has shown to i) improve neural coordination (Škarabot et al., 2021), ii) promote muscle, tendon, and bone growth (Gómez-Cabello et al., 2012; Lopez et al., 2021; Wiesinger et al., 2015), as well as iii) increase anabolic hormones and anaerobic substrate deposits (Kraemer & Ratamess, 2005; MacDougall et al., 1977).

Nevertheless, RT adaptations are modulated by training parameters like the relative intensity (Lopez et al., 2021), weekly volume (Ralston et al., 2017) or intraset fatigue (Jukic et al., 2023). Also, technical factors like the range of motion (Pallarés et al., 2021), execution intentionality (Wilk et al., 2021), or strategy used between concentric and eccentric phases of the execution (Martínez-Cava et al., 2021) would be meaningful determinants of RT adaptations. Another technical factor traditionally postulated as a potential modulator of RT adaptations would be the modality or freedom of movement used to perform resistance exercises (i.e., free-weight or machine-based modes). Free-weight RT allows multiplane movements as a function of the magnitude and direction of forces applied by the practitioner during the execution. On the contrary, machine-based modality limits the movement to one or two movement planes, thus commonly providing a more stable execution. Traditionally, it has been assumed that these biomechanical differences would in turn lead to different long-term adaptations.

3.2. Evidence comparing free-weight and machine-based training modalities

Most RT practitioners have supported the theoretically higher effectiveness of free-weight over machine-based exercises to increase physical performance and muscle structure (McQuilliam et al., 2020; Stone et al., 2000). This assumption has mainly been based on the higher acute activation produced during that modality in agonist and synergist muscles (Clark et al., 2019; McCaw & Friday, 1994; Schick et al., 2010). Nevertheless, findings from longitudinal interventions comparing both training modes question this widespread belief. In particular, a recent meta-analysis showed that neither physical performance nor muscle structure was meaningfully influenced by the resistance modality trained (Heidel et al., 2022). Despite this wayward finding, this meta-analysis also highlighted some methodological aspects of longitudinal studies on the topic that should be considered.

3.3. Programming methodologies used by traditional investigations

Comparing physical and structural changes produced by free-weight and machine-based modalities requires precise control of the other training variables capable of modulating long-term adaptations (e.g., relative intensity or intraset volume) (Jukic et al., 2023; Rodríguez-Rosell et al., 2021). To date, studies contrasting these training modalities have programmed the intensity by prescribing fixed weights (in kg) relative to a 1RM value determined at pre-training (Langford et al., 2007; Rossi et al., 2018). Nonetheless, since the initial 1RM usually increases throughout the intervention due to strength improvements (Riscart-Lopez et al., 2021; Rodríguez-Rosell et al., 2021), fixed weights prescribed to train at each target intensity would not accurately reflect it in most cases. On the other hand, traditional investigations comparing free-weight and machine-based exercises have programmed the intraset volume by prescribing a *n*RM value (e.g., 8RM or 12RM) (Saeterbakken et al., 2019; Wirth et al., 2016a, 2016b). By definition, the *n*RM method requires the practitioners to reach muscle failure in each training set, which could be dangerous (Santos et al., 2021), inefficient and even unfavorable to improve physical performance (Hernández-Belmonte & Pallarés, 2022).

Meaningful limitations around these conventional programming strategies could be solved by the velocity-based method. This methodology makes it possible to accurately program intensity by the L-V relationship (association between intensity and movement velocity), thus considering the practitioner's strength at each time point throughout an intervention (Riscart-Lopez et al., 2021; Rodríguez-Rosell et al., 2021). However, despite this step forward in the accurate intensity prescription, evidence on the L-V relationship of free-weight and machine-based modalities is limited (Hernández-Belmonte et al., 2022). Since the biomechanical characteristics of these modalities could affect the resulting velocity values, the accurate implementation of this velocity-based strategy during free-weight and machine-based exercises would require the previous analysis of their specific L-V relationships. On the other hand, the intraset volume could be precisely prescribed through the velocity loss approach (Sánchez-Medina & González-Badillo, 2011), which relies on monitoring the progressive decline of the execution velocity caused by a fatigue status (Westerblad et al., 1998). Nevertheless, the velocity loss approach requires i) highly reproducible technologies and protocols, ii) a coach trained in the use of this methodology, iii) a considerable deal of time for analyzing every single repetition, and iv) a prior familiarization of practitioners to perform all repetitions at maximal intended velocity (Hernández-Belmonte et al., 2022). All these aspects together would hinder the implementation of the velocity loss approach in contexts where many athletes are training simultaneously, thus making it necessary to examine more affordable and practical methodologies to accurately prescribe the intraset volume.

3.4. Modalities compared by traditional investigations

Some previous studies theoretically contrasting free-weight and machine-based modalities have compared different exercises rather than different modalities or freedoms of movement of the same exercise. For example, Wirth et al., (2016a, 2016b) and Rossi et al., (2018) compared the SQ and leg press, Augustsson et al., (1998) examined the SQ against the knee extension and hip adduction exercises, whereas Mayhew et al., (2010) contrasted the supine and horizontal chest presses. Similarly, other investigations have compared routines made up of exercises performed using free weights (e.g., dumbbell kickbacks) or a pulley (e.g., triceps press-down) (Schott et al., 2019). On the other hand, most of the free-weight and machine-based routines compared were composed of only one exercise (Cacchio et al., 2008; Saeterbakken et al., 2019, 2020; Schwarz et al., 2019). The latter aspect could have reduced the muscle synergies and hypertrophic environment generated during a comprehensive routine (Kraemer & Ratamess, 2005), thus weakening the findings obtained by these studies. Considering all these aspects together, it would be of great practical value to compare the effects of free-weight and machine-based modes by actually contrasting different modalities of the same exercise during a real-context routine.

3.5. Physical variables tested by traditional investigations

Strength changes produced by free-weight and machine-based modalities have mostly been limited to the 1RM variable (Cacchio et al., 2008; Mayhew et al., 2010; Rossi et al., 2018; Schwanbeck et al., 2020; Schwarz et al., 2019; Wirth et al., 2016a, 2016b). More importantly, this strength parameter has mostly been evaluated in the modality trained or even only in one of the two modalities compared (Schwarz et al., 2019; Wirth et al., 2016a, 2016b), which could lead to inaccurate conclusions due to the specificity principle.

Moreover, since the 1RM only informs about a single point within the force-velocity spectrum, it would lack information about the capacity of the subject to exert force against other resistances of different magnitudes (e.g., medium or low loads). On the other hand, information on athletic adaptations produced by both training modalities is scarce and heterogeneous. For example, there is evidence equally favouring free-weight (Wirth et al., 2016a, 2016b) and machine-based (Saeterbakken et al., 2019; Schwarz et al., 2019) RT for improving jumping capacity.

On the contrary, only one study has compared these training modalities on horizontal displacement (e.g., sprint or change of direction) (Schwarz et al., 2019) and balance capacities (Rossi et al., 2018). Similarly, no investigation to date has studied which modality would maximize upper-limb athletic abilities, whose information would be of great value to those sports highly dependent on this body part (e.g., rowing or swimming). Hence, it would be necessary to amplify the knowledge about physical performance changes produced by both modalities through a comprehensive battery of strength and athletic evaluations.

3.6. Musculoskeletal variables tested by traditional investigations

The higher acute muscle activity registered during free-weight exercises has also been used to support the superior efficacy of this modality to induce local hypertrophy (Vigotsky et al., 2022). Nevertheless, current evidence on the topic is reduced to two muscles (vastus lateralis and biceps brachii) (Saeterbakken et al., 2019; Schwanbeck et al., 2020) measured in a single point. It should be considered that training-derived muscle growth has shown to be inhomogeneous throughout these muscles (Earp et al., 2015; Pedrosa et al., 2023), so measuring muscle hypertrophy in a single point could lack the sensitivity to accurately detect this phenomenon (Franchi et al., 2018). Moreover, the aforementioned interventions used muscle thickness as the main hypertrophy parameter. Although muscle thickness is quick and practical when the panoramic option is not available, it is strongly influenced by different factors (e.g., the pressure exerted on the skin by the sonographer) (Sarto et al., 2021). All these aspects stand the need to extend information on possible differences in the hypertrophic capacity of free-weight and machine-based modalities by including more muscles and accurate evaluation parameters. Besides the scarce evidence on muscle hypertrophy, there is no information on whether muscle architecture could be meaningfully conditioned by training free-weight or machine-based exercises (Heidel et al., 2022). Elucidating the effect of the training modality on fascicle angle and length would be of great practical value due to the possible influence of these architectural parameters on athletic performance and risk of injury (Timmins et al., 2016).

OBJECTIVES AND HYPOTHESES

4. Objectives and hypotheses

The present Doctoral Thesis has multiple objectives and their corresponding hypotheses:

Objectives and hypotheses of Study I *(Articles 1 and 2)*

The general objective of Study I was to examine the suitability of velocity-derived strategies to program relative intensity and intraset volume in different modalities of SQ, BP, PBP, and SP exercises. For that purpose, Articles 1 and 2 had the following specific objectives:

i. To analyze and compare the L-V relationships of the free-weight and machine-based modalities of SQ, BP, PBP, and SP exercises (*Article 1*).

   Hypothesis*:* The adjustment of general and individual L-V relationships will be very high for both modalities of the four exercises. Nevertheless, we hypothesized that velocities attained to each relative intensity will be considerably different for the free-weight and machine-based modalities.

ii. To study the influence of the subject's strength level on L-V relationships of both modalities of SQ, BP, PBP, and SP exercises (*Article 1*).

   Hypothesis: Velocities derived from these L-V relationships will not be significantly influenced by the subject's strength level.

iii. To examine the suitability of the level of effort method to program the relative intensity and intraset volume in SQ, BP, PBP, and SP exercises (*Article 2*).

   Hypothesis*:* We hypothesized to find a reduced inter and intrasubject variability in nRM completed at each relative intensity (2^{nd} factor of the level of effort equation), as well as a close association between the number of repetitions completed and intraset velocity loss (1st factor of the level of effort equation).

Objectives and hypotheses of Study II *(Articles 3, 4 and 5)*

The general objective of Study II was to examine the validity and repeatability of panoramic ultrasound to measure ACSA of the main upper- and lower-limb muscles. For that purpose, Articles 3, 4, and 5 had the following specific objectives:

i. To quantify the errors made when acquiring and analyzing ultrasound-derived ACSA of the pectoralis major (*Article 3*) and quadriceps femoris (*Article 4*).

   Hypothesis*:* For both muscles, we hypothesized that errors made during these two procedures will be small. In particular, we expect to find a higher error magnitude during the image acquisition than during its analysis.

ii. To analyze the agreement between pectoralis *(Article 3)* and quadriceps femoris (*Article 4 and 5*) ACSA measured by panoramic ultrasound and MRI.

   Hypothesis*:* For both muscles, we expect to find a high level of agreement between ACSA obtained by ultrasound and MRI techniques.

iii. To examine the influence of the sonographer's experience on errors made when acquiring and analyzing ACSA of the pectoralis major (*Article 3*) and quadriceps femoris (*Article 4*) using ultrasound.

   Hypothesis*:* We hypothesized that the magnitude of error made by the trained and novice sonographers will be small enough to implement this technique to measure the ACSA of both muscles. Nevertheless, we expect that the trained sonographer will fewer errors, especially during image acquisition.

iv. To study the validity and repeatability of two approaches of the 2-point method (using the 30-60% or the 20-70% thigh regions) for estimating ultrasound-derived ACSA of quadriceps femoris (*Article 5*).

Hypothesis*:* The validity and repeatability of these two approaches, especially the one implemented using the 30-60% regions, will be high enough to be used for expediting the multi-region evaluation of the quadriceps femoris ACSA.

Objectives and hypotheses of Study III *(Articles 6 and 7)*

To study the effect of free-weight and machine-based training on physical performance and muscle structure. To address this general objective, Articles 6 and 7 had the following specific objectives:

i. To compare the effects of both training modalities on athletic performance and muscle architecture (*Article 6*).

Hypothesis*:* We postulated that these adaptations would not be significantly influenced by using free-weight or machines to perform resistance exercises.

ii. To compare the effects of free-weight and machine-based RT on strength, muscle hypertrophy, and discomfort levels (*Article 7*).

Hypothesis*:* We expect to find both modalities similarly effective in favoring these adaptations. For strength, we postulated that each group will achieve the highest improvements in the modality trained (i.e., specificity principle). Regarding pain levels, we hypothesized that participants training by using machines will considerably increase their level of lower- and upper-limb joint discomfort.

STUDY 1

5. Study I

Article 1: Velocity-based method in free-weight and machine-based training modalities: The degree of freedom matters

Journal of Strength and Conditioning Research

Abstract

This study aimed to analyze and compare the load-velocity relationships of free-weight and machine-based modalities of 4 resistance exercises. Moreover, we examined the influence of the subject's strength level on these load-velocity relationships. Fifty men completed a loading test in the free-weight and machine-based modalities of the bench press, full squat, shoulder press, and prone bench pull exercises. General and individual relationships between relative intensity (%1RM) and velocity variables were studied through the coefficient of determination (R^2) and standard error of the estimate (SEE). Moreover, the velocity attained to each %1RM was compared between both modalities. Subjects were divided into stronger and weaker to study whether the subject's strength level influences the mean test (mean propulsive velocity [MPV_{Test}]) and 1RM (MPV_{1RM}) velocities. For both modalities, very close relationships ($R^2 \geq 0.95$) and reduced estimation errors were found when velocity was analyzed as a dependent (SEE ≤ 0.086 $m \cdot s^{-1}$) and independent (SEE ≤ 5.7% 1RM) variable concerning the %1RM. Fits were found to be higher ($R^2 \geq 0.995$) for individual load-velocity relationships. Concerning the between-modality comparison, the velocity attained at each intensity (from 30 to 100% 1RM) was significantly faster for the free-weight variant. Finally, nonsignificant differences were found when comparing MPV_{Test} (differences ≤ 0.02 $m \cdot s^{-1}$) and MPV_{1RM} (differences ≤ 0.01 $m \cdot s^{-1}$) between stronger and weaker subjects. These findings prove the accuracy and stability of the velocity-based method in the free-weight and machine-based variants but highlight the need to use the load-velocity relationship (preferably the individual one) specific to each training.

Keywords: Strength training, Load-velocity relationship, Programming, Intensity, Athlete.

Link: https://pubmed.ncbi.nlm.nih.gov/37015023/

Article 2: Level of effort: A reliable and practical alternative to the velocity-based approach for monitoring resistance training

Journal of Strength and Conditioning Research

Abstract

This study analyzed the potential of the level of effort methodology as an accurate indicator of the programmed relative load (percentage of one-repetition maximum [%1RM]) and intraset volume of the set during resistance training in the bench press, full squat, shoulder press, and prone bench pull exercises, through 3 specific objectives: (a) to examine the intersubject and intra- subject variability in the number of repetitions to failure (*n*RM) against the actual %1RM lifted (adjusted by the individual velocity), (b) to investigate the relationship between the number of repetitions completed and velocity loss reached, and (c) to study the influence of the subject's strength level on the aforementioned parameters. After determining their individual load-velocity relationships, 30 subjects with low (n = 10), medium (n = 10), and high (n = 10) relative strength levels completed 2 rounds of *n*RM tests against their 65, 75, 85, and 95% 1RM in the 4 exercises. The velocity of all repetitions was monitored using a linear transducer. Intersubject and intrasubject variability analyses included the 95% confidence intervals (CI) and the standard error of measurement (SEM), respectively. Coefficient of determination (R^2) was used as the indicator of relationship. *n*RM showed a limited intersubject (CI ≤ 4 repetitions) and a very low intrasubject (SEM ≤ 1.9 repetitions) variability for all the strength levels, %1RM, and exercises analyzed. A very close relationship ($R^2 \geq 0.97$) between the number of repetitions completed and the percentage of velocity loss reached (from 10 to 60%) was found. These findings strengthen the level of effort as a reliable, precise, and practical strategy for programming resistance training.

Keywords: Repetitions in reserve, Intensity, Volume, Training to failure, Strength training, Barbell velocity.

Link: https://pubmed.ncbi.nlm.nih.gov/34027915/

STUDY 2

6. Study II

Article 3: Pectoralis cross-sectional area can be accurately measured using ultrasound: A validity and repeatability study

Ultrasound in Medicine & Biology

Abstract

The objective of the current study was to examine the validity and repeatability of panoramic ultrasound in evaluating the anatomical cross-sectional area (ACSA) of the pectoralis major. Specifically, we aimed to quantify the measurement errors generated during the image acquisition and analysis (repeatability), as well as when comparing with magnetic resonance imaging (MRI) (validity). Moreover, we aimed to analyze the influence of the operator's experience on these measurement errors. Both sides of the chest of 16 participants (n = 32) were included. Errors made by two operators (trained and novice) when measuring pectoralis major ACSA (50% of sternum-areola mammae distance) were examined. Acquisition errors included the comparison of two images acquired 5 min apart. Acquisition 1 was analyzed twice to quantify analysis errors. Thereafter, acquisition 1 was compared with MRI. Statistics include the standard error of measurement (SEM), expressed in absolute (cm^2) and relative (%) terms as a coefficient of variation (CV), and the calculation of systematic bias. Errors made by the trained operator were lower than those made by the novice, especially during the image acquisition (SEM = 0.25 vs. 0.66 cm^2, CV = 1.06 vs. 2.98%) and when compared with MRI (SEM = 0.27 vs. 1.90 cm^2, CV = 1.13 vs. 8.16%). Furthermore, although both operators underestimated the ACSA, magnitude and variability [SD] of these errors were lower for the trained operator (bias = -0.19 [0.34] cm^2) than for the novice (bias = -1.97

[2.59] cm^2). Panoramic ultrasound is a valid and repeatable technique for measuring pectoralis major ACSA, especially when implemented by a trained operator.

Keywords: Extended field of view, Hypertrophy, Atrophy, Muscle mass, Physiology, Reliability.

Link: https://pubmed.ncbi.nlm.nih.gov/34857426/

Article 4: Panoramic ultrasound requires a trained operator and specific evaluation sites to maximize its sensitivity: A comprehensive analysis of the measurement errors

Physiology & Behavior

Abstract

This study aimed to examine the validity and repeatability of panoramic ultrasound to evaluate the anatomical cross-sectional area (ACSA) of quadriceps femoris muscles. Specifically, we aimed to quantify the errors generated during the image acquisition and analysis (repeatability), as well as when comparing with magnetic resonance imaging (MRI) (validity). Moreover, we analyzed the influence of the operator's experience and the region of the thigh, on these errors. Both thighs of 16 subjects were included. The validity and repeatability study quantified the errors made by two operators (trained and novice) when measuring ACSA of vastus lateralis (VL), vastus medialis-intermedius (VMVI), and rectus femoris (RF), in six thigh regions (from 20 to 70%). Two ACSA images were acquired 5 min apart to examine acquisition errors, whereas acquisition #1 was analyzed twice to quantify analysis errors. Thereafter, ACSA of acquisition #1 was compared with that measured by MRI. Statistics included the standard error of measurement (SEM) expressed in absolute (cm^2) and relative terms (%) as a coefficient of variation (CV). Measurement errors were lower for the trained operator than for the novice: Acquisition (SEM = 0.05 – 0.78 vs. 0.25 – 1.42 cm^2), analysis (SEM = 0.03 – 0.34 vs. 0.10 – 0.87 cm^2) and compared-with-MRI (SEM = 0.13 – 1.93 vs. 0.30 – 3.05 cm^2). Regions with the lowest errors were those located at the middle of the thigh (40–50%), although slight between-muscle differences were found: VMVI (30–40%), VL (40–50%), RF (50–60%). These findings suggest that the accurate implementation of panoramic ultrasound to measure ACSA of quadriceps femoris muscles requires a trained operator and specific evaluation sites.

Keywords: Extended field of view, Hypertrophy, Atrophy, Cross-sectional area, Physiology, Reliability.

Link: https://pubmed.ncbi.nlm.nih.gov/35150708/

Article 5: The 2-Point Method: A Quick, Accurate, and Repeatable Approach to Estimate Ultrasound-Derived Quadriceps Femoris Cross-Sectional Area

International Journal of Sports Physiology and Performance

Abstract

Purpose: To analyze the feasibility of the 2-point method for estimating ultrasound-derived quadriceps femoris cross-sectional area ($QUAD_{ACSA}$). First, (1) the agreement between $QUAD_{ACSA}$ measured by panoramic ultrasound and magnetic resonance imaging (MRI) was studied, and thereafter, we examined 2 approaches of the 2-point method in terms of (2) estimation errors and (3) test-retest repeatability. **Methods:** Both thighs of 16 young men were analyzed. Ultrasound-$QUAD_{ACSA}$ versus MRI-$QUADA_{CSA}$ comparison was conducted at 6 thigh lengths (20%–70% of the thigh length). Thereafter, ultrasound-$QUAD_{ACSA}$ corresponding to 30% and 60% (2-$point_{30\%–60\%}$) or 20% and 70% (2-$point_{20\%–70\%}$) were used to estimate $QUAD_{ACSA}$ of the remaining regions. Estimated $QUAD_{ACSA}$ resulting from both 2-point approaches was compared with the measured one. Finally, the test-retest repeatability was examined by comparing the errors generated on 2 separate estimations. Statistics included the standard error of measurement (SEM) expressed in absolute (in square centimeters) and relative terms (in percentage) as a coefficient of variation (CV), as well as the intraclass correlation coefficient (ICC) and bias. **Results:** An excellent agreement (ICC ≥ 0.980) and reduced errors (SEM ≤ 2.43 cm^2) resulted from the ultrasound-$QUAD_{ACSA}$ versus MRI-$QUAD_{ACSA}$ comparison. Although estimation errors found were reduced (CV ≤ 7.50%), they proved to be lower and less biased for the 2-$point_{30\%-60\%}$, especially at the central regions (SEM ≤ 2.01 cm^2; bias ≤ 0.89 cm^2). Similarly, repeatability analysis revealed lower test-retest errors for the 2-$point_{30\%-60\%}$ (CV ≤ 1.9%) than for the 2-$point_{20\%-70\%}$ (CV ≤ 4.6%). **Conclusion:** The 2-

point method, especially that implemented using the 30% and 60% regions, represents an accurate and repeatable strategy to evaluate $QUAD_{ACSA}$.

Keywords: Atrophy, Extended field of view, Hypertrophy, Reliability, Testing.

Link: https://pubmed.ncbi.nlm.nih.gov/35894906/

STUDY 3

7. Study III

Article 6: Adaptations in athletic performance and muscle architecture are not meaningfully conditioned by training free-weight versus machine-based exercises: Challenging a traditional assumption using the velocity-based method

Scandinavian Journal of Medicine & Science In Sports

Abstract

Background: Although the superior effectiveness of free-weight over machine-based training has been a traditionally widespread assumption, longitudinal studies comparing these training modalities were scarce and heterogeneous. Objective: This research used the velocity-based method to compare the effects of free-weight and machine-based resistance training on athletic performance and muscle architecture.

Methods: Thirty-four resistance-trained men participated in an 8-week resistance training program allocated into free-weight (n = 17) or machine-based (n = 17) groups. Training variables (intensity, intraset fatigue, and recovery) were identical for both groups, so they only differed in the use of a barbell or specific machines to execute the full squat, bench press, prone bench pull, and shoulder press exercises. The velocity-based method was implemented to accurately adjust the planned intensity. Analysis of covariance and effect size (ES) statistics were used to compare both training modalities on a comprehensive set of athletic and muscle architecture parameters.

Results: No between-group differences were found for any athletic ($p \geq 0.146$) and muscle architecture ($p \geq 0.184$) variable. Both training modalities significantly and similarly improved vertical jump (Free-weight: ES ≥ 0.45, $p \leq 0.001$; Machine-based: ES ≥ 0.41, $p \leq 0.001$) and lower limb anaerobic capacity (Free- weight: ES ≥ 0.39, $p \leq 0.007$;

Machine-based: ES $\geq$ 0.31, $p \leq 0.003$). Additionally, the machine-based group meaningfully enhanced upper limb anaerobic power (ES = 0.41, $p = 0.021$), whereas the free-weight group significantly improved the change of direction (ES = -0.54, $p = 0.003$) and 2/6 balance conditions analyzed ($p \leq 0.012$). Changes in sprint capacity (ES $\geq$ -0.13, $p \geq 0.274$), fascicle length, and pennation angle (ES $\leq$ 0.19, $p \geq 0.129$) were not significant for either training modality.

Conclusion: Adaptations in athletic performance and muscle architecture would not be meaningfully influenced by the resistance modality trained.

Keywords: Fascicle length, Jump, Pennation angle, Sprint, Training modality.

Link: https://pubmed.ncbi.nlm.nih.gov/37340878/

Article 7: Free-weight and machine-based training are equally effective on strength and hypertrophy: Challenging a traditional myth

Under Review in Medicine & Science in Sports & Exercise journal

Free-weight and machine-based training are equally effective on strength and hypertrophy: Challenging a traditional myth

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ABSTRACT

Purpose: To compare the effects of free-weight and machine-based resistance training on strength, hypertrophy, and joint discomfort**. Methods:** Thirty-eight resistance-trained men participated in an 8-week resistance program allocated into free-weight (n=19) or machine-based (n=19) groups. Training variables were identical for both modalities, so they only differed in the use of barbells or machines to execute the full squat, bench press, prone bench pull, and shoulder press exercises. The velocity-based method was implemented to accurately adjust the intensity throughout the program. Strength changes were evaluated using 8 velocity-monitored loading tests (4 exercises x 2 modalities) and included the relative one-repetition maximum ($1RM_{Rel}$), as well as the mean propulsive velocity against low (MPV_{Low}) and high (MPV_{High}) loads. Ultrasound-derived cross-sectional area (CSA) of quadriceps (proximal and distal regions), pectoralis major, and rectus abdominis was measured to examine hypertrophy. Complementarily, WOMAC and DASH questionnaires were administrated to assess changes in lower- and upper-limb joint discomfort. Outcomes were compared using ANCOVA and percentage of change (Δ) statistics. **Results:** Each group significantly ($p < 0.001$) increased $1RM_{Rel}$, MPV_{Low}, and MPV_{High} for both modalities tested, but especially in the one they trained. When considering together the 8 exercises tested, strength changes for both modalities were similar (Δ differences ≤ 1.8%, $p \geq 0.216$). Likewise, the CSA of all the muscles evaluated was significantly increased by both modalities, with no significant differences between them (Δ difference ≤ 2.0%, $p \geq 0.208$). No between-group differences ($p \geq 0.144$) were found for changes in stiffness, pain, and functional disability levels, which were reduced by both modalities. **Conclusions:** Free-weight and machine-based modalities are similarly effective to promote strength and hypertrophy without increasing joint discomfort.

KEYWORDS: degree of freedom, load-velocity, one-repetition maximum, cross-sectional area, muscle mass, injury.

INTRODUCTION

Strength and hypertrophy adaptations derived from resistance training have proved to be modulated by technical factors like the range of motion (1,2), movement tempo (3), or strategy used between concentric and eccentric phases of the execution. Another technical factor postulated by practitioners as influencing these adaptations would be the modality used to perform resistance exercises (i.e., free-weight or machine-based modes). Traditionally, the greater acute muscle activity produced in agonist/synergist (4,5) and trunk (6) muscles during free-weight exercises has been used to support the superior effectiveness of this modality for increasing strength and muscle mass (7,8). However, results from intervention studies comparing the effectiveness of these modalities question this widespread belief (9,10).

A recent meta-analysis on the topic found that neither strength nor muscle hypertrophy was meaningfully influenced by the resistance modality trained (i.e., free-weight vs. machine-based) (11). However, this meta-analysis also highlighted some methodological aspects of included studies that should be considered. For example, some training interventions compared different exercises (e.g., squat vs. leg press or knee extension) rather than different degrees of freedom or modalities of the same exercise (10,12–14). Other studies based their training routine on a single exercise (15–18), thus reducing to some extent the ecological validity of their findings. Regarding the outcomes compared between free-weight and machine-based modalities, strength changes have mostly been limited to the one-repetition maximum (1RM) variable (9,10,12,13,15,17,19), which would only inform on an individual point within the force-velocity relationship (i.e., maximal dynamic strength). More importantly, this 1RM has been mostly evaluated in the modality trained or even only in one of the two modalities compared (12,13,15), thus making it difficult to accurately compare free-weight and machine-based modes due to the specificity principle (11,20). On the other hand, information to date on local hypertrophy produced by both training modalities is reduced to two muscles (vastus lateralis and biceps brachii) (9,16) measured in a single point, which would not take into account possible regional hypertrophy produced by each training mode (21,22). In addition to all this, there is no prior evidence on whether the biomechanical characteristics of these modalities could increase joint discomfort symptoms and therefore possible long-term injuries of practitioners. Therefore, it would be of great practical value to compare the effects of free-weight and machine-based modalities by training a real-context resistance routine and including a comprehensive battery of strength, hypertrophy, and discomfort measurements.

An exhaustive comparison of the adaptations produced by these resistance training modalities would require the use of a reliable method to control other training parameters capable of modulating long-term adaptations (e.g., intensity or intra-set volume) (23,24). A proper methodology for this purpose would be the velocity-based method, which has recently been found highly accurate to be implemented in free-weight and machine-based training modalities (25). This methodology would allow researchers to use the load-velocity relationship to accurately program intensity, thus avoiding the mismatches that normally occur when this parameter is solely programmed by using fixed weights relative to the pre-training 1RM (26). On the other hand, most previous investigations comparing free-weight and machine-based modalities set intra-set volume by prescribing a given number of repetitions to failure (e.g., 8RM) (12,13,16), which could be dangerous (27), inefficient (23), and even detrimental to neuromuscular performance (26). This limitation on the *n*RM methodology could be solved by using different velocity-derived strategies, such as the velocity loss (28), effort index (29) or level of effort (30), which make it possible to program different intra-set volume thresholds. In summary, the use of the velocity-based strategy would represent an important step forward to exhaustively isolate the main independent variable (training modality) by accurately matching the rest of the training parameters between both groups. Therefore, this study conducted a velocity-based intervention to compare the effects of free-weight and machine-based resistance training on strength, hypertrophy, and joint discomfort.

METHODS

Experimental design

After a familiarization period, free-weight and machine-based groups trained 3 sessions per week for 8 weeks, using the full squat (SQ), bench press (BP), prone bench pull (PBP), and seated shoulder press (SP) exercises. All training variables (intensity, intraset volume, number of sets, interset and between-sessions recoveries) were identical for both groups. Therefore, they only differed in the use of barbells or specific machines for performing the SQ, BP, PBP, and SP exercises. Velocity was measured to accurately adjust the planned intensity for each training modality. The changes generated by both groups were examined using a comprehensive set of strength and muscle mass evaluations measured before (T1) and after (T2) the training program. Complementarily, questionnaires were used to examine possible changes in upper-and lower-limb joint discomfort produced by each training modality.

Subjects

Thirty-eight resistance-trained men volunteered to take part in this study. Inclusion criteria were: i) having at least two years experience training the modalities examined, ii) not taking drugs or dietary supplements known to influence physical performance throughout the study; iii) not having physical limitations, disease, or health problems that could affect the testing or training sessions; and iv) not conducting any other resistance exercise during the time this research lasted. To assign the subjects to each training modality, their relative strength ($1RM_{Rel}$, 1RM divided by body mass) in the 8 exercises (4 exercises x 2 modalities) was measured during the initial evaluation. Thereafter, subjects were ordered from highest to lowest total $1RM_{Rel}$

(considering the 8 exercises) and allocated through stratified randomization into the free-weight group (n = 19) or machine-based group (n = 19) (Figure 1). One subject from each group dropped out during the training program for personal reasons not related to the training program. Compliance with the training intervention was ≥ 95.8% (≥ 23/24 sessions) for the rest of the subjects. Subjects from both groups were urged to consume > 1.2g/kg of protein in their daily diet according to the last ACSM statement (31). The study was conducted according to the Declaration of Helsinki and approved by the Ethics Commission of the Local University (ID: 3592/2021). All subjects signed a written consent form after being informed of the purpose and experimental procedures.

---- Figure 1 ----

Resistance training program

All subjects completed a 2-week familiarization period. During six sessions, they were instructed in the lifting technique of both modalities of resistance exercises, focusing on performing the concentric phase at maximal intended velocity while completing the full range of motion. After this familiarization phase and the initial evaluations (described later in detail), both groups completed an 8-week resistance training program only differing in the modality used to perform the four exercises: free-weight (SQ_{Free}, BP_{Free}, PBP_{Free}, and SP_{Free}) or machine-based ($SQ_{Machine}$, $BP_{Machine}$, $PBP_{Machine}$, and $SP_{Machine}$). The free-weight group performed the four exercises using a 20-kg bar, at which extra load was added by sliding calibrated weight discs (Eleiko, Sport AB, Halmstad, Sweden). The machine-based group performed each exercise by using a specific machine that mimicked the trajectory achieved with free weights. Except for the hack used in the $SQ_{Machine}$, which was loaded using calibrated discs, the weight stacks already installed in the machines were used for adding extra load to this modality. A comprehensive technical description and graphical representation of each exercise were provided elsewhere (25).

The frequency (3 sessions per week), number of sets (3 per exercise), interset recoveries (4 min), between-sessions rest (48 h), intra-set volume (half of the possible repetitions), total volume (1494 repetitions), and intensity (65 to 85% 1RM, linear programming) were identical for both training modalities. To increase the accuracy on each target intensity, the velocity attained in the first two repetitions (usually the fastest) of each exercise was measured at the first session of each intensity: session 1 (65% 1RM), session 6 (70% 1RM), session 11 (75% 1RM), session 15 (80% 1RM), and session 20 (85% 1RM). In these velocity-controlled sessions, the absolute load (in kilograms) was individually adjusted to match the mean propulsive velocity (MPV) (32) associated with the planned intensity for that day (± 0.03 $m\cdot s^{-1}$), according to the individual load–velocity relationship determined at T1. Once the specific absolute load was adjusted, it was used in subsequent sessions programmed with the same intensity. In turn, the intraset volume of all training sets corresponded to half of the total repetitions possible at each intensity, which would result in a velocity loss of ∼20% (30). This level of intra-set fatigue has been shown to be an effective and efficient stimulus to promote strength and hypertrophy adaptations (28). Subjects were required to complete the concentric phase of each repetition at the maximal intended velocity and using the full range of motion. All sets were supervised by two experienced researchers who verified adequate compliance with the aforementioned training parameters and gave feedback to the participants when appropriate.

Testing procedures

Muscle hypertrophy

Seventy-two hours after the last training session, the panoramic option of an ultrasound device (Versana Premier™, GE Healthcare, Chicago, IL, USA) was used to examine the changes in the anatomical cross-sectional area (CSA) of quadriceps femoris (right leg), pectoralis major (both sides) and rectus abdominis muscles. Images were acquired in the axial (quadriceps femoris and rectus abdominis) and longitudinal (pectoralis major) planes through a linear-array probe (38 mm field of view). Once at the laboratory, subjects rested supine on an examination bed with their knees fully extended (0° flexion), arms outstretched on both sides of the body and forearms in a prone position. After a time interval of 20 min to allow fluid shift stabilization, a trained sonographer marked the target regions. To consider possible regional hypertrophy in the quadriceps femoris (21), it was measured at 30% (proximal to the knee) and 60% (proximal to the hip) of the distance between the greater trochanter and mid patella. These thigh sites were found to be valid and highly repeatable to measure quadriceps femoris CSA (33). The CSA of each pectoralis major was measured at 50% of the sternum-areola distance (34), whereas rectus abdominis CSA was evaluated at the level of the fourth and fifth lumbar vertebrae (35). For each participant, the aforementioned evaluation sites were registered on a transparent acetate sheet at T1 to be traced back onto their skin at T2. Moreover, frequencies (range 8-13 MHz) and depths (range 6-10 cm) of the images were individually configured for each participant and held constant at both time points. For image acquisition, the sonographer moved the probe at a constant velocity, trying to maintain probe-skin contact and applying minimal pressure throughout the entire displacement. Reference guides were adhered to the participant's skin on both sides of each target region to avoid possible deviations during the image acquisition.

The CSA analysis was made by tracing the aponeurosis of each muscle using the polygon selection function of the public domain software ImageJ (v1.53a, National Institute of Health, USA). The average CSA value (in cm^2) obtained from two images was considered for further analysis, measuring and considering a third one when the coefficient of variation (CV) was higher than 5% (28).

Progressive loading test

To consider the specificity principle when comparing modalities (11), subjects from both groups completed a velocity-monitored loading test up to the 1RM for the free-weight and machine-based variants of SQ, BP, PBP, and SP exercises. A detailed description of the loading testing protocols was provided elsewhere (25). Briefly, the initial load (20 kg) was gradually augmented in 10-kg (SP) or 15-kg (SQ, BP, PBP) increments until the attained MPV was ≤ 0.5 $m\cdot s^{-1}$ (BP), ≤ 0.6 $m\cdot s^{-1}$ (SQ and SP), or ≤ 0.8 $m\cdot s^{-1}$ (PBP). Then, the load was individually adjusted in smaller increments (5 down to 2.5 kg) until reaching the heaviest load that each subject could properly lift completing the full range of motion (i.e., 1RM). Three repetitions were executed for light (<50% 1RM), 2 for medium (50%-80% 1RM), and 1 for the heaviest (>80% 1RM) loads. Interset rest intervals were 3 minutes for the light and medium loads (<80% 1RM) and 5 minutes for the heaviest loads (>80% 1RM). Only the best repetition (the fastest and correctly executed) at each load was considered for subsequent analysis. Participants were required to perform the concentric phase of each repetition at maximal velocity and the eccentric phase at a controlled velocity between 0.50-0.70 $m\cdot s^{-1}$. All repetitions were recorded using a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain) (36). During the free-weight exercises, this device was mounted on a rail that moved horizontally to favor the displacement of the measuring cable in the vertical plane. For the machine-based exercises, the linear velocity transducer was attached to the handles (BP, SP, and PBP) and the back of the backrest (SQ) to favor that the cable moved linearly (25).

To evaluate strength changes throughout a wide region of the force-velocity spectrum, the following variables were obtained from each of the 8 loading tests: $1RM_{Rel}$, average MPV attained against absolute loads lower than 60% 1RM common to T1 and T2 (MPV_{Low}), and average MPV attained against absolute loads higher than 60% 1RM common to T1 and T2 (MPV_{High}). Furthermore, loading tests were used to describe the individual load-velocity relationship for each subject, which was subsequently used for adjusting intensity during the training intervention.

Discomfort levels

The Western Ontario and McMaster Universities (WOMAC) (37) and the Disabilities of the Arm, Shoulder and Hand (DASH) (38) questionnaires were used to assess possible changes in lower- and upper-limb joint discomfort, respectively. Both questionnaires are composed of queries referring to stiffness, pain and physical disability symptoms. The average score considering all the queries included in each questionnaire was considered for further analysis. At both T1 and T2, questionnaires were administrated at the first evaluation session (i.e., before the loading tests).

Statistical analyses

Normality and homoscedasticity were verified with Shapiro–Wilk and Levene's tests, respectively. A 2 (group) × 2 (time) factorial analysis of covariance (ANCOVA), controlled by the score of each dependent variable at T1 (covariate), was conducted to examine between-group differences. Bonferroni's post hoc adjustment was used when significant differences ($p \leq 0.05$) were detected. The ES was obtained from mean T2–T1 differences and corrected for small sample bias (i.e., Hedges'*g*) (39). The percentage of change (Δ) was calculated as ((mean T2–mean T1)/mean T1) × 100. The CV for examining inter-image CSA agreement was obtained as (between-images SD/mean) × 100. The standard error of measurement (SEM) of the sonographer that acquired and analyzed the ultrasound images, already published for quadriceps femoris (30% region, SEM = ± 0.68 cm^2; 60% region, SEM = ± 1.00 cm^2) (33) and pectoralis major (SEM = ± 0.25 cm^2) (34), was used as the minimum threshold beyond which a real change in CSA could be assumed (40). Moreover, using the two different images analyzed at T1, the SEM for the rectus abdominis muscle was calculated from the square root of the mean square error term in a repeated-measures analysis of variance resulting in ± 0.16 cm^2. Statistical analyses were performed using the SPSS software (version 26.0, IBM Corp), and figures were designed using the GraphPad Prism software (version 6.0, GraphPad Software Inc).

RESULTS

Strength changes

Each group achieved the highest $1RM_{Rel}$ enhancements in the modality trained, although they also significantly ($p < 0.001$) improved the non-trained one (Figure 2). However, no significant "group × time" interaction was found for any of the 8 exercises (4 exercises x 2 modalities) concerning $1RM_{Rel}$ ($p \geq 0.100$, F-value ≤ 2.489). When considering together the 8 exercises tested, the change in $1RM_{Rel}$ produced by free-weight and machine-based modalities were similar (Δ of both groups = 11.2%, $p \geq 0.826$, F-value = 0.048).

---- Figure 2 ----

Likewise, each training group significantly ($p < 0.001$) increased MPV_{Low} and MPV_{High} for both modalities tested, but especially in the one they trained (Figures 3 and 4). The free-weight group achieved higher enhancements compared with the machine-based group when velocity variables were tested in free-weight exercises: MPV_{Low} (mean Δ = 11.3% vs. 9.0%) and MPV_{High} (mean Δ = 23.2% vs. 21.0%). A significant "group × time" interaction was found in the SP_{Free} exercise favoring the free-weight group: MPV_{Low} ($p = 0.001$) and MPV_{High} ($p = 0.037$). On the contrary, changes in velocity variables when tested on machine-based exercises were greater but not statistically different for the group training this modality: MPV_{Low} (mean Δ = 11.0% vs. 8.2%) and MPV_{High} (mean Δ = 25.7% vs. 18.2%). When considering together the 8 exercises tested, changes produced by two training modalities on MPV_{Low} (Δ difference

= 1.8%, p = 0.216, F-value = 1.668) and MPV_{High} (Δ difference = 1.6%, p = 0.584, F-value = 0.301) were found to be similar.

---- Figure 3 ----

---- Figure 4 ----

Muscle hypertrophy

The CV resulting from inter-image CSA analysis (i.e., repeatability) was: quadriceps 30% region (T1, ≤ 2.3%; T2, ≤ 2.7%), quadriceps 60% region (T1, ≤ 1.7 %; T2, ≤ 2.5%), pectoralis major (T1, ≤ 3.7%; T2, ≤ 3.9%), rectus abdominis (T1, ≤ 4.8%; T2, ≤ 4.0%). Both training modalities significantly increased the CSA of all the muscles evaluated, especially for the pectoralis major (Δ ≥ 12.6%, p ≤ 0.001, Figure 5B). Changes achieved by both groups in the proximal (Δ ≥ 3.4%, p ≤ 0.001, Figure 6B) and distal (Δ ≥ 3.5%, p ≤ 0.001, Figure 6E) quadriceps regions, as well as in rectus abdominis (Δ ≥ 2.3%, p ≤ 0.027, Figure 7B), were smaller but also statistically significant. Overall, CSA increases were found to be similar for both training modalities: pectoralis major (Δ difference = 1.2%, F-value = 0.605), quadriceps femoris (Δ differences ≤ 2.0%, F-value ≤ 1.653), and rectus abdominis (Δ difference = 0.2%, F-value = 0.029).

---- Figure 5 ----

---- Figure 6 ----

---- Figure 7 ----

Discomfort levels

When considering total scores, discomfort levels significantly decreased in the free-weight (lower limb: ES [95%] = -0.49 [-1.15 to 0.17], $p = 0.003$; upper limb: ES [95%] = -0.46 [-1.12 to 0.20], $p = 0.015$) and machine-based (lower limb: ES [95%] = -0.61 [-1.28 to 0.06], $p < 0.001$; upper limb: ES [95%] = -0.33 [-0.99 to 0.33], $p = 0.035$) groups, with no significant differences between them ($p \geq 0.483$, F-value ≤ 0.503). Detailed information on changes in upper-and lower-limb stiffness, pain, and functional disability was included in Supplemental Material 1.

DISCUSSION

The main findings of the current research were: i) free-weight and machine-based groups achieved the highest $1RM_{Rel}$, MPV_{Low}, and MPV_{High} enhancements in the modality trained (i.e., specificity principle), although ii) they also significantly improved the non-trained one. Considering together the 8 exercises tested, iii) strength changes achieved by both training modalities were similar. Furthermore, this study found significant and similar effectiveness of both training modalities iv) to increase CSA of quadriceps femoris, pectoralis major, and rectus abdominis muscles, as well as v) to reduce joint discomfort symptoms. These findings together suggest that free-weight and machine-based training modalities are similarly effective to promote strength and hypertrophy without increasing joint discomfort. Therefore, in practice, athletes could favor these adaptations by training either of these two modalities depending on their possibilities or preferences.

Contrary to traditional beliefs (7,8), this research found that free-weight and machine-based modalities were similarly effective to increase strength capacity throughout a wide region of the force-velocity spectrum (Δ differences $\leq$ 1.8%, Figures 2-4). The assumed superiority of free-weight modality conventionally widespread among practitioners has been mostly based on i) longitudinal studies testing only free-weight exercises as a dependent variable (12,13,15) and ii) acute investigations attributing a greater muscle activity to this modality (4–6). Regarding the modality tested, results of the current study, together with those obtained by a recent meta-analysis on the topic (11), demonstrated that comparing free-weight and machine-based modalities by testing only one of them (mostly free-weight) could lead to inaccurate conclusions due to the specificity principle (Figures 2-4). Indeed, the aforementioned meta-analysis also reported trivial differences (ES = 0.13) between the two training modalities when their strength changes were examined in a nonspecific test (e.g., isometric or isokinetic test) (11). Concerning the muscle activity theory traditionally used to favor free-weight exercises (7,8), it is important to note that higher muscle activity in an acute manner should not necessarily translate into greater long-term strength adaptations (41). All these findings together show that, except for sports disciplines that specifically compete using free-weight exercises (i.e., powerlifting or weightlifting) which would benefit the most from training in this modality, athletes could choose any of these modalities to similarly improve strength capacity.

Considering that muscle mass would explain ~ 60-70% of strength levels (42), it could be possible that part of the aforementioned strength gains come from the significant CSA increases achieved by both training modalities. Overall, these CSA changes were similar for both groups (Δ differences ≤ 2.0%, Figures 5-7), which agrees with that reported by the above-presented meta-analysis on the topic (11). To date, the higher acute activity detected in both agonist-synergist (4,5) and trunk (6) muscles during free-weight exercises has also been used to promote the superior efficacy of this modality for muscle gains. However, similar to strength, inferring longitudinal hypertrophy adaptations from acute comparisons of muscle activity should be avoided (41). To the best of our knowledge, this is the first research comparing hypertrophy levels produced by free-weight and machine-based modalities i) in pectoralis major and rectus abdominis muscles, ii) including CSA instead of muscle thickness (which would only inform on one dimension of the muscle (43)), and iii) considering possible regional hypertrophy for quadriceps femoris (22).

Importantly, it should be noted that our research compared both modalities by training a comprehensive routine made up of four common exercises, which were performed at a full range of motion and accurately monitored using the velocity-based method. The inclusion of these upper-and lower-limb exercises allowed the present study not only to examine the effects of the training modality on each of them individually but also to study the possible synergies and interrelationships generated during a real-context routine. Moreover, free-weight and machine-based groups performed the four exercises by completing the full range of motion, which in turn was very similar between the two modalities (25). This fact would have maximized the strength and hypertrophy adaptations for both groups (1,2) while allowing researchers to reduce the effect of another potential confounding factor (i.e., the range of motion trained) on the main comparison. Complementarily, having performed all the exercises using a full range of motion (thus requiring less weight to reach the target intensity) and far from muscle failure could explain the non-increase, even decrease, in discomfort symptoms this study found (27). In turn, the use of the velocity-based method was another key aspect in the exhaustive isolation of the main independent variable (training modality). Specifically, prescribing intensity by using the specific velocity for each modality matched this training parameter between groups regardless of the weight they were using. Since machines have hoists and/or an inclined plane, the intensity understood as "absolute kilograms" was not directly comparable between both modalities. Therefore, programming the same absolute load for the free-weight and machine-based groups would have led to these modalities to train at a meaningfully different intensity, thus introducing another potential confounding factor into the main comparison. Considering these strengths, the main results we obtained suggest that the training modality itself would not be an aspect meaningfully determining strength, hypertrophy, and joint discomfort changes derived from a resistance program. Therefore, athletes are encouraged to focus their attention on other training parameters widely shown to be key modulators of these adaptations, such as the intentionality of execution (44,45), intensity (24), volume (46), intra-set fatigue (23) or range of motion (1).

On the other hand, this investigation is not exempt from limitations. Firstly, although we considered the specificity principle by testing both modalities, this study did not include a neutral evaluation (e.g., isometric or isokinetic test) for analyzing strength adaptations in a nonspecific context. Secondly, only one muscle group from the upper limb (pectoralis major), lower limb (quadriceps femoris), and trunk (rectus abdominis) were evaluated. Regarding discomfort evaluation, the use of tests primarily designed for clinical populations could have reduced sensitivity to accurately assess this outcome. Moreover, although subjects were required to ensure a minimum of 1.2 g/kg of protein in their daily diet, compliance with this recommendation throughout the intervention could not be verified. On the other hand, the accurate programming and evaluation methodologies used limited the current study to enlarge the sample size, thus increasing the type II error (false-negative results). Finally, it would be of great practical value that future studies extend the knowledge on the topic by including female and untrained participants, a longer training time, other lower-limb exercises (e.g., hip thrust), and machines with different biomechanics.

CONCLUSIONS

The main findings of the current study suggest that free-weight and machine-based exercises are similarly effective to promote strength and muscle hypertrophy without increasing joint discomfort. Hence, athletes are encouraged to train using either of these two modalities depending on their possibilities or preferences, whereas focusing on other training parameters which have widely demonstrated to be key modulators of these adaptations (e.g., intensity, intra-set fatigue, range of motion).

ACKNOWLEDGMENTS

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

CONFLICTS OF INTEREST AND SOURCE OF FUNDING

The authors declare that they have no competing interests. No funding was received for this research.

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FIGURE CAPTIONS

Figure 1. Participant flowchart. $1RM_{Rel}$: Relative strength considering the 8 incremental tests (4 exercises x 2 modalities).

Figure 2. Mean and individual $1RM_{Rel}$ changes produced by each training group in free-weight (Panels A, C, E, and G) and machine-based (Panels B, D, F, and H) modalities of the squat (SQ), prone bench pull (PBP), shoulder press (SP), and bench press (BP) exercises. Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-group effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction.

Figure 3. Mean and individual MPV_{Low} changes produced by each training group in free-weight (Panels A, C, E, and G) and machine-based (Panels B, D, F, and H) modalities of the squat (SQ), prone bench pull (PBP), shoulder press (SP), and bench press (BP) exercises. Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-group effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction.

Figure 4. Mean and individual MPV_{High} changes produced by each training group in free-weight (Panels A, C, E, and G) and machine-based (Panels B, D, F, and H) modalities of the squat (SQ), prone bench pull (PBP), shoulder press (SP), and bench press (BP) exercises. Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-group

effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction.

Figure 5. Representative image illustrating pectoralis major CSA (Panel 5A). Mean and individual changes produced by both training modalities on pectoralis major CSA (Panel 5B). Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-group effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction. Panel 5C compared individual changes in pectoralis major CSA concerning the SEM of this evaluation highlighted in yellow (SEM = ± 0.25 cm^2 (40)).

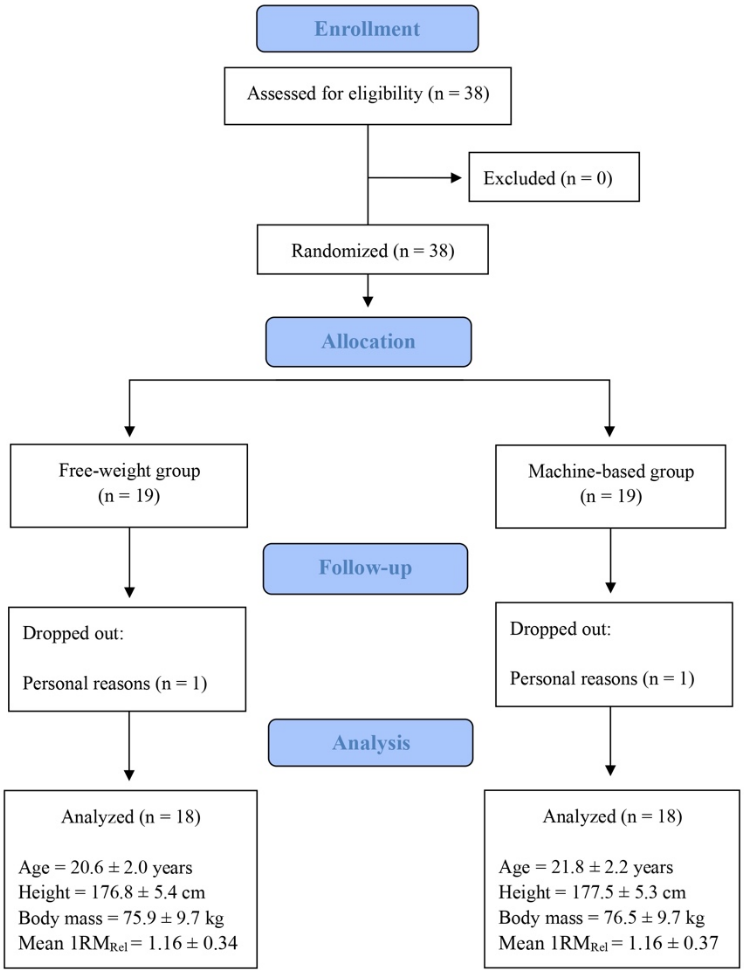
Figure 6. Representative image illustrating quadriceps femoris CSA at 30% (Panel 6A) and 60% (Panel 6D) thigh regions. Mean and individual changes produced by both training modalities at 30% (Panel 6B) and 60% (Panel 6E) regions. Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-group effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction. Panels 6C and 6F compared individual changes at 30% and 60% regions concerning the SEM of the evaluation at these thigh sites highlighted in yellow (30%, SEM = ± 0.68 cm^2; 60%, SEM = ± 1.00 cm^2 (33)).

Figure 7. Representative image illustrating rectus abdominis CSA (Panel 7A). Mean and individual changes produced by both training modalities on rectus abdominis CSA (Panel 7B). Δ: Percentage of change, ES: Effect size (Hedges'*g*). Values in square brackets indicate the 95% confidence interval for each statistical, while the p-value just below indicates the within-

group effect (pre-post). The p-value just above the bracket linking the two groups indicates the "group x time" interaction. Panel 7C compared individual changes in rectus femoris CSA concerning the SEM of this evaluation highlighted in yellow (SEM = ± 0.16 cm^2).

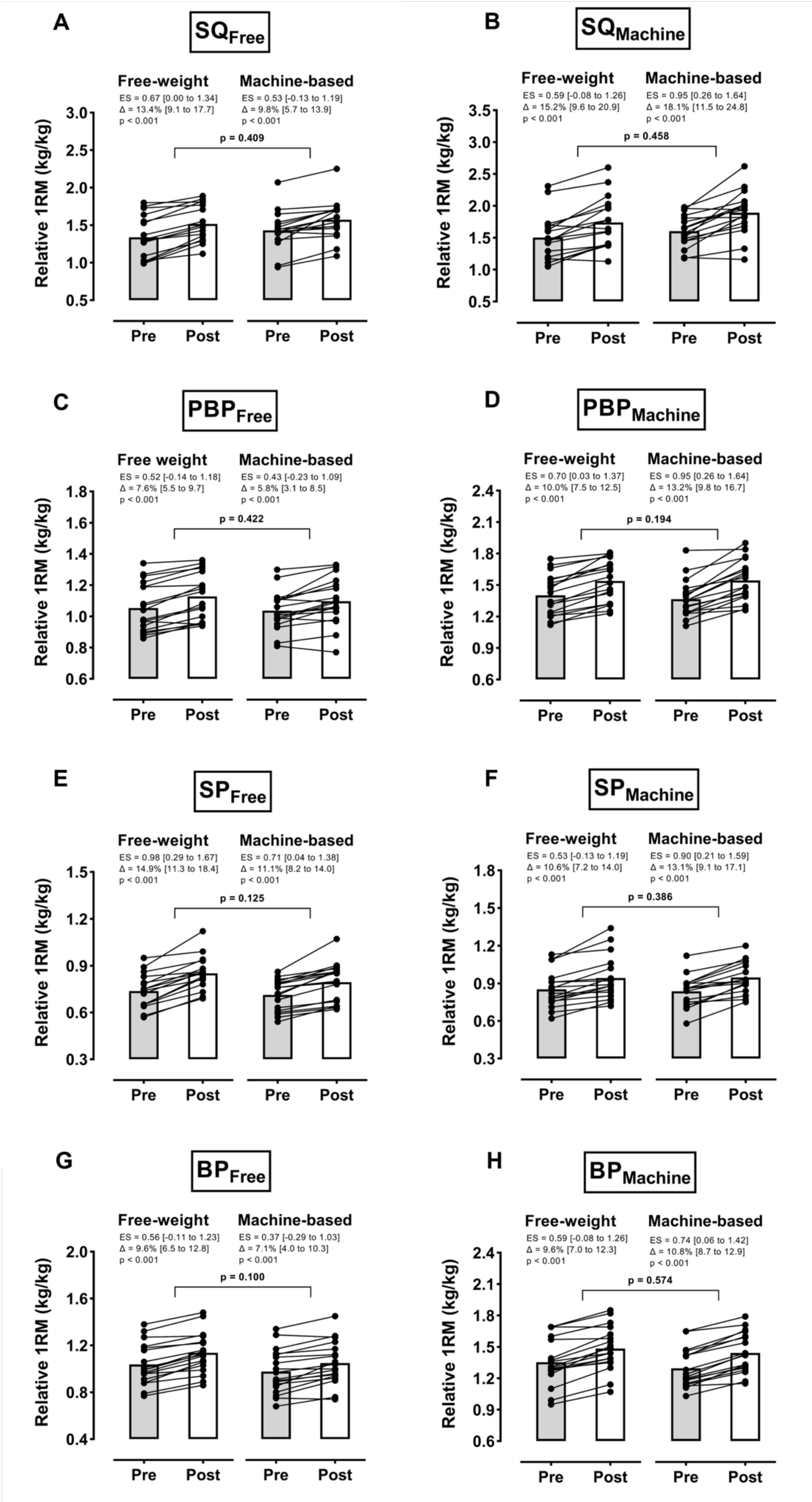
Supplemental Material 1. Changes in upper-and lower-limb stiffness, pain, and functional disability produced by each training modality.

Figure 1



Enrollment
Assessed for eligibility (n = 38)
Excluded (n = 0)
Randomized (n = 38)
Allocation
Free-weight group
(n = 19)
Machine-based group
(n = 19)
Follow-up
Dropped out:
Personal reasons (n = 1)
Dropped out:
Personal reasons (n = 1)
Analysis
Analyzed (n = 18)
Age = 20.6 ± 2.0 years
Height = 176.8 ± 5.4 cm
Body mass = 75.9 ± 9.7 kg
Mean 1RMRel = 1.16 ± 0.34
Analyzed (n = 18)
Age = 21.8 ± 2.2 years
Height = 177.5 ± 5.3 cm
Body mass = 76.5 ± 9.7 kg
Mean 1RMRel = 1.16 ± 0.37

Figure 2



A
SQFree
Free-weight
ES = 0.67 [0.00 to 1.34]
Δ = 13.4% [9.1 to 17.7]
p < 0.001
Machine-based
ES = 0.53 [-0.13 to 1.19]
Δ = 9.8% [5.7 to 13.9]
p < 0.001
p = 0.409
Relative 1RM (kg/kg)
3.0
2.5
2.0
1.5
1.0
0.5
Pre
Post
Pre
Post
B
SQMachine
Free-weight
ES = 0.59 [-0.08 to 1.26]
Δ = 15.2% [9.6 to 20.9]
p < 0.001
Machine-based
ES = 0.95 [0.26 to 1.64]
Δ = 18.1% [11.5 to 24.8]
p < 0.001
p = 0.458
Relative 1RM (kg/kg)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Pre
Post
Pre
Post
C
PBPFree
Free weight
ES = 0.52 [-0.14 to 1.18]
Δ = 7.6% [5.5 to 9.7]
p < 0.001
Machine-based
ES = 0.43 [-0.23 to 1.09]
Δ = 5.8% [3.1 to 8.5]
p < 0.001
p = 0.422
Relative 1RM (kg/kg)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Pre
Post
Pre
Post
D
PBPMachine
Free-weight
ES = 0.70 [0.03 to 1.37]
Δ = 10.0% [7.5 to 12.5]
p < 0.001
Machine-based
ES = 0.95 [0.26 to 1.64]
Δ = 13.2% [9.8 to 16.7]
p < 0.001
p = 0.194
Relative 1RM (kg/kg)
2.4
2.1
1.8
1.5
1.2
0.9
0.6
Pre
Post
Pre
Post
E
SPFree
Free-weight
ES = 0.98 [0.29 to 1.67]
Δ = 14.9% [11.3 to 18.4]
p < 0.001
Machine-based
ES = 0.71 [0.04 to 1.38]
Δ = 11.1% [8.2 to 14.0]
p < 0.001
p = 0.125
Relative 1RM (kg/kg)
1.5
1.2
0.9
0.6
0.3
Pre
Post
Pre
Post
F
SPMachine
Free-weight
ES = 0.53 [-0.13 to 1.19]
Δ = 10.6% [7.2 to 14.0]
p < 0.001
Machine-based
ES = 0.90 [0.21 to 1.59]
Δ = 13.1% [9.1 to 17.1]
p < 0.001
p = 0.386
Relative 1RM (kg/kg)
1.8
1.5
1.2
0.9
0.6
0.3
Pre
Post
Pre
Post
G
BPFree
Free-weight
ES = 0.56 [-0.11 to 1.23]
Δ = 9.6% [6.5 to 12.8]
p < 0.001
Machine-based
ES = 0.37 [-0.29 to 1.03]
Δ = 7.1% [4.0 to 10.3]
p < 0.001
p = 0.100
Relative 1RM (kg/kg)
2.0
1.6
1.2
0.8
0.4
Pre
Post
Pre
Post
H
BPMachine
Free-weight
ES = 0.59 [-0.08 to 1.26]
Δ = 9.6% [7.0 to 12.3]
p < 0.001
Machine-based
ES = 0.74 [0.06 to 1.42]
Δ = 10.8% [8.7 to 12.9]
p < 0.001
p = 0.574
Relative 1RM (kg/kg)
2.4
2.1
1.8
1.5
1.2
0.9
0.6
Pre
Post
Pre
Post

Figure 3

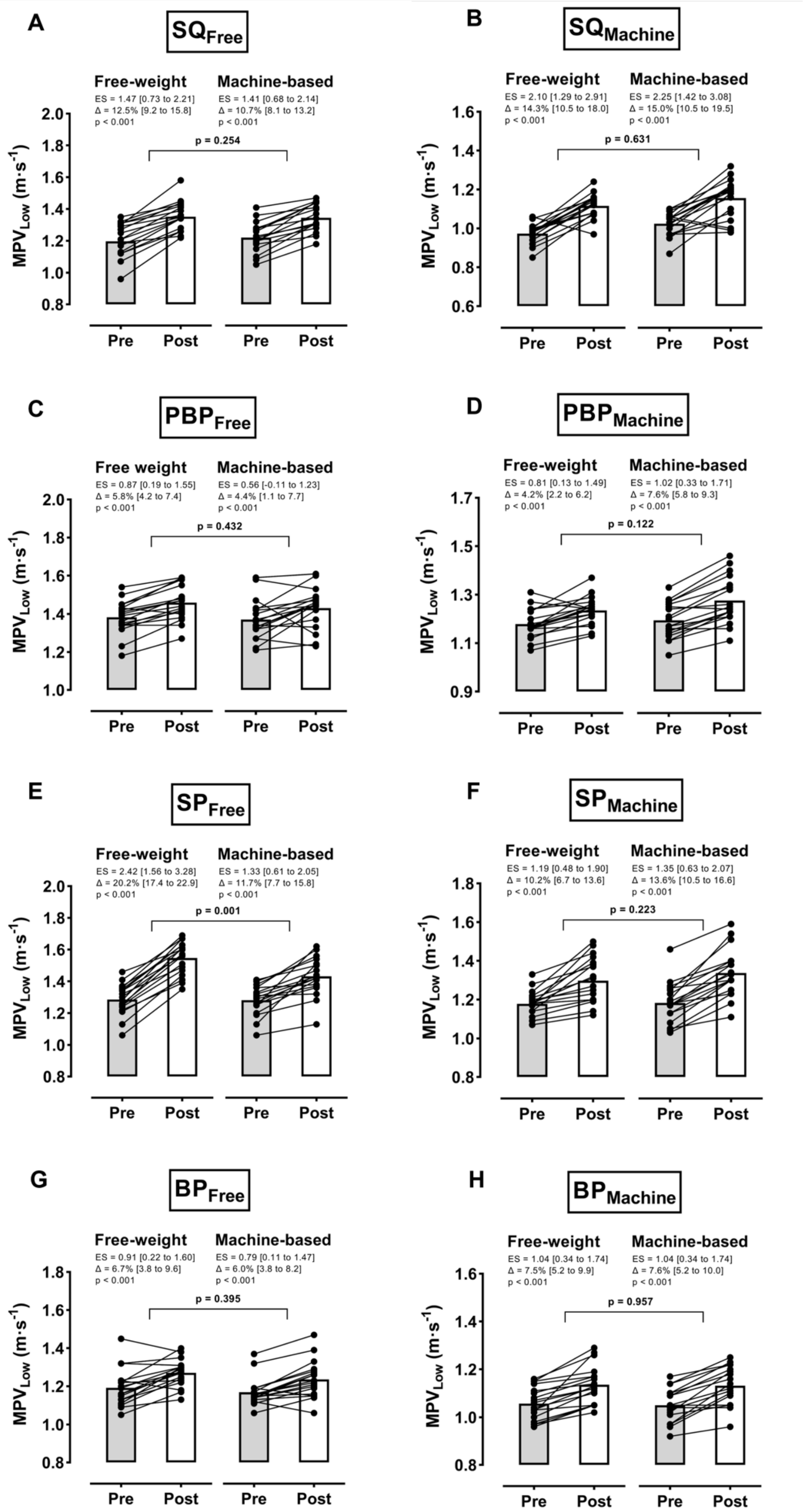

A
SQFree
Free-weight
ES = 1.47 [0.73 to 2.21]
Δ = 12.5% [9.2 to 15.8]
p < 0.001
Machine-based
ES = 1.41 [0.68 to 2.14]
Δ = 10.7% [8.1 to 13.2]
p < 0.001
p = 0.254
MPVLow (m·s-1)
Pre
Post
Pre
Post
B
SQMachine
Free-weight
ES = 2.10 [1.29 to 2.91]
Δ = 14.3% [10.5 to 18.0]
p < 0.001
Machine-based
ES = 2.25 [1.42 to 3.08]
Δ = 15.0% [10.5 to 19.5]
p < 0.001
p = 0.631
MPVLow (m·s-1)
Pre
Post
Pre
Post
C
PBPFree
Free weight
ES = 0.87 [0.19 to 1.55]
Δ = 5.8% [4.2 to 7.4]
p < 0.001
Machine-based
ES = 0.56 [-0.11 to 1.23]
Δ = 4.4% [1.1 to 7.7]
p < 0.001
p = 0.432
MPVLow (m·s-1)
Pre
Post
Pre
Post
D
PBPMachine
Free-weight
ES = 0.81 [0.13 to 1.49]
Δ = 4.2% [2.2 to 6.2]
p < 0.001
Machine-based
ES = 1.02 [0.33 to 1.71]
Δ = 7.6% [5.8 to 9.3]
p < 0.001
p = 0.122
MPVLow (m·s-1)
Pre
Post
Pre
Post
E
SPFree
Free-weight
ES = 2.42 [1.56 to 3.28]
Δ = 20.2% [17.4 to 22.9]
p < 0.001
Machine-based
ES = 1.33 [0.61 to 2.05]
Δ = 11.7% [7.7 to 15.8]
p < 0.001
p = 0.001
MPVLow (m·s-1)
Pre
Post
Pre
Post
F
SPMachine
Free-weight
ES = 1.19 [0.48 to 1.90]
Δ = 10.2% [6.7 to 13.6]
p < 0.001
Machine-based
ES = 1.35 [0.63 to 2.07]
Δ = 13.6% [10.5 to 16.6]
p < 0.001
p = 0.223
MPVLow (m·s-1)
Pre
Post
Pre
Post
G
BPFree
Free-weight
ES = 0.91 [0.22 to 1.60]
Δ = 6.7% [3.8 to 9.6]
p < 0.001
Machine-based
ES = 0.79 [0.11 to 1.47]
Δ = 6.0% [3.8 to 8.2]
p < 0.001
p = 0.395
MPVLow (m·s-1)
Pre
Post
Pre
Post
H
BPMachine
Free-weight
ES = 1.04 [0.34 to 1.74]
Δ = 7.5% [5.2 to 9.9]
p < 0.001
Machine-based
ES = 1.04 [0.34 to 1.74]
Δ = 7.6% [5.2 to 10.0]
p < 0.001
p = 0.957
MPVLow (m·s-1)
Pre
Post
Pre
Post

Figure 4

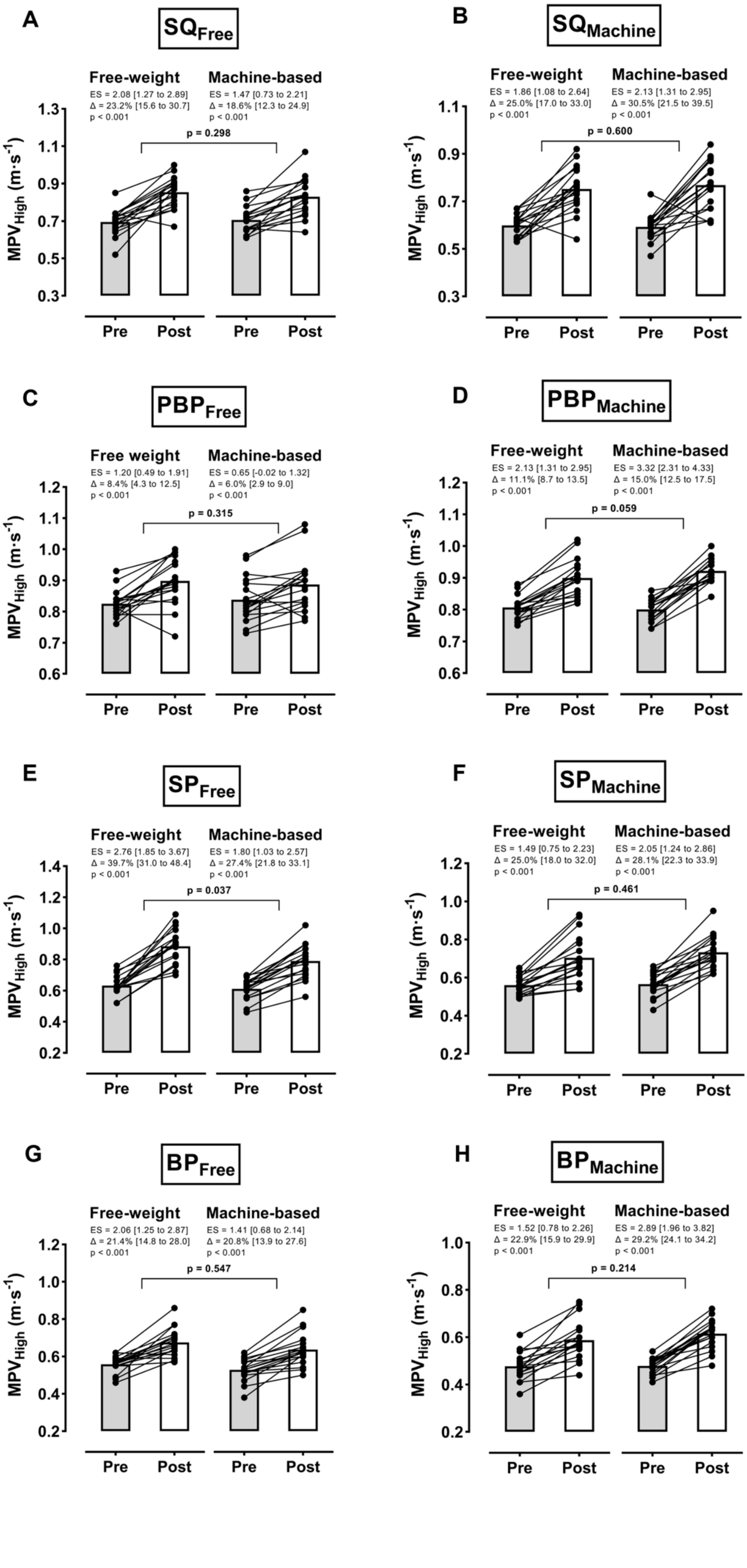

A
SQFree
Free-weight
ES = 2.08 [1.27 to 2.89]
Δ = 23.2% [15.6 to 30.7]
p < 0.001
Machine-based
ES = 1.47 [0.73 to 2.21]
Δ = 18.6% [12.3 to 24.9]
p < 0.001
p = 0.298
MPVHigh (m·s-1)
Pre
Post
Pre
Post
B
SQMachine
Free-weight
ES = 1.86 [1.08 to 2.64]
Δ = 25.0% [17.0 to 33.0]
p < 0.001
Machine-based
ES = 2.13 [1.31 to 2.95]
Δ = 30.5% [21.5 to 39.5]
p < 0.001
p = 0.600
C
PBPFree
Free weight
ES = 1.20 [0.49 to 1.91]
Δ = 8.4% [4.3 to 12.5]
p < 0.001
Machine-based
ES = 0.65 [-0.02 to 1.32]
Δ = 6.0% [2.9 to 9.0]
p < 0.001
p = 0.315
D
PBPMachine
Free-weight
ES = 2.13 [1.31 to 2.95]
Δ = 11.1% [8.7 to 13.5]
p < 0.001
Machine-based
ES = 3.32 [2.31 to 4.33]
Δ = 15.0% [12.5 to 17.5]
p < 0.001
p = 0.059
E
SPFree
Free-weight
ES = 2.76 [1.85 to 3.67]
Δ = 39.7% [31.0 to 48.4]
p < 0.001
Machine-based
ES = 1.80 [1.03 to 2.57]
Δ = 27.4% [21.8 to 33.1]
p < 0.001
p = 0.037
F
SPMachine
Free-weight
ES = 1.49 [0.75 to 2.23]
Δ = 25.0% [18.0 to 32.0]
p < 0.001
Machine-based
ES = 2.05 [1.24 to 2.86]
Δ = 28.1% [22.3 to 33.9]
p < 0.001
p = 0.461
G
BPFree
Free-weight
ES = 2.06 [1.25 to 2.87]
Δ = 21.4% [14.8 to 28.0]
p < 0.001
Machine-based
ES = 1.41 [0.68 to 2.14]
Δ = 20.8% [13.9 to 27.6]
p < 0.001
p = 0.547
H
BPMachine
Free-weight
ES = 1.52 [0.78 to 2.26]
Δ = 22.9% [15.9 to 29.9]
p < 0.001
Machine-based
ES = 2.89 [1.96 to 3.82]
Δ = 29.2% [24.1 to 34.2]
p < 0.001
p = 0.214

Figure 5

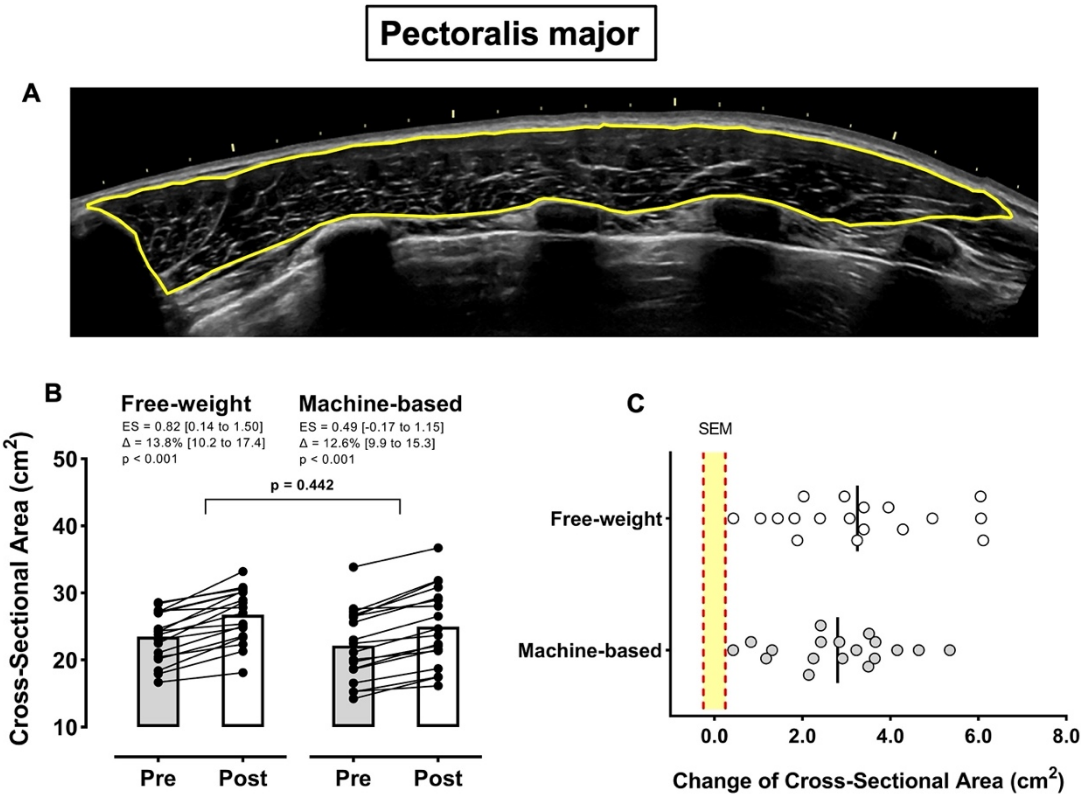


Figure 6

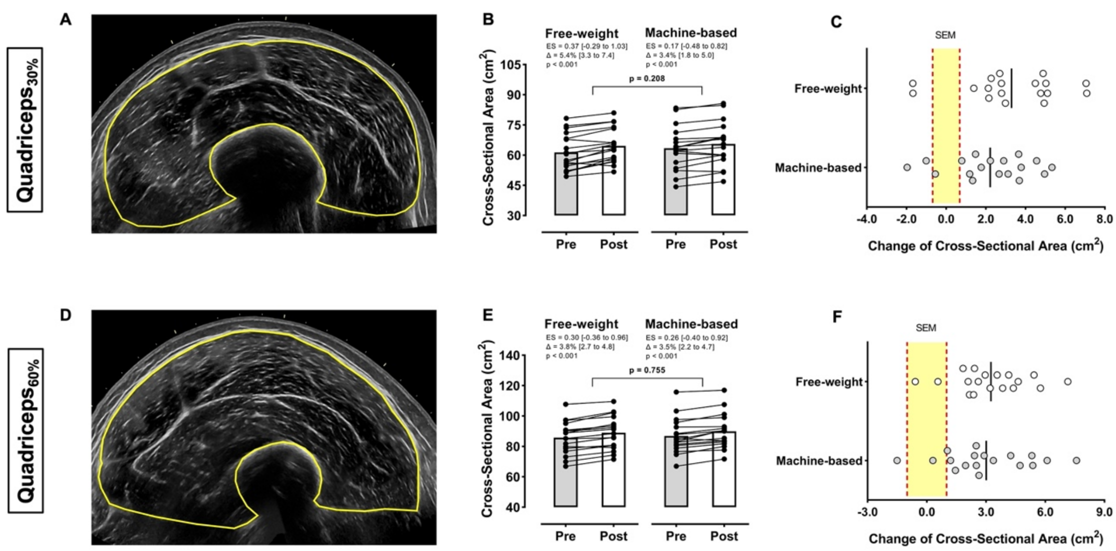
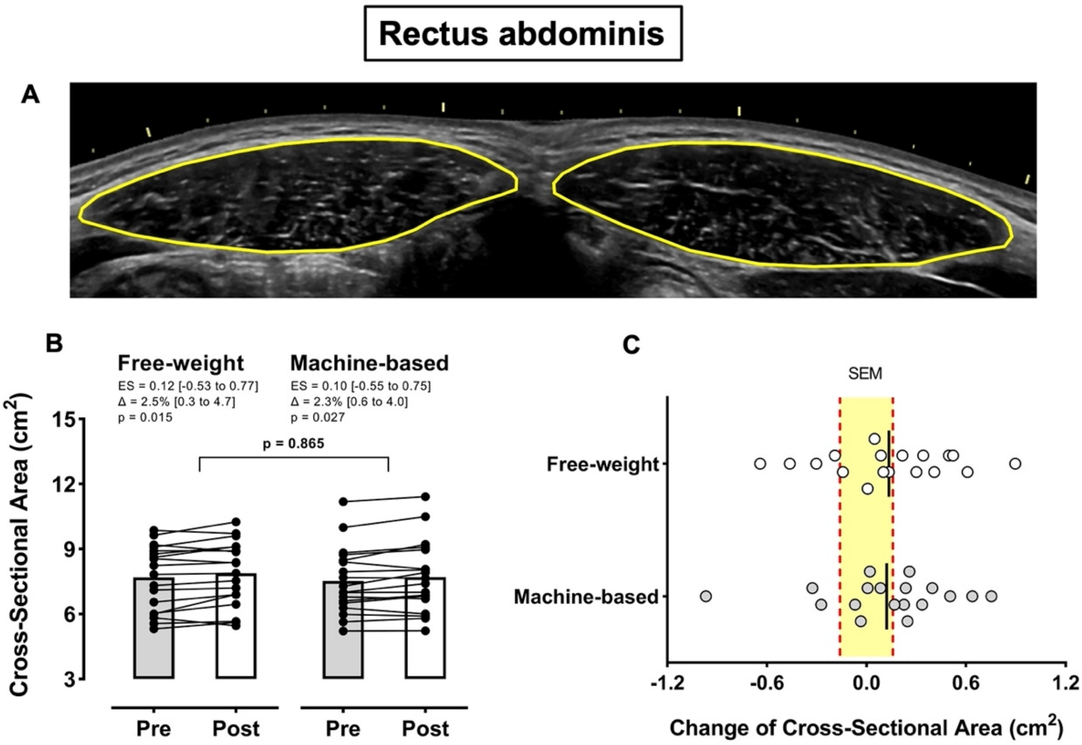


Figure 7



Supplemental Material 1

Supplemental Material 1. Changes in upper-and lower-limb stiffness, pain, and functional disability produced by each training modality after the intervention program

	Free-weight			**Machine-based**				
WOMAC *(lower limb)*	ES	CI 95% ES	P-value	ES	CI 95% ES	P-value	P-value Group x Time	F-value
Functional disability	-0.15	-0.80 to 0.50	0.837	-0.21	-0.87 to 0.45	0.365	**0.624**	0.245
Pain	-0.12	-0.77 to 0.53	0.543	-0.10	-0.75 to 0.55	0.478	**0.964**	0.002
Stiffness	-0.53	-1.19 to 0.13	< 0.001	-0.77	-1.45 to -0.09	< 0.001	**0.144**	2.245
DASH *(upper limb)*								
Functional capacity	0.86	0.18 to 1.54	< 0.001	0.84	0.16 to 1.52	< 0.001	**0.958**	0.003
Pain	-0.24	-0.90 to 0.42	0.494	-0.15	-0.80 to 0.50	0.100	**0.473**	0.528

ES: Effect size (Hedges'*g*); CI: Confidence interval. Except for functional capacity in the DASH questionnaire, the lower the ES the higher the reduction in these symptoms.

CONCLUSIONS

8. Conclusions

Below are the main conclusions of this Doctoral Thesis according to its initial objectives:

Conclusions of Study I

i. The very close adjustment found for the 8 L-V relationships examined and their independence from the subject's strength level suggests the accuracy and stability of this methodology to program intensity in both modalities of SQ, BP, PBP, and SP exercises. Nevertheless, the differences regarding velocity attained at each intensity suggest the specificity of the L-V relationships to each modality.

- This conclusion fully corroborates hypotheses i) and ii) of Study I.

ii. The reduced inter- and intra-subject variability in the *n*RM, as well as the high relationship between the repetitions completed and velocity loss incurred, stand the level of effort as an accurate and reliable methodology to prescribe relative intensity and intraset volume in SQ, BP, PBP, and SP exercises.

- This conclusion fully corroborates hypothesis iii) of Study I.

Conclusions of Study II

i. The small errors made when acquiring and analyzing pectoralis and quadriceps femoris ACSA using ultrasound, as well as its high agreement with MRI, support the validity and repeatability of this technique to evaluate muscle size.

- This conclusion fully corroborates hypotheses i) and ii) of Study II.

ii. The sonographer's experience influences the magnitude of errors made when acquiring and analyzing pectoralis and quadriceps femoris ACSA using ultrasound. Thus, the accuracy, repeatability and sensitivity of this technique would benefit from its implementation by a trained sonographer.

- This conclusion fully corroborates hypothesis iii) of Study II.

iii. The small estimation and test-retest errors found for the 2-point method, especially that implemented using the 30 and 60% regions, support the validity and repeatability of this approach to evaluate quadriceps femoris ACSA along the thigh.

- This conclusion fully corroborates hypothesis iv) of Study II.

Conclusions of Study III

i. The similar changes found for free-weight and machine-based modalities in both longitudinal investigations indicate that adaptations in strength, athletic performance, muscle size and architecture would not be meaningfully influenced by the resistance modality trained. Moreover, neither of these two training modalities considerably increased levels of upper- and lower-limb articular discomfort.

- This conclusion partially corroborates hypothesis iv) of Study II.

PRACTICAL APPLICATIONS

9. Practical applications

The following practical applications can be inferred from the Articles included in this Doctoral Thesis:

Practical applications of Study I

i. The very high L-V relationships found for both modalities of SP, BP, PBP, and SP exercises would allow coaches to use velocity as a monitoring and programming parameter in adult men. Each specific L-V relationship could be used i) to monitor the relative intensity that is being used as soon as the first repetitions of a set are performed, as well as i) to program a target velocity to be attained at the first repetitions of the set which would correspond to the planned relative intensity. Moreover, iii) the measurement of velocity achieved against the same absolute load (in kg) before and after a training or inactivity period can be used to quantify strength changes without the need to perform a 1RM or *n*RM test. For example, pre-post training differences in velocity of ~0.06-0.07 $m \cdot s^{-1}$ would represent a dynamic strength change of ~5% in the machine-based modality of PBP, SQ, and BP exercises.

ii. Regardless of their strength level**,** adult men could use the level of effort methodology to accurately prescribe the relative intensity and intraset volume in SP, BP, PBP, and SP exercises. For instance, a moderately-trained subject that programs a target velocity loss of 30% against the 75% 1RM in the SQ exercise should perform 8 repetitions with a weight that would allow him to complete a total of 11 repetitions. This practical methodology allows coaches to program these training variables without the need for i) reproducible technologies and protocols, ii) an expert in the use of velocity devices, iii) a considerable deal of time for analyzing every repetition, and iv) a prior familiarization of subjects to perform all repetitions at the maximal intended velocity.

Practical applications of Study II

i. Panoramic ultrasound can be used as an accurate, reliable, and practical technique to evaluate pectoralis and quadriceps femoris ACSA of adult men. Importantly, the implementation of this technique by a trained sonographer would decrease the measurement errors, and so the smallest change that should be detected after a training or detraining period to assume a true modification in the ACSA of these muscles. However, although errors reported by both articles could be used for guidance values, sonographers implementing panoramic ultrasound should quantify their own measurement errors beforehand. Finally, besides a trained sonographer, the accuracy and repeatability of ultrasound-derived quadriceps femoris ACSA could be favored by measuring at central thigh regions (30 to 60% of trochanter-patella distance).

ii. Clinicians, researchers, and sports practitioners could implement the 2-point method, especially that made up of 30 and 60% regions, for estimating quadriceps femoris ACSA of adult men. This practical approach would expedite the multiple-region evaluation of this parameter, thus reducing the fatigue incurred by the sonographer and increasing the hands-on implementation of this technique.

Practical applications of Study III

i. The main results of these articles suggest that physical performance and muscle structure adaptations are not meaningfully conditioned by training free-weight or machine-based modalities. Therefore, athletes are encouraged to use any of these training modalities depending on their possibilities or preferences, while focusing on other training parameters which have been shown to significantly condition these adaptations (e.g., intensity, intraset volume, execution intentionality or range of motion).

FUTURE PERSPECTIVES

10. Future perspectives

The current Doctoral Thesis developed a broad approach to compare the physical and structural adaptations produced by free-weight and machine-based RT modalities. The above-presented 7 Articles have represented an important step forward to clarify this controversial topic by means of i) a comprehensive RT routine (4 multi-joint exercises), which ii) has accurately been programmed using velocity-derived strategies (L-V relationships and the level of effort method). Moreover, it should be noted iii) the wide range of physical performance (strength and athletic capacity) and structural (muscle hypertrophy and architecture) evaluations we included. Nevertheless, to fully elucidate the effect of training modality would require further examination of the topic by complementing the results of the present Doctoral Thesis. Below, we included some future perspectives:

i. Future interventions comparing free-weight and machine-based RT modalities should be longer than 8 weeks. Moreover, using a crossover design (the same subject train both modalities separated by a washout period) would help to reduce heterogeneity between subjects allocated in each group, thus addressing this question more precisely.

ii. The knowledge on the effectiveness of free-weight and machine-based RT exercises we provided should be complemented by analyzing other modalities (e.g., Multipower-based training) and routines combining the two modalities examined.

iii. Future free-weight versus machine-based comparisons should complement SQ with another lower-limb exercise (e.g., hip thrust or deadlift). Beforehand, researchers should analyze the suitability of the velocity-based method to accurately program the intensity and intraset volume of this new lower-limb exercise.

iv. It would be of great value to extend the dependent variables included when contrasting both RT modalities. Regarding physical performance variables, other specific tests to compare upper-limb athletic adaptations should be developed and implemented. Concerning structural parameters, future projects are encouraged to examine whether the RT modality could meaningfully modulate the size and proprieties of other muscles and tissues (e.g., tendons).

v. Cross-sectional and longitudinal interventions on the topic should include electromyography. For example, cross-sectional studies could implement this technique, together with accurate programming methods (Articles 1 and 2), to quantify the acute muscle activation produced by each training modality. Similarly, longitudinal studies could include pre-post training measurements of electromyography to analyze adaptations produced by the free-weight and machine-based modalities on agonist, synergist, and antagonist muscle activity.

vi. All the analyses conducted in the current Doctoral Thesis should be transferred to other populations. Extending knowledge on velocity-derived strategies examined in Articles 1 and 2 to women, older or untrained adults would allow researchers to accurately program future interventions including these populations. Similarly, future studies are encouraged to examine whether results obtained on ultrasound validity and reliability would be similar when implementing this technique in the above-mentioned populations. Finally, including these populations in longitudinal interventions comparing free-weight and machine-based RT modalities would help to elucidate this research question more broadly.

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APPENDICES

12. Appendices

12.1. Appendix I. Certificate of Research Stays

Higher Education
Learning Agreement for
Traineeships

Student's name
Academic Year 2021/22

After the Mobility

Table D - Traineeship Certificate by the Receiving Organisation/Enterprise
Name of the trainee: ALEJANDRO HERNÁNDEZ BELMONTE
Name of the Receiving Organisation/Enterprise: UNIVERSITY OF JYVÄSKYLÄ
Sector of the Receiving Organisation/Enterprise: PUBLIC
Address of the Receiving Organisation/Enterprise [street, city, country, phone, e-mail address]**, website:** Building Liikunta (L), Keskussairaalantie 4, Jyväskylä, Finland, +358 40 805 4808, studyaffairs-sport(at)jyu.fi, https://www.jyu.fi/sport/en
Start date and end date of traineeship: from [day/month/year] 21/02/2022 **to [day/month/year]** 21/05/2022
Traineeship title: Training in musculoskeletal ultrasound
Detailed programme of the traineeship period including tasks carried out by the trainee: During the stay, the trainee has been assisting a Marie Skłodowska-Curie project, which included different techniques he was interested in. Especially, the trainee has been learning and assisting in the gait analysis, 3D ultrasound and elastography techniques. Below, I detailed some of the specific tasks the trainee has carried out: - Preparation and calibration of the set-up needed to conduct a 3D ultrasound measurement. - Checking the correct acquisition of each 3D ultrasound measurement in real-time. - Checking the correct acquisition of each elastography measurement in real-time. - Assistance during the proprioception and balance tests. - Preparation and calibration of the set-up needed to conduct a 3D gait analysis, as well as a dynamic ultrasound measurement. - Preparation of the set-up needed to perform an electromyography analysis. Furthermore, the trainee has assisted in the analysis of data related to muscle length, which will be presented in a future congress.
Knowledge, skills (intellectual and practical) and competences acquired (achieved Learning Outcomes): The trainee has acquired the basic knowledge of the different devices and procedures needed to apply the evaluation techniques that based on the current stay. In particular, after this training period, the trainee is able to: - Install the connections and technologies for a 3D ultrasound evaluation. - Identify different key points of the calf muscles using anatomical landmarks. - Make a basic 3D reconstruction and calculate some parameters such as the muscle and tendon lengths. - Recognize the key aspects that base an elastography acquisition, as well as analyse it using the ElastoGUI software. - Install the connections and technologies for a 3D gait analysis. - Identify the anatomical points in which the 3D markers have to be located to do the subsequent reconstruction. - Locate the key points of the rectus femoris, biceps femoris, and calf muscles in which the electromyography should be measured. - Prepare the participant's skin and correctly locate the electrodes. - Use the DL Track software to automatically measure the muscle architecture during a dynamic movement.
Evaluation of the trainee: The trainee accomplished an excellent visit at our university. He showed a very good attitude in learning new acquisition processing methods as well as in supporting the research activities. Such fruitful collaboration will continue remotely, allowing us to finalize the shared research project.
Date: *30/05/2022*
Name, signature and stamp of the Supervisor at the Receiving Organisation/Enterprise: TAIJA J TINEN, VICE DEAN

1

UNIVERSIDAD DE GRANADA

CERTIFICADO DE ESTANCIA PREDOCTORAL

Por medio de la presente, certifico que el doctorando Alejandro Hernández Belmonte ha completado satisfactoriamente una estancia de 3 meses (del 15-03-2023 al 15-06-2023) en el Departamento de Educación Física y Deportiva de la Universidad de Granada.

El doctorando ha cumplido de manera notoria los objetivos previstos a nivel profesional y académico, demostrando una clara evolución en el conocimiento teórico y práctico entorno a la principal técnica objetivo de la presente estancia. Además, ha mostrado una gran iniciativa y predisposición para el aprendizaje de otras técnicas desarrolladas por el grupo receptor, ayudando y colaborando con este durante todo el periodo de la estancia.

En virtud de lo anterior, firmo el presente certificando en Granada, a quince de junio de dos mil veintitrés.

Prof. Javier Courel Ibáñez
Departamento de Educación Física y Deportiva
Universidad de Granada

Firma

COUREL IBAÑEZ JAVIER - 76422730D

Firmado digitalmente por COUREL IBAÑEZ JAVIER - 76422730D
Fecha: 2023.06.15 12:07:42 +02'00'

12.2. Appendix II. Dissemination activities

I CONGRESO INTERNACIONAL SOBRE OPTIMIZACIÓN DEL ENTRENAMIENTO DE FUERZA Y RENDIMIENTO NEUROMUSCULAR

Se certifica que

Alejandro Hernández-Belmonte, Alejandro Martínez-Cava, Ángel Buendía-Romero, Eduardo Romero-Borrego, Jesús G. Pallarés han presentado la **comunicación oral** titulada "**Load-velocity relationship of free-weight and machine-based resistance exercises: A comparison in the bench press, squat, prone bench pull and shoulder press**" en el "I Congreso Internacional sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular" celebrado en la Facultad de Ciencias del Deporte de la Universidad de Granada los días 7 y 8 de Octubre de 2022.

Granada, 12 de octubre de 2022

D. Amador García Ramos
Presidente del congreso

III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte

21 y 22 de octubre de 2022 · Facultad del Deporte · San Javier · Murcia

Se certifica la presentación del trabajo titulado

Load-velocity relationship of free-weight and machine-based bench press and squat exercises are not influenced by the relative strength level

Cuya autoría pertenece a Hernández-Belmonte, A., Romero-Borrego, E., Buendía-Romero, A., Martínez-Cava, A., Pallarés, JG., bajo el formato de COMUNICACIÓN ORAL en el "III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte". Congreso que ha sido organizado por la Facultad de Ciencias del Deporte de la Universidad de Murcia, en la localidad de San Javier (Murcia), durante los días 21 y 22 de octubre de 2022.

Y, para que así conste, a petición del/los interesado/s, se certifica su contribución a los efectos oportunos en San Javier (Murcia), a 22 de octubre de 2022.

Fdo. J. Arturo Abraldes Valeiras
Director del III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte

UNIVERSIDAD DE MURCIA

Facultad de Ciencias del Deporte
Universidad de Murcia - Campus de San Javier

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50858 Cologne

GERMANY

VAT-ID: DE251715668 - St.Nr.: 223/5905/0216
register of associations: VR12508

Cologne, 06.10.2021 - 17:18:16

Confirmation of Presentation

This is to certify that the following title has been presented at the 26th Annual Congress of the European College of Sport Science between 8 - 10 September 2021.

Alejandro Martínez-Cava

Human Performance and Sports Science Laboratory, Faculty of Sport Sciences, Univ
Argentina S/N
30720 San javier, Spain

Abstr.-ID: 431, Presentation format: Oral , Session name: OP-AP03 - Training and Testing
Title: Level of effort: A reliable and practical alternative to the velocity-based approach for monitoring resistance training
Authors: Martínez Cava, A., Hernández Belmonte, A., Conesa Ros, E., Franco López, F., Buendía Romero, Á., Courel Ibáñez, J., Pallarés, J.G.
Institution: Human Performance and Sports Science Laboratory, Faculty of Sport Sciences, Univ
Presentation date: 11.09.2021, 00:00, Lecture room: -Track 6, No: 2

European College of Sport Science

This document has been created digitally and is valid without a signature

Gonzalo Márquez Sánchez, en calidad de ORGANIZADOR y RESPONSABLE de las ***"Jornadas sobre Optimización del Entrenamiento de Fuerza y Rendimiento Neuromuscular: últimos avances en investigación y transferencia"*** celebradas en la Facultad de CC del Deporte y la Educación Física de A Coruña (Universidade da Coruña) durante los días 17-18 de septiembre de 2021 con una duración de 15 horas,

HACE CONSTAR que, **Alejandro Hernández Belmonte,** con **DNI: 48728884-A,** ha participado en calidad de **PONENTE**, impartiendo la **CONFERENCIA** titulada:

"Uso de variables mecánicas para prescribir el entrenamiento de fuerza y evaluar la función neuromuscular"

Para que así conste, firmo el presente documento en A Coruña, a fecha de firma electrónica.

Se certifica la presentación del trabajo titulado

Pectoralis cross-sectional area can be accurately measured using panoramic ultrasound: A comprehensive analysis of the measurement errors

Cuya autoría pertenece a Hernández-Belmonte, A., Martínez-Cava, A., Buendía-Romero, A., Pallarés, JG., bajo el formato de COMUNICACIÓN ORAL en el "III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte". Congreso que ha sido organizado por la Facultad de Ciencias del Deporte de la Universidad de Murcia, en la localidad de San Javier (Murcia), durante los días 21 y 22 de octubre de 2022.

Y, para que así conste, a petición del/los interesado/s, se certifica su contribución a los efectos oportunos en San Javier (Murcia), a 22 de octubre de 2022.

Fdo. J. Arturo Abraldes Valeiras
Director del III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte

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VAT-ID: DE251715668 - St.Nr.: 223/5905/0216
register of associations: VR12508

Cologne, 05.10.2021 - 08:34:08

Confirmation of Presentation

This is to certify that the following title has been presented at the 26th Annual Congress of the European College of Sport Science between 8 - 10 September 2021.

Alejandro Hernández-Belmonte

University of Murcia
C/ Argentina, nº 19
30720 San Javier, Spain

Abstr.-ID: 373, Presentation format: Oral , Session name: OP-AP08 - Body Composition
Title: Repeatability and reproducibility of panoramic ultrasonography are highly dependent on the muscle region: A step-by-step analysis of the measurement errors.
Authors: Hernández Belmonte, A., Martínez Cava, A., Buendía Romero, Á., Courel Ibáñez, J., Franco López, F., Pallarés, J.G.
Institution: Human Performance and Sports Science Laboratory. Faculty of Sport Science, University of Murcia
Presentation date: 11.09.2021, 00:00, Lecture room: -Track 5, No: 8

European College of Sport Science

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III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte

21 y 22 de octubre de 2022 · Facultad del Deporte · San Javier · Murcia

Se certifica la presentación del trabajo titulado

Two-point method: A quick, accurate, and repeatable approach to estimate ultrasound-derived quadriceps femoris cross-sectional area

Cuya autoría pertenece a Hernández-Belmonte, A., Martínez-Cava, A., Pallarés, JG., bajo el formato de COMUNICACIÓN ORAL en el "III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte". Congreso que ha sido organizado por la Facultad de Ciencias del Deporte de la Universidad de Murcia, en la localidad de San Javier (Murcia), durante los días 21 y 22 de octubre de 2022.

Y, para que así conste, a petición del/los interesado/s, se certifica su contribución a los efectos oportunos en San Javier (Murcia), a 22 de octubre de 2022.

Fdo. J. Arturo Abraldes Valeiras
Director del III Congreso Internacional de Investigación Aplicada en Ciencias de la Actividad Física y el Deporte

12.3. Appendix III. Scientific studies derived from the Doctoral Thesis

1. **Hernández-Belmonte, A.,** Buendía-Romero, A., Martínez-Cava, A., Courel-Ibáñez, J., Mora-Rodríguez, R., Pallarés, J.G. (2020). Wingate test, when time and overdue fatigue matter: Validity and sensitivity of two time-shortened versions. *Applied Sciences,* 10(22), 8002. https://doi.org/10.3390/app10228002.

2. **Hernández-Belmonte, A.,** Martínez-Cava, A., Morán-Navarro, R., Courel-Ibáñez, J., & Pallarés, J.G. (2021). A comprehensive analysis of the velocity-based method in the shoulder press exercise: Stability of the load-velocity relationship and sticking region parameters. *Biology of Sport*, 38(2), 235-243. https://doi.org/10.5114/biolsport.2020.98453.

3. **Hernández-Belmonte, A.**, Courel-Ibáñez, J., Conesa-Ros, E., Martínez-Cava, A., & Pallarés, J.G. (2022). Level of effort: A reliable and practical alternative to the velocity-based approach for monitoring resistance training. *Journal of Strength and Conditioning Research*, 36(11), 2992-2999. https://doi.org/10.1519/JSC.0000000000004060 .

4. **Hernández-Belmonte, A.,** & Pallarés, J.G. (2022). Effects of velocity loss threshold during resistance training on strength and athletic adaptations: A systematic review with meta-analysis. *Applied Sciences,* 12(9), 4425. https://doi.org/10.3390/app12094425.

5. **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). Pectoralis cross-sectional area can be accurately measured using panoramic ultrasound: A

validity and repeatability study. *Ultrasound in Medicine and Biology*,48(3),460-468. https://doi.org/10.1016/j.ultrasmedbio.2021.10.017.

6. **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). Panoramic ultrasound requires a trained operator and specific evaluation sites to maximize its sensitivity: A comprehensive analysis of the measurement errors. *Physiology and Behavior*, 248, 113737. https://doi.org/10.1016/j.physbeh.2022.113737.

7. **Hernández-Belmonte, A.**, Martínez-Cava, A., & Pallarés, J.G. (2022). The 2-point method: A quick, accurate, and repeatable approach to estimate ultrasound-derived quadriceps femoris cross-sectional area. *International Journal of Sports Physiology and Performance*, 17(10), 1480-1488. https://doi.org/10.1123/ijspp.2021-0381.

8. **Hernández-Belmonte, A.**, Buendía-Romero, Á., Pallarés, J.G., & Martínez-Cava, A. (2023). Velocity-based method in free-weight and machine-based training modalities: The degree of freedom matters. *Journal of Strength and Conditioning Research*. (Online ahead of print). https://doi.org/10.1519/JSC.0000000000004480.

9. **Hernández-Belmonte, A.**, Buendía-Romero, Á., Franco-López, F., Martínez-Cava, A., & Pallarés, J.G. (2023). Adaptations in athletic performance and muscle architecture are not meaningfully conditioned by training free-weight versus machine-based exercises: Challenging a traditional assumption using the velocity-

based method. *Scandinavian Journal of Medicine and Science in Sports.* (Online ahead of print). https://doi.org/10.1111/sms.14433.

10. **Hernández-Belmonte, A.**, Martínez-Cava, A., Buendía-Romero, Á., Franco-López, F., & Pallarés, J.G. (2023). Free-weight and machine-based training are equally effective on strength and hypertrophy: Challenging a traditional myth.

12.4. Appendix IV. Ethics commission

UNIVERSIDAD DE MURCIA | Vicerrectorado de Investigación e Internacionalización | CEI Comisión de Ética de Investigación | CAMPUS MARE NOSTRUM

INFORME DE LA COMISIÓN DE ÉTICA DE INVESTIGACIÓN DE LA UNIVERSIDAD DE MURCIA

Jaime Peris Riera, Catedrático de Universidad y Secretario de la Comisión de Ética de Investigación de la Universidad de Murcia,

CERTIFICA:

Que D. Jesús García Pallarés ha presentado la memoria de trabajo del Proyecto de Investigación titulado *"Efectos del entrenamiento de fuerza a diferentes libertades de movimiento sobre las adaptaciones neurales, estructurales y de rendimiento físico"*, a la Comisión de Ética de Investigación de la Universidad de Murcia.

Que dicha Comisión analizó toda la documentación presentada, y de conformidad con lo acordado el día veintidós de noviembre de dos mil veintiuno, por unanimidad, se emite INFORME FAVORABLE, desde el punto de vista ético de la investigación.

Y para que conste y tenga los efectos que correspondan firmo esta certificación con el visto bueno de la Presidenta de la Comisión.

Vº Bº
LA PRESIDENTA DE LA COMISIÓN
DE ÉTICA DE INVESTIGACIÓN DE LA
UNIVERSIDAD DE MURCIA

Fdo.: María Senena Corbalán García

ID: 3592/2021