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EFECTOS FUNCIONALES Y ESTRUCTURALES DEL ENTRENAMIENTO CON SOBRECARGA EXCÉNTRICA EN DEPORTISTAS Y EN PERSONAS FÍSCAMENTE ACTIVAS

FUNCTIONAL AND STRUCTURAL EFFECTS OF ECCENTRIC-OVERLOAD RESISTANCE TRAINING IN ATHLETES AND PHYSICAL ACTIVE PEOPLE

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Sergio Maroto Izquierdo

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CONFERENCE PRESENTATIONS:

1. **Communication 1:** Maroto-Izquierdo (2017). La sobrecarga excéntrica y su aplicación en el alto rendimiento deportivo. National Strength & Conditioning Association (NSCA). Webinar. Madrid, Spain.

2. **Communication 2:** Maroto-Izquierdo et al. (2018). Hypertrophic effects of iso-inertial effects on the shoulder muscles of professional handball players. 5th Congreso Internacional Ejercicio Físico y Salud. Sonora, Mexico.

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ABBREVIATIONS

% 1-RM	Percentage of the one repetition maximum
1-RM	One repetition maximum
ADP	Adenosine diphosphate
AE	Aerobic exercise
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
BL	Bilateral
CCT	Clinical controlled trial
CI	Confidence interval
CMJ	Countermovement jump
CON	Concentric muscle action
CP	Creatine phosphate
CSA	Cross sectional area
DJ	Drop jump
DJ CT	Drop jump contact time
DOMS	Delayed onset muscle soreness
DXA	Dual-energy X-ray absorptiometry
ECC	Eccentric muscle action
EIMD	Excercise induced muscle damage
EMG	Electromyography
EO	Eccentric overload
EOT	Eccentric overload training
ES	Effect size
EX1	In paper 3, Experimental group 1
EX2	In paper 3, Experimental group 2
EXP	Experimental
FRTEO	Flywheel resistance training with eccentric overload
FW	Flywheel
GH	Growth hormone
IGF	Insulin growth factor

MRI	Magnetic resonance imaging
mRNA	messenger RNA
MU	Motor unit
MVC	maximal voluntary contraction
PO	Power output
POST	after intervention
PRE	Before intervention
QF	Quadriceps muscle
RCT	Randomized controlled trial
RFD	Rate of force development
ROM	Range of motion
RT	Resistance training
RE	Resistance exercise
RF	Rectus femoris muscle
SD	Standard deviation
SJ	Squat Jump
SMD	Standardized mean difference
TF	Faster training group
TS	Slower training group
UL	unilateral
VL	Vastus lateralis muscle
VI	Vastus intermedius muscle
WHO	World Health Organization
Δ	Increase
®	Registered trademark symbol

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RESUMEN EN ESPAÑOL

1. INTRODUCCIÓN

La inactividad física es la responsable de más de 5 millones de muertes al año en todo el Mundo (Hallal et al. 2014; Tremblay et al. 2015). Concretamente en España, el 13,4% de la tasa total de mortalidad corresponde a causas relacionadas con una falta de realización sistemática de ejercicio físico (Ramirez Varela et al. 2016). Lo que significa que el sedentarismo supone una tasa de mortalidad similar al tabaco o a la obesidad, constituyendo la cuarta causa de muerte en el Mundo (Bouchard et al. 2015). Es por ello que la inactividad física se ha convertido en una pandemia global, que implica millones de euros de pérdidas económicas y que se ha situado como una prioridad global en términos de salud.

El ejercicio físico, por su parte, ha demostrado cómo su realización sistemática mejora la función física y cognitiva de las personas que lo practican con independencia de su estado de salud, mejorando su calidad de vida, reduciendo el riesgo de caídas y combatiendo contra el sobrepeso (Garber et al. 2011; Riebe et al. 2015). Un millón y medio de muertes al año podrían preverse simplemente incrementando en un 10% el nivel de actividad física de la población (Lee et al. 2012). Numerosas instituciones a nivel Mundial, como es el caso de la Organización Mundial de la Salud (OMS), se han hecho eco de estos datos, promoviendo la elaboración de recomendaciones diarias de ejercicio físico. Estas guías prescriben la realización de 150 minutos semanales de ejercicio aeróbico a moderada intensidad o 75 minutos semanales a alta intensidad con el fin de mejorar los componentes de la condición física relacionados con la salud (Ramirez Varela et al. 2016). Sin embargo, y a pesar de que incrementos en la capacidad cardiorrespiratoria han sido relacionados con una disminución en la influencia de cierto predictores de mortalidad, estas recomendaciones de ejercicio aeróbico tan solo incrementan la función cardiovascular (Blair et al. 1996; Nauman et al. 2019).

No obstante, el entrenamiento de fuerza (modo de ejercicio referido a la aplicación de fuerza contra una resistencia dada) ha demostrado ser una modalidad de ejercicio físico superior para incrementar la fuerza, la potencia, la resistencia muscular, las ganancias de masa muscular y el control motor (Kraemer and Ratamess 2004; Kraemer et al. 2017a). Es por ello que el entrenamiento de fuerza se ha postulado como "la píldora" contra la inactividad física y comorbilidades asociadas a ella. Por ello, las recomendaciones más recientes de ejercicio físico incluyen el entrenamiento de fuerza realizado hasta tres veces por semana entre las pautas generales de ejercicio físico para diferentes poblaciones (niños, adultos sanos, adultos con patologías crónicas o salud comprometida, mujeres embarazadas y personas con obesidad) (Piercy and Troiano 2018; Piercy et al. 2018). Además de las mejoras relacionadas con la fuerza muscular y sus diferentes manifestaciones, el entrenamiento de fuerza también puede mejorar la capacidad cardiorrespiratoria con una correcta organización de ejercicios y cargas de entrenamiento (Ashton et al. 2018). De hecho, altos niveles de fuerza se correlacionan positivamente con un bajo riesgo de mortalidad (Garcia-Hermoso et al. 2018). Todo ello sitúa al entrenamiento de fuerza como una herramienta ideal, no solo para mejorar el nivel de condición física y habilidades relacionadas con la salud, sino también para optimizar el rendimiento deportivo (Suchomel et al. 2016a) y prevenir lesiones (Lauersen et al. 2014).

2. EL ENTRENAMIENTO DE FUERZA

Desde el punto de vista de la física, la fuerza es el producto de masa y aceleración, la cual incide en el estado de movimiento de un objeto. Por lo tanto, la fuerza muscular es considerada como la habilidad que tienen los músculos para acelerar, deformar, mantener un cuerpo inmóvil o decelerar una masa (Blazevich 2017). Esta aplicación de fuerza puede ser la ejercida para vencer la resistencia que la gravedad ejerce sobre nuestro cuerpo, o la aplicada sobre una resistencia externa para movilizarla, mantenerla o detenerla en el espacio. La aplicación de fuerza, por tanto, viene determinada por la capacidad de contracción de la musculatura esquelética.

Esta contracción muscular puede darse en varias direcciones y siempre implica una cierta velocidad (velocidad angular, positiva o negativa) en la articulación involucrada. Por lo que en Ciencias del Deporte, el concepto de fuerza es expresado como la tensión que un músculo o grupo muscular es capaz de producir a una determinada velocidad. Normalmente, la contracción muscular se produce en contra de una carga externa acelerada por la fuerza de la gravedad, como por ejemplo la que constituye la masa corporal en un salto vertical o cualquier implemento deportivo que deseemos movilizar, la cual actúa en dirección opuesta a la fuerza muscular.

Por lo tanto, dependiendo del movimiento que ocurra en las fibras musculares (acortamiento o alargamiento), o a la ausencia del mismo, durante la aplicación de fuerzas se observan diferentes tipos de contracción muscular. Cuando la cantidad de fuerza producida por un músculo es superior a la que la fuerza ejercida en sentido opuesto por la gravedad sobre una resistencia externa, hablaremos de contracción concéntrica. Durante una acción muscular concéntrica, la resistencia es vencida al mismo tiempo que el músculo se acorta. Por tanto, el resultado de una acción concéntrica es la movilización de cargas, es decir, la aceleración de las mismas. Por el contrario, si la cantidad de fuerza producida es inferior a la ejercida en dirección opuesta por una fuerza externa, el músculo se alargará, incluso cuando trata de acortarse. En este caso hablamos de contracción excéntrica. Como consecuencia, una acción muscular excéntrica producirá una disminución en la velocidad de la carga, es decir, implicará la deceleración de la misma. Por último, si la fuerza muscular es igual a la fuerza en sentido opuesto ejercida por una resistencia, tendrá lugar una contracción isométrica. En este caso, el músculo mantiene la misma longitud durante toda la contracción.

2.1 ASPECTOS FISIOLÓGICOS QUE AFECTAN A LA FUERZA MUSCULAR

Además de la herencia genética, el estado de salud, el nivel de entrenamiento y la experiencia en el mismo, así como las características biológicas (edad, sexo, etc) y antropométrica, otros muchos factores pueden tener influencia en la cantidad total de fuerza que el músculo esquelético es capaz de producir a través de la contracción. Entre esos factores destacan:

- ARQUITECTURA Y TAMAÑO MUSCULAR: Mayores tamaño de masa muscular han demostrado contribuir a una mayor producción de fuerza (Hakkinen and Keskinen 1989; Hakkinen et al. 2001). Además, la longitud de los fascículos en los que se agrupan las fibras musculares y el ángulo que dibujan con su inserción tienen un rol determinante en la producción de fuerza (Ando et al. 2018; Blazevich et al. 2007). De hecho, longitudes de fascículo mayores y ángulos fasciculares menores se relacionan con mayores niveles de producción de fuerza. Debido a esto, mayores picos de fuerza han sido observado en acciones de alargamiento muscular (Ando et al. 2018; Guilhem et al. 2013).

- RIGIDEZ MIOTENDINOSA: Las características estructurales del músculo mencionadas en el punto anterior también afectan al tejido conectivo elástico, es decir, a la aponeurosis y a los tendones. Estos son capaces de acumular energía elástica al reducir su espesor y aumentar su longitud durante las acciones musculares de alargamiento, lo que puede suponer un mayor rendimiento en la acción concéntrica subsecuente (Douglas et al. 2017a; Foure et al. 2013). Por tanto, se entiende como rigidez miotendionsa a la relación existente entre la fuerza producida durante el alargamiento del tejido conectivo elástico y la capacidad de extensión del mismo. Una proteína determinante en esta función elástica de la unión miotendinosa y del músculo es la titina (Hessel et al. 2017). Esta proteína funciona como un muelle viscoelástico dentro del sarcómero. Su rigidez puede verse aumentada mediante el estiramiento, lo que supondrá un aumento de la fuerza residual sobre la fuerza máxima isométrica basal después de un estiramiento (Herzog et al. 2015, 2016; Hahn et al. 2010).

• TIPOS Y CARACTERÍSTICAS DE LAS FIBRAS MUSCULARES: Las características de las fibras musculares que componen el músculo también es determinante en la cantidad de fuerza producida. De este modo, las fibras musculares que contienen “miosina rápida” (miosina capaz de hidrolizar ATP rápidamente, 600 veces por segundo) se contraen más rápidamente (40-90 ms) que las fibras musculares que contienen “miosina lenta” (miosina capaz de hidrolizar ATP a menor velocidad, 300 veces por segundo), que lo hacen más lentamente (90-140 ms) (Gonzalez-Badillo and Gorostiaga 2002). Por tanto, distinguimos 3 tipos de fibra muscular: Rápidas (tipo IIx), intermedias (tipo IIa) y lentas (tipo I). Las fibras tipo I difieren de las fibras tipo IIx en que tienen un ratio de contracción más lento, producen menos fuerza, poseen mejor vascularización y capacidad oxidativa, tiene mayor resistencia a la fatiga, utilizan energía procedente de la mioglobina en lugar de la ATPasa y tienen un menor número de miofibrillas en cada fibra muscular (Gonzalez-Badillo and Gorostiaga 2002). Las fibras tipo IIa, tienen características intermedias y son las únicas modificables con el entrenamiento (Andersen and Aagaard 2010).

• SISTEMA NEUROMUSCULAR. RECLUTAMIENTO Y SINCRONIZACIÓN DE UNIDADES MOTORAS: Desde una perspectiva neural, las fibras musculares se encuentran agrupadas en función de sus propiedades (isoforma de miosina rápida o lenta) en Unidades Motoras (MU), y por tanto, están enervadas por el mismo nervio motor (Gonzalez-Badillo and Gorostiaga 2002). De este modo, las MUs que contienen fibras de tipo rápido tiene una velocidad de conducción más rápida y una mayor frecuencia de descarga del impulso eléctrico que las UMs que integran fibras de tipo lento (Andersen and Aagaard 2010). El tipo de fibra también influye de manera directa en el reclutamiento de la UMs. Así, cuando los requerimientos de fuerza son grandes y esta debe ser desarrollada rápidamente (RFD), como por ejemplo en movimientos balísticos, las MUs grandes que contienen fibras de tipo IIx/IIa son reclutadas (Duchateau et al. 2006). Mientras que por el contrario si los requerimientos de fuerza necesarios para vencer una determinada resistencia no son tan grandes, MUs más pequeñas que contienen fibras de tipo I son las que serán activadas. Además, la aplicación de fuerza puede ser mayor si existe una determinada coordinación intramuscular o sincronización entre MUs.

3. EVOLUCIÓN DE LA INVESTIGACIÓN EN ENTRENAMIENTO DE FUERZA: EFECTOS FISIOLÓGICOS Y ADAPTACIONES INDUCIDOS POR EL ENTRENAMIENTO

A lo largo de la literatura científica, la importancia del entrenamiento de fuerza sobre las adaptaciones que implican una mejora en los componentes de la condición física relacionados con la salud (ganancias de fuerza, masa muscular y potencia) ha sido demostrada. La investigación en Ciencias del Deporte, concretamente en el entrenamiento de fuerza, comenzó a finales del siglo XIX, a través de investigación anecdótica recogida por practicantes. A lo largo del siglo pasado, junto con la aparición de nuevas tecnologías para la valoración funcional y fisiológica del sistema muscular durante el entrenamiento de fuerza o después de un programa de entrenamiento, se consolidaron hipótesis y hallazgos relacionados con la función neuromuscular y con el tipo de contracción (Kraemer et al. 2017a). Además se profundizó en los mecanismos fisiológicos subyacentes a algunas adaptaciones posteriores al entrenamiento de fuerza (Kraemer et al. 2017a). Todo ello condujo a diversas líneas de investigación en las que se analizaron las respuestas y adaptaciones de los principales sistemas, los efectos de la nutrición y las ayudas ergogénicas, la biomecánica durante el ejercicio, el efecto de diferentes equipamientos e implementos deportivos, el componente psicológico, el rendimiento deportivo y la prevención de lesiones. Y además, estas líneas de investigación fueron aplicadas a diferentes grupos de población (hombres y mujeres físicamente activos, deportistas, niños, ancianos o personas con patologías crónicas). Todo esto nos permite establecer los principales efectos inducidos por el entrenamiento y adaptaciones crónicas que actualmente se atribuyen al entrenamiento de fuerza.

El entrenamiento de fuerza ha demostrado poseer un efecto positivo en cambios neurológicos (mejora de la conducción nerviosa, de la amplitud electromiográfica, del reclutamiento de MUs, de la frecuencia de descarga del potencial de acción, y de la actividad cortical, así como una disminución de la coactivación agonista-antagonista) (Hakkinen et al. 1985a; Hakkinen et al. 2001; Aagaard et al. 2000; Aagaard et al. 2002; Duchateau et al. 2006; Maffiuletti et al. 2016), cambios estructurales (incrementos del tamaño de las fibras musculares, especialmente las fibras tipo II, y por tanto, un incremento en la hipertrofia muscular, optimización de las longitudes y ángulos de los fascículos musculares, y mejoras en la rigidez del tendón y en la densidad mineral ósea) (Blazevich et al. 2007; Schoenfeld et al. 2017a; Schoenfeld et al. 2017b; Schoenfeld et al. 2018, Douglas et al. 2017a; Franchi et al. 2017), cambios endocrinos (elevación en la concentración de hormonas anabólicas como son la testosterona y IGF-1 y somatotropina, e incremento en el ratio testosterona-cortisol y una disminución de las catecolaminas) (Kraemer and Ratamess 2005; Kraemer et al. 2017b), cambios metabólicos (aumento de la resistencia muscular a través de una disminución de la respuesta del lactato y un incremento del umbral láctico) (Tesch et al. 1990; Pascoe et al. 1993), y cambios funcionales (incrementos en la producción de fuerza, RFD, potencia muscular, habilidad de salto, velocidad de carrera y habilidades específicas del deporte, además de un efecto preventivo ante las lesiones musculares y de potenciación del rendimiento explosivo) (Suchoeml et al. 2018).

4. MÉTODOS DEL ENTRENAMIENTO DE FUERZA

La importancia del entrenamiento de fuerza sobre la capacidad funcional de las personas ha promovido la investigación en este ámbito, lo que ha favorecido la emersión de numerosas recomendaciones de entrenamiento de fuerza. La prescripción de ejercicio físico basada en la investigación científica requiere de la manipulación apropiada de diferentes variables del entrenamiento: intensidad (carga), volumen (número de series y repeticiones), tipo de ejercicio (multiarticular/monoarticular, bilateral/unilateral), tipo de acción muscular (concéntrico, excéntrico o isométrico), densidad (relación entre el tiempo de activación y tiempo de descanso), velocidad del movimiento (velocidad de desplazamiento del implemento utilizado durante el entrenamiento) y frecuencia de entrenamiento (número de sesiones por semana o por mesociclo). Las manipulación de estas variables, en combinación con diferentes equipamientos y materiales, estrategias de organización de las cargas y los objetivos perseguidos por el programa de entrenamiento han dado lugar a la aparición de diferentes métodos de entrenamiento. Entre estos métodos destacan: el entrenamiento con el propio peso corporal, el entrenamiento con resistencias gravitacionales, los levantamiento olímpicos, el entrenamiento pliométrico, el entrenamiento con elásticos y el entrenamiento excéntrico.

4.1. EJERCICIO CON EL PROPIO PESO CORPORAL

El entrenamiento de fuerza con el propio peso corporal constituye una modalidad de entrenamiento en la que la única resistencia a vencer es la que la gravedad ejerce contra nuestro propio cuerpo. Entre los ejercicios más comunes de este paradigma de entrenamiento se encuentran: las sentadillas, las flexiones de brazos de cúbito prono en el suelo o las dominadas. Se trata de una modalidad de ejercicio de fuerza de gran versatilidad, dado que no requiere de materiales (aunque habitualmente se complementa con materiales inestables, como son los bosus, fitballs o cintas de entrenamiento en suspensión) (Behm et al. 2015; Saeterbakken et al. 2011); involucrando, además, numerosos grupos musculares a través de ejercicios multiarticualres. La principal limitación que presenta este método es la dificultad para producir una sobrecarga de trabajo o incrementar la intensidad. Por tanto, las adaptaciones producidas con esta metodología de entrenamiento están destinadas a mejorar la resistencia muscular (Suchomel et al. 2018). Y además, es un tipo de entrenamiento muy interesante para mejorar aspectos básicos de la fuerza y enseñar la técnica de ejercicios multiarticulares. Por lo que su aplicación es de un elevado interés en niños, tercera edad o personas con patologías crónicas y deportistas que se están recuperando de una lesión (Baechle and Earle 2008; Yamauchi et al.

2009). Por último, el entrenamiento con el propio peso corporal, ha demostrado inducir ganancias en fuerza explosiva cuando se realizan ejercicios a alta velocidad y baja intensidad, demostrando ser beneficiosa para mejorar la capacidad pliométrica (Jiménez-Reyes et al. 2016).

4.2. ENTRENAMIENTO CON PESO LIBRE

El uso de resistencias gravitacionales, es decir, de peso libre, es el método más utilizado para desarrollar la fuerza y sus diferentes manifestaciones (Kraemer et al. 2017a). Mancuernas, barras, discos, kettlebells, y máquinas guiadas han sido y son altamente utilizadas para el entrenamiento y la rehabilitación en diferentes poblaciones. Este tipo de entrenamiento se basa en el levantamiento y en el descenso de una determinada carga. Esta metodología, a diferencia del empleo del propio peso corporal, permite la ejecución de ejercicios analíticos en los que se trabajan grupos musculares concretos a través de ejercicio monoarticulares normalmente realizados con máquinas guiadas. Aunque esta forma de aplicación del entrenamiento con resistencias gravitacionales puede ser interesante en investigación y en rehabilitación, esos movimientos analíticos no suelen aparecer en las acciones cotidianas diarias (Boyle 2016). Por lo que ejercicios multiarticulares realizados con peso libre han demostrado involucrar en mayor medida la coordinación y estabilización, generando así mayores ganancias de fuerza, potencia e hipertrofia (Stone et al. 2002).

Especialmente en la preparación física deportiva, los levantamiento olímpicos son prescritos como una vía óptima para desarrollar la fuerza y la potencia muscular. Estos ejercicios incluyen la cargada, la arrancada o el envión, y los derivados que omiten una porción del levantamiento completo, como por ejemplo el peso muerto (Coburn, 2012). Es altamente empleado entre atletas debido a que ha demostrado mayores ganancias funcionales que el entrenamiento tradicional con peso libre (Arabatzi and Kellis 2012; Channell and Barfield 2008; Hoffman et al. 2004) y que el entrenamiento pliométrico (Berton et al. 2018; Tricoli et al. 2005). Esto puede deberse a que durante estos ejercicios las cargas se mueven con intenciones balísticas (es decir, lo más rápido posible), explotando tanto la fuerza como la velocidad, y por ende la potencia (Suchomel et al. 2017). Su principal limitación es que requiere altos niveles de experiencia y un alto conocimiento de la ejecución técnica (Coburn, 2012).

La prescripción de entrenamiento de fuerza con medios gravitacionales suele realizarse a una determinada intensidad, ya que esta ha demostrado ser determinante en las adaptaciones inducidas por el entrenamiento (Schoenfeld et al. 2017a; Schoenfeld et al. 2016b). Actualmente, el método más empleado para prescribir entrenamiento de fuerza y cuantificar la intensidad del entrenamiento es el porcentaje del 1-RM (% 1-RM) (Baechle and Earle 2008). Por tanto, el entrenamiento de fuerza consiste en acelerar y frenar una carga externa absoluta y constante basada en un % 1-RM o en la velocidad de ejecución en un ejercicio dado (Gonzalez-Badillo and Sanchez-Medina 2010). Lo cual implica la evaluación de la fuerza máxima dinámica antes de la prescripción del entrenamiento y el empleo de materiales de evaluación (por ejemplo acelerómetros o traductores lineales de posición) para analizar el perfil fuerza-velocidad y cuantificar la carga del entrenamiento (Baechle and Earle 2008).

4.3. ENTRENAMIENTO DE FUERZA VARIABLE: ELÁSTICOS

Los programas de entrenamiento de fuerza tradicional suelen emplear cargas externas constantes. Sin embargo, el estudio del patrón cinético del movimiento y de las características mecánicas del peso libre puede ayudar a comprender las razones por las que el empleo de una carga absoluta constante no es un estímulo óptimo para mejorar la fuerza en acciones ejecutadas a alta velocidad (Avrillon et al. 2017). Cuando se realiza un entrenamiento explosivo con peso libre empleando cargas bajas, la máxima producción de fuerza ocurre durante el inicio del movimiento ("*momentum*") (Frost et al. 2010), y la habilidad para generar fuerza disminuye a medida que la carga es desplazada y adquiere velocidad (Newton et al. 1997), resultando, en última instancia, una deceleración al final de la acción concéntrica si la carga no es proyectada (Avrillon et al. 2017; Cormie et al. 2007). Por tanto, con intención de modificar la fuerza externa y ampliar la aplicación de fuerza muscular a lo largo de todo el rango de movimiento, diferentes implementos han demostrado su eficacia. Entre estos implementos destacan las bandas elásticas. Al añadir bandas elásticas al peso libre, proporcionamos un estímulo de fuerza incremental a medida que la carga se desplaza (Saeterbakken et al. 2016). Varios estudios han corroborado que el entrenamiento con resistencias variables induce mayores ganancias en la fuerza, tanto en miembros inferiores como en superiores, en comparación con el entrenamiento tradicional (Garcia-Lopez et al. 2014; Nilo Dos Santos et al. 2018; Soria-Gila et al. 2015). Además, se trata de un método que potencia la producción de fuerza y el RFD (Mina et al. 2016; Mina et al. 2019).

4.4. ENTRENAMIENTO PLIOMÉTRICO

El uso del ciclo estiramiento-acortamiento durante los movimientos explosivos es denominado ejercicio pliométrico, lo cual quiere decir que las acciones explosivas concéntricas se encuentran potenciadas cuando se realiza una acción excéntrica con carácter previo, como por ejemplo ocurre cuando realizamos un salto en contramovimiento o cuando un tenista golpea la pelota. El entrenamiento pliométrico se realiza mediante saltos en múltiples planos sin material o sobre vallas y cajones, así como cayendo desde determinadas alturas. Además, los movimientos balísticos con resistencias predefinidas (por ejemplo una sentadilla con salto) o movimientos que impliquen lanzamiento (por ejemplo, un lanzamiento de balón medicinal) también se consideran ejercicios pliométricos. Recientes hallazgos científicos han demostrado que el entrenamiento pliométrico puede producir adaptaciones similares en la altura del salto vertical en comparación con levantamientos olímpicos (Hackett et al. 2016). No obstante, cuando la persona entrenada posee un alto nivel de entrenamiento, los ejercicios balísticos con peso libre pueden inducir mayores ganancias de fuerza, velocidad, potencia y activación muscular (Lake et al. 2012; Suchomel et al. 2016b).

4.5. ENTRENAMIENTO EXCÉNTRICO

El entrenamiento excéntrico es aquel que implica acciones de alargamiento muscular como resultado de la aplicación de una fuerza decelerativa sobre una determinada carga. Normalmente, estas acciones de deceleración ocurren cuando la fuerza aplicada es menor a la generada por la carga aplicada o cuando se realiza un alargamiento muscular voluntario (Douglas et al. 2017a; Douglas et al. 2017b). Varios métodos han sido propuestos a lo largo de la literatura científica para ofrecer un estímulo excéntrico. Entre ellos destacan el tempo/velocidad utilizado durante el entrenamiento (Dias et al. 2015; Gillies et al. 2006); el uso de cargas supramáximas y la asistencia de terceros o dispositivos que movilizan la carga durante la fase concéntrica (Fernandez-Gonzalo et al. 2011; García-López et al. 2007; Jiménez-Jiménez et al. 2008); cicloergómetros excéntricos y tapices rodantes en bajada (Isner-Horobeti et al. 2013; Penailillo et al. 2015); y dispositivos isocinéticos (Guilhem et al. 2013).

Las adaptaciones que supone este tipo de entrenamiento han sido ampliamente estudiadas (Roig et al. 2009), en comparación con el entrenamiento concéntrico, isométrico y tradicional, se ha demostrado que podría favorecer en mayor medida cambios funcionales (fuerza, potencia y RFD), adaptaciones morfológicas (cambios en el área de sección transversal de fibras musculares y tendones), adaptaciones neuromusculares (reclutamiento de MUs, velocidad y frecuencia de activación de las mismas) y habilidades relacionadas con el rendimiento deportivo (salto vertical y velocidad de carrera) (Douglas et al. 2017a; Douglas et al. 2017b). Por lo que este método parece optimizar de manera eficaz el rendimiento (Meylan et al. 2008; Roig et al. 2008). De hecho, en la revisión de Suchomel et al. (2018) el entrenamiento excéntrico es propuesto como el mejor método para desarrollar la fuerza, la potencia y la masa muscular (tabla 1).

Tabla 1. (Adaptada de Suchomel et al. 2018). Potencial teórico de los diferentes métodos de entrenamiento de fuerza sobre las ganancias de masa muscular, fuerza y potencia.

Método de entrenamiento	Hipertrofia	Fuerza	Potencia
Ejercicio con el peso corporal	+	+	++
Ejercicios en máquina guiada	++	++	++
Levantamiento olímpicos	+++	+++	+++++
Entrenamiento variable (elásticos)	+++++	++++	++++
Entrenamiento pliométrico	+	++	+++++
Entrenamiento balístico	++	+++	+++++
Entrenamiento excéntrico	+++++	+++++	+++++

Métodos categorizados en escala desde + (1 punto, informando de un bajo potencial), a +++++ (5 puntos, informando de un alto potencial).

4.5.1. EJERCICIO EXCÉNTRICO: BASES Y CARACTERÍSTICAS FISIOLÓGICAS

Dado el hecho de que la habilidad para producir fuerza en la acción concéntrica limita la intensidad utilizada durante el ejercicio de fuerza. Lo que implica que la intensidad utilizada durante el entrenamiento tradicional con peso libre no sea óptima durante la fase excéntrica del movimiento, ya que la acción excéntrica se refiere a la actividad muscular que ocurre cuando la resistencia aplicada excede la fuerza generada por el músculo. Por tanto, el entrenamiento excéntrico inducirá un estrés y una tensión que supondrán un estímulo único y novedoso. La repetición sistemática de este estímulo ha demostrado inducir importantes beneficios. Douglas y colaboradores (2017a), han establecido que las ganancias en variables relacionadas con la fuerza son claramente específicas del modo de entrenamiento empleado (siendo más favorables para el entrenamiento excéntrico). Estas adaptaciones surgen como resultado de cambios neutrales, morfológicos y estructurales:

- Tras un periodo de entrenamiento aislado excéntricamente, la fuerza excéntrica aumenta debido a un incremento en la conducción nerviosa del músculo agonista al mismo tiempo que disminuye la coactivación del antagonista, debido a un reclutamiento de MUs específico de la acción excéntrica (Aagaard et al. 2003).

• Este reclutamiento específico de la acción excéntrica, tras un periodo de entrenamiento, supone un incremento en la capacidad para reclutar MUs grandes (tipo IIx y IIa) más rápidamente y a disminuir el umbral de reclutamiento y aumentar la frecuencia del impulso (Cormie et al. 2010; Van Cutsem et al. 1998). Esto, contribuye a un mayor aumento en el rendimiento del ciclo de estiramiento-acortamiento (potencia conéntrica (Colliander and Tesch 1990; Elmer et al. 2012; Gross et al. 2010) y RFD (Blazevich et al. 2008)).

• Además, el rendimiento explosivo también se ve mejorado por los cambios que el entrenamiento excéntrico induce en el tejido conectivo elástico. Así, aumentos en la rigidez del tendón (Malliaras et al. 2013) y en su área de sección transversal (Farup et al. 2014) han sido descritos como una probable vía de almacenamiento de energía y de utilización de esa energía elástica, permitiendo al músculo operar más cerca de su longitud y velocidad de acortamiento óptimas (Ando et al. 2018).

• Algunos autores han incidido en la importancia del entrenamiento excéntrico en las ganancias de volumen muscular. Si bien, los mecanismos por los que la hipertrofia tiene lugar no han sido ampliamente descritos (Schiaffino et al. 2013). Sin embargo, existe evidencia científica de que a tensión inducida por el estiramiento y los altos niveles de tensión mecánica a los que as MUs activas son sometidas (Fry 2004; Toigo and Boutellier 2006), junto con la mayor presencia de daño muscular después del ejercicio excéntrico (Garcia-Lopez et al. 2007; Jimenez-Jimenez et al. 2008), caracterizan la capacidad del entrenamiento excéntrico para generar una mayor respuesta anabólica en comparación con el entrenamiento tradicional puramente concéntrico (Schoenfeld 2010).

• La hipertrofia muscular ha demostrado no ser homogénea en todo el músculo y la región en la que se produce en mayor medida depende el estímulo otorgado con el entrenamiento. Siendo predominante en las regiones medias y dislates del músculo tras el entrenamiento excéntrico, mientras que tiene lugar en mayor medida en el vientre muscular tras el entrenamiento concéntrico (Franchi et al. 2014). Además, el entrenamiento excéntrico implica cambios en la longitud de los fascículos (aumentando su longitud) y una mayor presencia de sarcómeros en serie (Blazevich et al. 2007; Franchi et al. 2014). Esto va a permitir una mayor velocidad de acortamiento muscular y un aumento de producción de fuerzas a mayores longitudes musculares (Franchi et al. 2017). Estas diferencias en la respuesta hipertrófica pueden ser explicadas a nivel molecular, pues a pesar de que las vías AKT-mTOR y MATK son vías de señalización de la síntesis proteica, únicamente la vía MATK (proteínas p-38 MAPK, ERK 1/2, y p90RSK) fueron alteradas después del entrenamiento excéntrico (Franchi et al. 2014).

- El entrenamiento excéntrico también parece tener una incidencia directa en el área de sección transversal y en la distribución de las fibras rápidas tipo II (Friedmann-Bette et al. 2010; Hather et al. 1991; Hortobagyi et al. 2000).

Sin embargo, aunque existe evidencia del mayor efecto que posee el entrenamiento excéntrico aislado en comparación con el entrenamiento concéntrico aislado, existe cierta controversia. En numerosas revisiones, como son las de Wernbom (2007), Roig (2009), Schoenfeld (2017b) y Franchi (2017) no se encontraron diferencias estadísticamente significativas en el área de sección transversal del músculo entre ambos tipos de entrenamiento. Con respecto a la fuerza, a pesar de que varios artículos científicos han demostrado que existen mayores ganancias en la “fuerza total” después del entrenamiento aislado excéntricamente, esto es debido a que las ganancias de fuerza excéntrica después del entrenamiento excéntrico son muchos mayores que las ganancias concéntricas después del entrenamiento puramente concéntrico. De hecho, los efectos sobre la fuerza isométrica no muestran diferencias. Por tanto, existe una adaptación específica, pero no una clara ventaja de un método sobre el otro en el desarrollo de la fuerza. Por lo que, a pesar de que existe una cierta evidencia de superioridad del entrenamiento excéntrico aislado sobre algunas variables, la evidencia general de supremacía de este tipo de entrenamiento no es consistente. Sin embargo, si que existe un claro consenso en la importancia de la incorporación de acciones excéntricas en el entrenamiento de fuerza.

No obstante, numerosos estudios han destacado la importancia de las características fisiológicas únicas que presenta la contracción excéntrica, y que hacen que la inclusión de una fase de frenado durante el entrenamiento de fuerza sea un requisito para amplificar los efectos agudos y las adaptaciones crónicas inducidas por el entrenamiento con resistencias. Entre estas características únicas que presenta la contracción excéntrica, desde una perspectiva puramente fisiológica, y que además la diferencian de la contracción concéntrica y de la contracción isométrica, destacan:

1) Capacidad de producir mayores picos de fuerza: La contracción excéntrica es capaz de producir un 20-30% más de fuerza que una contracción isométrica con el mismo nivel de actividad electromiográfica. Durante acciones dinámicas con peso libre (Hollander et al. 2007) o con dispositivos isocinéticos (Colliander and Tesch 1990), se ha demostrado que la producción de fuerza en la acción excéntrica es un 20-60% mayor que en la concéntrica, acentuándose aún más este porcentaje en mujeres (60-160%) (Colliander and Tesch 1990). Además, la producción de fuerza durante el alargamiento muscular se incrementa de manera proporcional a la velocidad de contracción (Douglas et al. 2017b).

2) Menor activación muscular para vencer una misma carga: El ejercicio excéntrico ha demostrado una menor actividad electromiográfica en comparación con el ejercicio isométrico y concéntrico, incluso cuando la producción de fuerza es mayor (Duchateau and Baudry 2014; Tesch et al. 1990). Esta menor actividad eléctrica del músculo es debida a una menor activación de la fibras reclutadas y a una activación selectiva de fibras (Enoka 1995; Enoka 2002).

3) Menor coste metabólico: Además de que el ejercicio excéntrico requiere un menor número de MUs activas durante el mismo, se ha

demostrado que también las demandas metabólicas son menores durante el alargamiento muscular (Penailillo et al. 2013). Además, el consumo de oxígeno y la respuesta cardiaca también han demostrado ser menores durante las actividades que implican alargamiento muscular, como por ejemplo caminar cuesta abajo o el empleo de cicloergómetros excéntricos (Abbott et al. 1952; Kilgas and Elmer 2017). Esto resulta en una menor percepción de esfuerzo, concentración de lactato, energía requerida y una mayor oxidación de grasas (Penailillo et al. 2013).

4) Reclutamiento específico de unidades motoras: Las MUs de mayor tamaño que agrupan fibras de tipo rápido son reclutadas más rápidamente e implican una disminución del umbral de reclutamiento y un aumento de la frecuencia de estimulación (Cormie et al. 2010; Van Cutsem et al. 1998), especialmente cuando la velocidad de contracción es rápida (Kulig et al. 2001; Nardone et al. 1989). Esto puede ser explicado por el aumento del área de sección transversal y la distribución de las fibras rápidas (Fibras tipo Ida se convierten en fibras tipo IIx) (Friedmann-Bette et al. 2010).

5) Menor fatiga muscular: La fatiga muscular durante la contracción excéntrica es menor. En comparación con el ejercicio isocinético concéntrico, este muestra una disminución en la amplitud de la señal electromiográfica del 40% mientras que esta no se vio alterada durante el ejercicio isocinético excéntrico a la misma carga de trabajo (Tesch et al. 1990). Además, aumentos de fuerza excéntrica han demostrado reducir la fatiga muscular en torno a un 10% (Hortobagyi et al. 1996a).

6) Efecto protector ante el daño muscular ("repeated bout effect"): El efecto de la contracción excéntrica sobre el daño muscular es ampliamente estudiado. Generalmente, el daño muscular se produce como consecuencia de la realización de ejercicio excéntrico poco familiar, lo que requiere una mayor aplicación de fuerza por MU activa (Guilhem et al. 2010; Guilhem et al. 2012). Por tanto, una mayor tensión es aplicada en un menor número fibras musculares, causando lesiones mecánicas en

las mismas (Garcia-Lopez 2008). El daño muscular inducido por el ejercicio conlleva un incremento de las enzimas circulantes intramusculares (como la creatinkinasa o la mioglobina), y supone un perjuicio en la capacidad neuromuscular (reducción del 10-60% de la fuerza generada durante un máxima contracción voluntaria) (Guilhem et al. 2010). Esto también supone unas consecuencias a nivel metabólico, disminuyendo el aporte de glucosa y la sensibilidad a la insulina, repercutiendo en la síntesis de glucógeno y elevando el ratio metabólico y el metabolismo no oxidativo (Tee et al. 2007). Esto desencadena en una serie de síntomas que a parecen a partir de las 12 horas posteriores al ejercicio, acentuándose a las 24-48 horas y desapareciendo a los 5-7 días (Isner-Horobeti et al. 2013), entre los que destacan dolor y rigidez muscular, pérdida de la capacidad contráctil, reducción de la amplitud del rango de movimiento, hinchazón y déficit propioceptivo (Garcia-Lopez 2008). Todo ello puede verse acentuado cuando se emplean altas velocidades de contracción (Chapman et al. 2006), altas intensidades (McHugh and Tetro 2003), ejercicios o ángulos de trabajo que implican un mayor estiramiento de las fibras musculares (Proske and Allen 2005), y sujetos poco experimentados en el entrenamiento de fuerza (Newton et al. 2008). Sin embargo, el entrenamiento excéntrico sistematizado a demostrado reducir el daño muscular inducido por el ejercicio de manera significativa (Fernandez-Gonzalo 2011; Garcia-Lopez 2006). Este fenómeno se denomina “repeated bout effect”.

El entrenamiento aislado excéntricamente ha demostrado inducir ganancias neurales (aumento en la respuesta inhibidora y de la excitabilidad de la motoneurona, así como, alteración en el orden del reclutamiento de unidades motoras, induciendo, además, un efecto cruzado en la pierna no entrenada), estructurales (es decir, hipertrofia muscular y cambios en la arquitectura muscular) y en la función mecánica del músculo (longitud de fascículos y función miotendinosa) (Douglas et al. 2017a; Franchi et al. 2017; Hyldahl et al. 2015). Lo que contribuye a que el entrenamiento excéntrico induzca un fenotipo más fuerte y rápido en comparación con el entrenamiento de fuerza concéntrico y concéntrico-excéntrico tradicional en personas sanas y en deportistas (Douglas et al. 2017a; Friedmann-Bette et al. 2010) (figura 1). Esto otorga un carácter de superioridad al entrenamiento excéntrico, o en el que se acentúa la fase excéntrica respecto a la concéntrica, en comparación con el entrenamiento tradicional o únicamente concéntrico (Isner-Horobeti et al. 2013). Pero sin embargo, a pesar de los beneficios mostrados por el entrenamiento excéntrico y de las respuestas únicas a nivel mecánico, neural y celular producidas por la contracción excéntrica, este método de entrenamiento presenta ciertos inconvenientes que limitan su prescripción.

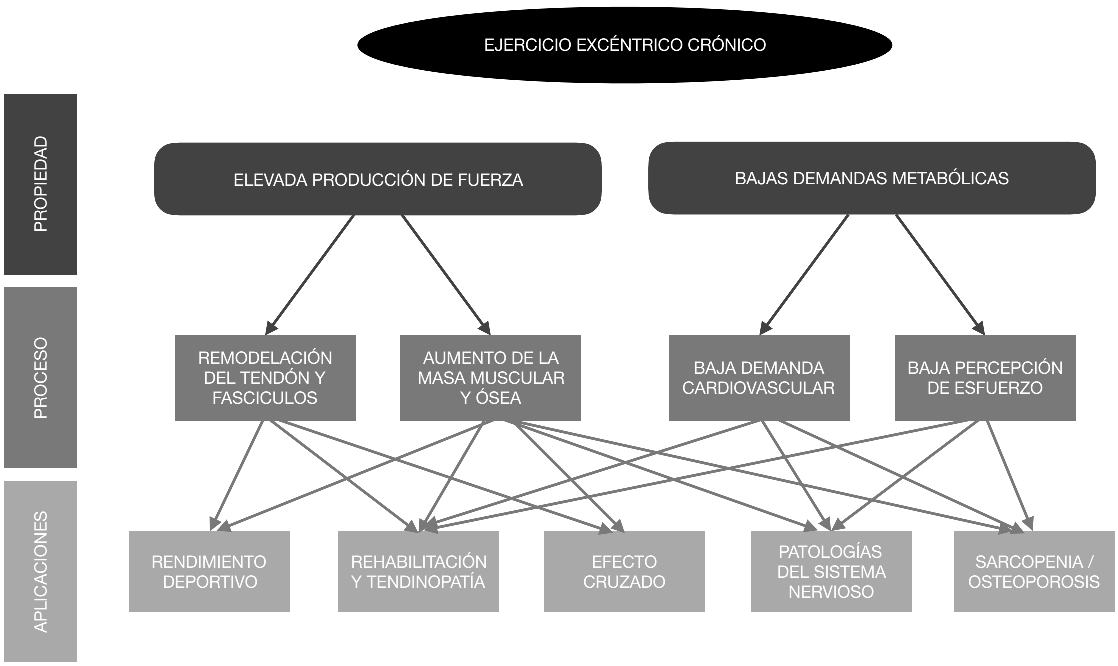

Figura 1. (Adaptado de Hessel et al. 2017) Diagrama resumen de las propiedades características de la contracción excéntrica, procesos fisiológicos que desencadena su aplicación sistemática y posibles aplicaciones a tales adaptaciones.

4.5.2. LIMITACIONES DEL EJERCICIO EXCÉNTRICO

El entrenamiento tradicional de fuerza consiste en el levantamiento (requiriendo una acción concéntrica) y en el descenso (requiriendo una acción excéntrica o decelerativa) de pesos. Sin embargo, el músculo esquelético no es capaz de acelerar cargas en la fase concéntrica con las mismas garantías que puede hacerlo decelerando cargas, debido a, como se mencionaba anteriormente, las características de la contracción excéntrica. Por lo tanto, las cargas movilizadas durante el entrenamiento de fuerza se encuentran limitadas por la capacidad de aplicación de fuerzas que posee la fase concéntrica, aportando un estímulo submáximo a la fase excéntrica, ya que la fisiología muscular nos permite aplicar una mayor cantidad de fuerza durante el alargamiento muscular que durante el acortamiento. Por ello, investigadores, y entrenadores prescriben el entrenamiento excéntrico aislado en sus programas de entrenamiento de fuerza. Sin embargo, el ejercicio excéntrico aislado presenta una serie de limitaciones que hacen que no sea ampliamente utilizado (Hortobagyi et al. 2001). Entre estas limitaciones destacan:

1) Dificultad para cuantificar la carga de entrenamiento.

2) Problemas para aislar el movimiento de la fase concéntrica.

3) Grandes requisitos de experiencia en el entrenamiento de fuerza y altos niveles de ejecución técnica.

4) Utilización de material económicamente costoso (por ejemplo, los dinamómetros isocinéticos).

5) Eliminación del ciclo estiramiento-acortamiento, lo que implica que este método de trabajo tenga poca aplicabilidad, funcionalidad y transferencia al rendimiento deportivo y a las actividades de la vida cotidiana.

4.5.3. ENTRENAMIENTO DE FUERZA ACENTUADO EXCÉNTRICAMENTE

El entrenamiento de fuerza con sobrecarga excéntrica (o acentuado excéntricamente) ha emergido como un método alternativo para prescribir entrenamiento de fuerza de forma óptima, al considerar la capacidad de producción de fuerza de la acción muscular excéntrica y evitar la eliminación del ciclo de estiramiento-acortamiento que acontecía con el entrenamiento aislado excéntricamente (Wagle et al. 2017). Este método consiste, por tanto, en la prescripción de una carga excéntrica acentuada o incrementada respecto a la carga concéntrica (Schoenfeld and Grgic 2018). Esto requiere la realización de ambas fases del movimiento y mantiene las características mecánicas naturales del movimiento humano. Varios estudios previos han documentado evidencia científica de que la producción de fuerza y potencia se ve aumentada (Aboodarda et al. 2013; Ojasto and Hakkinen 2009; Sheppard and Young 2010), y de este modo, las adaptaciones logradas por el entrenamiento se ven acentuadas (Wagle et al. 2017). Para ello, se han empleado dispositivos que permiten aportar una resistencia adicional durante la acción decelerativa, como es el caso de los liberadores de carga (Walker et al. 2016), y también dispositivos con un mayor componente tecnológico, como los motores eléctricos que asisten el movimiento (Friedmann et al. 2004; Friedmann-Bette et al. 2010; Yarrow et al. 2008). Tradicionalmente, el entrenamiento con sobrecarga excéntrica ha sido realizado con estos medios tradicionales, suponiendo, a pesar de la falta de consenso existente sobre el empleo de carga excéntricas submáximas, máximas o supramáximas, importantes adaptaciones crónicas, en algunos casos superiores a la inducidas por el entrenamiento tradicional (Wagle et al. 2017):

- Incrementos en la fuerza máxima dinámica entre el 5 y el 20% han sido documentados tras programas de entrenamiento con cargas submáximas (Friedmann et al. 2004) y supramáximas (Yarrow et al. 2008). Estos resultados sugieren que el empleo de grandes porcentajes de sobrecarga (es decir, cargas concéntricas bajas y excéntricas altas) durante el entrenamiento con sobrecarga excéntrica puede ser más efectivo que el entrenamiento con cargas concéntricas altas. Por lo que un potencial uso de este método puede ser mantener la capacidad de fuerza máxima mientras se enfatiza en la alta velocidad de movimiento concéntrico o se reduce la carga total de trabajo en función de la planificación y periodización del entrenamiento (Ojasto and Hakkinen 2009; Wagle et al. 2017).
- Aumentos de la fuerza máxima isométrica del 18 al 23% también han sido observados empleando cargas tanto submáximas como supramáximas

(Hortobagyi et al. 2001; Walker et al. 2016), e induciendo cambios mayores que el entrenamiento tradicional. Esto puede deberse a una mayor sensibilidad al calcio y a un aumento de la conducción neural inducido por la sobrecarga de trabajo excéntrico (Wagle et al. 2017).

- Mejora de aproximadamente un 28% en la resistencia muscular después del entrenamiento con cargas excéntricas supramáximas (Walker et al. 2016). Esta eficiencia mecánica, la cual parece ser independiente de la condición de la carga excéntrica, se atribuye a los cambios neurales que conlleva la acentuación de la acción excéntrica (Coratella and Schena 2016; Vogt and Hoppeler 2014).

- Estos cambios neurales, son transferibles favorablemente a las actividades que implican al ciclo de estiramiento-acortamiento, el cual tiene un efecto directo en el rendimiento deportivo. Así, se ha observado una mayor producción de potencia muscular en una acción concéntrica cuando esta se encontraba precedida de una acción excéntrica acentuada (Sheppard et al. 2007). Esta mayor producción de potencia observada en una acción concéntrica subsecuente puede ser la justificación de las adaptaciones encontradas relativas al rendimiento explosivo tras el entrenamiento aislado o reforzado excéntricamente. Sin embargo, esto no ha sido observado cuando se emplean amplios tiempos de vuelo en movimientos que implican una fase aérea, debido a la larga transición entre fase excéntrica y concéntrica y a la gran cantidad de energía disipada durante el aterrizaje del salto (Moore et al. 2007; Cormie et al. 2008). Por lo tanto, acciones excéntricas que se dan en periodos cortos de tiempo y a altas velocidades excéntricas son favorables, favoreciendo cambios positivos en el rendimiento pliométrico (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2019; Douglas et al. 2018).

- Todos estos efectos positivos que tienen lugar en variables funcionales están relacionadas con cambios estructurales. Además, el efecto potencial del entrenamiento excéntrico aislado sobre la hipertrofia eleva la posibilidad de que el entrenamiento con sobrecarga excéntrica aumente la cantidad de masa muscular (English et al. 2004; Schoenfeld and Grgic 2018). No obstante, varios estudios han encontrado diferencias en la fuerza (Brandenburg and Docherty 2002; Walker et al. 2016) y en el salto vertical pero no en la cantidad de masa muscular después de aplicar un entrenamiento acentuado excéntricamente en comparación con un protocolo de entrenamiento tradicional (Friedmann-Bette et al. 2010). Aunque esto puede deberse a una falta de consideración de la región específica del músculo en la que se mide el área de sección transversal (Franchi et al. 2017). Puesto que el entrenamiento reforzado excéntricamente, al igual que sucede con el entrenamiento excéntrico aislado, induce cambios en la arquitectura muscular que también son favorables en la producción de fuerza y potencia (Franchi et al. 2017). Además, el entrenamiento con sobrecarga excéntrica ha demostrado incrementar el área de sección transversal específico de las fibras tipo II y tipo I, y favorecer la transferencia de fibras tipo IIa a IIx (Friedmann-Bette et al. 2010).

Mas recientemente, varios dispositivos no dependientes de la gravedad han emergido para facilitar la realización de ejercicio reforzado excéntricamente (Tinwala et al. 2017). Entre ellos destacan los motores eléctricos, que generan resistencia por si solos en ambas fases del movimiento (no limitándose a movilizar la carga durante la fase concéntrica); y, los dispositivos de rueda inercial, que requieren de una acción concéntrica máxima para acumular energía cinética rotacional, la cual ha de ser disipada durante un momento concreto de la fase excéntrica, para obtener una sobrecarga de trabajo (Carroll et al. 2018). Los dispositivos de motor eléctrico y los de rueda inercial destacan entre los métodos existentes por otorgar al entrenamiento con sobrecarga excéntrica una fácil y rápida aplicación al mismo tiempo que mantienen los beneficios anteriormente señalados, y así no requerir de la asistencia de terceros o de pesados materiales que añadir al ejercicio durante la acción de frenado (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a). Por ello, su uso se ha extendido durante los últimos años. Como consecuencia, el interés de investigadores, entrenadores y practicantes ha crecido enormemente, por lo que una línea de investigación que analice sus efectos y lo compare con otros medios de entrenamiento es necesaria.

5. OBJETIVOS

El objetivo de la presente tesis doctoral fue profundizar en el análisis de los efectos inducidos por el entrenamiento con sobrecarga excéntrica con medios no gravitacionales sobre las capacidades neuromusculares y estructurales de deportistas y jóvenes físicamente activos, además de comparar los cambios en la fuerza, potencia y masa muscular con los producidos por otros métodos de entrenamiento. Con el fin de proporcionar a entrenadores y practicantes una herramienta óptima para la prescripción de entrenamiento orientado a la mejora los aspectos de la condición física relacionadas con el estado de salud y el rendimiento deportivo. Los objetivos específicos de la presente tesis doctoral están recogidos individualmente en las publicaciones que la integran, y fueron:

1. Elaborar una revisión sistemática de la literatura científica para examinar los efectos del entrenamiento con sobrecarga excéntrica con medios de rueda isoinercial sobre la masa muscular y capacidades funcionales en atletas y sujetos físicamente activos, además de comparar (meta-análisis) esas adaptaciones con las logradas por otros métodos de entrenamiento (peso libre). Véase publicación 1.

2. Analizar los efectos del entrenamiento isoinercial sobre diferentes variables funcionales y estructurales en comparación con el mismo ejercicio realizado con medios gravitacionales en el miembro inferior en jugadores profesionales de balonmano. Véase publicación 2.

3. Analizar el efecto del incremento de la sobrecarga excéntrica en términos de rango de movimiento y velocidad excéntrica, empleando un motor-eléctrico y un dispositivo de rueda isoinercial, sobre las adaptaciones

inducidas por el entrenamiento, y comparar las diferencias entre dispositivos. Véase publicación 3.

6. PUBLICACIONES

La modalidad de la presente tesis doctoral es por compendio de publicaciones. Por lo que lo que la metodología y resultados de esta tesis se encuentran descritos a lo largo de diferentes artículos científicos publicados en revistas indexadas en el ámbito de las Ciencias del Deporte:

6.1. PUBLICACIÓN 1

Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, de Paz JA (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: A systematic review and meta-analysis. J Sci Med Sport, 20(10), 943–951. doi:10.1016/j.jsams.2017.03.004

Introducción: Aunque el entrenamiento con peso libre y máquinas guiadas es el método más popular de entrenamiento de fuerza, la habilidad de producir fuerza durante la fase concéntrica y las características de la contracción excéntrica hacen que la carga de entrenamiento no sea óptima durante la fase excéntrica del movimiento. El entrenamiento excéntrico ha demostrado importantes aumentos a nivel funcional y estructural. Sin embargo, las acciones excéntricas aisladas son complejas y técnicamente difíciles de aplicar, eliminando además el ciclo de estiramiento-acortamiento. Los dispositivos de rueda inercial han despertado la atención de la comunidad científica durante los últimos años por ofrecer sobrecarga excéntrica sin eliminar la fase concéntrica. Estos dispositivos han demostrado mejorar la masa muscular, la fuerza máxima dinámica, isométrica y excéntrica, la potencia muscular, el salto vertical, la velocidad de carrera y la actividad electromiográfica en sujetos sanos y en deportistas. Como consecuencia su uso se ha incrementado en los últimos años, pero no existe ninguna investigación que compare la efectividad del entrenamiento con sobrecarga excéntrica con el entrenamiento tradicional, y que sistemáticamente revise la literatura científica en este ámbito. Por lo tanto, el objetivo de este meta-análisis fue examinar los efectos inducidos por el entrenamiento con sobrecarga excéntrica isoinercial sobre la masa muscular y capacidades funcionales en deportistas y personas físicamente activas, así como, comparar estas adaptaciones con las inducidas por el entrenamiento tradicional con peso libre.

Metodología: Se realizó una búsqueda en diferentes bases de datos (PubMed; Medline (SportDiscus); Web of Science, Scopus y PEDro) para identificar todas las publicaciones en las que se empleó el entrenamiento con sobrecarga excéntrica hasta el 30 de abril de 2016. Las variables dependientes fueron analizadas utilizando un "random effects model" para calcular la diferencia estándar de las medias y el intervalo de confianza al 95%. Un total de 9 estudios con 276 sujetos y 92 tamaños de efecto cumplieron los criterios de inclusión y fueron, por tanto, incluidos en el análisis estadístico.

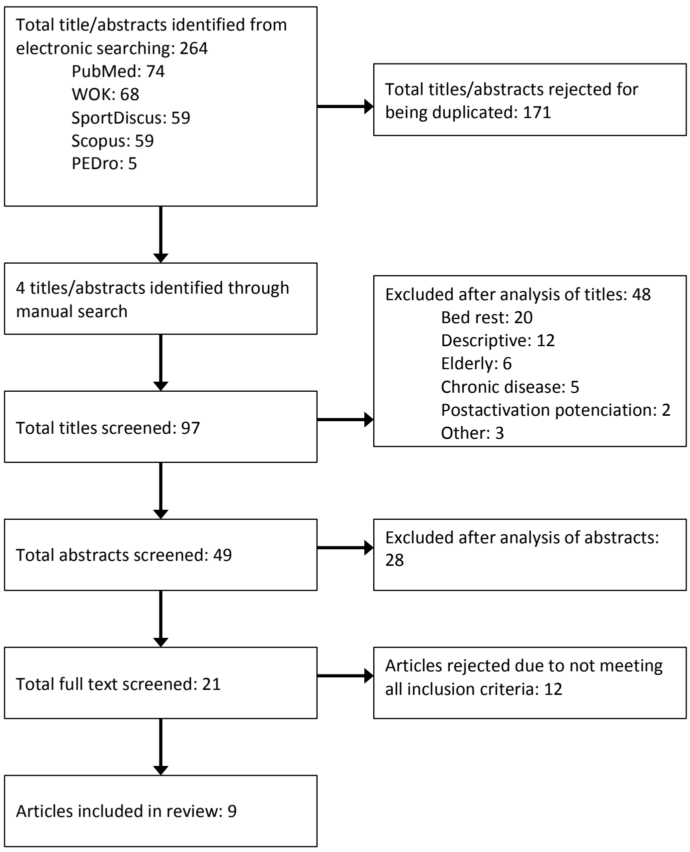

Figura 2. Diagrama de flujos de las diferentes fases de la búsqueda y selección de los artículos incluidos en la revisión (según las recomendaciones PRSIMA).

Resultados: La figura 3 muestra un diagrama de flujos con las diferentes fases de la búsqueda y la selección de estudios incluidos en la revisión. La media de calidad metodológica de estos estudios, según la escala PEDro, fue de 7 puntos sobre 11. El efecto individual de cada estudio, la estimación de todos los estudios juntos de una misma variable y su heterogeneidad están recogidos en la figura 2. El meta-análisis de los subgrupos demostró diferencias significativas en las adaptaciones inducidas por el entrenamiento favorables al entrenamiento de sobrecarga excéntrica con medios isoinerciales en comparación con el grupo control en la fuerza concéntrica y excéntrica (SMD: 0,66; 95% CI: 0,44-0,89), potencia muscular (SMD: 0,8; 95% CI: 0,53-1,07), hipertrofia muscular (SMD: 0,57; 95% CI: 0,25-0,9), rendimiento en el salto vertical (SMD: 0,46; 95% CI: 0,09-0,83) y velocidad de carrera (SMD: 0,41; 95% CI: 0,0-0,82).

	Eccentric Overload			Weight training				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Fixed, 95% CI**
1.1.1 Strength								
Norrbrand (2010)	47	128	9	29	152.9	8	2.0%	0.12 [−0.83, 1.08]
Tesch (2004)	50	269	10	5	226	10	2.3%	0.17 [−0.71, 1.05]
Maroto-Izquierdo (2016)	31.6	60.81	15	19.1	53.13	14	3.4%	0.21 [−0.52, 0.94]
Naczk (2015) ext TS	8	20.16	10	0	25.64	9	2.2%	0.33 [−0.57, 1.24]
Naczk (2014) T5	9.99	24.04	11	2.35	12.81	13	2.7%	0.39 [−0.42, 1.21]
Askling (2003) CON	20	33.42	15	3	31	15	3.4%	0.51 [−0.22, 1.24]
Naczk (2014) T10	11.99	22.13	11	2.35	12.81	13	2.7%	0.53 [−0.29, 1.35]
Naczk (2014) T0	13.62	23.17	11	2.35	12.81	13	2.7%	0.60 [−0.23, 1.42]
Naczk (2015) flex TS	17	17.47	10	0	32.18	9	2.1%	0.64 [−0.29, 1.57]
Naczk (2015) ext TF	14	26.11	10	−2	20.64	9	2.1%	0.65 [−0.28, 1.57]
Askling (2003) ECC	28	32.56	15	−2	34	15	3.2%	0.88 [0.12, 1.63]
Naczk (2015) flex TF	34	25.66	10	1	24.16	9	1.8%	1.26 [0.26, 2.27]
Naczk (2013) T10	53	29.86	18	4	26.96	10	2.2%	1.65 [0.74, 2.55]
Naczk (2013) T0	47	25.18	19	−5	37.9	11	2.4%	1.67 [0.80, 2.54]
Subtotal (95% CI)			**174**			**158**	**35.0%**	**0.66 [0.44, 0.89]**
Heterogeneity: $Chi^2 = 16.48$, df = 13 (P = 0.22); $I^2 = 21\%$								
Test for overall effect: Z = 5.73 (P < 0.00001)								
1.1.2 Muscle Power								
Naczk (2015) ext TS	12	41.24	10	−6	53.07	9	2.2%	0.36 [−0.55, 1.27]
Naczk (2014) T10	18.75	41.28	11	3.02	30.57	13	2.7%	0.42 [−0.39, 1.24]
Naczk (2014) T5	27.28	54.48	11	3.02	30.57	13	2.7%	0.54 [−0.28, 1.36]
Naczk (2015) flex TS	19	26.38	10	−11	70.52	9	2.1%	0.55 [−0.37, 1.47]
Naczk (2014) T0	26.81	48.23	11	3.02	30.57	13	2.7%	0.58 [−0.24, 1.40]
Naczk (2015) ext TF	30	60.02	10	−15	46.33	9	2.0%	0.80 [−0.15, 1.74]
Maroto-Izquierdo (2016)	129.24	76.13	15	57.46	67.16	14	3.0%	0.97 [0.19, 1.75]
Naczk (2015) flex TF	59	66.8	10	−3	51.77	9	1.9%	0.98 [0.02, 1.95]
Naczk (2013) T0	102	75.04	19	−8	84.02	11	2.6%	1.37 [0.54, 2.20]
Naczk (2013) T10	100	73.62	18	−5	73.75	10	2.4%	1.38 [0.52, 2.25]
Subtotal (95% CI)			**125**			**110**	**24.3%**	**0.80 [0.53, 1.07]**
Heterogeneity: $Chi^2 = 6.49$, df = 9 (P = 0.69); $I^2 = 0\%$								
Test for overall effect: Z = 5.75 (P < 0.00001)								
1.1.3 Hypertrophy								
Norrbrand (2008)	80	315.16	7	42	526.93	8	1.7%	0.08 [−0.93, 1.10]
Tesch (2004)	71	421	10	−13	387	10	2.3%	0.20 [−0.68, 1.08]
Naczk (2015) TS	0.4	0.72	10	0	0.72	9	2.1%	0.53 [−0.39, 1.45]
Naczk (2013) T0	3.66	5.14	19	0.56	4.95	11	3.1%	0.59 [−0.17, 1.35]
Naczk (2015) TF	0.46	0.72	10	0	0.72	9	2.1%	0.61 [−0.32, 1.54]
Naczk (2013) T10	4.99	6.86	18	0.56	4.95	10	2.8%	0.69 [−0.11, 1.48]
Maroto-Izquierdo (2016)	6.2	5.1	15	1.2	4.24	14	2.9%	1.03 [0.25, 1.82]
Subtotal (95% CI)			**89**			**71**	**17.2%**	**0.57 [0.25, 0.90]**
Heterogeneity: $Chi^2 = 3.02$, df = 6 (P = 0.81); $I^2 = 0\%$								
Test for overall effect: Z = 3.47 (P = 0.0005)								
1.1.4 Jump								
Maroto-Izquierdo (2016)	3.49	7.89	15	1.12	5.84	14	3.3%	0.33 [−0.40, 1.06]
Naczk (2013) T0	6.81	19.08	19	−0.43	8.12	11	3.2%	0.44 [−0.31, 1.19]
Naczk (2013) T10	3.15	6.62	18	−0.43	8.12	10	2.9%	0.48 [−0.30, 1.27]
De Hoyo (2015)	2.6	5.87	18	−0.6	4.67	15	3.7%	0.58 [−0.12, 1.28]
Subtotal (95% CI)			**70**			**50**	**13.1%**	**0.46 [0.09, 0.83]**
Heterogeneity: $Chi^2 = 0.24$, df = 3 (P = 0.97); $I^2 = 0\%$								
Test for overall effect: Z = 2.44 (P = 0.01)								
1.1.5 Speed								
De Hoyo (2015)	0.04	0.184	18	−0.01	0.17	15	3.8%	0.27 [−0.41, 0.96]
Askling (2003)	0.08	0.215	15	0	0.141	15	3.4%	0.43 [−0.30, 1.15]
Maroto-Izquierdo (2016)	0.38	0.361	15	0.19	0.306	14	3.2%	0.55 [−0.19, 1.29]
Subtotal (95% CI)			**48**			**44**	**10.5%**	**0.41 [−0.00, 0.82]**
Heterogeneity: $Chi^2 = 0.29$, df = 2 (P = 0.87); $I^2 = 0\%$								
Test for overall effect: Z = 1.94 (P = 0.05)								
Total (95% CI)			**506**			**433**	**100.0%**	**0.63 [0.49, 0.76]**
Heterogeneity: $Chi^2 = 30.06$, df = 37 (P = 0.78); $I^2 = 0\%$								
Test for overall effect: Z = 9.17 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 3.54$, df = 4 (P = 0.47), $I^2 = 0\%$								

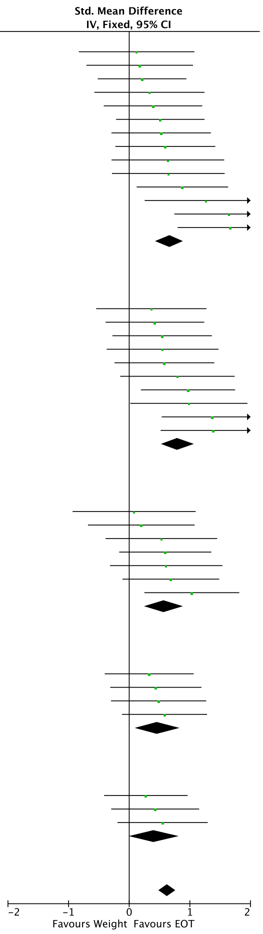

Figura 3. Forest plot con meta-análisis de las diferencias en las medias estandarizadas mostrando los efectos del entrenamiento con sobrecarga excéntrica en comparación con el entrenamiento tradicional sobre la fuerza potencia muscular, hipertrofia, rendimiento del salto vertical y velocidad de carrera

Conclusiones: Los resultados de esta revisión sistemática indican que breves episodios de sobrecarga excéntrica inducidos por dispositivos de rueda inercial y ejecutados a alta intensidad están asociados a mayores mejoras en la fuerza, potencia y masa muscular en sujetos sanos y atletas. Además, el entrenamiento con sobrecarga excéntrica parece ser más efectivo que el entrenamiento tradicional en la promoción de mejoras en las capacidades altamente relacionadas con el rendimiento deportivo. La eficacia de este entrenamiento es posible que esté mediada por la capacidad de aplicar mayores fuerzas durante la acción muscular excéntrica, maximizando el uso del ciclo estiramiento-acortamiento, y por tanto, la capacidad de producir mayor fuerza en la acción concéntrica subsecuente. Parece que el entrenamiento de fuerza con medios inerciales a alta velocidad y bajos momentos de inercia es el método más efectivo empleando esta tecnología para inducir adaptaciones musculares. Finalmente, la potencia muscular es la manifestación de la fuerza que ha experimentado los mayores aumentos después de un periodo de entrenamiento con resistencia isoinercial.

6.2. PUBLICACIÓN 2

Maroto-Izquierdo S, García-López D, de Paz JA (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball Players. J Hum Kinet, 60, 133–143. doi:10.1515/hukin- 2017-0096 27.

Introducción: La fuerza y potencia muscular son críticas en el deporte de equipo, ya que estas habilidades constituyen la base de las acciones específicas que determinan el rendimiento deportivo (lanzamientos, saltos, carreras, cambios de dirección, etc). Por lo tanto, continuamente se buscan nuevos métodos de entrenamiento que desarrollen el rendimiento explosivo muscular (entrenamiento pliométrico, ejercicios balísticos y levantamientos olímpicos). El entrenamiento con sobrecarga excéntrica inducida por medios isoinerciales emerge como una alternativa a estos métodos para generar sobrecarga excéntrica y así proporcionar un nuevo estímulo no dependiente de la gravedad que optimice el rendimiento y reduzca la incidencia lesional. Por ello, el objetivo de este estudio fue analizar los efectos de 6 semanas de entrenamiento con sobrecarga excéntrica isoinercial en diferentes variables funcionales y anatómicas en jugadores profesionales de balonmano.

Metodología: 29 jugadores profesionales de balonmano participaron voluntariamente en el estudio y fueron aleatorizados en dos grupos de entrenamiento. Ambos grupos realizaron 15 sesiones de entrenamiento de la musculatura del miembro inferior en el ejercicio de prensa de pierna (4 series de 7 repeticiones máximas). El grupo experimental realizó el ejercicio en un dispositivo de rueda inercial (figura 4), mientras que el grupo control ejecutó el mismo ejercicio (en términos de intensidad percibida y volumen) en una máquina guiada de peso libre. Antes y después de la intervención se midió la fuerza máxima dinámica (1-RM), la potencia muscular realizada a diferentes intensidades (del 40 al 90% del 1-RM), la altura del salto vertical (CMJ y SJ) y la velocidad de carrera en el test de 20 metros y en la prueba T-test. Además, se valoró el espesor del vasto lateral a nivel proximal, medial y distal con ecografía.

Figura 4. Dispositivo isoinercial usado en el programa de entrenamiento con sobrecarga excéntrica por los participantes del grupo experimental.

Resultados: La tabla 2 muestra los principales efectos inducidos por el entrenamiento sobre las variables funcionales para cada grupo y la interacción entre grupos para todas las variables funcionales. El grupo experimental mejoró significativamente todas ellas: 1-RM (12,2%), potencia media entre el 50% y 90% 1-RM (del 10% al 21,6%), SJ (9,6%), CMJ (9,8%), 20m (-10%) y T-test (-7%). Mientras que el grupo control tan solo mejoró de manera significativa el 1-RM (7,9%), el CMJ (4,5%) y el 20m (-5,1%). En cuanto a la masa muscular (figura 5), el grupo experimental mostró mejoras significativas (P < 0,01) en las 3 regiones donde el espesor del vasto lateral fue medido (tamaño del efecto entre 0,63 y 1,64) mientras que el grupo control tan solo mejoró significativamente (P < 0,05) en las regiones medial y distal del vasto lateral (tamaño del efecto entre 0,15 y 0,39). Además, se encontraron diferencias significativas entre grupos, favorables al grupo experimental en las variables CMJ (P < 0,05), velocidad de carrera (P < 0,01) e hipertrofia del vasto lateral a nivel proximal (P < 0,001), medial (P < 0,001) y distal (P < 0,01) respecto al grupo control (tabla 2).

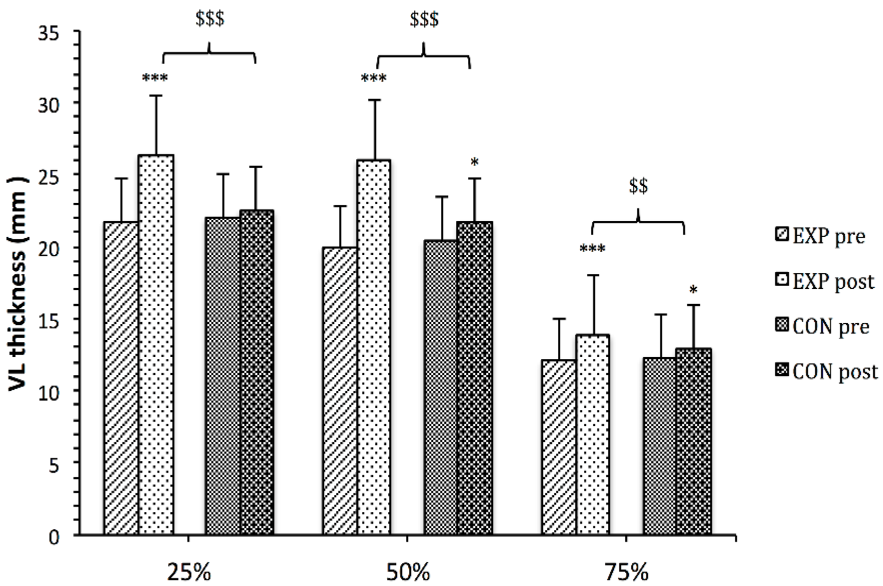

Figura 5. Mediciones del espesor del vasto lateral a nivel proximal (25%), a nivel medial (50%) y a nivel distal (75%) antes (pre) y después (post) del programa de entrenamiento para los grupos experimental (EXP) y control (CON).
* Diferente significativamente respecto al valor basal, dónde *p<0.05 y ***p<0.00. $ Diferente significativamente respecto al grupo CON, dónde $ p<0.05 y $$$ p<0.001.

Conclusiones: Ya que el balonmano es un deporte en el que se alternan acciones cortas y explosivas a alta intensidad, como las aceleraciones y deceleraciones que se producen durante los sprints y los cambios de dirección, los resultados de este estudio concluyen que el entrenamiento con sobrecarga excéntrica con medios isoinerciales induce cambios estructurales y funcionales que podrían ser beneficiosos para mejorar el rendimiento en jugadores de balonmano altamente entrenados.

Tabla 2. Valores antes y después del periodo de intervención del 1-RM, potencia media a diferentes intensidades SJ, CMJ, 20-m y T-test para los grupos experimental y control (valores expresados como media ± error típico).

	EXPERIMENTAL			CONTROL		
	Pre	Post	Δ%	Pre	Post	Δ%
1RM (kg)	258.7 ± 9.5	290.3 ± 12.5 ***	12.2	242.9 ± 10.9	262 ± 9.1 *	7.9
PO50 (w)	835.1 ± 30.4	943.1 ± 59 **	12.9	894.2 ± 52.3	943.4 ± 47.4	5.5
PO60 (w)	918 ± 39.2	1009.5 ± 67.4 *	10	908.3 ± 50.8	954.9 ± 45.1	5.1
PO70 (w)	916.8 ± 38.6	1030.4 ± 65.4 **	12.4	922.5 ± 49.3	982.7 ± 37.6	6.5
PO80 (w)	840.2 ± 38.7	1005.8 ± 68.7 **	19.7	886.2 ± 40.4	948.4 ± 34.8	7
PO90 (w)	777.4 ± 42	944.9 ± 70*	21.6	871.9 ± 41	941 ± 42.7	7.9
SJ (cm)	33.4 ± 1.5	36.7 ± 1.5 ***	9.6	31.5 ± 1.2	32.9 ± 0.8 *	4.5
CMJ (cm)	35.7 ± 1.3	39.2 ± 1.5 *** $	9.8	33 ± 1.2	34.1 ± 0.9	3.4
20m (s)	3.7 ± 0.1	3.3 ± 0.1 ***	-10	3.6 ± 0.1	3.5 ± 0.1 **	-5.1
T-test (s)	9.2 ± 0.1	8.6 ± 0.1 *** $$	-7	9.5 ± 0.2	9.1 ± 0.1	-4.4

Abreviaciones: 1RM, fuerza máxima dinámica; PO, potencia muscular; PO50-90 potencia concéntrica pico a diferentes intensidades (50, 60, 70, 80 y 90% del 1-RM); SJ, salto "squat jump"; CMJ, salto con contramovimiento; 20m, 20-m sprint time.
* Significativamente distinto respecto a PRE, siendo *p<0.05, **p<0.01, y ***p<0.001. $ Significativamente diferente respecto al valor del grupo control, siendo $p<0.05 and $$p<0.01.

6.3. PUBLICACIÓN 3

Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, Manzano-Rodriguez S González-Gallego J, de Paz, JA (2019). Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor. Eur J Sport Sci. doi:10.1080/17461391.2019.1588920

Introducción: Entre las diferentes tecnologías existentes para sobrecargar la fase excéntrica del movimiento destacan los dispositivos de rueda isoinercial, los cuales constituyen uno de los paradigmas de entrenamiento más utilizados en diferentes escenarios, como son la prevención y rehabilitación de lesiones y el rendimiento deportivo. Una de las limitaciones de los dispositivos isoinerciales es que requieren de una acción concéntrica máxima para generar sobrecarga excéntrica únicamente en un rango pequeño y concentrado al final de la fase excéntrica. Ciertos motores eléctricos se sobreponen a estas limitaciones, permitiendo la aplicación de sobrecarga excéntrica en el rango completo y posibilitando modificar la velocidad excéntrica. Estas modificaciones sobre el rango de movimiento y la velocidad con la que el estímulo excéntrico es aplicado, podrían tener consecuencias significativas en las adaptaciones subyacentes al entrenamiento con sobrecarga excéntrica. Por lo que el objetivo de este estudio fue analizar y comparar los efectos del entrenamiento isoinercial con sobrecarga excéntrica a diferentes velocidades y en diferentes rangos de movimiento, generada por un dispositivo de motor eléctrico y un dispositivo de rueda inercial.

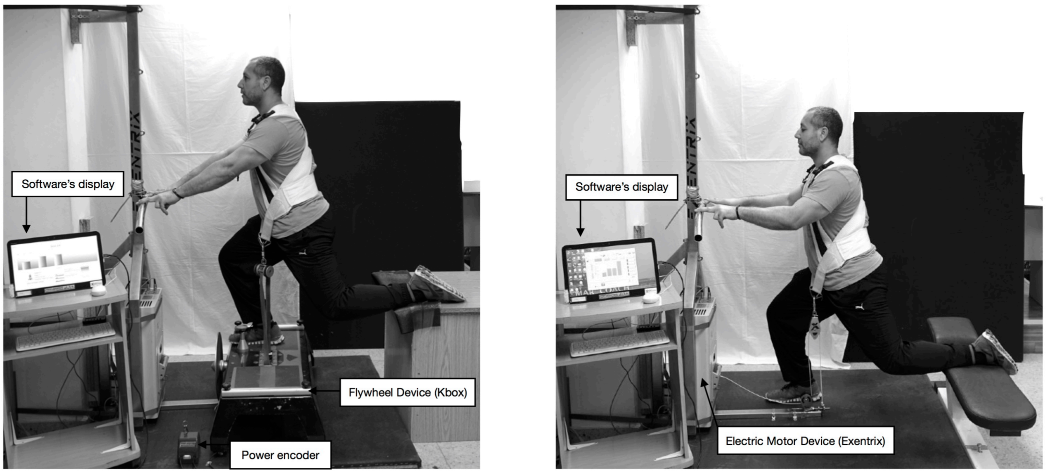

Figura 6. A. Ejercicio de sentadilla a una pierna en dispositivo de rueda inercial. B: Ejercicio de sentadilla a una pierna en dispositivo de motor eléctrico.

Metodología: 40 estudiantes universitarios físicamente activos (21,7 ± 3,4 años) participaron voluntariamente en este estudio y fueron divididos aleatoriamente en 4 grupos (10 participantes por grupo). Uno de los grupos no realizó ningún entrenamiento (grupo control), mientras que los otros 3 grupos realizaron 12 sesiones del ejercicio de sentadilla a una pierna. El grupo FW realizó el ejercicio con una máquina de rueda inercial convencional (figura 6.A), mientras que los grupos EX1 y EX2 realizaron el ejercicio con un motor eléctrico (figura 6.B) en modo isoinercial a la misma intensidad que el grupo FW, pero el grupo EX2 lo realizó a una velocidad excéntrica un 50% más rápida que la de los grupos EX1 y FW. El 1-RM, la potencia muscular a diferentes intensidades, el salto vertical (CMJ, SJ y DJ) y la masa magra medida con densitometría fueron analizados antes y después de 6 semanas de intervención.

Resultados: Los efectos del entrenamiento para cada grupo en las variables masa muscular, fuerza y salto vertical aparecen recogidos en la tabla 3. La figura 7 muestra los efectos del entrenamiento sobre la potencia media concéntrica a diferentes intensidades del 1-RM. Se encontraron incrementos significativos similares en todas las variables analizadas después del programa entrenamiento en los 3 grupos experimentales. Los participantes del grupo control no mejoraron ninguna variable. El grupo que entrenó con una mayor velocidad excéntrica mostró mayores ganancias en la potencia pico excéntrica durante el entrenamiento en comparación con los grupos FW y EX1.

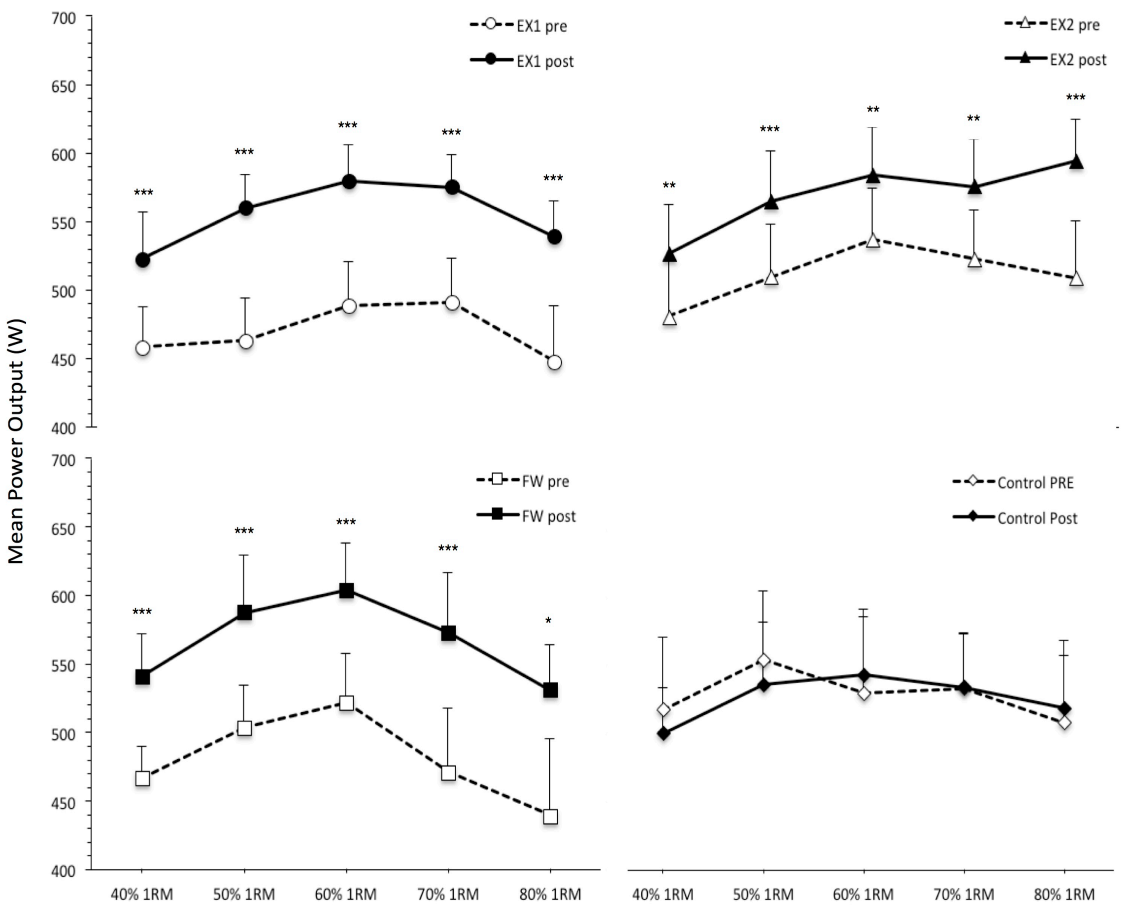

Figura 7. Potencia media (w) en el ejercicio de prensa de pierna a diferentes porcentajes del 1-RM antes (pre) y después (post) del entrenamiento. * Significativamente diferente respecto al valor pre, siendo * $p<0.05$, ** $p<0.01$ and *** $p<0.001$.

Tabla 3. Cambios en las variables funcionales (fuerza y salto vertical) y estructurales (masa magra) antes y despúes de la intervención.

	EX1 grupo					EX2 grupo					FW grupo					CONTROL grupo				
	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P
Masa muscular																				
Distal (g)	189.0 ± 15.0	194.6 ± 17.4	2.9	0.35	*	194.9 ± 31.7	205.3 ± 34.8	5.4	0.31	***	186.7 ± 20	197.4 ± 18.2	5.7	0.56	***	200.3 ± 33.5	202.8 ± 36.2	1.3	0.07	
Medial (g)	309.3 ± 37.7	317.1 ± 36.1	2.5	0.21	*	324.2 ± 50.2	336.7 ± 55.8	3.9	0.24	***	305.3 ± 30.5	317.4 ± 25.6	4.0	0.43	***	328.3 ± 48.4	332.0 ± 50.0	1.1	0.07	
Proximal (g)	418.6 ± 38.5	425.8 ± 41.7	1.7	0.18		431.0 ± 51.7	452.2 ± 54.0	4.9	0.41	***	426.8 ± 37.8	441.1 ± 32.5	3.4	0.41	***	443.6 ± 59.4	444.8 ± 58.2	0.3	0.02	
Total (g)	6793.9 ± 758.3	6967.9 ± 776.2	3.4	0.30	**	6912.2 ± 974.9	7222 ± 1073.8	4.5	0.30	***	6549.2 ± 708.8	6881 ± 791.2	5.1	0.44	***	6783.0 ± 1102.9	6684.3 ± 995.1	-1.5	0.09	
Fuerza																				
1-RM (kg)	187.8 ± 36.7	244.4 ± 39.1	30.2	1.49	***	177.2 ± 41.8	226.1 ± 26.9	27.6	1.39	***	210.0 ± 34.7	256.1 ± 41.6	21.9	1.20	***	225.0 ± 40.3	225.7 ± 46.9	0.3	0.02	
Salto vertical UL																				
CMJ (cm)	21.6 ± 3.3	23.7 ± 3.2	9.8	0.65	*	21.8 ± 3.5	23.8 ± 3.3	9.1	0.59	*	21.1 ± 4.2	23.8 ± 3.1	12.8	0.73	**	23.8 ± 7.4	21.4 ± 5.3	-9.9	0.37	*
SJ (cm)	20.5 ± 3.6	22.8 ± 3.2	11.2	0.67	*	21.3 ± 3.8	22.7 ± 3.2	6.6	0.40		19.7 ± 3.8	23.1 ± 2.7	17.3	1.03	***	22.8 ± 7.9	20.8 ± 4.3	-8.8	0.31	
DJ (cm)	18.3 ± 4.4	21.6 ± 2.9	18.0	0.89	***	18.4 ± 4.4	21.4 ± 2.9	15.9	0.81	***	18.3 ± 2.6	21.5 ± 2.2	17.5	1.33	***	19.9 ± 4.1	18.9 ± 3.8	-5.0	0.25	
DJ CT (ms)	0.577 ± 0.16	0.386 ± 0.08	33.1	1.51	***	0.499 ± 0.12	0.364 ± 0.05	27.1	1.47	***	0.525 ± 0.10	0.463 ± 0.07	11.8	0.72		0.528 ± 0.07	0.524 ± 0.13	-0.8	0.04	
Salto vertical BL																				
CMJ (cm)	38.5 ± 4.3	40.6 ± 4.1	5.5	0.50	***	39.1 ± 6.4	42.2 ± 6.9	8.0	0.47	***	38.7 ± 6.9	41.3 ± 6.4	6.9	0.39	***	40.2 ± 4.6	39.6 ± 4.3	-1.6	0.13	
SJ (cm)	36.2 ± 3.9	38.6 ± 3.9	6.6	0.62	***	37.1 ± 5.2	39.7 ± 5.8	7.0	0.47	***	37.2 ± 5.6	39.1 ± 4.8	4.8	0.36	**	38.3 ± 4.7	38.6 ± 5.3	0.6	0.08	
DJ (cm)	35.7 ± 4.7	38.6 ± 5.2	8.4	0.59	*	36.7 ± 8.4	40.9 ± 8.4	11.3	0,5	***	35.6 ± 8.8	39.1 ± 5.8	9.5	0.47	**	38.2 ± 6.0	37.1 ± 5.4	-2.8	0.19	
DJ CT (ms)	0.502 ± 0.15	0.417 ± 0.08	16.9	0.71		0.451 ± 0.12	0.389 ± 0.08	13.9	0.61		0.458 ± 0.11	0.428 ± 0.10	6.7	0.29		0.488 ± 0.09	0.518 ± 0.09	6.0	0.33	

Abbreviation: 1-RM: One-Repetition Maximum; BL: Bilateral; CMJ: Countermovement Jump; DJ: Drop Jump; DJ CT: Drop Jump Contact Time; UL: Unilateral;. * Significantly different from pre-training value, where * $p<0.05$, ** $p<0.01$ and *** $p<0.001$

Conclusiones: A pesar de las diferencias en rango de movimiento y velocidad del estímulo excéntrico, y por tanto en los porcentajes de sobrecarga excéntrica experimentados por cada uno de los grupos, podemos concluir que 6 semanas de entrenamiento de fuerza empleando ruedas inerciales o motores eléctricos en modo isoinercial inducen ganancias similares en masa muscular, fuerza, potencia y salto vertical. Si bien, el dispositivo de motor elector funciona como un dispositivo isoinercial ideal, permitiendo obtener sobrecarga excéntrica sin necesidad de realizar una acción concéntrica máxima y aportando sobrecarga en toda la fase excéntrica. Además, parece que mayores porcentajes de sobrecarga excéntrica están relacionados con mayores ganancias de masa muscular, mientras que menores porcentajes de sobrecarga excéntrica están más relacionados con incrementos en la potencia muscular concéntrica.

7. COMUNICACIONES EN CONGRESOS INTERNACIONALES Y FUTURAS PUBLICACIONES

Además, parte de los hallazgos más recientes de la presente tesis doctoral han sido publicados en comunicaciones en congresos internacionales. Entre estos hallazgos se ha demostrado la existencia de ganancias, especialmente en fuerza y masa magra, en la pierna contralateral no entrenada cuando un protocolo de 6 semanas de entrenamiento con medios isoinerciales fue llevado a cabo. Así como la existencia de adaptaciones similares en fuerza máxima, máxima contracción isométrica voluntaria, resistencia muscular, potencia muscular e hipertrofia en pequeños grupos musculares del miembro superior con medios isoinericales, y también a diferentes intensidades de entrenamiento isotónico, tras el entrenamiento acentuado excéntricamente con cargas submáximas y supramáximas con un motor eléctrico. A pesar de que únicamente el entrenamiento supramáximo induce cambios significativos en la concentración de hormonas anabólicas, y que por tanto, cargas supramáximas pueden estar más relacionadas con adaptaciones en fuerza y en masa muscular, el entrenamiento acentuado excéntricamente con cargas submáximas induce ganancias similares con un menor trabajo mecánico.

8. CONCLUSIONES

Los resultados obtenidos en nuestros trabajos y divulgados en las publicaciones que constituyen esta tesis permiten establecer las siguientes conclusiones:

- CONCLUSIÓN PRIMERA: El entrenamiento con sobrecarga excéntrica realizado con medios isoinerciales, independientes de la gravedad, es un método efectivo para generar cambios funcionales y estructurales en jóvenes sanos físicamente activos y en deportistas.

- CONCLUSIÓN SEGUNDA: Breves episodios de sobrecarga excéntrica inducida por acciones concéntricas, realizadas con medios isoinerciales a máxima intensidad, pueden producir mayores incrementos, en comparación con el entrenamiento de fuerza tradicional, en la fuerza, potencia, masa muscular y habilidades relacionadas con el rendimiento deportivo, como son el salto vertical y la velocidad de carrera, en deportistas y personas físicamente activas.

- CONCLUSIÓN TERCERA: Seis semanas de entrenamiento con sobrecarga excéntrica empleando dispositivos de rueda inercial produjeron aumentos significativos en la fuerza máxima dinámica, en la potencia muscular medida a diferentes intensidades, en la altura de salto vertical, en la velocidad de carrera y en la hipertrofia muscular en jugadores de balonmano. Además, las ganancias en potencia muscular, velocidad de carrera y masa muscular fueron mayores que las inducidas por el mismo ejercicio realizado en una máquina guiada con peso libre a similar intensidad y volumen.

- CONCLUSIÓN CUARTA: Seis semanas de entrenamiento con sobrecarga excéntrica, con diferentes dispositivos isoinerciales, indujeron adaptaciones significativas sobre la fuerza, potencia muscular, salto vertical y masa magra en varones jóvenes físicamente activos. Las adaptaciones generadas por el entrenamiento con sobrecarga excéntrica producida por un motor eléctrico fueron similares a las inducidas por un dispositivo de rueda inercial.

A modo de conclusión general, nuestros estudios permiten establecer de forma clara que el entrenamiento con sobrecarga excéntrica es un método efectivo para desarrollar la masa muscular e incrementar el rendimiento neuromuscular (fuerza, potencia y velocidad) en deportistas y en jóvenes físicamente activos. Intervenciones de seis semanas con dispositivos isoinerciales que acentúan las fase excéntrica del movimiento produjeron cambios significativos sobre la fuerza máxima, potencia muscular a diferentes intensidades, salto vertical, velocidad de carrera y otras habilidades relacionadas con el rendimiento deportivo. Además, estas ganancias fueron mayores que las conseguidas con otros métodos de entrenamiento (por ejemplo, peso libre), especialmente en el desarrollo de la masa muscular, pero también en la capacidad funcional. Por lo tanto, acentuar la fase excéntrica con nuevas tecnologías, como son los dispositivos isoinercial (motores eléctricos y dispositivos de rueda inercial), constituyen un método de trabajo efectivo que requiere menos esfuerzo mecánico y una conlleva aplicación más sencilla en comparación con otros métodos tradicionales para acentuar la acción excéntrica durante el entrenamiento de fuerza. Además, los motores eléctricos son dispositivos de elevado interés en el ámbito del entrenamiento de fuerza, pues permiten la prescripción de cargas máximas (o submáximas) durante la fase excéntrica sin que la fuerza concéntrica limite su potencial. Los motores eléctricos permiten modificar a voluntad la velocidad de la acción excéntrica independientemente de la concéntrica, por lo que constituyen una interesante perspectiva de aplicación del entrenamiento en entornos clínicos y de alto rendimiento deportivo.

ABSTRACT

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

ABSTRACT

Resistance Training (RT) has been demonstrated to be a superior exercise modality for increasing muscle strength, muscle endurance, muscle power, muscle hypertrophy and motor performance. Therefore, RT has been postulated as “the pill” against physical inactivity and associated comorbidities. As a result, the most recent physical activity for health recommendations include RT among the weekly exercise program activities for different populations. All this ranks RT as an optimal tool to improve not only health- and skill-related fitness components, but also to optimize sports performance and injury prevention. It has encouraged research in this field, favoring the emergence of numerous RT methods throughout the scientific literature. However, given the unique physiological characteristics of the eccentric contraction, the inclusion of an eccentric phase during RT is needed to amplify the acute effects and chronic adaptations of RT.

Traditional RT is performed by the lifting and lowering of weights. However, muscles are not capable of lifting as much load in the concentric phase as they can lower with control in the eccentric phase due to the force-velocity characteristics of muscles. Therefore, the loads lifted during strength training are limited to those that can be lifted in the concentric phase, and the eccentric phase is never performed with maximal (or near-maximal) loads. Thus, a sub-optimum stimulus is applied during the eccentric phase. So, scientists, coaches and practitioners have studied and applied eccentric-only training. Isolated muscle lengthening has been shown to lead to significant neural, structural, and muscle mechanical function adaptations. Consequently, a stronger and faster phenotype has been observed in healthy and trained subjects after eccentric-only training compared with concentric-only or traditional concentric/eccentric RT. However, isolated eccentric exercise is not widely used due to the shortcomings involved in: 1) quantifying the load, 2) isolate the movement from the concentric phase; 3) high levels of experience and technique required by participants; 4) the financial restrictive material involved (e.g. dynamometers); and 5) little application or

transfer to athletic performance and daily-life activities (i.e. avoiding strength-shortening cycle use).

Hence, eccentric overload (EO) RT emerges as an alternative method to more optimally prescribe intensity relative to the force generation capabilities of eccentric muscle action and avoiding the negative work isolation (i.e. favoring the strength-shortening cycle use). Then, it consists of prescribing an accentuated eccentric load in excess of the concentric load, requiring coupled eccentric and concentric actions and maintaining the natural mechanics of movement. Prior studies have reported evidence of force and power production enhancements and chronic adaptations using various systems to accentuate the eccentric loading, such as weight releasers, electric-motor devices or iso-intertial flywheel devices. Electric-motor and flywheel devices stand out among them, since they present as easier and faster application way. Therefore, the studies of this doctorate thesis aimed to analyze the effects of EO-RT induced by flywheel or electric-motor devices on functional capacities and muscle mass in athletes and physically active population. As well as to compare the training-induced effects on strength, power, muscle mass and sports-related tasks performance with other training methods.

This thesis includes the following studies:

- Maroto-Izquierdo S, Garcia-Lopez D, de Paz JA (2017a). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. *J Hum Kinet*, 60 (133-143). doi:10.1515/hukin-2017-0096

- Maroto-Izquierdo S, Garcia-Lopez D, Fernandez-Gonzalo R, Moreira OC, Gonzalez-Gallego J, de Paz JA (2017b). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport*, 20 (10): (943-951). doi:10.1016/j.jsams.2017.03.004

- Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, Manzano-Rodriguez S, Gonzalez-Gallego J, de Paz JA (2019). Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor. *Eur J Sport Sci*,(1-11). doi:10.1080/17461391.2019.1588920

The results from the different publications that constitute this doctoral thesis concluded that EO-RT with iso-inertial devices is an effective method to develop muscle mass and increase neuromuscular performance (strength, power and speed) in athletes and physically active people. Furthermore, these increases were larger than those found with other training methods (e.g., free-weight). Consequently, the superiority of this method is attributed to the presence of an accentuated eccentric action that allows us to provide an adapted stimuli to the muscular force production capacity in each muscle contraction. Finally, electric-motor devices have potential benefits for accentuated eccentric training, functioning as an ideal inertial device without requiring a maximum concentric action to generate EO, and allowing the achievement of larger percentages of EO by increasing the eccentric velocity with respect to the concentric. Although no different training-induced effects have been found between electric-motor and flywheel devices.

INTRODUCTION

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

INTRODUCTION

Currently, more than 5.3 million people worldwide die every year due to physical inactivity (Hallal et al. 2014; Tremblay et al. 2015). Specifically in Spain, 13.4% of total deaths are due to a lack of systematic exercise (Ramirez Varela et al. 2016). Even though physical exercise effects on health and life quality have been widely studied in scientific literature, a third of adults and 80% of adolescents do not reach recommended levels for daily physical activity (Hallal et al. 2014). In addition, it also increases the risk of high blood pressure, stroke, metabolic syndrome, depression and falls (Kohl et al. 2012; Naci and Ioannidis et al. 2015). Moreover, the risk of suffering diseases such as coronary heart disease, type 2 diabetes, breast or colon cancer and age-adjusted all-causes mortality increases around 10%. It means that physical inactivity leads to as many deaths as smoking or obesity, and constitutes the fourth leading cause of premature death worldwide (Bouchard et al. 2015). Therefore, the lack of physical activity is a global pandemic that leads to millions of euros of economic loss and has become a global public health priority.

Exercise has proven scientific evidence to reduce risk of all-cause and disease-specific mortality and fall-related injuries, improved physical and cognitive function, and quality of life, and fight against excessive weight gain in different populations (Garber et al. 2011; Riebe et al. 2015). Half a million deaths per year may be prevented by increasing physical activity levels (i.e. exercising)l by 10% (Lee et al. 2012). Hence, World Health Organization (WHO) guidelines for physical activity recommend that every adult should perform aerobic activity of moderate-intensity for at least 150 minutes a week (2 hours and 30 minutes), or vigorous-intensity aerobic physical activity for 75 minutes (1 hour and 15 minutes) a week, or a combination of moderate- and vigorous-intensity aerobic activity using an equivalent energy expenditure (Ramirez Varela et al. 2016). Following these daily exercise recommendations, WHO claimed to reduce the prevalence of inactivity and improve the health status of the general population. Consequently, the term "health" means not only the physical, mental, social wellness and the absence of pathologies, but also the fitness level to achieve greater autonomy and higher adaptation to environment conditions. Therefore, the health status improvement is related to the fitness components enhancement, since these components will determine performance on specific daily-life tasks. These health-related fitness components include: cardiovascular endurance, muscular strength, muscular endurance, flexibility and body composition. These well correlated with life quality, since they have a direct impact on skill-related health components: speed, power, agility, coordination, balance and reaction time. However, WHO recommendations only address the cardiovascular component, not involving other capabilities such as strength or power, which are needed for many daily activities.

There is a scientific-based relation of cardiorespiratory fitness to cardiovascular disease mortality and to all-cause mortality within strata of other personal characteristics that predispose to early mortality (e.g. obesity, smoking, elevated cholesterol levels or blood pressure, unhealthy and healthy persons) (Blair et al. 1996). Therefore, a sedentary lifestyle is precursor of a low cardiorespiratory fitness level, which is correlated to a high risk of premature mortality (Blair et al. 1996; Nauman et al. 2019). While moderate fitness condition seems to prevent the influence of mortality predictors. This may be the main reason for which 30 minutes a day of aerobic exercise is currently prescribed by worldwide organizations as a method to enhance health-related fitness level.

Notwithstanding, Resistance Training (RT) (i.e. general terms referring to exercise requiring the application of force against a resistance) has been demonstrated to be a superior modality for increasing muscle strength (muscles' ability to exert a maximum amount of force in one effort), muscle endurance (muscles' ability to exert force repeatedly or for an extended period of time), muscle power (muscles' ability to produce force in the minor period of time), muscle hypertrophy (muscles' ability to increase its size) and motor performance (Kraemer and Ratamess et al. 2004; Kraemer et al. 2017a). As a result, the most recent physical activity for health recommendations include RT, up to three times a week, among the weekly exercise program activities for children, healthy adults, adults with chronic health conditions and adults with disabilities, pregnant women, and people with obesity (Piercy and Troiano et al. 2018; Piercy et al. et al. 2018). It should be noted, that RT prescription is complementary to the 150 minutes a week of moderate-intensity aerobic activity (Piercy and Troiano et al. 2018; Piercy et al. 2018). However, RT is also able to improve cardiovascular capacity with correct training loads and organization of exercises (e.g. circuit training) (Ashton et al. 2018). All this ranks RT as an optimal tool to improve health-related and skill-related fitness components. In fact, it has also been shown that higher levels of muscular strength are well correlated with a lower risk of mortality (Garcia-Hermoso et al. 2018). Thus, adults with lower levels of upper- or lower-body muscular strength possess high risk of mortality (Garcia-Hermoso et al. 2018). Therefore, muscle-strengthening activity may be an ideal tool to improve life quality and provide numerous health benefits. In addition, this may implicate huge economic savings in health care costs and a significant reduction of mortality index. Additionally, RT has proven to induce significant improvements in athletic performance (Suchomel et al. 2016a) and injury prevention (Lauersen et al. 2014). Hence, RT is not only employed as a way to improve health and fitness by general population, but also to optimize sporting performance by strength and conditioning specialist and practitioners.

1. RESISTANCE TRAINING

In Physics, force is the product of mass and acceleration, which induces a change in the mobile state of an object (Blazevich 2017). Accordingly, muscle strength is considered as the muscle's ability to produce acceleration, deformation, static maintenance or deceleration of a mass. This application of force can be the resistance of the body itself to the gravitational force or applied to external resistances in order to mobilize, maintain or stop them in space. This force is determined by the muscular contraction of the skeletal muscles.

Muscle contraction generates movement in the joint (approaching or separating bones), by means of muscular fiber nervous stimulation. Although these muscle fibers are grouped in muscle fascicles, and each fasciculus is surrounded (perimysium, endomysium) and connected to bones (tendons) by connective tissue that intervenes in the production of force, we can say that muscle action (contraction) occurs at cellular level. Therefore, a muscle fiber is a cell that is specialized to contract and generate force (i.e. tension). This cell is constituted by a sarcolemma (encloses the contents of the cell, and receives and conducts the neural electrical impulses [i.e. action stimuli]), nuclei (multinucleated cell, which content genetic material), cytoplasm (contains cell's energy sources, specially ATP and CP), and some organelles, such as mitochondria (ATP production) and sarcoplasmic reticulum (stores calcium and regulates the muscle action by altering intracellular calcium concentration). The muscle fiber also possess columnar protein structures that run parallel to the length of the fiber, called myofibrils, which consists of myosin and actin filaments. These myosin and actin proteins constitute the sarcomere, which is the basic contractile unit of the muscle. Basically, the process of muscle activation will be performed when thin myofilaments of actin glide over thick myosin myofilaments, all regulated by other protein intervention (titin, G-actin, tropomyosin and troponin) nerve intervention and calcium involvement. More specifically, the muscle contraction process is initiated when an action potential transfers to the interior of the muscle fiber releasing stored calcium from the sarcoplasmic reticulum. At this state, calcium will bind with tropomyosin molecules located along the actin filaments. Since tropomyosin is attached to troponin, there will be an approach between actin and myosin filaments. When the binding sites on actin are exposed to the myosin head (which is storing the energy resulting from the breakdown of ATP to ADP and phosphate), it will be able to attach actin, forming a cross-bridge, and attempting to pull the actin filament toward the center of the sarcomere. Thus, a muscle shortening will occur, which will depend on the amount of force generated by the cross-bridges and the external force that opposes the cross-bridges.

Even though in physiology it is considered that the cross-bridges always attempt to pull actin toward the center of the sarcomere, which would cause shortening of the sarcomere and thus the muscle. However, as I mentioned above, muscles are typically contracting against any external resistance opposite to gravitational force, such as body mass in a jump or any sport or training implement, which may be acting in opposition to the muscle force. Therefore, depending on the movement (shortening or lengthening), or absence of movement, that occurs in the muscles involved during force application, different muscle contraction types will be observed. If the amount of force produced by a muscle is greater than gravitational force or the external resistance acting in the opposite direction, a concentric muscle action will result. During a concentric muscle action, the resistance is overcome and the muscle shortens. A concentric contraction will produce, as a result, the mobilization of a load (i.e. acceleration). If the amount of force produced by a muscle is less than an opposing external resistance, the muscle will lengthen even as it attempts to shorten. This lengthening muscle action is known as an eccentric muscle action. An eccentric contraction will produce, consequently, the stoppage of a load (i.e. deceleration). Lastly, if the muscle force is equal and opposite to that of an external resistance, an isometric muscle action occurs. In this case, the muscle neither shortens nor lengthens, but remains the same length.

Therefore, we must bear in mind that a muscle contraction may occur in different directions and it will always result in a certain velocity (positive or negative) in the joint involved in the movement. So the proper definition of muscle force, in sports science, is the tension that a muscle or group of muscles are capable of producing at a certain velocity. Two concepts arise which will determine the effects and adaptations of RT: Work and Power. The amount of work done is equal to the amount of force (average force) multiplied by the distance over which it is applied. For example, in a vertical jump, work is equal to the applied force in the opposite direction to the gravitational force from the squat position until feet are raised from the ground. When time is also considered among movement characteristics, then we will talk about power. The amount of power produced is equal to the amount of work divided by time. For example, if we know the weight of a bar, and the amount of time from when the bar is raised from the floor against gravity till the end of the concentric phase, then average power is known. These biomechanical concepts are crucial to understand the physiological RT effects, since they will determine different aspects of the training prescription.

1.1 PHYSIOLOGICAL FACTORS AFFECTING MUSCULAR FORCE

Muscle contraction has shown to produce a certain amount of force in order to modify an external load. But it should be noted that, additionally to genetics, health status, training level and experience, biological (e.g. sex, age) and anthropometric characteristics, some other factors may influence the total amount of force produced by the skeletal muscle. Hence, understanding the underlying physiological factors that contribute or affect force production is important before understanding muscular strength development.

1.1.1. MUSCLE ARCHITECTURE AND SIZE

Skeletal muscle size can greatly impact on muscle's ability to produce work and power. In fact, greater muscle's cross-sectional area (CSA) have been well correlated ($r = 0.70$) with greater absolute force production (Hakkinen and Keskinen 1989; Hakkinen et al. 2001). Further literature suggested that particularly type II fibers may alter the entire muscle's force-velocity profile (Schoenfeld et al. 2017b). In addition, after short-term RT intervention, muscle's CSA increased significantly, leading to changes in force production for approximately of 50-60%. These enhancements showed with greater muscle CSA may be induced by an increase in the number of cross-bridge interactions between actin and myosin within the previous and training-induced sarcomeres (Suchomel et al. et al. 2018). In addition, fascicle length and angle, play an indisputable role in force production (Ando et al. 2018; Blazevich et al. 2007). In this way, longer fascicle lengths and smaller pennation angles, are related with higher force production levels. Since it has been suggested that muscle operates with higher gear ratio (Δ muscle length/Δ fascicle length) when higher peak forces were observed (Azizi and Roberts 2014; Eng et al. 2018). Because of this, higher peaks of force are observed during lengthening, where fascicle lengthening and rotation (i.e. decrease in angle) were clearly observed (Ando et al. 2018; Guilhem et al. 2013). In fact, it has been suggested that the muscle operates with a higher gear ratio during eccentric than concentric contractions, i.e. the increase in muscle length is much greater than the increase in fascicle length due to the significant rotation of fascicles during contraction, which would influence both the force–length and force–velocity relationships (Azizi and Roberts 2014). Importantly, this would allow for greater maximum forces to be developed within the muscle and contribute to the storage of elastic energy and potentiation through residual force enhancement effects; if used during training, this may trigger an accelerated adaptive process.

1.1.2. MUSCULOTENDINOUS STIFFNESS

Cumulatively, the aforementioned architectural changes also affect the connective elastic tissues (e.g. aponeurosis and tendons), causing them to accumulate energy by reducing width and increasing length during muscle lengthening (i.e. stiffness, relation between a given lengthen force and the amount of stretch the tissue undergoes), which could lead to greater muscle performance (force and power amplification) in the consequent concentric muscle contraction (Douglas et al. 2017a; Foure et al. 2013). Hence, an enhancement in force transmission is produced (Butler et al. 2003). This strongly influences collagen-based connective tissues and other aspects of the extracellular matrix may be explained by the role of titin protein (Hessel et al. 2017). Titin constitutes a viscoelastic spring within the sarcomere, generating passive tension (Hessel et al. 2017). Recently, has been proven that this protein increases in active muscles prior to force generation (Rassier et al. 2015) and persists some seconds after muscles have been deactivated (Herzog et al. 2016). This increase in its stiffness may be due to an increase in the amount of sarcoplasmic calcium, which contributes to the stiffness of the entire sarcomere (Herzog et al. 2015). Lastly, titin stiffness also contributes to residual force enhancement (Herzog et al. 2016). This phenomenon supposes a persistent increase in force in the steady-state phase following stretch, when compared with a maximal isometric contraction at the same joint angle (Hahn et al. 2010).

1.1.3. MUSCLE FIBERS TYPES AND CHARACTERISTICS

Not only muscle architecture or its size and the elastic connective tissue, but also the muscle fibers characteristics determine the force production. Muscle fibers characteristics are determined by the type of myosin (in terms of energy production) that their sarcomeres have. Thus, when myosin is able to rapidly hydrolyze ATP (600 times per second) it is called “fast myosin”, whereas when myosin hydrolyzes ATP at 300 times per second it is called “slow myosin” (Gonzalez-Badillo and Gorostiaga 2002). This is directly related to contraction speed. So muscle fibers that contain fast myosin contract more rapidly (40-90 ms) than muscle fibers that contain slow myosin (90-140 ms) (Gonzalez-Badillo and Gorostiaga 2002). Consequently, 3 types of muscle fibers are distinguished: fast (type IIx), intermediate (type IIa) and slow muscle fibers (type I). Type I muscle fibers differ from type IIx muscle fibers in that they have a slower rate of contraction, produce less force, possess greater vascularization and oxidative capacity, more fatigue endurance, use energy obtained from myoglobin instead of ATPase and have a lower number of myofibrils in each muscle fiber (Gonzalez-Badillo and Gorostiaga 2002). Type IIa muscle fibers have intermediate characteristics between slow-twitch type I and fast-twitch type IIx fibers, and are modifiable with training (Andersen and Aagaard et al. 2010). On this basis, athletes or physically active people who possess a higher fast-twitchtype IIx/IIa fibers percentage are characterized by a greater force production ability and rate of force development (RFD), regardless of the speed of movement (Andersen and Aagaard et al. 2010).

1.1.4. NEUROMUSCULAR SYSTEM: MOTOR UNIT RECRUITMENT AND SYNCHRONIZATION

Finally, it is important to note the relevance of the nervous system in muscle contraction, and therefore, in force production. From a neural perspective, muscle fibers are grouped in Motor Units (MU), and are enervated by the same motor nerve (Gonzalez-Badillo and Gorostiaga 2002). Thus, muscle fibers that are inside the same MU have similar properties and the same type of myosin isoform. Hence, MUs that innervate fast-twitch fibers have a higher conduction velocity of the motor nerve and a greater frequency of discharge of the electrical impulse than the MUs that innervate slow-twitch fibers (Andersen and Aagaard 2010; Gonzalez-Badillo and Gorostiaga 2002). The type of muscle fiber that innervates each MU also determines its size, which determines the recruitment sequence. Inasmuch as smaller Mus that include slow-twitch type I fibers are recruited when smaller force magnitudes and RFD are required, whereas larger MUs that include fast-twitch type IIx/IIa fibers are recruited when higher force magnitudes and RFD are required (Duchateau et al. 2006). This recruitment order is generally maintained independently of the activity intent, although there are MUs with a significant lower threshold recruitment (Duchateau et al. et al. 2006; Maffiuletti et al. 2016). These lower thresholds MUs usually content type IIx fibers, and their recruitment usually occurs during ballistic-type movements due to the large RFD required (Maffiuletti et al. 2016; Van Cutsem et al. 1998). Furthermore, the synchronization of MUs, which means the activation of more than 2 MUs at the same time, has been shown to increase force production in a short period of time (i.e. RFD) (Semmler 2002). Thus, intramuscular coordination is also determinant in the force production (Semmler 2002). In addition to lower threshold MUs activation, ballistic training and also heavy RT have been demonstrated that may increase MU synchronization and force production (Aagaard et al. 2000; Van Cutsem et al. 1998).

Accordingly, the degree of experience in RT (i.e. the systematic performance of RT) seems to have a determining effect on the frequency at which the α-motoneurons discharge action potentials to the MU's muscle fibers (spike firing frequency). This firing frequency can modify the force production properties (Suchomel et al. et al. 2018). Research indicated that force magnitude may increase by 300-1500% (Enoka 1995) and RFD in a minor magnitude (Van Cutsem et al. 1998), when the firing frequency of MUs increases from its minimum to its maximum. Contrastingly, a reduction in the neural drive when a determined muscle group is activated (neuromuscular inhibition) may negatively affect force production due to the neural feedback received from muscle receptors (Gabriel et al. 2006). However, following a RT program it is possible to enhance neural drive from both the spinal and supraspinal levels (down-regulating Ib afferent feedback to the spinal motoneuron) and, therefore, decrease neuromuscular inhibition (Aagaard et al. 2000; Aagaard et al. 2002).

2. EVOLUTION OF RESISTANCE TRAINING RESEARCH: PHYSIOLOGICAL EFFECTS AND TRAINING-INDUCED ADAPTATIONS

Throughout scientific literature, the importance of RT in the development of adaptations involving increases in health- and skill-related fitness components performance (strength gains, muscle mass and muscle power) has been demonstrated. In the same way, the acute effects and underpinning mechanisms of these adaptations have also been studied. In fact, the scientific interest in the last 50 years for strength training has grown exponentially. Kraemer and colleagues (2017a), in their work entitled "*Understanding the Science of Resistance Training: An evolutionary Perspective*", offer detailed information of the scientific findings evolution in strength training. The history of RT research began with anecdotal ideas by practitioners. Some of them were medical doctors or educators who prematurely appreciated the health benefits and performance implications of RT. Prior to 1940, the first experimental RT studies took place. These investigations showed the effect of weight training in the enhancement of muscular endurance and contralateral non-training leg effects (Scripture et al. 1894). While other authors were focused on more physiological studies (filament theory of muscular contraction (Huxley and Niedergerke 1954), ATP role in muscle contraction (Huxley 1974), primary mechanism of muscle hypertrophy in animals (Steinhaus 1932), and motor units effects on force production capabilities also in animals (Sherrington 1929)). Between 1940 and 1960, the "one-repetition maximin" (1-RM) reference as an exercise loading characteristic was employed for the first time (Houtz et al. 1946). In addition, numerous studies showed that RT (prescribed employing 1-RM, circuit training with free-weight or by isometric exercises) increased muscle strength, power, endurance and speed besides cardiovascular enhancements (Chui 1950; Chui 1964; McMorris and Elkins 1954; Wilkin 1952). But it was between 1960 and 1980 when RT studies evolved from just strength assessments to importance in physiological systems, physical health, and physical performance capabilities for individuals interested in physical fitness through to those seeking elite athletic performances. Isokinetic dynamometers, surface-electromyography (EMG) and muscle biopsy began to be used just before the 70's (Bergstrom 1962; deVries 1968). Also in this era, research focused on sport-specific improvements via RT (Dintiman 1964; O'Shea 1966) and comparative RT methods commenced (Bamey and Bamgerter 1961; Berger 1962a; Berger et al. 1962b; Berger 1963; Berger 1966; O'Shea 1966), and strength coaching emerged as a profession. With the appearance of new technologies for functional and physiological assessment, new research comparing differential responses of concentric- and eccentric-only muscle action effects as well as of variable RT. Apart from that, various investigation initiated to analyze hormones, the muscle fibers type and the transition from one to another after RT, biochemical changes within skeletal muscle, and training-induced effects at extracellular matrix (Fahey et al. 1976; Komi and Viitasalo 1976; Komi et al. 1978).

Since the 80's, the major categories of research studies have been those designed to examine training adaptations (performance and physiological) and those designed to identify mechanisms of physiologic adaptations: primarily physiologic responses and adaptations of key systems, nutritional and ergogenic aids, exercise biomechanics, overtraining/detraining, equipment development and strength implements, psychological components, RT integrated with plyometric, speed, flexibility, and agility training, sports performance, recovery, and injury prevention and rehabilitation. These studies have been done in different populations such as untrained individuals, physically active individuals of both male and female genders, athletes, children, elderly, and special clinical populations. All this has enabled us to establish the main training-induced effects and chronic adaptations (table 1) that are currently attributed to RT.

Table 1. Brief explanation of the training-induced effects and chronic adaptations of RT.

Variable	Brief explanation of underpinning mechanisms	Chronic adaptations
	Neurological Changes	
Neural Drive	Several studies have indicated that RT increase strength due to a greater electrical efficiency of agonist muscle (Hakkinen et al. 2001). These strength enhancements are influenced by neural factors, which are dominant in an early-phase (Baechle and Earle 2008; Milner-Brown et al. 1975). Enhancements of neural drive are possible from both the spinal and supraspinal levels, down-regulating Ib afferent feedback to the spinal motoneuron (Aagaard et al. et al. 2002; Aagaard et al. et al. 2000). Mechanisms of neural drive include: MU recruitment, firing rate, intermuscular coordination (Milner-Brown et al. 1975) and antagonist co-contraction.	+++
EMG amplitude	Surface EMG has been traditionally employed to quantify changes in neural activity. EMG amplitude increases during a maximal voluntary contraction (MVC). After a RT period, a lower EMG amplitude is needed to mobilize a same submaximal load (Hakkinen et al.. 1985a).	+
MU recruitment	An increase in EMG amplitude reports an enhancement in MU recruitment. RT has proven to activate available inactive MU, especially high-threshold MU. However, when high loads were employed lower-threshold MU were also activated (Duchateau et al. 2006; Maffiuletti et al. 2016). Resulting in a large force production capability, independently of training level.	+
Firing frequency	Not all studies have demonstrated increases on EMG amplitude, but the frequency at which the α-motoneurons discharge action potentials to the MU's muscle fibers can modify the force production properties (Suchomel et	+++

	al. et al. 2018). Research indicated that force magnitude may increase (Enoka 1995; Van Cutsem et al. 1998), when the firing frequency of recruited MUs increases.	
Cocontraction	Decreased agonist-antagonist coactivation would decrease the antagonist force that must be overcome by the agonist during a muscle action, thus enhancing the expression of strength (Baechle and Earle 2008; Milner-Brown et al. 1975).	---
V-wave and H-reflex	Increases in evoked V-wave (overall magnitude of efferent motor output from α-motoneurons pool) and H-reflex (excitability of spinal α-motoneurons and stimulus transmission efficiency, i.e. presynaptic inhibition) responses were observed during maximal muscle contraction after RT. Collectively, an increase in motoneuronal output induced by RT may comprise of both supraspinal and spinal adaptation mechanisms (i.e., increased central motor drive, elevated motoneuron excitability, reduced presynaptic inhibition) (Aagaard et al. 2002). Resulting in significant gains in reflex potentiation (Carroll et al. 2011).	+++
Cortical activity	Greater cortical activity, assessed by magnetic resonance imaging has been observed after high-intensity RT (Flanagan et al. 2012). In addition, different cortical activity levels have been shown depending on the exercise mode (e.g. eccentric vs concentric), showing a huge “learning” effect (Duchateau and Baudry 2014; Duchateau and Enoka 2008; Duchateau and Enoka 2016). Resulting in a greater brain activity when the participant is accustomed to RT stimulus (Duchateau and Baudry 2014; Duchateau and Enoka 2008; Duchateau and Enoka 2016). Although changes in the excitability of cortical, subcortical, or spinal neurons have been related with increases in force output (Gabriel et al. 2006), only supraspinal adaptations (transcranial magnetic stimulation, used to stimulate corticospinal neurons in the motor cortex	+

	producing a motor evoked potential, which is detected by surface EMG) leading to neural economy (Falvo et al. 2010).	
	Structural Changes	
Muscle fibers	RT has been a fiber subtype shift from type IIx to type IIa muscle fibers (Green et al. 1999; Vissing et al. 2008). These subtype shifts are observable after just a few training sessions and likely to reflect a change in the myosin heavy-chain composition of the muscle cell (Staron et al. 1994; Staron et al. 1991). However, to date there is little evidence to suggest that RT can induce a shift from slow- to fast-twitch fibers (Andersen and Aagaard 2010). On this basis, people who possess a higher fast-twitch type IIx/IIa fibers percentage are characterized by a greater force production ability and RFD (Andersen and Aagaard 2010). In addition, both type I and II fibers have showed hypertrophic effects, the type II fibers demonstrated a greater capacity for hypertrophy, were more varied in their range of sizes, and were larger than type I fibers (McCall et al. 1996). Eccentric training, have led to greater gains in Type IIx and IIa specific cross-sectional area (Friedmann-Bette et al. 2010; Hortobagyi et al. 1996b).	+++
Muscle Architecture	Several studies have emphasized the importance of RT on muscle hypertrophy, especially when high-RT loads are applied although training frequency, repetition duration, training volume and other parameters should be consider (Schoenfeld 2010; Schoenfeld 2012; Schoenfeld 2013; Schoenfeld et al. 2018; Schoenfeld. et al. 2017a; Schoenfeld et al. 2016a; Schoenfeld et al. 2017b; Schoenfeld et al. 2015). The increase in cross-sectional area is attributed to an increase in both the size and number of myofibrils within a given muscle fiber (Baechle and Earle 2008; Milner-Brown	+++

	et al. 1975). Thus, resistance exercise induces the secretion of anabolic and/or anticatabolic hormones; such as testosterone, insulin growth factor 1 (IGF-1) and growth hormone (GH), which enhances the anabolic environment (Hendy and Lamon 2017). In addition, these blood-circulating factors have an important effect on the Akt-mTOR signal pathway, which regulates muscle protein balance (synthesis/degradation) (Hendy and Lamon 2017; Schiaffino et al. 2013). More optimal fascicle length and angles have been observed after RT. It is clearly established that muscle operates better when longer fascile lengths and smaller pennation angles, resulting in a higher peak force production (Ando et al. 2018; Blazevichet al. 2007).	
Tendon structure	Longitudinal training studies have shown that resistance training can alter tendon mechanical and structural properties. Hence, tendon stiffness has been shown to be increased following heavy load resistance exercise (Pearson and Hussain 2014), but not with light load training. In addition, tendon cross-sectional area has been reported to increase with RT; specially when eccentric exercise was performed (Douglas et al. 2017a).	+++
Skeletal changes	In addition to the obvious effects of RT on muscle mass and strength, RT may lead to increases in bone tissue (Barry and Kohrt 2008). Various studies have concluded that RT enhance bone mineral density, especially in women at lumbar spine level (Martyn-St James and Carroll 2006). These effects may significantly decrease risk for osteoporosis, fractures and falls in later life. In addition, both magnitude and intensity affect the stimulus for bone formation, and these would be expected to be higher with explosive and plyometric training (Barry and Kohrt 2008).	+

Endocrine Changes		
Anabolic Hormones	Anabolic hormones, such as testosterone, IGF-1 and GH, play a decisive role in protein synthesis, and numerous studies have shown their elevations after RT (Kraemer and Ratamess 2005). Moreover, some studies have shown no changes in resting testosterone or GH following a period of several weeks to months of RT (Kraemer et al. 2017b). In addition, higher chronic IGF-1 concentrations have been observed when high intensity and volume RT programs were applied (Raastad et al. 2003). It should be noted that IGF binding proteins (e.g. IGFBP-3), which regulate and prolong IGF availability, also showed increases after RT (Kraemer and Ratamess et al. 2005). Another anabolic hormone is insulin. Insulin has been shown to significantly affect muscle protein synthesis when adequate amino acid concentrations are available, especially by reducing protein catabolism (Dimitriadis et al. 2011). Its concentration appears to decrease after a single bout of RT, but it seems to be mostly affected by blood glucose concentrations and/or dietary intake (Kraemer and Ratamess et al. 2005) .	+++
Catabolic hormones	Cortisol, has been postulated as the major catabolic hormone, which increases protein degradation and decreases protein synthesis in muscle cells. Segregation of cortisol increases significantly after RT, but no important chronic changes have been observed (Kraemer and Ratamess 2005). Although, testosterone-cortisol ratio increased and correlated with strength gains after a RT program (Hakkinen et al. 1985b).	+
Catecholamines	Catecholamines reflect are important for increasing force production, muscle contraction rate, energy availability, as well as several other functions including the augmentations of hormones such as testosterone. Epinephrine,	+

	norepinephrine and dopamine concentration in plasma has been enhanced after a single bout of RT. However, it has been suggested that RT reduces the catecholamines response (Guezennec et al. 1986). Thus, they are determinant only during training, and depends on periodization and training stimulus.	
	Metabolic Changes	
Glycolytic activity	Enzymes involved in the glycolytic pathway (e.g., phosphofructokinase, lactate dehydrogenase) are not found in higher concentration after RT. However, it seems that high-volume resistance training may induce glycolytic enzymatic adaptations that increase muscle endurance (Tesch et al. 1990). It has been shown that RT can reduce the lactate response and increase lactate threshold, thereby increasing local muscle endurance (Pascoe et al.1993).	+
Phosphagen system	No clear effects have been reported regarding the effect of RT on ATP or CP concentrations. Similarly, some controversy exists regarding the enzymes involved in this system, creatine kinase and myokinase. The importance on these enzymes is due to training volume and intensity (Pascoe et al.1993).	-
	Functional Changes	
Strength & RFD	Positive adaptations on strength through RT lead to greater RFD characteristics. Maximal muscular strength may account as much as 80% of the variance in voluntary RFD (150-250 ms) (Andersen and Aagaard 2006).	+++

Muscle Power	Since acceleration is directly proportional to the forces impressed. The amount of force applied on a given period of time, will produce greater acceleration, resulting in a greater velocity. Thus, increases in both force and velocity will ultimately result in an increase in power. Thereby, RT programs in which strength gains occurred, normally led to an increase in absolute or relative external mechanical power (moderate or high relationship with strength) (Suchomel et al. 2016a).	+++
Jumping	Greater muscular strength may modify the force-time characteristics of an individual. Specifically, increases in muscular strength achieved through RT can increase both peak jumping performance as well as the shape of the force-time curve drawn during a jump. Resulting in higher vertical height, larger rebound ability, jump distance or minor contact time from a drop jump.	+++
Running	Maximal strength is strongly correlated with RFD and, therefore, strength is also correlated with running velocity. In fact, strength and RFD determine force application, ground contact time and stride length. Hence, increases in strength coincide with sprint performance enhancements (Alcaraz et al. 2011; Chelly et al. 2009; Chelly et al. 2010)	+++
Specific sport skills	In the specific case of sports, it is widely studied that muscular strength is one of the underlying determinants of strength-power performance , as well as is associated with enhanced endurance performance (Suchomel et al. 2016a). As mentioned by Suchonmel et al. (2016a), stronger cyclists had a faster 25-m track cycling time compared to weaker cyclists (Stone et al. et al. 2004); stronger handball players had a greater standing and 3-step running throwing velocity compared to weaker handball players (Gorostiaga et al. 2005); and that stronger sprinters had a faster 100-m time compared to weaker sprinters (Meckel et al. 1995). Thereby, the comparisons between stronger and weaker	+++

	athletes provides substantial support that stronger athletes within a relatively homogenous level of skill perform better in comparison to weaker athletes. The importance of muscular strength, and also this correlation among stronger and weaker athletes was also observed on change-of-direction ability, which is present in the majority of team-sports (Spiteri et al. 2014). Hence, muscular strength is determinant in anaerobic and endurance sporting activities.	
Potentiation	Research indicates that greater magnitudes of power potentiation complexes to enhance explosive performance can be achieved following RT (Miyamoto et al. 2013). This may be due to the ability to develop fatigue resistance to high loads as an adaptation to high intensity RT (Jo et al. 2010). However, to achieve the greatest potentiation effects after a single bout of RT, a strength level of near twice times body mass is required (Berning et al. 2010; Bullock and Comfort 2011).	+
Injury rate	Several investigations have reported beneficial effects of RT in reducing the occurrence of injuries (Fleck and Falkel 1986; Lauersen et al.. 2014). In fact, a very cited meta-analysis indicated that RT protocols reduced sports injuries to less than one-third and that overuse injuries could be almost halved (Lauersen et al. 2014). This protective effect of RT may be due to increases in the structural strength of ligaments, tendons, junctions, bone mineral content and connective tissue sheaths within muscles (Fleck and Falkel 1986). Collectively, athletes who showed higher values of strength were less likely to get injured (Lauersen et al. 2014). Therefore, a primary focus of RT programs should be to increase the overall strength, not only to increase performance, but also to decrease the likelihood of an injury occurrence.	+++

Strength training-induced adaptations ranked on scale from + (1 point, meaning low effect) to +++ (3 points, meaning high effect), and – (1 negative point) when no effects were demonstrated.

3. RESISTANCE TRAINING METHODS

Scientific-based RT prescription involves the appropriate manipulation of the program variables: intensity (load), volume (number of sets and repetitions), exercise selection (multiarticular or monoarticular, bilateral or unilateral exercises), muscle action (concentric, eccentric or isometric), density (relation between activation and resting time), raising velocity (speed of movement) and training frequency (number of sessions per week or mesocycle). This prescription of RT has evolved over the last 30 years. In the 90's, a growing interest in physical conditioning led to the apparition of the first guide with recommendations for modern strength training by the American Colleague of Sports Medicine. This guide, recommended the realization of 1 series of 8-10 repetitions of 8 to 10 exercises of the main muscle groups. But it was at the beginning of the next decade, when the same association. revised the document and included recommendations for different levels of experience with RT and populations with different training goals (e.g., muscle strength, power, hypertrophy, endurance, health) manipulating the different RT variables. Currently, updates will continue as research uncovers new phenomena. Of particular interest currently is the expansion of RT exercise selection (i.e., body weight, implements, vibration, and other equipment), the loading/volume interaction (i.e., heavy vs. light loading with and without vascular occlusion), and integration with other exercise modalities, as other variables such as sequence, velocity, frequency, and rest intervals continue to be extensively studied. Future studies need to address these variable manipulations especially in different populations. All this leads to the emergence of different methods of RT and each of its manifestations.

3.1 BODYWEIGHT EXERCISE

Training with own body weight, or in which the only resistance that offered the gravity force against myself, is called bodyweight exercising. The most common exercises that include this RT method: squats, pull-ups, push-ups, and exercises performed with implements (e.g., suspension training or unstable material). This type of training has many advantages, among them it should be highlighted that: It can be done anywhere, it does not require complementary material or the required material is minimal, several muscle groups are involved at the same time, it is very versatile and functional (Baechle and Earle 2008). However, the ability to produce an overload stimulus is limited, and therefore, adaptations on strength or power are limited in healthy subjects and athletes. Normally, given its complications to increase intensity, these exercises are performed in a very high volume (i.e. many repetitions), being a good stimulus to develop muscular endurance (Suchomel et al. 2018). This method is supplemented with unstable material to produce an overload. Some of the materials that complement bodyweight exercises are: bosus, fitballs or suspension training (Behm et al. 2015; Saeterbakken et al. 2011). This way of training should be considered to work the basic strength and technique of multi-joint exercises in children, novices, elderly people with pathologies or compromised health and athletes who are recovering from an injury (Baechle and Earle 2008; Yamauchi et al. 2009). In addition, some studies have proven evidence about the importance that bodyweight or reduced-bodyweight activities could have in increasing explosive strength when trained at high-speed and low-load, thus showing the advantages of plyometric training without external resistances (Jimenez-Reyes et al. 2016) (see section 3.4).

3.2 FREE-WEIGHT TRAINING

The use of gravity-based resistance (i.e. free weight) is the most worldwide used method for the development of strength-related abilities (Kraemer et al. 2017a). Dumbbells, bars, discs, kettlebells, guided machines and weight-stack machines are highly used for training and rehabilitation in different populations (Coburn 2012). This RT method is based on lifting (requiring concentric muscle actions) and lowering (requiring eccentric muscle actions) of weights. In addition, it allows the execution of analytical exercises, in which only one muscle group is working in a monoarticular movement. This may be interesting in an area of research or rehabilitation, but these movements rarely appear during daily-life movements (Boyle 2016). In addition, isolation of a single-joint that is typically performed during machine-based exercises may improve strength, but may fail to improve coordination capacity to improve subsequent sporting performance or daily-life movements due to lack of transfer of coordinative patterns (Stone et al. 2002). Therefore, free-weight exercises, that involve several joints and muscle groups, may induce greater adaptations in strength, power and muscle mass (Stone et al. 2000). In addition, some authors have shown that free-weight training may require greater involvement of the stabilizing musculature compared to weight-stack and guided machines (Behm and Anderson 2006). Although the guided machines are recommended for novices in learning the technique of exercise. Collectively, it appears that multi-joint free-weight exercises require greater coordination and muscle recruitment demands, which is related to greater neuromuscular and structural adaptations.

Especially in sports, Olympic weightlifting movements are prescribed as a training way to enhance strength-power adaptations. These exercises include: snatch, clean and jerk and their derivatives that omit a portion of the full lift (e.g. dead lift) (Coburn 2012). It is a widely used method in sports, since it has been proven to instigate superior RT-induced effects compared to traditional RT (Arabatzi and Kellis 2012; Channell and Barfield 2008; Hoffman et al. 2004) and jump training (Berton et al. 2018; Tricoli et al. 2005). This may be due to the fact that during these exercises moderate to heavy loads are mobilized with ballistic intentions (i.e. as fast as possible), exploiting both the force and velocity aspects for power development (Suchomel et al. 2017). The main limitation of this method is that it requires a high execution technique level. Problems in technique may lead to joint and muscle injuries (Coburn 2012). Therefore, it is only prescribed to advanced trainees highly experienced in strength training (Suchomel et al. 2018).

RT prescription with free-weights uses to be performed at a certain intensity. Since RT intensity has been observed in some studies to be a key factor mediating adaptive responses (Schoenfeld et al. 2017a; Schoenfeld et al. 2016b). Currently, the most commonly used way to prescribe RT and quantify training intensity is the percentage of the dynamic one-repetition maximum (%1-RM). In fact, a certain %1-RM to perform a certain number of repetitions is established (Baechle and Earle 2008), as well as, a correlation of the %1-RM to a determined lifting speed during some strength exercises (Gonzalez-Badillo and Sanchez-Medina 2010). Therefore, traditional weight-training consists of raising (concentric), and lowering (eccentric) an identical externally-imposed absolute load, based on the % 1-RM or the lifting speed. This implies the evaluation of the concentric maximum dynamic force (1-RM) before prescribing training and the use of evaluation materials (e.g. accelerometers or power encoders) to assess the force-velocity lifting profile and to quantify training load 2008).

Hence, loading strategies also play a key role in further training-induced effects (Suchomel et al. 2018). The two most common loading strategies when free-weight is employed are: a) training to failure, and b) combined heavy and light loading. Failure is considered when previous full ROM repetitions can no longer be completed in a certain repetition or the barbell stops moving (Izquierdo et al. 2006a; Izquierdo et al. 2006b). Thus, RT to failure is commonly used due to the belief that a relative maximum effort is made when muscle failure is achieved, providing an adequate overload for hypertrophy and strength gains (Schoenfeld and Grgic 2019). However, although training to failure seems to stimulate high-threshold MU, some meta-analysis have proven scientific evidence it does not lead to larger gains than non-failure-training (Davies et al. 2016; Schoenfeld and Grgic 2019). In fact, it may be detrimental (Davies et al. 2016; Peterson et al. 2005), with important implications in the total training volume completed after training (Scudese et al. 2013; Senna et al. 2011; Willardson and Burkett 2006). Therefore, it is not an ideal stimulus to enhance performance nor optimize RT programs. Conversely, combined heavy and light loading is used since both strength and power objectives are trained at the same time. Literature has provided enough information about the effects of heavy loading on maximal strength, and light loading on RFD underpinning power (Schoenfeld et al. 2017a; Schoenfeld et al. 2016a; Suchomel et al. 2016b). Hence, a combination loading model, in which both high and low loads are used, may be achieved through combining traditional free-weight exercises and plyometric exercises. When the explosive movement is performed just after the slow-heavy exercise, then complex training is performed (Freitas et al. 2017). Complex training induces greater adaptations on 1-RM, vertical jump height and running sprint than traditional RT (Bauer et al. 2019; Freitas et al. 2017). This contrast method has also proven to be effective when high and light loads were applied alternatively on different days (Toji and Kaneko 2004).

3.3 VARIABLE RESISTANCE TRAINING: ELASTIC BANDS

Traditional RT programs usually employ a constant external load throughout the ROM. However, the pattern of kinetics, in terms of how the mechanical properties of weight training are applied, may help to understand that constant loading does not provided an appropriate stimulus to generate force at high-velocity (Avrillon et al. 2017). When explosive RT with light loads is performed, the maximal force production occurs during the initiation of the movement (i.e. momentum) (Frost et al. 2010), and the ability to generate force decrease while load is displaced increasing its velocity (Newton et al. 1997), resulting in an ultimately deceleration action at the end of the concentric phase, if the load is not projected (Avrillon et al. 2017; Cormie et al. 2007). Thereby, in order to modify the external resistance and maximize muscle force production throughout the ROM, external implements are used in addition to weight (Saeterbakken et al. 2016). Among these implements, elastic bands stand out (Saeterbakken et al. 2016). Elastic bands (as well as other implements like chains) may alter an exercise's loading profile by altering force and power production and velocity (Saeterbakken et al. 2016). Resistance provided by bands is directed opposite to the direction of the stretch, furthermore the distance that the elastic material is stretched increases proportionally the load (Coburn 2012). Thus, resistance is minimal at the beginning of the exercise and increases as the movement is performed. Various studies have corroborated larger strength gains after variable RT during upper and lower body exercises compared to traditional RT methods (Garcia-Lopez et al. 2014; Nilo Dos Santoset al. 2018; Soria-Gila et al. 2015). Lately, the use of elastic bands has also been established as a proper way to maximize potentiation stimulus (Mina et al. 2016; Mina et al.

2019). In addition, elastic bands can also be employed individually, providing a light load stimulus and allowing for an eccentric-overload at the beginning of the eccentric phase. It should be noted that intensity is determined by thickness and width of the material.

3.4 PLYOMETRIC AND BALLISTIC TRAINING

The use of the stretch-shortening cycle during a maximal explosive movement is called plyometric exercise. This concept means that concentric actions are enhanced by a previous eccentric one, such occurs when a countermovement jump is performed or when a tennis player hits the ball. Plyometric training is normally performed with multiplanar jumps without material or over hurdles and boxes, dropping from a height and with a predefined load (e.g. jump squats). In addition, explosive ballistic movements, such as jumping with a predefined load (e.g. jump squats) and throwing movements (e.g. bench press throws and medicine ball throws) are also considered plyometric exercise. A recent meta-analysis has pinpointed that plyometric training may produce similar improvements in vertical jump height compared to weightlifting training, positioning this method as a proper way to maximize the ability to transfer maximal strength to RFD and power production (Hackett et al. 2016). Even though the high functionality of this training for athletes and healthy population, the main limitation is the difficulty to overload the bodyweight plyometric stimulus to produce positive adaptations on muscular strength (Suchomel et al. 2018). Since heavier loads may result in greater impact forces and extend the transition time between eccentric and concentric actions (Suchomel t al. 2018). So volume management or moderate to high exercise intensity selection strategies should be followed to produce desired adaptations (Jarvis et al. 2016). Notwithstanding, when trainee has high levels of strength (Suchomel et al. 2016c), ballistic exercises with free-weight (e.g. jump squat) may produce greater force, velocity, power and muscle activation compared to the same high-velocity non-ballistic exercise (e.g. weight squat) (Lake et al. 2012; Suchomel et al. 2016b). These mechanical effects may lead to lower-threshold MU recruitment, and thereby, a greater force production, RFD and power development (Moir et al. 2018). Thus, ballistic exercise is advantageous on promoting explosive strength adaptations.

3.5 ECCENTRIC TRAINING

When musculotendinous units are lengthening as a result of a decelerative force application over a determined load, an eccentric action is performed. Typically, these lengthening actions results as a consequence of the magnitude of the load, i.e. the force applied by the muscle itself is inferior to the load, or an active lengthening action is conducted (Douglas et al. 2017a; Douglas et al. 2017b). Several methods have been designed and proposed to offer an eccentric stimulus during RT, such as 1) controlling and adjusting the time/velocity of concentric and eccentric movement during resistance exercise (e.g. 2/1 tempos technique or “superslow” actions) (Dias et al. 2015; Gillies et al. 2006); 2) negative phases with supramaximal loads (i.e. loads higher than concentric 1-RM) using third-party assistance or devices for moving/rising the load during the concentric phase (Fernandez-Gonzalo et al. 2011; Garcia-Lopez et al. 2007; Jimenez-Jimenez et al. 2008); 3) eccentric cycle ergometers and downhill treadmills (Isner-Horobeti. et al. 2013; Penailillo et al. 2015), and 4) employing isokinetic dynamometers (Guilhem et al. 2013). Eccentric training has been extensively studied in scientific literature (Roig et al. 2009). In comparison with concentric, isometric and traditional RT, isolated eccentric actions may lead to favorable adaptation in mechanical function (strength, muscle power, RFD), morphological adaptations (tendon and muscle fiber CSA changes), neuromuscular adaptations (MU recruitment velocity and firing frequency) and sports-related performance tasks (such as vertical jump and running sprint) (Douglas et al. 2017a; Douglas et al. 2017b). Thereby, eccentric actions seem to optimize the efficacy of training (Meylan et al. 2008; Roig et al. 2008).

Besides, as a summary, Suchomel et al. (2018) proposed a classification of the above-mentioned RT methods (Table 2) regarding the theoretical potential of each one to develop muscle mass gain (i.e., hypertrophy), strength and power. The method that these authors highlight as eccentric training is more effective, which is why our study area will focus on this type of training, its physiological characteristics, its limitations and its forms of application.

Table 2. (Adapted from Suchomel et al., 2017). Theoretical potential of RT methods to elicit muscle size, strength and power gains.

Resistance Training Method	Hypertrophy	Strength	Power
Bodyweight exercise	+	+	++
Machine-based exercise	++	++	++
Weightlifting exercise	+++	+++	+++++
Variable RT with elastic bands	+++++	++++	++++
Plyometric Training	+	++	+++++
Ballistic Training	++	+++	+++++
Eccentric training	+++++	+++++	+++++

RT methods ranked on scale from + (1 point, meaning low potential), to +++++ (5 points, meaning high potential).

3.5.1 ECCENTRIC EXERCISE: BASIS AND PHYSIOLOGIAL CHARACTERISTICS

The singular features of eccentric muscle contraction mean that more and more researchers, coaches and sports professionals are interested in its study and application. Given the fact that the ability to produce force in the concentric action limits the load/weight to be used during training. Since eccentric contraction, as defined above, refers to a muscle activity that occurs when the force applied to the muscle exceeds the momentary force produced by muscle, resulting in a lengthening action (Hortobagyi and Katch 1990). Therefore, muscle forces during eccentric actions tend to be higher (Hortobagyi and Katch 1990). As a result, the loads used during traditional free weights or weight-stack exercise are sub-optimal during the eccentric phase of the movement (Hollander et al. 2007; Hortobagyi 2003; Reeves et al. 2009). In addition, the training stress and physiological strain imposed by eccentric training (i.e. loads above maximal concentric strength) induces a unique and novel training stimuli that seems to enhance muscle neuromechanical functions, musculotendinous junction and muscle architecture (Douglas et al. 2017a). Thereby, exercises using a strictly eccentric regime is used by strength and conditioning coaches and practitioners as a way to optimize RT (Hortobagyi et al. 2001).

Among these beneficial training-induced effects of RT, Douglas and co-workers (2017a), in their recent manuscript entitled "*Chronic Adaptations to Eccentric Training: A Systematic Review"* summarized that strength improvements are largely mode-specific (favors to eccentric), pinpointed , as other authors did (Roig et al. 2009), that these effects on strength-related variables arise from a combination of neural, morphological and architectural adaptations. Hence, increased agonist volitional drive (disinhibition of Golgi Ib and joint afferents known to inhibit excitatory muscle spindle Ia afferents) and decreased antagonist coactivation, due to the specific MU discharge rate experienced during eccentric contraction, is posited as the primary neural contributing factor to the marked increases in eccentric strength after training (Aagaard 2003). Eccentric training also led to greater increases on stretch-shortening cycle performance (concentric muscle power (Colliander and Tesch 1990; Elmer et al. 2012; Gross et al. 2010) and RFD (Blazevich et al. 2008)) compared to concentric or traditional RT. Increases in explosive performance are likely related to improvements in total strength, as well as in the capability to rapidly recruit larger MUs (i.e. type IIx and IIa fibers) by lowering the threshold of recruitment or by preferential recruitment, and increases on MU firing frequency (Cormie et al. 2010; Van Cutsem et al. 998). Furthermore, increases in both tendon stiffness (Malliaras et al. 2013) and tendon cross-sectional area (Farup et al. 2014) probably enhance the storage and utilization of elastic strain energy during explosive movements, such as vertical jump or drop jump, and allowed the muscle to operate closer to its optimum length and shortening velocity (Ando et al. 2018). Additionally, these strength-related adaptations may also be influenced by contraction velocity. Since fast eccentric training appears to induce the largest improvements in strength and explosive performance (Farthing and Chilibeck 2003), the greatest muscle gains (Farthing and Chilibeck 2003) and IIx fiber composition (Paddon-Jones et al. 2001). Regarding muscle volume, it has been demonstrated that eccentric training can elicit greater increases in muscle size than concentric or traditional RT. Even though, the mechanisms of muscle hypertrophy, by which this response occurs, have not been widely described yet (Schiaffino et al. 2013), there is evidence that the high levels of mechanical tension per active motor unit, stretch-induced strain (Toigo and Boutellier 2006), and a greater propensity for exercise induced muscle damage et al. 2007; Jimenez-Jimenez et al. 2008) which mark eccentric training may stimulate anabolic signaling to a greater extent than concentric or traditional RT (Schoenfeld 2010). This may be explained by the mechanical tension, since it is well established that muscle tension is a crucial factor influencing muscle hypertrophy (Fry 2004). Furthermore, the nature of hypertrophy appears to differ with eccentric training versus concentric training, and the addition of sarcomeres in series, as inferred from changes in muscle fascicle length, may contribute to muscle hypertrophy (Blazevich et al. 2007; Franchi et al. 2014). Besides, muscle hypertrophy was predominant in the mid to distal regions for eccentric training, and predominant in the mid to belly region for concentric training (Franchi et al. 2014). These architectural differences may be explained by training-induced differences at molecular level. It should be noted that, although both AKT-mTOR and phosphorylated MATK pathways are related with protein synthesis, and thereby, with muscle growth, only MATK (e.g. p-38 MAPK, ERK I/2 and p90RSK proteins) was only significantly altered after eccentric training (Franchi et al. 2014). Another important structural factor is the presence of a greater number of sarcomeres in series after eccentric training (Franchi et al. 2017). This may subsequently increase muscle shortening velocity and increase force production at longer muscle lengths (Franchi et al. 2015; Vogt and Hoppeler 2014). In addition, various studies have found significant increases in either of cross-sectional area or distribution of fast-twitch fibers (type II) (Friedmann-Bette et al. 2010; Hather et al. 1991; Hortobagyi et al. 2000). Finally, some studies have stand out that the upregulation of IIx mRNA signaling can occur (Friedmann-Bette et al. 2010), leading to an attenuated IIx to IIa shift (Raue et al. 2005), or an increase in IIx composition with fast contractions (Paddon-Jones et al. 2001). All this together, led to a subtly faster gene expression pattern and induced a shift towards a faster muscle phenotype plus associated adaptations (Friedmann-

Bette et al. 2010), this may contribute to improvements in strength and power performance with eccentric training.

However, while there is some evidence of a greater effect of eccentric-only compared to concentric-only training in some studies, the evidence is not totally clear. In numerous reviews, including Wernbom's (Wernbom et al. 2007), Roig's (Roig et al. 2009), Schoenfeld's (Schoenfeld et al. 2017b), and Franchi's (Franchi et al. 2017) no statistical difference was observed in muscle cross-sectional area between both training types. In fact, when measured using the gold standard magnetic resonance imaging (MRI) method, there is no statistical difference (Franchi et al. 2017). With regard to strength, some papers cite that 'total strength' is greater after eccentric-only training, but this is because the increase in eccentric strength after eccentric training is much greater than the increase in concentric strength after concentric training. Indeed, effects on isometric strength were about the same. So there's a specificity of adaptation, but no clear strength advantage otherwise. So I would conclude that, while there is some evidence of a greater effect of eccentric-only in some studies, there is no consistent benefit. However, there is plenty of evidence that the inclusion of an eccentric phase, even an accentuated eccentric phase regarding the concentric, is much better in terms of acute effects and chronic adaptations. Hence, a deep knowledge of muscle physiology during eccentric actions is necessary to understand its underpinning training-induced effects and also its modes of application.

A number of molecular mechanism and neural strategies have been proposed throughout the literature to describe the unique physiological characteristics of the eccentric contraction, as well as the existing differences between concentric contractions:

MOLECULAR CHARACTERISTICS

It is broadly studied that eccentric contraction involves both higher force and lower metabolic cost properties compared to concentric or isometric voluntary contractions, and also electrically induced contractions. Nevertheless, several muscle models have been proposed to explain these previous findings (Douglas et al. 2017b; Hessel et al. 2017). Linari et at. (2000) In an animal model, exposed that the cross-bridge theory alone is inadequate in explaining the greater force produced during active lengthening and the reduced energy expenditure of eccentric contractions (Hessel et al. 2017). The increased force production during lengthening contractions above isometric force capabilities may be related to differences in the number of attached cross-bridges and mechanical detachment of active cross-bridges. During isometric and concentric contractions only one myosin head is bound, whereas the increased strain on a single myosin head during lengthening contractions may facilitate the activation of the second head (Linari et al. 2000). This mechanism would lead to twice the number of active cross-bridges during active lengthening (Linari et al. 2000). Besides, cross-bridges do not complete a full cycle during eccentric contractions (Linari et al. 2004); they become suspended in an active state bound to actin and become forcibly detached followed by a rapid re-attachment, because a full cross-bridge cycle is not completed less ATP is required to maintain force (Huxley 1998). Further studies have shown a greater maximal voluntary contraction force after a lengthening action (Herzog et al. 2015). This finding supports the idea that passive factors beyond cross-bridge mechanisms may also underpin a determinant role in the greater force production during eccentric contractions. This phenomenon is called residual force enhancement (Herzog 2014; Herzog et al. 2015), in which the stiffness of the molecular spring titin seems to play an indisputable role (Herzog et al. 2016). Titin, which spans a half sarcomere, is posited as an important contributor to the regulation of muscle force (Herzog et al. 2015), since it provides stability to sarcomeres, provides elastic energy when muscle is strengthened, and is placed parallel with cross-bridge forces (Herzog et al. 2016). Additionally, it should be noted that calcium binding to certain regions of titin is able to increase titin's stiffness and subsequently enhance its force production upon lengthening (Herzog et al. 2016; Leonard and Herzog

2010). So, titin, therefore, acts as a spring that binds calcium upon activation and bids to actin upon cross-bridge attachment (Herzog et al. 2016).

NEUROPHYSIOLOGICAL CHARACTERISTICS

There are some neural factors that also contribute to the higher force production and the lower metabolic cost that constitute the main characteristics of eccentric contraction. The neural strategies controlling eccentric actions seem to be exclusive in comparison with concentric and isometric actions. Three neural changes are pinpointed in this regard (Douglas et al. 2017b):

- EMG amplitude has been shown to be lower during maximal eccentric contractions than maximal concentric or isometric contractions (Aagaard et al. 2000). This phenomenon is greater in unaccustomed participants and with light loads (Aagaard et al. 2000).

- MVC and maximal muscle activation induced by superimposed electrical stimulation has proved evidence that a greater voluntary activation deficit exist in eccentric contraction compared to concentric in untrained participants (Herbert and Gandevia 1999).

- Lower and more variable MU discharge rates during maximal eccentric contractions has been observed by single MU evaluation in untrained participants (Del Valle and Thomas 2005; Duchateau and Baudry 2014).

- Thus, the greater intrinsic force capacity of muscle during eccentric contractions means that fewer motor units are required to attain a given absolute force (Del Valle and Thomas 2005; Duchateau and Baudry . In addition, it has been demonstrated that high-threshold MUs can be selectively and preferentially recruited during eccentric contractions, particularly at fast eccentric velocities (Kulig et al. 2001; Nardone et al.

1989). Furthermore, a progressive highest threshold MUs de-recruitment may occur during eccentric contractions with submaximal loads requiring fewer or smaller MUs to attend to lower strength demands (Douglas et al. 2017b). However, cortical excitability appears to be enhanced during eccentric contractions independently of the load condition and lower motor unit activity (Fang et al.. 2004). The enhanced cortical excitability and descending drive has been postulated as a compensatory response to spinal inhibition (probably the primary mechanism underpinning a reduced motor activity during lengthening muscle actions) (Duchateau and Baudry 2014). As a result of this inhibition, the motoneuron pool is also suppressed, as H-reflex study indicates in some investigations. Furthermore, when transcranial magnetic stimulation was employed, smaller motor evoked potentials during eccentric contractions were observed (Sekiguchi et al. 2001), probably as a result of both pre- and post-synaptic mechanisms at the level of the motoneuron (Duchateau and Baudry 2014). Given a similar response across maximal and submaximal eccentric conditions, a tension-related Golgi tendon organ inhibition is unlikely to be a primary factor in the lower metabolic cost of eccentric contractions (Pinniger et al. et al. 2000). Douglas et al. (2017b) concluded that eccentric contractions possess an unique neural behavior under both maximal and submaximal conditions primarily mediated by spinal inhibition and associated mechanisms. Heavy RT seems to play an important role, enhancing neuromuscular activation and maximal eccentric strength as a result of reflex inhibition attenuation (Duchateau and Enoka 2016).

Hence, it is possible to establish 6 physiological characteristics (table 3) that make the eccentric contraction unique, and certify that eccentric actions must be used and included in health and conditioning training programs:

Table 3. Brief explanation of the 6 factors that characterize the eccentric contraction.

6 unique physiological aspects of eccentric contraction	
1) Eccentric contraction is able to generate higher peaks of force compared to concentric contraction	Classical studies showed that eccentric contraction is capable of producing higher force peaks (i.e. greater tension) than concentric contractions. In 1986, Komi et al. (1986) demonstrated that an eccentric contraction is capable of producing a higher force (between 20 and 30%) than an isometric contraction (at the same level of electromyographic activation). When both dynamic free-weight during conventional RT (Hollander et al. et al. 2007) or using isokinetic dynamometers (Hortobagyi and Katch 1990), individuals are 20-60% stronger eccentrically than concentrically. Additionally, this percentage may be increased by females, in which reported higher eccentric strength increases (between 60 and 160% greater than the concentric force) in both free-weight (Hollander et al. 2007) and isokinetic (Colliander and Tesch e1990) resistance exercises. It also should be noted that force during lengthening activities increases with velocity (Douglas et al. 2017b). But it depends on RT experience, since it is shown that resistance-trained participants may increase force production at higher eccentric velocities (Duchateau and Enoka 2016). Age, sex and RT experience all appear to influence eccentric/concentric strength ratio possibly due to differences in elastic energy storage, MUs recruitment and inhibition of maximal force (Douglas et al. 2017b; Duchateau and Baudry 2014; Duchateau and Enoka 2016).
2) Eccentric contraction leads to fewer muscle activation than concentric contraction	It has been found that muscle activation, measured with surface EMG, is lower when eccentric contractions are made in comparison with isometric or concentric contractions (Duchateau and Baudry 2014; Tesch et al. 1990), even though force production is higher in the eccentric contraction compared to the concentric contraction. It has been suggested that the reduction on muscle activity, or lower EMG activity, may be due to a lower activation of all the fibers recruited, a selective activation of certain types of muscle fibers (which would lead to an inhibition or decrease of other types of fibers) (Enoka 1995; Enoka 2002).

3) Specific MUs' recruitment order during eccentric contraction	MUs can be selectively and preferentially recruited during eccentric contractions, particularly at fast eccentric velocities (Kulig et al. 2001; Nardone et al. 1989). Therefore, although some controversy exists in the field (Beltman et al.. 2004), muscle fibers capability to rapidly recruit larger MUs (i.e. type IIx and IIa fibers) by lowering the threshold of recruitment or by preferential recruitment, and increases on MU firing frequency (Cormie et al. 2010; Van Cutsem et al. 1998) during lengthening is reported. In addition, some authors argued that this may also be the explanation for the increases in the fast-twitch fiber (i.e. type IIx and IIa fibers) cross-sectional area observed after eccentric training (Friedmann-Bette et al. 2010).
4) Lower metabolic cost during eccentric contractions	In addition to the fewer MU required for the same work findings, eccentric exercise has demonstrated less metabolic demanding compared to concentric exercise for the same work (Penailillo et al. 2013). Subsequently, oxygen consumption is lower during activities, in which a lengthening contractions is implied, such as eccentric cycling or downhill walking or running, in comparison with their homologues activities in the opposite direction (e.g. uphill activities) (Abbott et al. 1952; Kilgas and Elmer 2017). Thus, eccentric activities requires 4-5 times less oxygen, thereby fewer oxygen consumption (around three times less), and fewer cardiac responses (heart rate and cardiac output) compared to the same mechanical workload in concentric exercises (Douglas et al. 2017b). This effects results in lower perceived exertion, blood lactate concentration, energy expenditure and higher fat oxidation (Penailillo et al. 2013).
5) Less muscle fatigue induced by eccentric contractions compared to concentric contractions	Muscular Fatigue is defined as the loss capacity to generate force. It has been shown that muscle fatigue is fewer during eccentric exercise compared to concentric exercise (Douglas et al. 2017b). Tesch et al. (Tesch et al. 1990) corroborated that EMG amplitude signal decreased around 40% during isokinetic concentric exercise, while non diminutions on EMG signal were registered during isokinetic eccentric exercise at an equivalent workload. Alling with these results, Hortobagyi et al. (1996a) found that increasing eccentric strength (i.e. a 42 % increase)

	somewhat attenuated (i.e. *10 %) the fatigue resistance during an eccentric exercise protocol, albeit non-significantly. Fatigue resistance during eccentric actions may be particularly influenced by the capacity to maximally recruit muscle (Grabiner and Owings 1999), and it is also showed that both central and peripheral factors contributed to the MVC decrease (Souron et al. 2018).
6) Muscle damage after eccentric contraction	The effect of eccentric exercise on muscle damage is widely studied (Douglas et al. 2017a; Douglas et al. 2017b; Isner-Horobeti et al. 2013). Exercise-induced muscle damage (EIMD) is generally produced by an unfamiliar eccentric exercise (Douglas et al. 2017b). This eccentric exercise is characterized by unique contractile capacities (i.e. fewer motor units for a given load in comparison with a concentric action), which require greater force (i.e. tension) applied per active MU (Guilhem et al. 2010; Guilhem et al. 2012). A greater tension applied on a smaller number of muscle fibers causes mechanical injuries to these activated muscle fibers (Garcia-Lopez 2008). Thereby, EIMD leads to increase circulating intramuscular enzymes (such as creatine kinase, troponin I, myoglobin and myosin heavy chain) (Tee et al. 2007), and is known to impair neuromuscular detrimental effects (Isner-Horobeti et al. 2013). Indeed, maximal voluntary contraction has been shown to diminish 10–60 % for up to a week after eccentric RT (Guilhem et al. 2010; Murayama et al. 2000). A number of metabolic consequences of EIMD have also been reported, including decreased glucose uptake and insulin sensitivity, impaired glycogen synthesis, elevated metabolic rate and a shift towards non-oxidative metabolism (Tee et al. 2007). Symptoms of EIMD become prominent 12-48h after eccentric stimulus, peaking between 24-72 hours, and gradually disappearing in 5-7 days in concert with neuromuscular capacities (Guilhemet al. 2010; Isner-Horobeti et al. 2013). Among these symptoms are: delayed-onset muscle soreness, muscle stiffness, reduced range of motion, swelling, loss of contractile capacity and proprioception deficit (Garcia-Lopez. In addition, it is well-known that higher loads (McHugh and Tetro 2003), fast contraction velocities (Chapman et al. 2006), long muscle lengths during exercise (Proske and Allen. 2005) and experience with RT

(Newton et al. 2008) accentuate muscle damage. However, previous thesis from our laboratory have indicated that EIMD is significantly attenuated after a systemic RT program including eccentric exercises (Fernandez-Gonzalo 2011; Garcia-Lopez 2006). The phenomenon whereby a repeated exposure to similar eccentric exercise bout substantially decrease EIMD and delayed-onset muscle soreness is called "repeated bout effect" (Hyldahl et al. 2017). This protective effect has proven to last from a week to several months (Nosaka et al. 2001). Finally, hence in order to avoid EIMD, eccentric training should be incorporated in any exercise routine in a progressive incremental way (Douglas et al. 2017b; Nosaka 2018).

Traditionally eccentric exercise has been employed to incorporate a reinforced mechanical stimuli (i.e. strength or power) with lower metabolic demands (i.e. energy expenditure) in RT programs. Isolated muscle lengthening has been shown to lead to significant neural (strength, cross-education effect, increased inhibitory feedback and a-motoneuron excitability, and shift in motor unit recruitment), structural (i.e. muscle hypertrophy), and muscle mechanical function adaptations (reduced fascicle elongation and increased tendon compliance) (figure 1) (Douglas et al. 2017a; Franchi. et al. 2017; Hyldahl et al. 2015). In addition, eccentric training has demonstrated to be a safe stimulus, since EIMD is not necessarily an issue if progressive loads are applied, used with different population such as healthy physically active and sedentary, athletes, elderly and people with chronic pathologies (Isner-Horobeti et al. 2013). Consequently, Isner-Horobeti et al. (2013) reviewed the literature asserting that eccentric training can: 1) induce muscle hypertrophy and improve muscle strength and explosive performance (e.g. vertical jump) in healthy and trained subjects (Douglas et al. 2017a); 2) improve muscle strength and body composition and reduce fall risk in elderly populations ; 3) enhance muscle function, balance, gait and functional performance (quality of life in general) in patients with coronary insufficiency, multiple sclerosis, Parkinson, stroke and cancer survivors. Furthermore, in comparison with concentric, isometric and traditional RT, the superiority of eccentric training has been demonstrated by the observed changes associated with a stronger and faster phenotype in healthy and trained subjects (Douglas et al. 2017a; Friedmann-Bette et al. 2010), as well by the enhancements in muscular strength in the contralateral non-trained limb when an unilateral RT protocol was applied (i.e. cross-education effects) (Cirer-Sastre et al. 2017; Manca et al. 2017; Manca et al. 2018). However, this training method still presenting some inconvenient that limit its prescription by coaches and practitioners.

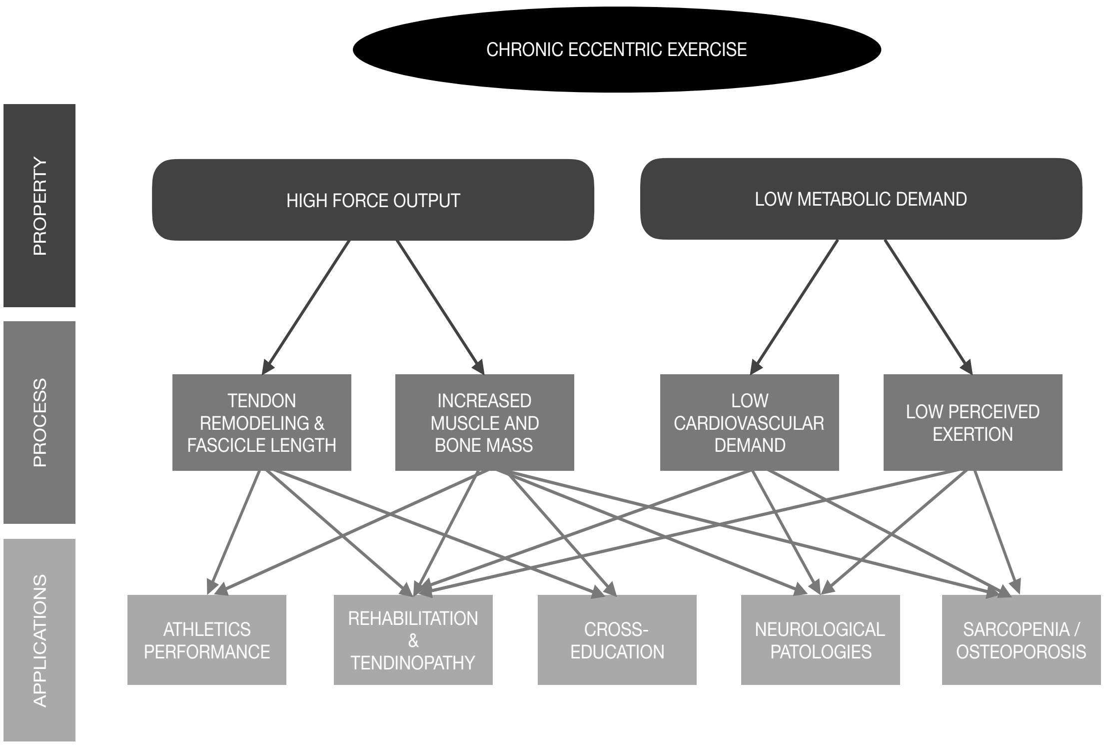

Figure 1. (Adapted from Hessel et al. 2017) Summary diagram of the characteristic properties of the eccentric contraction, physiological processes that triggers its systematic application and possible applications to such adaptations.

3.5.2 LIMITATIONS OF ECCENTRIC EXERCISE

Despite the significant benefits shown by eccentric training and the unique mechanical, neural and cellular responses produced by the eccentric contraction, there are some difficulties and limitations that make this RT method not widely used. Indeed, in spite of being an old concept, certain modalities of exercise are currently emerging or adapting, such as cycling, walking or stepping, due to the difficulty of application.

Traditional strength training is performed by lifting (requiring concentric muscle actions) and lowering (requiring eccentric muscle actions) of weights, usually with the load being set at a specific proportion of an individual's maximum strength capacity. However, muscles are not capable of lifting as much load in the concentric phase as they can lower with control in the eccentric phase due to the well-described force-velocity characteristics of muscles. Therefore, the loads lifted during strength training are limited to those that can be lifted in the concentric phase, and the eccentric phase is never performed with maximal (or near-maximal) loads. Thus, a suboptimum stimulus is applied during the eccentric phase during strength training. However, optimization of RT using a strictly eccentric regime is rather complex and technically difficult to apply (Hortobagyi et al. 2001). In addition, eccentric actions are rarely isolated in real-life situations, and usually appear during the stretch-shortening cycle, inducing a greater contribution of the elastic components in the muscle-tendon unit; the stretch-shortening cycle increases the potential to produce force in the subsequent concentric action due to increased storage and use of elastic energy (Meylan et al. 2008; Roig 2010). In addition, difficulties arise in assessing the optimal eccentric load (i.e. eccentric force-velocity relation), measuring the maximum eccentric force and providing eccentric stimuli at different speeds which requires research material to its application.

In summary, isolated eccentric exercise is not widely used due to the shortcomings involved in: 1) quantifying the load, 2) isolating the movement from the concentric phase; 3) high levels of experience and technique required by participants; 4) the financial restrictive material involved (e.g. dynamometers); and 5) little application or transfer to athletic performance and daily-life activities (i.e. avoiding strength-shortening cycle use). Thus, researchers, practitioners and strength and conditioning specialists have sought alternative methods in order to overload or accentuate the eccentric action.

3.4.3 ACCENTUATED ECCENTRIC TRAINING

Given the limitations of eccentric training and the importance of including an eccentric contraction during RT, new alternatives emerged in scientific literature. Devices created to isolate or overload the eccentric phase of the muscle action have emerged as an alternative method that may produce greater muscle adaptations, and therefore have been developed and/or tested for multiple rehabilitation and performance purposes.

During traditional concentric-eccentric resistance exercise performed at maximal intensity, the eccentric phase is clearly under-loaded (e.g. about 40-50% (Dudley et al. 1991b)). Multiple studies using different protocols have shown the critical role of the eccentric muscle action to improve contractile characteristics and muscle size in humans (Dudley et al. 1991b; Hather et al. 1991; Hortobagyi et al. 1996b). Therefore, it seems reasonable to believe that accentuating or overloading the eccentric action during resistance exercise could increase force production capability (Hortobagyi et al. 2001). Therefore, accentuated eccentric loading has been proposed as an alternative method to optimize RT due to lesser recruitment and discharge rates observed during eccentric actions when compared to concentric actions under similar absolute loading, which provides justification for higher magnitude of eccentric loading (Franchi et al. 2017). Furthermore, eccentric overload (EO) RT has revealed increase force production in the subsequent concentric action, not only by motor cortex activation and spinal inhibition occurring during eccentric contractions, but also by a selective recruitment of high-threshold MUs (Duchateau and Enoka 2016). In addition, architectural muscle gearing may contribute to these greater force production mechanisms, since muscle fascicle functions closer to its optimal length and angle (Ando et al. 2018). By means of this approach, stimulation of Type Ia afferent nerves will occur, inducing a myostatic reflex, and elastic energy stored in series and parallel elastic components during lengthening will be used in the following concentric contraction, which is also maybe due to the titin protein contribution (Hessel et al. 2017). Thus, after a EO-RT program, neuromuscular adaptations may be obtained which favor greater increases in strength and power compared to traditional training (Barstow et al. 2003; Brandenburg and Docherty 2002; Douglas et al. 2018; English et al. 2014; Friedmann et al. 2004; Friedmann-Bette et al. 2010; Kaminski et al. 1998; Maroto-Izquierdo et al. 2017a; Walker et al. 2016).

Hence, EO-RT emerges as an alternative method to prescribe effectively intensity, relative to the force generation capabilities of eccentric muscle action, and avoid the negative work isolation (i.e. favoring the strength-shortening cycle use) (Wagle et al. 2017). Then, it consists of prescribing an eccentric load in excess of the concentric load, requiring coupled eccentric and concentric actions, while creating minimal interruption in the natural mechanics of the selected exercise and movement (Schoenfeld and Grgic 2018). Prior studies have reported evidence of force and power production enhancements (Aboodarda et al. 2013; Ojasto and Hakkinen 2009; Sheppard and Young 2010) and chronic adaptations using various systems to accentuate the eccentric loading, such as weight releasers (Walker et al. 2016; Walker et al. 2017), computer-driven devices (Friedmann et al. 2004; Friedmann-Bette et al. 2010; Yarrow et al. 2008) or iso-inertial flywheel devices (Maroto-Izquierdo et al. 2017b; Tesch et al. 2017).

Traditionally, accentuated eccentric training has been performed by means of gravitational resistances (e.g. weight releasers or third-party assistance), and sometimes with modern machines which incorporated an electric-motor to raise the weight during the concentric phase (Tinwala et al. 2017). Despite the lack of consensus between the EO magnitude and the loading condition (maximum, submaximal or supramaximal eccentric loads) among the existing studies, the traditional methods to reinforce the lengthening action during RT have shown chronic adaptations, and in some cases greater than those induced by traditional RT (Wagle et al. 2017). Walker and colleagues (2016) demonstrated that EO training with 40% greater load in the eccentric phase led to greater increases in maximum force production, muscle endurance capacity and muscle activation in comparison with traditional concentric-eccentric weight training, although anabolic hormonal responses (testosterone, cortisol and growth hormone) and hypertrophic effects were similar to traditional strength training. English and collaborators (2014), showed increases in lean tissue mass only when high percentages of the concentric maximum strength (138% of 1-RM) were used during lengthening. In addition, Friedmann-Bette and co-workers (2010) found greater improvements in SJ height and type IIA fiber CSA as well as a shift towards faster myosin heavy chain isoforms after 10 weeks of EO training using an electric-motor device (1.9 times the concentric load during the eccentric action) when compared to traditional strength training. Thereby, EO-RT with gravitational resistances seems to lead to significant training-induced changes on functional and structural variables related with health and performance optimization.

ACCENTUATED ECCENTRIC TRAINING CHRONIC ADAPTATIONS

After accentuated eccentric training, maximum force production has shown significant increases in 1-RM, as well as in MVC (Wagle et al. 2017). Regarding submaximal loading, a prior study showed muscle torque enhancements of 5% after training (Friedmann et al. 2004). Although no differences among the EO-RT group and the traditional RT group (30/30% 1-RM) were observed, the traditional group did not show any improvement in strength (Friedmann et al. 2004). Therefore, these gains have been attributed to the EO applied during RT (Wagle et al. 2017). Regarding supramaximal loading training, Yarrow and co-workers (2008), showed gains of 19% in lower limb 1-RM after training with supramaximal loads (upon 120% 1-RM) with high EO percentages (concentric load of ~45% 1-RM) employing free-weight and an electric-motor device to raise the weight during the concentric phase. Similarly, Friedmann-Bette and associates (2010) demonstrated significant increases of 11-15 kg in the 1-RM test when a supramaximal loading training was applied with an electric-motor device in the knee extensor muscles. These results suggested that EO-RT with higher EO percentages (i.e. low concentric loads) may work more efficiently compared to accentuated eccentric training with higher concentric loads (upon 75% 1-RM). Thus, one potential application of EO-RT may be to retain maximum strength while emphasizing higher movement velocities or reducing volume load according to individual objectives or periodization (Ojasto and Hakkinen 2009;

Wagle et al. 2017). In addition, other authors have shown gains of 18-23% in isometric strength after EO-RT with submaximal and supramaximal loads (Hortobagyi et al. 2001; Walker et al. 2016). These strength changes may be due to decreased neural inhibition and subsequent increases in MU discharge rate (Aagaard 2003). Resulting in higher levels of voluntary muscle activation after accentuated eccentric training compared to traditional training (Walker et al. 2016). Thereby, the enhancement of force production capabilities observed may be induced by calcium sensitivity and neural drive increase provided by the EO stimulus (Wagle et al. 2017). This response is similar under both supramaximal and submaximal loading conditions (Duchateau and Baudry 2014), suggesting that the nervous system employs a unique activation pattern during the eccentric contraction, regardless of the magnitude used during lengthening (Wagle et al. 2017).

Also, it is important to note that accentuated eccentric load training elicited an improvement in the muscle fatigue resistance ability (Coratella and Schena 2016). This was evidenced by Walker and co-workers (2016), who found improvements in the unilateral knee extension repetition-to-failure test (~28%) after supramaximal EO-RT with high concentric loads that led to failure in at least one training set. These effects may be due to the fact that the eccentric action leads to an increased and longer neural drive, regardless of the load magnitude (Wagle et al. et al. 2017), which could improve the mechanical efficiency and consequently the muscle endurance (Coratella and Schena 2016; Vogt and Hoppeler 2014).

This task-specific neural adaptations may transfer favorably to sporting activities in which the stretch-shortening cycle is involved and its optimization has a direct impact on performance. Sheppard and Young (2010), demonstrated a greater concentric performance in the ballistic bench press preceded by an accentuated eccentric action, especially when the eccentric loading prior to the plyometric movement was inferior (Sheppard et al. 2007). This greater production in muscle power observed in the subsequent concentric contraction to an EO action, may be the justification of the adaptations found in explosive performance after eccentric-only and EO-RT programs. However, this behavior of the stretch-shortening cycle has not been observed when high training loads were used (80/30% 1-RM) in exercises involving an aerial phase (e.g. jump squat) (Moore et al. 2007). Therefore, eccentrically reinforced training to improve explosive performance should consider that those wide ranges of motion, high magnitudes of EO, and eccentric loads higher than concentric 1-RM may be inappropriate. This is probably due to lengthening amortization phase and; subsequently, limiting the use of the stretch-shortening cycle for concentric potentiation (Cormie et al. 2008; Komi et al. 1984). Therefore, exercises in which EO occurs during a very short action have been shown to induce adaptations in muscle power and plyometric performance (Maroto-Izquierdo et al. 2017b; Wagle et al. 2017). Thus, flywheel devices, in which a very short and concentrated EO action occurs at the end of the range of motion after a maximum concentric action, whether technique is accurate (Martinez-Aranda and Fernandez-Gonzalo et al. 2017), have proven to increase muscle power at low (40-50% 1 -RM), medium (60-70% 1-RM) and high intensity (80-90% 1-RM) in athletes (Maroto-Izquierdo et al. 2017a) and physically active people (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2019).

Likewise, these more favorable explosive adaptations are also noticeable in plyometric movements. Although the magnitude of the EO seems to have a direct impact on the explosive performance on the subsequent jump, similar adaptations in the vertical jump height have recently proven with different eccentric loads and different methods to produce overload (e.g. weight releasers, elastic bands, flywheels and electric-motors) (Aboodarda et al. 2013; Douglas et al. 2018; Maroto-Izquierdo et al. 2017a). Lately, one of the studies included in this thesis (Maroto-Izquierdo et al. 2019), showed comparable improvements (17 and 14%) in the DJ CT when different magnitudes of EO (17 and 51% of EO in terms of peak force) were applied using an electric-motor device. These effects were not significant when the overload was performed at the end of the range of motion (i.e. large eccentric-concentric transition) by means of a flywheel device (Maroto-Izquierdo et al. 2019), even though iso-inertial training is established as an accurate method to optimize jump abilities (Maroto-Izquierdo et al. 2017b;

Tesch et al. 2017). Consequently, EO-RT effects on the ability to store and reutilize elastic energy with a shorter amortization phase was attributed to a short eccentric-concentric transition time and high eccentric velocities in subjects with similar strength levels (Douglas et al. 2018; Maroto-Izquierdo et al. 2019).

All these positive changes experienced by functional variables could be linked to increases in muscle mass. Since the potential hypertrophic benefits of eccentric training raise the possibility that skeletal muscle growth may be enhanced by EO-RT (Schoenfeld and Grgic 2018). Therefore, muscle hypertrophy could be a possible contributor to favorable changes experienced in performance (Wagle et al. 2017). So, it is possible that EO magnitude plays an indisputable role in architectural adaptations. Thus, larger EO percentages (~50%) induced by an iso-inertial electric-motor device led to total thigh lean mass increases of 4.5%, compared to gains of 3.4% induced by slight EO percentages (~20%) (Maroto-Izquierdo et al. 2019). Using free weight, a large EO of ~85-45% was the only one to induce changes in lean mass compared to lower percentages of EO (English et al. 2014). Furthermore, it is expected that EO magnitude has a greater incidence than the loading condition (i.e. submaximal, maximal or supramaximal eccentric loads) (Maroto-Izquierdo et al. 2019), since positive effects on lean muscle mass have not been found with low EO percentages (i.e. higher concentric loads) (Fisher 2016).

Notwithstanding, similar significant increases in muscle mass after accentuated eccentric loading have been shown by other studies in which submaximal or supramaximal loads were used (English et al. 2014; Friedmann et al. 2004; Friedmann-Bette et al. 2010; Walker et al. 2016). Hence, it seems to indicate that the submaximal or supramaximal eccentric loads during EO-RT does not have a determining effect on the post-training structural adaptations. Several studies have not found differences between traditional training and EO-RT in muscle mass, despite the fact that there were significant differences in strength (Brandenburg and Docherty 2002; Walker et al. 2016) and vertical jump performance (Friedmann-Bette et al. 2010). These differences seem to be due to a lack of region-specific consideration in analysis of CSA (Friedmann et al. 2004;

Friedmann-Bette et al. 2010; Yarrow et al. 2008). Since eccentric-only training has been shown to favor increases in fascicle length and hypertrophy of the distal muscle area, while concentric-only training results in pennation angle increases and greater hypertrophy at the medial level of the muscle (Franchi et al. 2014). In addition, Franchi and colleagues (2014; 2017) concluded that these EO training-induced effects in strength may be due to the fact that muscle hypertrophy occurs in parallel, and in the case of increases of vertical jump at a high contraction rate serial hypertrophy occurs. In addition, muscle mass gains may be determined by the increased stretch-induced mechanical tension caused by the reinforced eccentric action as well as the stimulation of the concentric phase, stimulating hormonal factors involved in anabolic signaling (Friedmann et al. 2004; Friedmann-Bette et al. 2010; Ojasto and Hakkinen 2009; Walker et al. 2017; Yarrow et al. 2007; Yarrow et al. 2008). Friedmann-Bette and co-workers (2010) found changes in androgen receptor content only after EO-RT, which may influence the effects of hormones like testosterone, in stimulating muscle protein synthesis . Additionally, insulin-like growth factors (such as IGF-1 and IGFBP3) and myogenic regulatory factors, which suggested an increase in satellite cells activation and proliferation, were also observed only after EO-RT (Friedmann-Bette et al. 2010). These changes in anabolic signaling have been shown to induce morphological changes (Wagle et al. 2017). Chiefly, within faster muscle fiber types, increasing Type IIx and IIa specific CSA (Friedmann-Bette et al. 2010), and secondly, reducing Type I fiber-type percentage and enhancing Type IIx and IIa fiber-type percentage in muscle groups involved in EO-RT (Friedmann et al. 2004).

However, as it occurs with eccentric-only training, eccentrically reinforced RT with gravitational resistances is not widely used. This is due to the mechanical difficulties encountered with this method. Since it requires assistants or financially restrictive material which implies high mechanical difficulty and little practical application, making it untransferable to daily-movements or athletics performance. Therefore, new non-gravity-dependent iso-inerical devices, such as flywheel and electric-motors (not only lifting attendees, but also a device that generates resistance by itself and also allows to quantify work done) have emerged to provide an easier and faster way to overload RT.

These iso-inertial devices use the flywheel principle to produce unlimited resistance during the entire concentric action. The energy produced in the system during a maximum concentric action is stored and maintained during the subsequent eccentric action due to its inertial characteristics, and must be braked in a short and concentrated moment at the end of the eccentric phase to reinforce the lengthening action (Maroto-Izquierdo et al. 2017b). By means of this approach, EO is generated in the system, and greater amounts of overload are achieved with higher inertial loads (Carroll et al. 2018). Thus, five- to 15-week flywheel EO-RT programs of the lower limbs, have shown strong skeletal muscle adaptations, with gains of 5-13% in muscle mass (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a), 11-39% in maximal voluntary contraction (Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a), 12-25% in 1 repetition maximum (1-RM) (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a), 21-90% in ECC force (Berg and Tesch et al. 1994; Hortobagyi et al. et al. 2001; Romero-Rodriguez et al. et al. 2011), 10-33% in muscle power (Maroto-Izquierdo et al. 2017a; Naczk et al. 2013), 6-15% in jump ability (de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a; Naczk et al. 2013), 2-10% in running speed (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a) and up to 35% in EMG activity (Caruso et al. 2006; Norrbrand et al. 2011; Pozzo et al. 2006; Seynnes et al. 2007). Additionally, these devices have shown to be very effective in counteracting the decrements in muscle mass and strength during weightlessness (Alkner and Tesch 2004a; Alkner et al. 2003; Alkner and Tesch 2004a; Rittweger et al. 2005; Tesch et al. 2004b), as well as improving muscle function, balance, gait and functional performance in elderly (Brzenczek-Owczarzak et al. 2013; Onambele et al. 2008) and stroke patients (Fernandez-Gonzalo et al. 2016; Fernandez-Gonzalo et al. 2014b).

Notwithstanding, flywheel devices require a maximum concentric action to generated EO only in the last third of the eccentric action (Tesch et al. 2017).

Moreover, the applicability of available flywheel hardware to functional training is limited due to the fact that flywheel exercise hardware tends to be uniaxial and bilateral weight-stack training machines (Maroto-Izquierdo et al. 2017a; Maroto-Izquierdo et al. 2017b). However, these flywheels' shortcomings have been resolved with electric-motor devices, which work as an iso-inertial or isotonic load provider (Tinwala et al. 2017). These devices are potentially capable of generating EO in the entire ROM (i.e. reducing the active braking phase is not necessary, as it occurs with flywheel devices) and, other possibilities to modify the training stimulus while using electric-motor driven devices are changes in the specific concentric and/or eccentric intensity (no need for a maximum concentric action), adjustments in the transition time between concentric and eccentric phases, and modifications in the eccentric velocity, related to the concentric velocity (Tinwala et al. 2017). Despite the best characteristics of electric-motors to provide EO, however, their training-induced effects are still unknown.

Given the current options to produce EO during RT and the belief that the amount of EO during exercise may promote different musculoskeletal adaptations, and therefore, the training device employed to provide EO is determinant in further physiological changes, this doctorate thesis aimed to study and provide profound insights into functional and structural changes after EO-RT in athletes and physically active people.

OBJECTIVES & PUBLICATIONS

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

OBJECTIVES

The aim of this doctoral thesis was to analyze the effects of eccentric overload resistance training with alternative training devices (i.e. non-gravity-dependent devices) on neuromuscular performance and muscle mass in athletes and physically active people. In addition to comparing the training-induced effects on strength, power, muscle mass and sports-related tasks performance with other training methods. These objectives are divided into specific objectives included in the scientific publications that constitute this thesis.

SPECIFIC OBJECTIVES

1) Elaborate a systematic review and meta-analysis to examine the effect of iso-inertial flywheel training with eccentric overload on muscle size and functional capabilities (i.e. strength and power) in athletes and healthy subjects, and to compare flywheel-induced adaptations with those triggered by traditional resistance exercise interventions.

   See Paper 1.

2) Analyze the effects of flywheel resistance training with eccentric-overload on different functional and structural variables in lower limb musculature in comparison to the same intensity and volume exercise performed with traditional free-weight in professional handball players.

   See Paper 2.

3) Analyze whether increasing the eccentric overload during resistance training, in terms of range of motion and/or velocity using an electric-motor device, would induce different muscle adaptations than conventional flywheel-eccentric-overload resistance training.

   See Paper 3.

PUBLICATIONS

Part of the results presented in this doctoral thesis have been published in indexed scientific journals of Sports Science.

REVIEW ARTICLES

4. Paper 1: Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R, Moreira OC, González-Gallego J, de Paz JA (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: A systematic review and meta-analysis. J Sci Med Sport, 20(10), 943–951. doi:10.1016/j.jsams.2017.03.004

ORIGINAL ARTICLES

5. Paper 2: Maroto-Izquierdo S, García-López D, de Paz JA (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball Players. J Hum Kinet, 60, 133–143. doi:10.1515/hukin- 2017-0096 27.

6. Paper 3: Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, Manzano-Rodríguez S, González-Gallego J, de Paz JA (2019). Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor. Eur J Sport Sci: p. 1-11. doi:10.1080/17461391.2019.1588920

PAPER 1

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

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Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis

Brief title: Eccentric overload training using flywheel technology: a meta-analysis

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Abstract

Background Although free weights and weight-stack devices are the most popular modes of resistance training, flywheel (FW) devices have gained attention in the last years, becoming an important component of strength and conditioning programs.

Objective The purpose of this meta-analysis was to examine the effect of FW resistance training with Eccentric Overload (FW-EOT) on muscle size and functional capacities (i.e. strength and power) in athletes and healthy subjects, and to compare FW-induced adaptations with those triggered by traditional resistance exercise interventions.

Methods A search of electronic databases [PubMed, MEDLINE (SportDiscus), Web of Science, Scopus and PEDro] was conducted to identify all publications employing FW-EOT up to April 30, 2016. Outcomes were analyzed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A total of 9 studies with 276 subjects and 92 effect sizes met the inclusion criteria and were included in the statistical analyses.

Results The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49 to 0.76) with a significant ($p<0.001$) Z overall effect of 9.17. No significant heterogeneity (p value = 0.78) was found. The meta-analysis showed significant differences between FW-EOT vs. conventional resistance training in concentric and eccentric strength, muscle power, muscle hypertrophy, vertical jump height and running speed, favoring FW-EOT.

Conclusion This meta-analysis provides evidence supporting the superiority of FW-EOT, compared with traditional weight-stack exercise, to promote skeletal muscle adaptations in terms of strength, power and size in healthy subjects and athletes.

Key Points

Iso-inertial flywheel resistance exercise, a technology originally developed to combat muscle deconditioning during spaceflight, is a powerful tool to induce muscle force and power increments, as well as muscle hypertrophy in healthy subjects and athletes.

The available scientific literature indicates flywheel resistance exercise, calling for brief episodes of eccentric overload, triggers significantly greater skeletal muscle adaptations (i.e. strength, power and muscle mass) compared to traditional, gravity-dependent resistance exercise paradigms.

Eccentric overload flywheel resistance exercise boosts performance-related abilities (i.e. jump height and running speed). The magnitude of these adaptations is greater than those reported after weight-stack or free weight resistance training, which highlights the efficacy of iso-inertial exercise training.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Introduction

Eccentric (ECC) training has been extensively studied in the scientific literature (Roig et al. 2009). In comparison with concentric (CON) exercise, isolated ECC actions are characterized by producing higher peaks of force (Hollander et al. 2007) with lower muscle activation (Higbie et al. 1996; Hortobagyi et al. et al. 1996b) and metabolic cost (Dudley et al. 1991a), as well as higher solicitation of Type IIx fibers (Duchateau and Baudry 2014), increased cross-education effect (Hortobagyi et al. 1997) and greater cortical activity (Fang et al. 2001). Furthermore, despite producing high levels of muscle damage and soreness after the initial bout (Paulsen et al. 2010), ECC-based resistance exercise training has been associated with effective muscle damage prevention mechanisms (Fernandez-Gonzalo et al. 2011; Garcia-Lopez et al. 2007; Goode et al. 2015; Jimenez-Jimenez et al. 2008), increased muscle mass (Farthing and Chilibeck 2003) and improved jumping performance (Garcia-Lopez et al. 2007; Meylan et al. 2010). Thereby, ECC actions seem to optimize the efficacy of training (Meylan et al. 2008; Roig et al. 2008).

The ability to produce force in the CON phase limits the load/weight to be used during training. As a result, and given the higher force production capacity of skeletal muscle during ECC actions, the loads used during traditional free weights or weight-stack exercise are sub-optimal during the ECC phase of the movement (Hollander et al. 2007; Hortobagyi 2003; Reeves et al. 2009). However, optimization of resistance training using a strictly ECC regime is rather complex and technically difficult to apply (Hortobagyi et al. 2001). In addition, ECC actions are rarely isolated in real-life situations, and usually appear during the stretch-shortening cycle, inducing a greater contribution of the elastic components in the muscle-tendon unit; the stretch-shortening cycle increases the potential to produce force in the subsequent CON action due to increased storage and use of elastic energy (Meylan et al. 2008; Roig et al. 2010). Several methods have been designed and proposed to offer an eccentric overload (EO) during resistance training, such as (1) controlling and adjusting the time/velocity of CON and ECC movement during resistance training (Dias et al. 2015; Gillies et al.

2006); (2) using third-party assistance or devices for moving/rising the load during the CON phase (Fernandez-Gonzalo et al. 2011; Garcia-Lopez et al. 2007; Jimenez-Jimenez et al. 2008); and (3) employing isokinetic dynamometers (Guilhem et al. 2013).

Devices created to isolate or overload the ECC phase of the muscle action have emerged as an alternative method that may produce greater muscle adaptations, and therefore have been developed and/or tested for rehabilitation and performance purposes. The iso-inertial devices were originally designed by Berg & Tesch (1994) in 1994 to counteract the deleterious effect of microgravity on skeletal muscle. Such technology presents one of the most-used exercise paradigms to produce EO during resistance training. The iso-inertial devices more frequently employed are “The Flywheel Exercise Device” (Berg and Tesch 1994; Berg and Tesch 1998), “VersaPulley” (Chiu and Salem 2006) and “Inertial Training and Measurement System” (Naczk et al. 2014). These iso-inertial devices use the flywheel (FW) principle to produce unlimited resistance during the entire range of motion. During the CON phase the force applied unwinds a cord/strap connected to the shaft with the FW, which starts to rotate and store energy. Kinetic energy will increase as a function of the rotational speed. Once the CON action is completed, the cord/strap rewinds and the trainee must resist the pull of the FW by performing a braking, ECC muscle action. By using appropriate technique, i.e. resisting the inertial force gently during the first third of the ECC action, and then applying maximal effort to stop the movement at the end of the range of motion, EO can be produced in force/power values (Berg and Tesch 1998; Tous-Fajardo et al. 2006). Then, the next CON action is immediately initiated.

The effects of inertial training using FW devices have been extensively investigated over the past 20 years. The majority of studies assessed the effects of eccentric overload training (EOT) on lower body muscle mass in healthy and active subjects. These studies employed a mean workload of 4 sets of 7 maximum repetitions during 5-15 weeks. Results indicate that EOT employing FW technology induce gains of 5-13% in muscle mass (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a), 11-39% in maximal voluntary contraction (Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a), 12-25% in 1 repetition maximum (1 RM) (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a), 21-90% in ECC force (Berg and Tesch 1994; Hortobagyi et al. 2001; Romero-Rodriguez et al. 2011), 10-33% in muscle power (Maroto-Izquierdo et al. 2017a; Naczk et al. 2013), 6-15% in jump ability (de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a; Naczk et al. 2013), 2-10% in running speed (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a) and up to 35% in electromyography activity (Caruso et al. 2006; Norrbrand et al. 2011; Pozzo et al. 2006; Seynnes et al. 2007). Despite EOT being associated with a high magnitude of muscle damage and inflammatory responses during the initial phase of training, a significant attenuation of these processes occur shortly after (Fernandez-Gonzalo et al. 2014a; Neme Ide et al. 2013), indicating no counterproductive effects on muscle. Additionally, these devices have been shown very effective in counteracting the decrements in muscle mass and strength during weightlessness (Alkner and Tesch 2004a; Alkner et al. 2003; Alkner and Tesch 2004a; Rittweger et al. 2005; Tesch et al. 2004b), as well as improving muscle function, balance, gait and functional performance in elderly (Brzenczek-Owczarzak et al. 2013; Onambele et al. 2008) and stroke patients (Fernandez-Gonzalo et al. 2016; Fernandez-Gonzalo et al. 2014b).

While there has been an increase use of these technology and a significant amount of research comparing the effectiveness of eccentric overload flywheel resistance training (FW-EOT) with traditional weight-stack exercise programs, there is no systematic review that summarizes the results of such studies, and adequately assess their scientific rigor. When confronting with a task of this magnitude, there are inherent methodological limitations, such as the difficulty to isolate or enhance the ECC phase from the CON (Roig et al. 2009), and the diversity of devices employed to generate EO. To circumvent these limitations, we performed a systematic review including only training studies using FW technology to generate the EO vs. traditional free-weight or weight-stack training. Therefore, the purpose of the current review and meta-analysis was to systematically review the literature on randomized clinical trials examining the effects of FW-EOT, and how the intervention affects functional and structural muscle adaptations among athletes and healthy subjects, and to perform a quantitatively comparison of FW-EOT vs. traditional resistance exercise training in inducing gains in muscle mass, force and power.

Methods

Study Design

This systematic review was designed following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P) (Moher et al. 2015; Shamseer et al. 2015). The PRISMA-P statement includes 26 points, grouped in 17 kinds of items checklist and it is designed to be used as a basis for reporting systematic review of randomized trials. A review protocol was not registered for this review.

Literature Search

A systematic, computerized search of the literature in PubMed, Web of Science (including Web of Science and MEDLINE results), Scopus, SportDiscus and PEDro was conducted by an independent researcher with controlled vocabulary and keywords related to eccentric training, eccentric overload training and flywheel training. Our search time frame was restricted to 22 years (1 January 1994 to 30 April 2016); 1994 was chosen because research on FW technology began that year (Berg and Tesch 1994). We developed our search strategy based on the lack of reviews and meta-analysis about FW-EOT (Goode et al. 2015; Roig et al. 2009). To do this, the search strategy used by previous reviews in the field of resistance training was employed (Goode et al. 2015). The search language was restricted to English, and a filter containing Medical Subject Headings (MeSH) terms was applied. First, a general search including the terms “eccentric training”, “eccentric exercise”, “negative work” was performed. A more specific search included the terms of “eccentric-overload”, “eccentric-overload training”, “inertial training”, “inertial exercise”, “isoinertial training”, “flywheel”,

“flywheel resistance”, “gravity-independent” and “enhanced-eccentric”. These terms were chosen because they have been traditionally used to describe this training methodology. The results of this specific search were then combined with the following terms: “device”, “strength”, “force”, “power”, “hypertrophy” and “muscle mass”.

The reference list of all selected publications was verified to retrieve relevant publications that were not identified by the computerized search. References of selected and included original articles, abstracts and available conference proceedings were also searched, including publications, posters, abstracts or conference proceedings. To identify relevant articles, titles and abstracts of all selected publication after the first search were analyzed looking for training methods where the ECC phase was overloaded or reinforced. In the specific search, in addition to the identified citations of the first search, titles and abstracts of all recognized publications were examined in detail. Full-text papers were recovered if the abstract provided insufficient information to establish eligibility or if the article abstract had passed the first eligibility review.

Inclusion and Exclusion Criteria

All articles examining FW-EOT were eligible for full-text review. An article was eligible for study inclusion if it met all of the following criteria:

1. The original article was a randomized controlled trial (RCT) or clinical controlled trial (CCT) published in peer-reviewed journals.

2. The article reported on athletes or physical active subjects of either sex who had completed an EOT protocol during at least 4 weeks with a minimum training frequency of 2 days per week.

3. The study described healthy subjects without a history of injury in the trained limb.

4. The manuscript included a FW-EOT intervention and a control or alternative intervention group, comparing training adaptations in strength

and/or power, and/or muscle mass.

An article was excluded if:

1. Had subjects with any pathology or included subjects with existing, or under treatment for, musculoskeletal injuries in the trained limb.
2. Did not have the minimum requirements regarding in the training protocol (e.g, duration or frequency).
3. Reports focused on elderly above the age of 60 years.
4. Were not written in English.

All criteria were independently applied by two reviewers to the full text of the articles that passed the eligibility screening of titles and abstracts. Any disagreement was resolved by discussion.

Methodological Quality of Included Studies

Two investigators independently performed quality assessments of the included studies, and disagreements were resolved during a consensus meeting by a third part. The methodological quality of individual studies was assessed using the Physiotherapy Evidence Database (PEDro) scale (t http://www.pedro.fhs.usyd.edu.au et al; Elkins et al. et al. 2013). Results from individual study analysis of quality were used to identify common areas of methodological weaknesses across studies.

PEDro uses 11 criteria, and reviewed studies were awarded one point for each criterion that was clearly satisfied, for a potential maximum value of 11 points. Criteria included:

1. Eligibility criteria reported
2. Random assignment
3. Concealed allocation

4. Groups similar at baseline regarding most important prognostic indicator
5. Blinding of participants
6. Blinding of therapists who administered the therapy
7. Blinding of assessors who measured key outcome
8. Measures of at least one key outcome were obtained from more than 85% of initial participants
9. All participants received treatment or control condition as allocated
10. Results of between-group statistical comparisons are reported
11. Study provides point measures and measures of variability for at least one key outcome

Although PEDro does not provide specific instructions to classify studies according to the score obtained, we have used the criteria established by others (Roig et al. et al. 2009; Roig et al. et al. 2008). Thus, a study was considered of high quality when the score was greater than 5, of moderate quality when the score was 5 or 4, and of low quality when the study was scored 3 or less (table 1).

Statistical Methods and Data Extraction

The meta-analysis was conducted using to RevMan 5.3 (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen 2012. Free to download at http://tech.cochrane.org/revman/download) to determine the efficacy of FW-EOT in increasing strength, power and muscle mass, as well as jump ability and speed. Data were pooled in different subgroups according to five physical variables: Strength (CON, ECC or both), muscle power (isotonic or isokinetic conditions only in CON movements), hypertrophy (increases in muscle size, volume or thickness in muscle groups subjected to training), jump ability (CMJ height) and speed. Outcomes were analyzed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A *P* value less than 0.05 indicated a statistical significance for an overall effect, and a *P* value less than 0.1 indicated statistical significance for heterogeneity between studies. When the articles selected did not provide sufficient data for the analysis, authors were contacted to obtain relevant data. Studies were not included in the meta-analyses if summary statistics of means, standard deviations and number of participants allocated in each group were not available.

Results

Study Characteristics

Figure 1 shows a flow chart with the different phases of the search and selection of the studies included in the review. The initial search of electronic databases identified 264 titles, of which 171 were rejected for duplication issues. Four titles/articles (Lundberg et al. 2014a; Lundberg et al. 2013; Maroto-Izquierdo et al. 2017a; Naczk et al. 2016) were identified through manual search. Thus, 97 titles were identified, but 48 of them were rejected because they did not meet the intervention criteria: 20 studies of bed rest (Alkner et al.2003a; Alkner and Tesch 2004a; Alkner and Tesch 2004a; Carrithers et al. 2002; Caruso et al. 2008; Cervinka et al. 2011; Cotter et al. 2015; Dupont-Versteegden et al. 2006; Edgell et al. 2007; Fernandez-Gonzalo et al. 2014a; Guinet et al. 2009; Holt et al. 2016; Lee et al. 2014; Nicastro et al. 2011; Reeves et al. 2005; Rittweger and Felsenberg 2009; Rittweger et al. 2007; Rittweger et al. 2005; Schneider et al. 2009; Smith et al. 2008; Tesch et al. 2004b), 12 descriptive studies (Albert et al. 1994; Berg and Tesch 1994; Berg and Tesch 1998; Braghin et al. 2013; Elmer et al. 2013; Friedmann-Bette et al. 2010; Frohm et al. 2005; Kingma et al. 2007; Leeper et al. 2007; Pearson et al. 2001; Ruttley et al. 2001; Tous-Fajardo et al. 2006), 6 studies of elderly (Bruseghini et al. 2015; Brzenczek-Owczarzak et al. 2013; Hortobagyi and DeVita 2000; Hortobagyi et al. 2009; Hortobagyi et al. 2002; Onambele et al. 2008), 5 studies with chronic patients (Fernandez-Gonzalo et al. 2016; Fernandez-Gonzalo et al. 2014b; Romero-Rodriguez et al. 2011; Sarmiento et al. 2014; Silbernagel et al. 2001), 2 studies of postactivation potentiation (Cuenca-Fernandez et al. 2015; de Hoyo et al. 2015a), and 3 studies with other intervention methodology (Caruso and Hernandez 2002; de Paula Simola et al. 2016; de Paula Simola t al. 2015; Sanz-Lopez et al. 2016). From a total of 49 abstracts that were screened, 24 were excluded because they had insufficient requirements regarding the training protocol, and 4 studies were excluded for lack of comparison between groups. Twenty-one full texts were reviewed, but only 9 studies satisfied the inclusion criteria to be considered for this review (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a; Naczk et al. 2014; Naczk et al. 2013; Naczk et al. 2016; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a). The main reasons for exclusion were: lack of control group (n=4) (Fernandez-Gonzalo et al. 2014a; Lundberg et al. 2014a; Lundberg et al. 2013; Seynnes et al. 2007), lack of information (n=2) (Caruso et al. 2009; de Hoyo et al. 2015c; Seynnes et al. 2007), combination FW-EOT with other training methodology (n=2) (Owerkowicz et al. 2016; Tous-Fajardo et al. 2016) and different mechanism to produce EO (n=4) (Barstow et al. 2003; English et al. 2014; Friedmann et al. 2004; McLoda et al. 2003).

Quality Assessment

A detailed description of the PEDro scores obtained is shown in table 1. The mean methodological quality of the studies was 7 ± 0.5, out of 11, with scores ranging from 6 to 8. All studies were categorized as high quality. The most common flaws were the lack of blinding of participants, therapists and assessors. It should be considered however, that blinding of participants in these studies is a difficult requisite to satisfy. Inter-rater reliability was significantly high (ICC = 0.98).

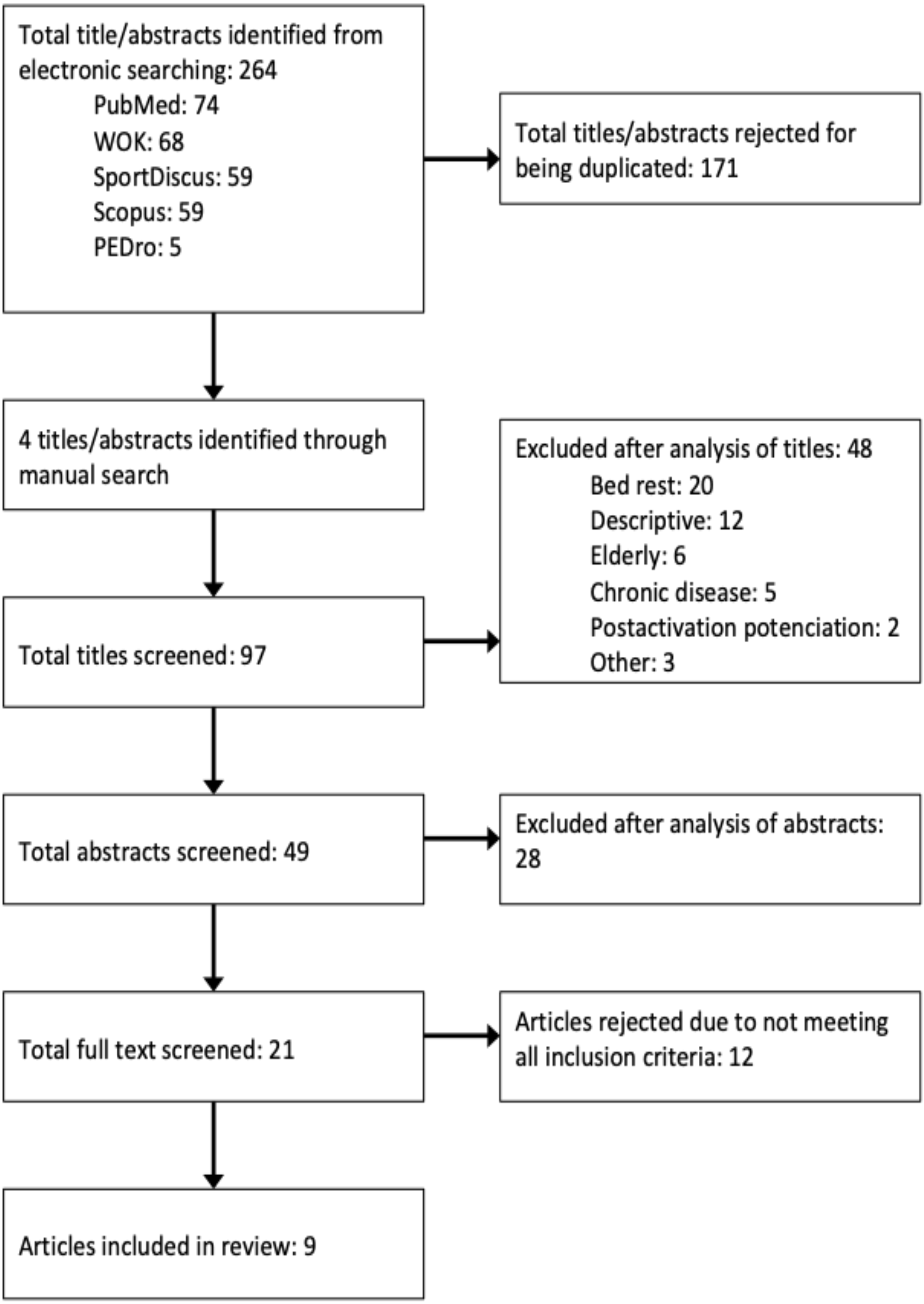

Figure 1. Flow chart illustrating the different phases of the search and selection of the studies included in the review (PRISMA).

Table 1. Detailed description of the PEDro scores

Journal article	PEDro scale											
	1	2	3	4	5	6	7	8	9	10	11	Score
Askling et al (2003)	+	+	−	+	−	−	+	+	+	+	+	8
De hoyo et al (2015b)	+	+	−	+	−	−	−	+	+	+	+	7
Maroto-Izquierdo et al (2017a)	+	+	−	+	−	−	−	+	+	+	+	7
Nazck et al (2013)	+	+	−	+	−	−	−	+	+	+	+	7
Nazck et al (2014)	+	+	−	+	−	−	−	+	+	+	+	7
Nazck et al (2016)	+	+	−	+	−	−	−	+	+	+	+	7
Norrbrand et al (2008)	+	+	−	+	−	−	−	+	+	+	+	7
Norrbrand et al (2010)	+	+	−	+	−	−	−	+	+	+	+	7
Tesch et al (2004a)	+	−	−	+	−	−	−	+	+	+	+	6

1. Eligibility criteria were specified.
2. Subjects were randomly allocated to groups.
3. Allocation was concealed.
4. Groups were similar at baseline regarding most important prognostic indicators.
5. Blinding of all participants.
6. Blinding of therapists who administered the therapy.
7. Blinding of all assessors who measured at least one key outcome.
8. Measures of at least one key outcome were obtained from more than 85% of the participants.
9. All subjects for whom outcome measures were available received the treatment or control condition as allocated.
10. Results of between-group statistical comparisons are reported for at least one key outcome.
11. Study provides both point measures and measures of variability for at least one key outcome.

+, met criteria; −, criteria not met.
PEDro, Physiotherapy Evidence Database.

Characteristics of Participants and Interventions

The main characteristics of the studies included in the review regarding participants, interventions and results are illustrated in table 2. After adjusting for dropouts, the total number of participants in the studies included was 276. Of these 276 participants, 165 performed FW-EOT. The rest (n=111) served as controls or performed resistance training without EO. Demographic data were provided for all studies; the estimated mean age of the experimental and control groups were 25.8 ± 8.5 and 23.2 ± 10.6, respectively. The distribution of sex among studies was not proportional, with only one study including female subjects (Tesch et al. 2004a), with a total of 3 women and 273 men in both the experimental and control groups.

Training interventions ranged from 4 to 10 weeks with a mean frequency of 2.33 ± 0.72 sessions per week, with a mean total of 14 ± 2 sessions per study. The total number of sets (3 to 6) and repetitions (6 to 8) per session differed across studies. Inertial Training and Measurement System (ITMS) studies used a training load of 15-20 seconds per set (between 8 and 11 repetitions) (Naczk et al. 2014; Naczk et al. 2013; Naczk et al. 2016). All studies employed FW devices to produce EO. Exercise devices employed were FW leg press (Maroto-Izquierdo et al. 2016), YoYo squat (de Hoyo et al. 2015b), Multi-Gym FW (Fernandez-Gonzalo et al. 2014a), FW supine leg curl (Askling et al. 2003; de Hoyo et al. 2015b) and FW prone leg extension device (Lundberg et al. 2013; Lundberg et al. 2014b; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a). Also, three studies employed ITMS (Naczk et al. 2014; Naczk et al. 2013; Naczk et al. 2016). The muscle groups trained were knee extensors (Lundberg et al. 2013; Lundberg et al. 2014b; Naczk et al. 2013; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a), knee flexors (Askling et al. 2003) or both (de Hoyo et al. 2015b; Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a). Also, two studies of upper limb targeting shoulder abductors (Naczk et al. 2014) and elbow flexors and extensors (Naczk et al. 2016) were included. In the flywheel devices, the workload is provided by the inertia of a rotating mass, which in turns depends on its geometrical and physical properties, and may vary depending on the total number of flywheels installed (Lundberg et al. 2013; Tesch et al. 2004a). The most common moment of inertial employed was between 0.07 and 0.145 $kg \cdot m^2$ (Maroto-Izquierdo et al. 2017a; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a). Given the fact that muscles are capable of achieving higher absolute forces when contracting eccentrically as compared with concentrically (Roig et al. 2009), it is important to quantify the intensity of the training during FW exercise. In most of the studies (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a) subjects were asked to push with maximal effort through the entire CON action. At the end of this CON action, the FW strap winds back due to inertial forces, which initiate the reversed ECC action. During the first third of the ECC action, subjects were instructed to resist gently, and thereafter to apply maximal breaking force to stop the movement. Then, the next CON action was instantly initiated. In these studies, CON and ECC power during training was assessed with an encoder or by means of rate perceived exertion (Maroto-Izquierdo et al. et al. 2017a). Some studies adjusted the inertia to the higher CON power output (de Hoyo et al. 2015b). Only one study failed to use any methodology to quantify the load during training (Askling et al. 2003).

Main Meta-Analysis Results

Individual main effect analysis, overall pooled estimate and measures of heterogeneity are illustrated in figure 2. This figure depicts SMD and 95% CI of the included studies for strength, muscle power, muscle hypertrophy, jump height and running speed adaptations following EOT. The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49 to 0.76) with a significant ($P <$ 0.001) Z overall effect of 9.17. No significant heterogeneity (heterogeneity P value = 0.78) was found.

Meta-analyses of subgroups demonstrated significance differences in training-induced adaptations favoring FW-EOT vs. control group in both CON and ECC strength (SMD 0.66; 95% CI 0.44 to 0.89), muscle power (SMD 0.8; 95% CI 0.53 to 1.07), muscle hypertrophy (SMD 0.57; 95% CI 0.25 to 0.9), vertical jump performance (SMD 0.46; 95% CI 0.09 to 0.83) and running speed (SMD 0.41; 95% CI 0.0 to 0.82) (fig 2).

Study or Subgroup	Eccentric Overload Mean	SD	Total	Weight training Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
1.1.1 Strength								
Norrbrand (2010)	47	128	9	29	152.9	8	2.0%	0.12 [−0.83, 1.08]
Tesch (2004)	50	269	10	5	226	10	2.3%	0.17 [−0.71, 1.05]
Maroto-Izquierdo (2016)	31.6	60.81	15	19.1	53.13	14	3.4%	0.21 [−0.52, 0.94]
Naczk (2015) ext TS	8	20.16	10	0	25.64	9	2.2%	0.33 [−0.57, 1.24]
Naczk (2014) T5	9.99	24.04	11	2.35	12.81	13	2.7%	0.39 [−0.42, 1.21]
Askling (2003) CON	20	33.42	15	3	31	15	3.4%	0.51 [−0.22, 1.24]
Naczk (2014) T10	11.99	22.13	11	2.35	12.81	13	2.7%	0.53 [−0.29, 1.35]
Naczk (2014) T0	13.62	23.17	11	2.35	12.81	13	2.7%	0.60 [−0.23, 1.42]
Naczk (2015) flex TS	17	17.47	10	0	32.18	9	2.1%	0.64 [−0.29, 1.57]
Naczk (2015) ext TF	14	26.11	10	−2	20.64	9	2.1%	0.65 [−0.28, 1.57]
Askling (2003) ECC	28	32.56	15	−2	34	15	3.2%	0.88 [0.12, 1.63]
Naczk (2015) flex TF	34	25.66	10	1	24.16	9	1.8%	1.26 [0.26, 2.27]
Naczk (2013) T10	53	29.86	18	4	26.96	10	2.2%	1.65 [0.74, 2.55]
Naczk (2013) T0	47	25.18	19	−5	37.9	11	2.4%	1.67 [0.80, 2.54]
Subtotal (95% CI)			**174**			**158**	**35.0%**	**0.66 [0.44, 0.89]**
Heterogeneity: $Chi^2 = 16.48$, df = 13 (P = 0.22); $I^2 = 21\%$								
Test for overall effect: Z = 5.73 (P < 0.00001)								
1.1.2 Muscle Power								
Naczk (2015) ext TS	12	41.24	10	−6	53.07	9	2.2%	0.36 [−0.55, 1.27]
Naczk (2014) T10	18.75	41.28	11	3.02	30.57	13	2.7%	0.42 [−0.39, 1.24]
Naczk (2014) T5	27.28	54.48	11	3.02	30.57	13	2.7%	0.54 [−0.28, 1.36]
Naczk (2015) flex TS	19	26.38	10	−11	70.52	9	2.1%	0.55 [−0.37, 1.47]
Naczk (2014) T0	26.81	48.23	11	3.02	30.57	13	2.7%	0.58 [−0.24, 1.40]
Naczk (2015) ext TF	30	60.02	10	−15	46.33	9	2.0%	0.80 [−0.15, 1.74]
Maroto-Izquierdo (2016)	129.24	76.13	15	57.46	67.16	14	3.0%	0.97 [0.19, 1.75]
Naczk (2015) flex TF	59	66.8	10	−3	51.77	9	1.9%	0.98 [0.02, 1.95]
Naczk (2013) T0	102	75.04	19	−8	84.02	11	2.6%	1.37 [0.54, 2.20]
Naczk (2013) T10	100	73.62	18	−5	73.75	10	2.4%	1.38 [0.52, 2.25]
Subtotal (95% CI)			**125**			**110**	**24.3%**	**0.80 [0.53, 1.07]**
Heterogeneity: $Chi^2 = 6.49$, df = 9 (P = 0.69); $I^2 = 0\%$								
Test for overall effect: Z = 5.75 (P < 0.00001)								
1.1.3 Hypertrophy								
Norrbrand (2008)	80	315.16	7	42	526.93	8	1.7%	0.08 [−0.93, 1.10]
Tesch (2004)	71	421	10	−13	387	10	2.3%	0.20 [−0.68, 1.08]
Naczk (2015) TS	0.4	0.72	10	0	0.72	9	2.1%	0.53 [−0.39, 1.45]
Naczk (2013) T0	3.66	5.14	19	0.56	4.95	11	3.1%	0.59 [−0.17, 1.35]
Naczk (2015) TF	0.46	0.72	10	0	0.72	9	2.1%	0.61 [−0.32, 1.54]
Naczk (2013) T10	4.99	6.86	18	0.56	4.95	10	2.8%	0.69 [−0.11, 1.48]
Maroto-Izquierdo (2016)	6.2	5.1	15	1.2	4.24	14	2.9%	1.03 [0.25, 1.82]
Subtotal (95% CI)			**89**			**71**	**17.2%**	**0.57 [0.25, 0.90]**
Heterogeneity: $Chi^2 = 3.02$, df = 6 (P = 0.81); $I^2 = 0\%$								
Test for overall effect: Z = 3.47 (P = 0.0005)								
1.1.4 Jump								
Maroto-Izquierdo (2016)	3.49	7.89	15	1.12	5.84	14	3.3%	0.33 [−0.40, 1.06]
Naczk (2013) T0	6.81	19.08	19	−0.43	8.12	11	3.2%	0.44 [−0.31, 1.19]
Naczk (2013) T10	3.15	6.62	18	−0.43	8.12	10	2.9%	0.48 [−0.30, 1.27]
De Hoyo (2015)	2.6	5.87	18	−0.6	4.67	15	3.7%	0.58 [−0.12, 1.28]
Subtotal (95% CI)			**70**			**50**	**13.1%**	**0.46 [0.09, 0.83]**
Heterogeneity: $Chi^2 = 0.24$, df = 3 (P = 0.97); $I^2 = 0\%$								
Test for overall effect: Z = 2.44 (P = 0.01)								
1.1.5 Speed								
De Hoyo (2015)	0.04	0.184	18	−0.01	0.17	15	3.8%	0.27 [−0.41, 0.96]
Askling (2003)	0.08	0.215	15	0	0.141	15	3.4%	0.43 [−0.30, 1.15]
Maroto-Izquierdo (2016)	0.38	0.361	15	0.19	0.306	14	3.2%	0.55 [−0.19, 1.29]
Subtotal (95% CI)			**48**			**44**	**10.5%**	**0.41 [−0.00, 0.82]**
Heterogeneity: $Chi^2 = 0.29$, df = 2 (P = 0.87); $I^2 = 0\%$								
Test for overall effect: Z = 1.94 (P = 0.05)								
Total (95% CI)			**506**			**433**	**100.0%**	**0.63 [0.49, 0.76]**
Heterogeneity: $Chi^2 = 30.06$, df = 37 (P = 0.78); $I^2 = 0\%$								
Test for overall effect: Z = 9.17 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 3.54$, df = 4 (P = 0.47), $I^2 = 0\%$								

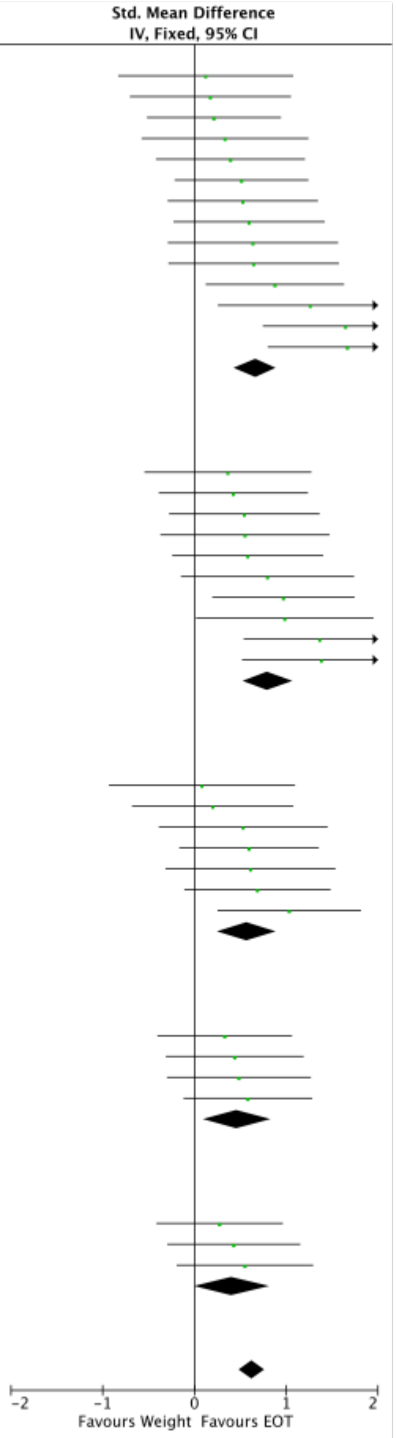

Figure 2. Forest plot with meta-analysis of standardized mean difference showing comparison of eccentric overload training versus control/weight training on strength (N), muscle power (W), muscle hypertrophy (cm³, mm or kg), jump height (cm) and running speed (sec).

Table 2. Characteristics of the studies included in the meta-analysis.

Study	Participants *	Muscle group	Interventions	Results ^
Askling et al. (2003)	30 male field soccer athletes from 2 Swedish premier league teams	Knee flexors	Exp (n=15), additional training: leg curl FW device 10 weeks (16 sessions) 4 sets of 8 reps / session	Significant increases in CON and ECC peak torque and running speed in exp. No training effects in control group. No difference between groups
De Hoyo et al. (2015)	33 junior soccer players (under 17 to under 19)	Knee extensors and flexors	Exp (n=18): Half-squat and leg curl FW device 10 weeks (15 sessions) 3-5 sets of 6 reps / session	Significant increases in CMJ and running speed in exp. No differences in control group
Maroto-Izquierdo et al. (2017a)	29 professional handball players	Knee extensors and flexors	Exp (n=15): Leg press FW device 6 weeks (15 sessions) 4 sets of 7 reps / session	Exp showed significant increases in 1 RM, muscle power in all % of 1 RM, SJ and CMJ, running speed, agility T-test and muscle mass. Control showed smaller training effect in 1 RM, SJ and running speed
Naczk et al. (2013)	58 male physical education students	Knee extensors	2 training groups: T0 (no additional load) and T10 (10 kg additional load). No control. ITMS 5 weeks (15 sessions) 3 sets of 15 seconds/set	Significant increases in muscle force, muscle power, CMJ, SJ and muscle mass No significant differences between training groups
Naczk et al. (2014)	46 male physical education students	Shoulder abductors	Exp (n=33) divided in 3 groups: T0 (no additional load), T5 (5 kg additional load) and T10 (10 kg additional load). ITMS 4 weeks (12 sessions) 3 sets of 20 seconds/set	All groups showed significant training effects in torque and power No significant differences between training groups

Naczk et al. (2016)	38 male physical education students	Elbow flexors and extensors	Exp (n=20) divided in 2 groups: TF (7.5 rad·s^{-1}) and TS (5.76 rad·s^{-1}). ITMS 5 weeks (15 sessions) 3 sets of 15 seconds/set. Flexion and extension, right and left arms worked separately	Greater improvements in elbow flexor force and power in TF than in TS Elbow extensor force and power increased significantly only in TF
Norrbrand et al. (2009)	15 men (mean age 39)	Knee extensors	5 weeks (12 sessions) Exp (n=7). Seated knee extension FW device 4 sets of 7 reps / session Control (n=8). Standard seated weight stack machine 4 sets of 7 RM / session	QF volume improved significantly in both groups, greater gains in exp
Norrbrand et al. (2010)	17 men (mean age 39)	Knee extensors	Same protocol than Norrbrand et al (2008)	Both groups improved significantly MVC and strength. Higher EMG activity in ECC in exp
Tesch et al. (2004a)	10 middle-age (30-53 year) men and women	Knee extensors	Unilateral (Bouleftour et al. et al.) leg extension exercise in a seated knee extension FW device 5 weeks (12 sessions) 4 sets of 7 reps / session	CON and ECC strength, maximal isometric strength and QF volume increased significantly

* Number of participants at the end of the studies.
^ Only results for the outcomes of interest are provided.
% 1 RM: percentage repetition maximum; AE: aerobic exercise; CMJ, countermovement jump; CSA, cross-sectional area; con, concentric; ecc, eccentric; Ext, experimental group; MVC, maximal voluntary contraction; QF, quadriceps; RE, resistance exercise; RF, rectus femoris; SJ, squat jump; TF, faster training group; TS, slower training group; VL: vastus lateralis; VI: vastus intermedius.

Discussion

This is the first systematic review that analyzes the efficacy of eccentric overload flywheel resistance training as a method to improve strength, muscle power and muscle mass. In addition, the statistical approach employed, allows comparing the efficacy of FW-EOT vs. traditional resistance exercise training in eliciting functional and structural muscle adaptations in athletes and healthy subjects. The search performed yielded 9 studies that met the inclusion criteria (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a; Naczk et al. 2014; Naczk et al. 2013; Naczk et al. 2016; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a). Using data from these sources, strong effects towards higher gains after FW training compared with other methodologies, in terms of force, muscle power and hypertrophy, as well as jump ability and speed were found. The heterogeneity among studies in the subgroup analysis reported in the current investigation was mainly caused by the different methods of evaluation employed in each investigation. Interestingly, the only studies assessing FW-EOT adaptations in the upper limbs were the ones reporting the largest effect sizes (ES between 0.52 and 1.75) of all investigations analyzed (Naczk et al. 2014; Naczk et al. 2016).

During traditional CON-ECC resistance exercise performed at maximal intensity, the ECC phase is clearly under-loaded (e.g. about 40-50% (Dudley et al. 1991b)). Multiple studies using different protocols have shown the critical role of the ECC muscle action to improve contractile characteristics and muscle size in humans (Dudley et al. 1991b; Hather et al. 1991; Hortobagyi et al. 1996b). Therefore, it seems reasonable to believe that applying eccentric overload during resistance exercise could increase force production capability (Hortobagyi et al. 2001). Indeed, studies employing eccentric overload training by means of inertial gravity-independent devices (i.e. FW), show robust increments in force production (de Hoyo et al. 2015b; Fernandez-Gonzalo et al. 2014a; Romero-Rodriguez et al. 2011; Tous-Fajardo et al. 2006). The current systematic review confirm these data, showing that resistance training offering brief episodes of EO employing FW devices, is associated with significantly greater improvements in maximal dynamic strength when compared to traditional resistance exercise programs. These results are supported by Fernandez-Gonzalo et al. (Fernandez-Gonzalo et al. 2014a), who reported increases of 25% in maximal dynamic strength in both men (ES = 1.78) and women (ES = 0.62). Furthermore, those studies assessing both CON and ECC force, showed larger increments in ECC than CON force (Askling et al. 2003; Lundberg et al. 2014a). In addition, anecdotal data seem to indicate that the use of lower inertia (Naczk et al. 2014; Naczk et al. 2013) or high movement velocity (Naczk et al. 2016) during FW training may induce greater force gains. However, this hypothesis needs to be tested in future investigations.

Originally, FW devices were created to counteract the muscle mass and strength losses during space-like, microgravity situations (Alkner et al. 2003; Alkner and Tesch 2004a; Alkner and Tesch 2004b; Rittweger et al. 2005; Tesch et al. 2004b). Thus, the efficacy of FW training to reduce the muscle atrophy and neuromuscular deconditioning during unloading has been analyzed in multiple occasions during the last 15 years, eliminating or greatly reducing loss in muscle mass during long term bed rest studies (Alkner et al. 2003a; Alkner and Tesch 2004a; Alkner and Tesch 2004b; Carrithers et al. 2002; Caruso et al. 2008; Cervinka et al. 2011; Cotter et al. 2015; Dupont-Versteegden et al. 2006; Edgell et al. 2007; Fernandez-Gonzalo et al. 2014a; Guinet et al. 2009; Holt et al. 2016; Lee et al. 2014; Nicastro et al. 2011; Reeves et al. 2005; Rittweger and Felsenberg 2009; Rittweger et al. 2007; Rittweger et al. 2005; Schneider et al. 2009; Smith et al. 2008; Tesch et al. 2004b), and even increasing muscle volume during unilateral lower limb suspension (Tesch et al. 2004b). The results of the current meta-analyses indicate that not only FW-EOT is effective in increasing muscle mass, but also that is more potent than traditional resistance training in inducing hypertrophy adaptations ($P < 0.001$). The high variability in the effect size of the different studies in terms of muscle hypertrophy after EOT employing FW vs. traditional resistance exercise training could be partly explained by the different methods used to evaluate changes in muscle mass. While some studies used bioelectrical impedance (Naczk et al. 2013; Naczk et al. 2016) or ultrasonography (Maroto-Izquierdo et al. 2017a), only 2 studies employed magnetic resonance imaging (Norrbrand et al. 2008; Tesch et al. 2004a), which is considered the “gold-standard” for muscle mass assessment (Roig et al. 2009). Thus, even though all studies showed benefits on muscle mass, magnetic resonance imaging studies were those showing the lower effect (ES = 0.23-0.34). In addition to the studies included in the meta-analysis, two additional investigations (Fernandez-Gonzalo et al. 2014a; Seynnes et al. 2007) reported significant gains in muscle mass in young subjects after FW-EOT employing magnetic resonance imaging and DXA, respectively. Interestingly, it seems that adding aerobic exercise 6 hours (Lundberg et al. 2013) or 15 minutes (Lundberg et al. 2014a) prior to FW-EOT elicits even greater muscle hypertrophy (ES = 0.57 and 0.27, respectively) than FW-EOT alone (ES = 0.31 and 0.14, respectively). Finally, the largest effect of FW-EOT training in muscle mass were found in a study describing FW-induced adaptations in well-trained athletes (ES = 0.6 in FW-EOT group versus ES = 0.38 in weight training group) (Maroto-Izquierdo et al. 2017a. Indeed, the EO produced during FW training is generally greater in athletes with experience in FW training, highlighting the importance of an appropriate technique to maximize the benefits of this training paradigm (Tous-Fajardo et al. 2006).

The greatest overall effect of subgroups analysis was found for the variable “muscle power” ($Z = 5.75$; $p<0.001$. SMD 0.8 W; 95% CI 0.53 to 1.07). Thus, regardless of the specific exercise device or muscle group analyzed, FW-EOT induced very robust adaptations in terms of muscle power, which are greater than those seen after traditional resistance exercise training. Apart from the studies included in the meta-analysis, the first investigation assessing FW-induced adaptations in muscle power at different loads (i.e. 40-80 % of 1 RM) was Fernandez-Gonzalo et al. (2014a), who interestingly, showed that power increments at high percentages of 1 RM were greater for men than women. Expanding on these data, FW-EOT induced power gains at high loads (70-90 %) of 1 RM in athletes (Maroto-Izquierdo et al. 2017a). These major improvements in muscle power may be explained by the particular characteristics of the FW training to induce EO, since the EO is usually applied in the last portion of the range of motion during the ECC action. That is, the EO is produced mainly at a joint angle close to 70º during leg press (Maroto-Izquierdo et al. 2017a) and elbow flexion exercise (Naczk et al. 2016), or at 90º during knee extension (Naczk et al. 2013; Norrbrand et al. 2008; Norrbrand et al. 2010; Tesch et al. 2004a), just before the subsequent CON action is initiated. This exercise technique would maximize the stretch shortening cycle, allowing for greater production of force during the first part of the CON action (Maroto-Izquierdo et al. 2017a), and therefore, a higher velocity during the entire movement (i.e. increased power).

The significant improvements in vertical jump after FW training corroborate the efficacy of this training model to induce positive power adaptations in healthy and well-trained subjects. Thus, the articles included in the current meta-analysis indicate that vertical jump improvements induced by FW-EOT are higher than traditional resistance training, as long as the jump modality used to assess jumping ability includes an eccentric phase (i.e. a counter movement jump, CMJ). Of note however, De Hoyo et al. (de Hoyo et al. et al. 2015c) showed that under specific circumstances, i.e. FW exercise (VersaPulley device) performed in the horizontal plane vs. free weights using guided (vertical) squat exercise, gains in jumping height were lower for FW than traditional training (ES = 0.4 and 0.9, respectively). Therefore, vertical FW training is recommended to increase jumping ability.

The selection of running speed as an outcome in this meta-analysis is based on the fact that it is an important performance factor in many sports, and it is usually related with vertical jump and multi-joint strength training. Although the findings in this variable showed the lowest significance of all outcomes analyzed ($P < 0.05$), FW-EOT training appeared more effective to improve running speed than traditional resistance training (Askling et al. 2003; de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a) (ES between 0.3 and 1.45 in FW-EOT groups and -0.08 and 0.55 in control groups). These results are supported by Tous-Fajardo et al. (2016), not included in the meta-analysis, who showed greater improvements in soccer-specific performance tasks such as change of direction and linear running speed, after a combined FW-EOT and vibration training protocol vs. conventional training (plyometric, speed and weight-loaded training). Adding to this, from a molecular perspective, it seems EOT favors increments of mRNA levels of genes preferentially expressed in fast glycolytic fibers, ultimately inducing a faster muscle phenotype. Such changes may help the muscle to become better suited for explosive, high-speed actions (Friedmann-Bette et al. 2010).

Conclusions

Although free weights and weight-stack machines are the most popular modes of resistance training, the results of this systematic review indicate that brief episodes of eccentric overload induced by flywheel devices, and performed at high intensity are associated with greater improvements in both concentric and eccentric force, muscle power and muscle hypertrophy in healthy and well-trained subjects. In addition, eccentric overload training appeared to be more effective than traditional resistance exercise in promoting increases in capacities highly related to athletic performance, such as vertical jump height and running speed. The efficacy of eccentric overload flywheel training to promote functional and structural adaptations is possibly mediated by the capacity to achieve higher forces during the eccentric muscle action, which maximizes the stretch-shortening cycle and thus, the capacity to produce greater force in the subsequent concentric action. However, these gains could even be greater considering the possibilities offered by FW technology. Thus, it appears at high speed and with light moments of inertia is the most effective training protocol to induced muscle adaptations employing FW. Finally, muscle power is the training outcome that experienced the greatest increase after a period of FW-EOT in healthy subjects and athletes. Future studies should analyze FW resistance training with eccentric overload programs using and comparing different training devices, volumes, intensities and exercise modes to fine-tune FW training routines.

PAPER 2

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

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Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players

Brief title: Flywheel training-induced effects in handball players

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Abstract

The aim of the study was to analyse the effects of 6-week (15 sessions) flywheel resistance training with eccentric-overload (FRTEO) on different functional and anatomical variables in professional handball players. 29 athletes were recruited and divided into two groups. The experimental group (EXP, n = 15) carried out 15 sessions of FRTEO in the leg-press exercise, with 4 sets of 7 repetitions at a maximum-concentric effort. The control group (CON, n = 14) performed the same number of training sessions including 4 sets of 7 maximum repetitions (7RM) using a weight-stack leg-press machine. The results which were measured included maximal dynamic strength (1RM), muscle power at different submaximal loads (PO), vertical jump height (CMJ and SJ), 20-m sprint time (20m), T-test time (T-test), and Vastus-Lateralis muscle (VL) thickness. The experimental group (EXP) results showed a substantially better improvement (p<0.05-0.001) in PO, CMJ, 20m, T-test and VL, compared to the control group (CON). EXP participants showed significant improvements concerning all the variables measured: 1RM (ES = 0.72), PO (ES = 0.42 - 0.83), CMJ (ES = 0.61), SJ (ES = 0.54), 20m (ES = 1.45), T-test (ES = 1.44), and VL (ES = 0.63 - 1.64). Since handball requires repeated short, explosive effort such as accelerations and decelerations during sprints with changes of direction, these results suggest that FRTEO effects functional and anatomical changes in a way which improves performance in well-trained professional handball players.

Key words

Muscle power, hypertrophy, iso-inertial, sport performance

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Introduction

Muscle strength and power are critical in competitive team sports as these capacities are the basis of specific actions that determine performance (i.e. throwing, jumping, running and hitting). In these sport modalities, among which handball is included, players are required to repeatedly carry out short, explosive effort such as accelerations and decelerations during sprints with changes of direction. Handball involves high-intensity short duration exercise, requiring a well-developed aerobic fitness, velocity and strength (Massuca et al. 2014). Therefore, new training methods are continuously being sought to improve the ability of skeletal muscle to develop explosive force (Perez-Gomez and Calbet 2013). Common exercises for explosive-force improvement are plyometric, ballistic exercises and weightlifting (i.e. power snatch).

As an alternative to these traditional methods, inertial-resistance training emerges as a paradigm that can be applied through different systems, such as flywheel devices. Flywheel devices provide a gravity-independent stimulus (Alkner et al. 2003; Trappe et al. 2004) that in addition to causing greater muscle activation (Caruso et al. 2006; Norrbrand et al. 2010) they allow brief episodes of eccentric-overload (EO) (Berg and Tesch 1994; Tesch et al. 2004a). Given the general consensus which exists regarding the importance of eccentric action in resistance-training, induced hypertrophy (Hather et al. 1991) and strength gains (Dudley et al. 1991b), the main application of flywheel-resistance training with eccentric-overload (FRTEO) is to develop muscle mass (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2004a), and specially to avoid muscle atrophy caused by weightlessness situations (Alkner and Tesch 2004a; Alkner et al. 2003; Rittweger et al. 2007), These benefits have also been observed in people with chronic diseases that involve functional impairments (i.e. strokes and multiple sclerosis) (Fernandez-Gonzalo et al. 2014b), and the elderly (Brzenczek-Owczarzak et al. 2013; Hortobagyi et al. 2009).

Specifically in competitive sport, FRTEO-related research has been focused on the prevention and treatment of injuries (Askling et al. 2003; de Hoyo et al. 2015b; Romero-Rodriguez et al. 2011) and as a part of warm-ups (de Hoyo et al. 2015a). Much less is known about the effects of FRTEO on athletic performance and muscle hypertrophy in well-trained sportsmen. De Hoyo and co-workers (2015b) have recently reported significant improvements in vertical jump height, sprint time (10 m and 20 m) and on kinetic parameters during changes of direction (de Hoyo et al. 2016) after a 10-week FRTEO, carried out by junior soccer players. These results reinforce the input of Askling et al. (2003). In addition, Tous-Fajardo et al. (2016) suggested that iso-inertial EO in combination with vibration training performed once a week could serve as a viable adjunct to improve performance tasks specific to soccer such as changes of direction and linear speed abilities. Naczk et al. (2013; 2014; 2016) have also observed significant improvements in muscle power in healthy active men, although these benefits have not been demonstrated in athletes. To the best of our knowledge, no studies have analyzed the FRTEO chronic effects on handball players.

Therefore, the aim of this study was to analyse the effects of a 6-week FRTEO on maximal, dynamic strength and power output at different submaximal loads, vertical jump height, sprint time, agility and muscle thickness in professional handball players. These effects were compared to those induced by traditional in-season weight training. We hypothesized that FRTEO would lead to a higher increase in all the functional, structural, dependent variables which were analysed.

Methods

A randomized controlled study was designed to compare the effects of FRTEO with those induced by traditional weight training in a group of professional handball players. Twenty-nine athletes completed six weeks (15 sessions) of resistance training with the leg-press exercise. Participants were randomly divided into 2 groups: experimental group (EXP, n = 15), which carried out the leg press on a FRTEO basis, and control group (CON, n = 14), which performed a similar program (volume and intensity) using a traditional weight-stack machine. Each week included 2-3 sessions consisting of 4 sets of 7 repetitions performed at maximal concentric effort. Before and after the training program, athletes came to the lab on four occasions separated by a minimum of 24 h. The first test session was used in order to collect descriptive data and to familiarize EXP group players with the flywheel leg-press device. Vastus-Lateralis muscle thickness was also measured in this first experimental session. The 1RM test was carried out during the second test session. The third session was used to measure maximal power output with different loads. The last test session was focused on measuring vertical jump height, 20-m sprint time and T-test time.

Participants

Twenty-nine professional male handball players were recruited from the same handball club (*Club Balonmano Atlético Valladolid*), which plays in the first division of the Spanish handball league (ASOBAL). The biometric data and characteristics of the participants are presented in Table 1. Their regular weekly exercise practice consisted of 4 handball routines (~9 h), 3 sessions including strength/power exercises, 3 on-track specific physical training sessions (changes of direction and plyometric exercises) and 1 competitive match (at weekends). The participants were highly experienced with free-weight resistance exercises, but none of them had previously used flywheel devices. Before giving their written informed consent to participate, participants were informed of the purposes, benefits and risks involved in the study, being aware that they could terminate their participation in the study when they desired. The study protocol was approved by the Ethics Committee of the University of León, and conformed to the standards set by the Declaration of Helsinki.

Concerning the annual periodization, the study was carried out during the beginning of the second round of the first division of the Spanish handball league (January to February). The main exclusion criteria used for this study was to have had a lower limb joint injury in the previous 6 months prior to the study (Fernandez-Gonzalo et al. et al. 2014a), and/or severe lower limb muscle injury (strains for more than 27 days) in the previous 2 months (de Hoyo et al. et al. 2014). Athletes who suffered an injury during the experimental phase of the study were excluded, as well as participants who did not follow the prescribed training program or players that did not carry out the exercises correctly. None of the participants were excluded from the study. Moreover, athletes were not allowed to change their sleeping, eating, and drinking habits throughout their participation in the study.

Table 1. Descriptive data of the participants, Mean ± SEM

	Age (y)	Height (cm)	Mass (kg)	BMI (kg/m^2)
Experimental Group	19.8 ± 1.0	186.0 ± 8.0	82.3 ± 3.3	23.7 ± 0.6
Control Group	23.8 ± 1.6	184.0 ± 1.0	85.6 ± 3.7	25.2 ± 0.9

Measures

Maximal Dynamic Strength

The 1RM leg-press was assessed using a previously established protocol (Fernandez-Gonzalo et al. et al. 2014a). A 45° leg press device (Ortus Fitness S.L., Valencia, Spain) was used. Briefly, after a light warm up on the leg press, participants attempted to lift a progressively increasing load, allowing 3 minutes of resting periods between attempts. The 1RM value was obtained using as few attempts as possible (5 attempts as a maximum). To consider a repetition as valid, a knee full extension (180º) had to be reached, starting from a 90º-knee flexion.

Power Output

The same leg press device employed in the 1RM testing was used to measure maximal concentric power output (PO) at different intensities (50, 60, 70, 80 and 90% of 1RM). For each load, participants completed a set of 3 repetitions from 90° knee flexion to full extension (180°) with a 3-min recovery between sets. To avoid any use of the stretch-shortening cycle, each repetition started from a complete static position, at 90º-knee flexion. Players were requested to perform the concentric phase of each repetition as fast as possible. Power for each repetition was sampled at 100 Hz using a rotary encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L., Murcia, Spain) and the associated software (T-Force v. 2.28). The repetition with the highest mean power at each load was used for data analysis. The order of tested intensities was randomized without replacement. Participants were aware of the percentage and amount of weight they were using. For the post-training evaluation, the same order was used as in the pre-training session.

Vertical Jump

Countermovement jump (CMJ) and squat jump (SJ) heights were assessed using a contact platform (ChronoJump, BoscoSystem, Barcelona, Spain) and the associated software (ChronoJump 1.5.0). Participants carried out three attempts of each vertical jump, trying to jump as high as possible with their hands on their hips. For the SJ the eccentric phase was eliminated, starting from a standardized position with a 90°-knee flexion. CMJ was started from a standing position without any pause between the eccentric and the concentric phase. Knee flexion angle was self-selected. A 30-s active recovery was allowed between attempts. The highest value of SJ and CMJ was selected for further analysis.

Speed and Agility

20-m sprint time and T-test time were measured using photocells (ChronoJump, BoscoSystem, Barcelona, Spain) and the associated software (ChronoJump 1.5.0). The 20-m sprint test consisted of a maximal intensity straight sprint between two photocell gates separated by 20 m. The T-test was administered using the protocol outlined by Pauole et al. (2000) with minor modifications. The clock started when players passed the electronic sensors, and the clock stopped the instant the participants crossed the sensor plane again. Three trials were performed for each test, with a 120 s active recovery period between attempts. All assessments were always performed on a competition parquet surface and players wore specific handball shoes. The fastest trial was used for statistical analysis.

Vastus Lateralis muscle thickness

The thickness of the Vastus Lateralis (VL) of the right leg of all participants was estimated using a previously described protocol (Alegre et al. 2015; Alegre et al. 2014). VL muscle was measured in vivo by B-mode ultrasonography (MyLab™50, Esaote, Genoa, Italy) with a 5-cm, 12-MHz linear array probe, which was coated with water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. Before measurements, the subjects were laid on a couch for 15 min to allow osmotic fluids to shift. During measurements, the participants were laid in a supine position with their knees fully extended and muscles relaxed. The images for the measurements of muscle thickness were recorded at 25, 50 and at a 75% distance between the greater trochanter and lateral condyle of the femur (VL25, VL50 and VL75, respectively), with the ultrasound probe placed on the transversal plane and perpendicular to the skin. VL muscle thickness was determined by measuring the perpendicular distance between the medial and lateral limits of the muscle with ultrasound software (MyLab™ Desk, Esaote, Genoa, Italy) before and after the training intervention. In order to increase the reliability of the measurements obtained, the measuring points were marked daily on the skin with indelible ink and muscle architecture images from before and after the intervention were compared.

Procedures

Participants performed a lower-limb resistance-training program based on the leg press exercise. The training program lasted 6 weeks, and included 2 (weeks 1, 3, 5) or 3 (weeks 2, 4, 6) sessions per week, with at least 48 hours between sessions (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008). Each session included 4 sets of 7 repetitions, with a 3-min recovery period between sets. All the training sessions started with a light warm-up consisting of 5 minutes cycling and 2 sets of 10 non-maximal repetitions in specific leg press exercises.

The flywheel device (Leg Press, Inc YoYo Technology, Stockholm, Sweden) used by the EXP group was equipped with two 6.5 Kg flywheels (45 cm diameter) with moment inertia of 0.145 kg·m^2 (figure 1).

Figure 1. Iso-inertial device used in the FRTEO program.

FRTEO performed by the EXP group consisted of accelerating/braking flywheels through the extension-flexion of the knees and hips, as previously described (Fernandez-Gonzalo et al. 2014a). Briefly, each repetition consisted of a maximum concentric action of thrust on the platform where the feet were placed, rotating the wheels. Participants were asked to push with maximal effort through the entire concentric action, which ranged from a 70° knee flexion to near full extension. At the end of this concentric action, the flywheel strap wound back due to inertial forces, which initiated the reversed eccentric action. During the first third of the eccentric action, participants were instructed to resist gently, and thereafter to apply maximal breaking force to stop the movement at about a 70° knee flexion (Fernandez-Gonzalo et al. 2014a). By means of this approach, EO was produced (Norrbrand et al. 2010; Romero-Rodriguez et al. 2011; Tesch et al. 2004a).

The CON group carried out leg presses on a traditional weight-stack machine (Ortus Fitness S.L., Valencia, Spain). They performed the same training volume with a load equivalent to 7 maximum repetitions (7RM) for each set.

Participants were instructed to do the concentric phase of each repetition at a maximal velocity. At the end of each set, the participants were asked to rate their perceived exertion according to a resistance-training specific scale (OMNI scale) (Lagally and Robertson 2006). The participants were accustomed to the OMNI scale, as strength and conditioning staff used it regularly often during pre-season and in-season workouts. Research personnel gave strong verbal encouragement during all repetitions performed by players from both groups.

Statistical Analysis

Statistical analysis was performed with SPSS v.20.0 (SPSS Inc., IBM, USA). The data is presented as mean ± SEM. Data distribution was examined for normality using the Shapiro–Wilk test. VL thickness, 1RM, power at different loads, SJ, CMJ, 20-m sprint time and T-test time were examined using a two-way ANOVA. The 2 factors considered were experimental condition (EXP vs. CON) and time (PRE vs. POST). When a significant interaction was found, post hoc comparisons with Bonferroni adjustment were employed. The effect size (ES) of the training was calculated for paired variables (Cohen 1998). Cohen suggested ES of 0.2, 0.5, 0.8 and 1.3 to represent small, moderate, large and very large effects, respectively. Practical relevance was defined as an ES > 0.8 (Hopkins et al. 2009). The significance level was set to $p<0.05$.

Results

Participants from both groups completed all the training sessions which were designed. Perceived exertion reported after the training sets was similar in the EXP and the CON groups. Table 2 displays the maximal dynamic strength (1RM), power output, vertical jump, sprint time and agility results.

Maximal Dynamic Strength

A significant time effect was observed ($F_{1,29} = 33.71$). Thus, the EXP (12.2%, $p<0.001$; ES = 0.72) and the CON (7.9%, $p<0.01$; ES = 0.49) groups showed a significant increase in 1RM value. No significant condition or condition x time main effects were observed.

Table 2. 1RM, PO at different loads, SJ, CMJ, 20-m and T-test results before and after the training period for EXP and CON groups. Values are mean ± SEM

	EXPERIMENTAL			CONTROL		
	Pre	Post	Δ%	Pre	Post	Δ%
1RM (kg)	258.7 ± 9.5	290.3 ± 12.5 ***	12.2	242.9 ± 10.9	262 ± 9.1 *	7.9
PO50 (w)	835.1 ± 30.4	943.1 ± 59 **	12.9	894.2 ± 52.3	943.4 ± 47.4	5.5
PO60 (w)	918 ± 39.2	1009.5 ± 67.4 *	10	908.3 ± 50.8	954.9 ± 45.1	5.1
PO70 (w)	916.8 ± 38.6	1030.4 ± 65.4 **	12.4	922.5 ± 49.3	982.7 ± 37.6	6.5
PO80 (w)	840.2 ± 38.7	1005.8 ± 68.7 **	19.7	886.2 ± 40.4	948.4 ± 34.8	7
PO90 (w)	777.4 ± 42	944.9 ± 70*	21.6	871.9 ± 41	941 ± 42.7	7.9
SJ (cm)	33.4 ± 1.5	36.7 ± 1.5 ***	9.6	31.5 ± 1.2	32.9 ± 0.8 *	4.5
CMJ (cm)	35.7 ± 1.3	39.2 ± 1.5 *** $	9.8	33 ± 1.2	34.1 ± 0.9	3.4
20m (s)	3.7 ± 0.1	3.3 ± 0.1 ***	-10	3.6 ± 0.1	3.5 ± 0.1 **	-5.1
T-test (s)	9.2 ± 0.1	8.6 ± 0.1 *** $$	-7	9.5 ± 0.2	9.1 ± 0.1	-4.4

Abbreviations: 1RM, maximal dynamic strength; PO, power output; PO50-90 maximal concentric power output (PO) at different intensities (50, 60, 70, 80 and 90% of 1RM); SJ, squat jump; CMJ, countermovement jump; 20m, 20-m sprint time.
* Significantly different from pre-training value, where *p<0.05, **p<0.01, and ***p<0.001. $ Significantly different from CON group value, where $p<0.05 and $$p<0.01.

Power Output

Regarding PO, there was a significant time effect for all the loads tested: PO50 ($F_{1,29}$ = 10.247; p<0.01), PO60 ($F_{1,29}$ = 7.576; p<0.05), PO70 ($F_{1,29}$ = 13.344; p<0.01), PO80 ($F_{1,29}$ = 10.454; p<0.01) and PO90 ($F_{1,29}$ = 5.195; p<0.05). Although no significant condition or condition x time main effects were observed, only the EXP players showed significant changes in PO, with increases ranging from 10 to 21.6% (ES = 0.42 – 0.83).

Vertical Jump

A significant time effect was observed in SJ ($F_{1,29}$ = 26.233; p<0.001), with significant increases showed by the CON (p<0.05, ES = 0.36) and the EXP (p<0.001; ES = 0.54) groups. No significant condition or condition x time main effects were observed.

Results regarding CMJ pointed out a significant time ($F_{1,29}$ = 28.452; $p<0.001$), condition ($F_{1,29}$ = 5.513; $p<0.05$) and condition x time ($F_{1,29}$ = 5.691; $p<0.05$) main effects. Thus, only the EXP participants enhanced their CMJ value after the training period ($p<0.001$; ES = 0.61). Posthoc analysis pointed out that the CMJ value after the training period was significantly higher in the EXP group in comparison to the CON group ($p<0.05$).

Speed and Agility

Significant time ($F_{1,29}$ = 58.417; $p<0.001$) and condition x time ($F_{1,29}$ = 6.503; $p<0.05$) main effects were observed concerning the 20-m sprint time. Post-hoc analysis revealed that both groups significantly reduced their sprint time (EXP: $p<0.01$, ES = 1.45; CON: $p<0.01$, ES = 0.85), with a larger reduction in the EXP group.

Results regarding T-test time showed significant time ($F_{1,29}$ = 26.345; $p<0.001$), condition ($F_{1,29}$ = 5.226; $p<0.05$) and condition x time ($F_{1,29}$ = 5.713; $p<0.05$) main effects. Thus, only the EXP participants significantly reduced their T-test time value after the training period ($p<0.001$; ES = 1.44). Post-hoc analysis pointed out that the T-test time after the training period was significantly higher in the EXP group in comparison to the CON group ($p<0.05$).

Vastus-Lateralis muscle thickness

Results regarding Vastus-Lateralis muscle thickness are displayed in figure 1.

A significant time effect was observed concerning VL25 ($F_{1,29}$ = 22.801; $p<0.001$), VL50 ($F_{1,29}$ = 168.772; $p<0.001$) and VL75 ($F_{1,29}$ = 39.229; $p<0.001$). Likewise, data showed a significant interaction condition x time effect for VL25 ($F_{1,29}$ = 15.028; $p<0.01$), VL50 ($F_{1,29}$ = 74.665; $p<0.001$) and VL75 ($F_{1,29}$ = 9.651; $p<0.01$). Thus, the EXP participants showed a significant VL hypertrophy at proximal ($p<0.001$; ES = 1.61), medial ($p<0.001$; ES = 1.64) and distal ($p<0.001$; ES = 0.63) levels. Although CON participants also showed a significant increase in muscle thickness at media (VL50, $p<0.05$; ES = 0.39) and distal (VL75, $p<0.05$;

ES = 0.15) measurements, the VL muscle hypertrophy experienced by the EXP participants was significantly higher (p<0.001-0.01) than that showed by the CON group at all measurement levels (VL25, VL50 and VL75).

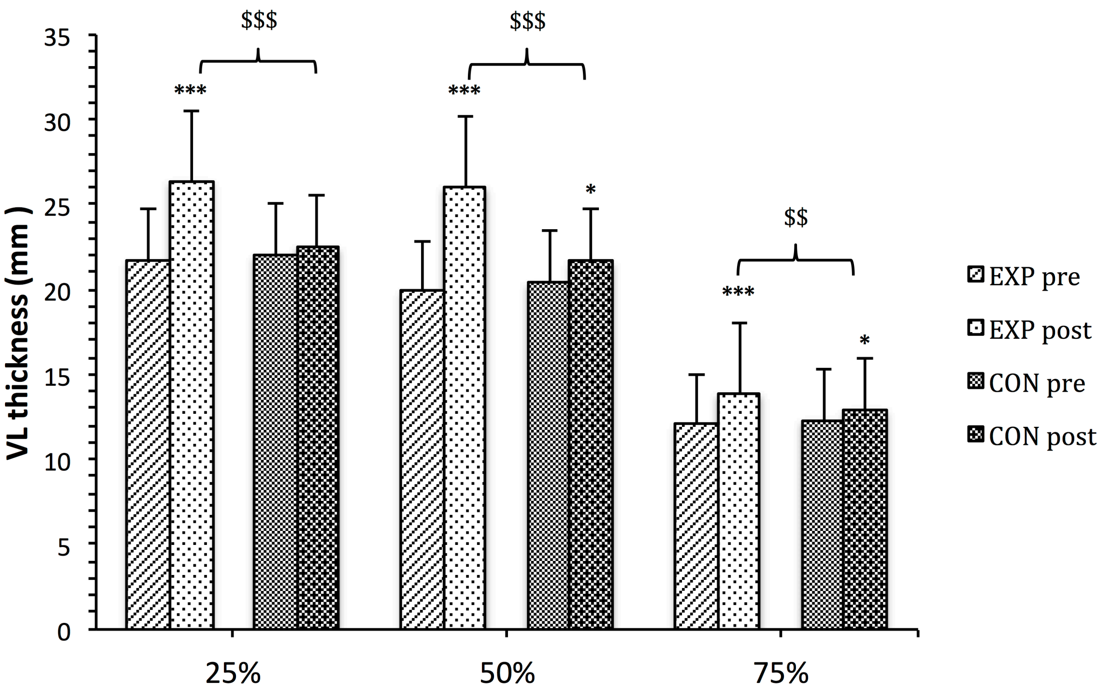

Figure 2. Vastus Lateralis thickness at proximal (25%), medial (50%) and distal (75%) measurements before and after the training program for both, experimental (EXP) and control (CON) groups. * Significantly different from pre-training value, where *p<0.05 and ***p<0.001Significantly different from CON group value, where $ p<0.05 and $$$ p<0.001.

Discussion

In addition to technical and tactical game skills, performance in handball is related to power, strength, speed and agility. (Massuca et al. et al. 2014) Therefore, training approaches that led to improvements in those capacities should be taken into account by coaches and strength and conditioning specialists focused on handball performance. To the best of our knowledge, this is the first study comparing functional and structural effects of a flywheel resistance-training program with eccentric-overload (FRTEO) to those induced by a traditional weight-training program, in professional handball players. The main finding pointed out by results is that a 6-week FRTEO including 15 sessions with 4 sets of 7 repetitions performed at maximal concentric intensity using the leg press exercise induces significant improvements in maximal dynamic strength (1RM), maximal power at different loads, vertical jump height, 20-m sprint time and T-test time. Moreover, the FRTEO induced a significant hypertrophy in Vastus-Lateralis muscle at proximal (VL25), medium (VL50) and distal (VL75) levels. All these positive effects were significantly higher than those showed by subjects who have carried out a similar (volume and perceived effort) training program in a conventional leg/press weight/stack machine.

During traditional concentric-eccentric resistance exercise performed at maximal intensity, the eccentric phase is clearly under-loaded (e.g. about 40-50%) which the series of studies shows (Dudley et al. 1991b; Hather et al. 1991). These studies used a variety of experimental manipulation ans demonstrated the role of eccentric contractions to improve contractile characteristics and muscle size in humans. it make sense to apply eccentric-overloads during resistance training in order to increase neuromuscular adaptations (Hortobagyi et al. 2001). Specific literature includes research studies in which this EO is applied through an iso-inertial gravity-independent stimulus, with positive results concerning structural (Alkner and Tesch 2004a; Alkner et al. 2003; Tesch et al. 2004a) and functional adaptations (de Hoyo et al. 2015b; Fernandez-Gonzalo et al. 2014a; Romero-Rodriguez et al. 2011) when applied to different populations, mainly recreationally trained subjects or physical education students. Our results point out that adding an FRTEO exercise can significantly increase the 1RM value in well-trained handball players, although this improvement is similar to that obtained after a traditional weight training program. Although the EXP participants were exposed to an EO, the 1RM test carried out is similar in nature to the training performed by the CON group. After a similar 6-week FRTEO study (Fernandez-Gonzalo et al. 2014a) which was also carried out with the leg press exercise, a group of physical education students increased the 1RM value by 25%. As the participants in our study were professional handball players and thus well-trained athletes, the lower increase observed in maximal dynamic strength of the athletes compared to the students could be due to the initial physical ability of the athletes before the study.

The significant improvements concerning PO at different intensities (50, 60, 70, 80 and 90% of 1RM) after the FRTEO carried out by the EXP participants are in line with previous studies. Moreover, Fernandez-Gonzalo and co-workers (2014a) also observed significant increases in muscle power at loads equivalent to 60, 70 and 80% of the 1RM after a similar FRTEO. Furthermore after analysing a sample of students, Naczk et al. (2014; 2013; 2016) showed significant muscle power improvements in lower and upper limbs. However, our study is the first to demonstrate the positive effects of FRTEO on increasing muscle power at high percentages of 1RM in athletes. Interestingly, participants from the CON group did not increase their PO at any load, even though the training stimulus could be considered more similar in nature to that found during the PO test. These major improvements in muscle power may be explained by the particular characteristics of the flywheel training to induce EO, since the eccentric EO is usually applied in the last portion of the range of motion during the eccentric action. That is, the EO is produced mainly at a joint angle close to 70° during the leg press just before the subsequent concentric action is initiated. This exercise technique would maximize the stretch shortening cycle, allowing for greater production of force during the first part of the concentric action, and therefore, a higher velocity during the entire movement (i.e. increased power).

PO results together with vertical jump (SJ and CMJ) and significant improvements observed in the EXP group indicate that FRTEO appears to be an effective tool to increase muscle power in well-trained handball players. Although a similar training program carried out by physical education students did not induced any significant increases in SJ or CMJ (Fernandez-Gonzalo et al. 2014a), a study focused on elite soccer players has pointed out significant gains in CMJ height after a 10-week FRTEO program (de Hoyo et al. 2015b). The significant interaction condition x time showed by our results in regards to CMJ height could suggest that vertical jump improvements induced by FRTEO are higher in comparison with traditional resistance training when the jump modality includes an eccentric phase (i.e. a counter movement jump, CMJ). Since leg power has been suggested as an essential component for top elite handball players (Massuca et al. 2014), these results could support the inclusion of FRTEO in handball training routines. In a recent study, the authors (de Hoyo et al. 2015c) showed that under specific circumstances, i.e. FW exercise performed in the horizontal plane vs. free weights using a guided (vertical) squat exercise, the gains in jumping height were lower for FW than traditional training.

As quickness and agility are characteristics of top elite handball players (Massuca et al. 2014), the present results concerning 20-m sprints and T-tests indicate that FRTEO is a useful training approach producing performance-related adaptations. These adaptations are relevant given the importance of the decelerating phases in the sprinting technique, either in a linear or in a change-of-direction approach. Efficient eccentric activation timing and force production of the quadriceps and hamstring muscle groups are necessary during the stance phase in order to provide better elastic energy absorption and storage for impulse during take-off. In the same line, De Hoyo and co-workers (2015b; 2016) showed significant improvements in kinetic parameters, changes of direction and 20-m sprints time after a 10-week FRTEO carried out with half squat and leg curl flywheel devices by junior elite soccer players. Similar to linear-sprint results, and probably more representative in terms of performance, our data pointed out a significant improvement in a change-of-direction test, such as the T-test. These results are in line with Tous-Fajardo et al. (2016) who suggested that flywheel training performed once a week could serve as a viable adjunct to improve performance tasks specific to soccer.

Greater muscle mass is often an advantageous characteristic in sports, as in team handball, where speed is so much of the essence of the sport (Massuca et al. 2014). Our results indicate that the significant increase in Vastus-Lateralis muscle thickness achieved after the FRTEO program was significantly higher than that induced by a traditional weight training program. The efficacy of FRTEO to induce muscle hypertrophy has been well documented (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Tesch et al. 2004a). After a similar FRTEO training program, physical education students also showed a significant hypertrophy of the thigh muscles (Fernandez-Gonzalo et al. 2014a). In a similar line, Norrbrand et al. (2008) observed a significant increase in quadriceps muscle volume after a 5-week FRTEO carried out by untrained men in leg-extension exercises. At a physiological level, the enhanced eccentric load apparently led to a subtly faster gene expression pattern, inducing a faster muscle phenotype plus associated adaptations that make a muscle better suited for fast, explosive movements (Friedmann-Bette et al. 2010). However, since the mechanism of hypertrophy is not yet completely understood, future studies should delve into these potential pathways, helping us to understand the underlying mechanism of the high hypertrophic role of the FRTEO.

Conclusions

In summary, a 6-week FRTEO with 2-3 sessions a week, including 4 sets of 7 repetitions of the leg-press exercise performed at maximum concentric intensity induces significant improvements in maximal dynamic strength, power output at different loads, vertical jump height, sprint time, agility and muscle thickness in professional handball players. The adaptations regarding muscle power at different submaximal loads, countermovement jump, 20-m sprint time, T-test time and muscle thickness of the Vastus Lateralis were significantly larger than those observed after a similar (volume and intensity) resistance training program carried out with a traditional weight-stack leg press machine and including a similar volume and perceived effort. Therefore, the EO applied through a flywheel device seems to be a useful tool inducing functional and anatomical adaptations related with performance in well-trained handball players. Future studies should analyze FRTEO programs using different training volumes and exercises in order to reinforce these results.

PAPER 3

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

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Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. Electric-Motor

Brief title: Flywheel vs. Electric-motor training-induced effects

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Abstract

This study aimed to analyse whether increasing the eccentric overload (EO) during resistance training, in terms of range of motion and/or velocity using an electric-motor device, would induce different muscle adaptations than conventional flywheel-EO resistance training. Forty physically active university students (21.7±3.4 years) were randomly placed into one of the three training groups (EX1, EX2, FW) and a control group without training (n=10 per group). Participants in the training groups completed 12 sessions (4 sets of 7 repetitions) of iso-inertial single-leg squat training over 6 weeks for the dominant leg. Resistance was generated either by an electric-motor device at two different velocities for the eccentric phase; 100% (EX1) or 150% (EX2) of concentric speed, or by a conventional flywheel device (FW). Thigh lean tissue mass, unilateral leg press one-repetition maximum (1-RM), unilateral muscle power at different percentages of the 1-RM and bilateral/unilateral vertical jump were assessed before and after the 6-week training. There were significant ($p<0.05$-0.001) main effects of time in the 3 training groups, indicating increased thigh lean tissue mass (2.5-5.8%), 1-RM load (22.4-30.2%), vertical jump performance (9.1-32.9%) and muscle power (8.8-21.7%), without differences across experimental groups. Participants in the control group did not improve any of the variables measured. In addition, EX2 showed greater gains in eccentric average peak power during training than EX1 and FW ($p<0.001$). Despite the different EO offered, 6 weeks of resistance training using flywheel or electric-motor devices induced similar significant gains in muscle mass, strength, muscle power and vertical jump.

Keywords

Eccentric overload, strength, muscle power, hypertrophy, range of motion

Highlights

- 12 sessions (4 sets of 7 repetitions) of iso-inertial RT in physically active young men induces significant skeletal muscle mass and performance adaptations.
- Eccentric-overload application over the entire ROM or over the last part of the ROM led to similar training-induced effects.
- Electric-motor devices have potential benefits for accentuated eccentric training, functioning as an ideal inertial device without requiring a maximum CON action to generate eccentric-overload, and allowing the achievement of larger percentages of eccentric-overload by increasing the eccentric velocity with respect to the concentric.
- Higher eccentric-overload percentages seems to be related with greater increases in muscle size, while lower eccentric-overload percentages seems to be related with greater increases in muscle power.

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Conflicts of interest

The authors declare that they have no conflicts of interest

Introduction

The potential benefits of isolated or overloaded eccentric (ECC) resistance exercise, compared with concentric (CON) or conventional CON-ECC exercise regimens, have been widely studied (Maroto-Izquierdo et al. 2017b; Roig et al. 2009). Among different technologies allowing for eccentric overload (EO), iso-inertial flywheel resistance exercise is one of the most utilized exercise paradigms with established efficacy in different scenarios such as injury prevention/rehabilitation (de Hoyo et al. 2015b; Gual et al. 2015; Monajati et al. 2018) and performance (de Hoyo et al. 2015a; Maroto-Izquierdo et al. 2017a; Naczk et al. 2017; Sabido et al. 2017a). Furthermore, iso-inertial flywheel resistance exercise has been suggested to improve muscle function, and functionality in elderly subjects (Brzenczek-Owczarzak et al. 2013) and stroke patients (Fernandez-Gonzalo et al. 2016). Originally designed to counteract the deleterious effect of microgravity on skeletal muscle (Tesch et al. 2017), the superiority of flywheel-EO resistance training (RT) over weight-stack RT (i.e. guided resistance exercise machines) to promote functional and structural adaptations in terms of strength, power, muscle size, running speed, and jump ability in healthy subjects and athletes has been demonstrated (Maroto-Izquierdo et al. 2017b). It appears that the greater overall load and mechanical stress placed on the muscle, caused by the maximal nature of the CON action during the entire range of motion (ROM), as well as the EO in the last portion of the ECC action, are responsible for the stronger physiological responses and training-induced musculoskeletal adaptations of flywheel RT vs. traditional gravity-dependent protocols (Tesch et al. 2017).

The different protocols that can be employed using flywheel RT are characterized by the different moment of inertia of the flywheel, which in turn is a function of its geometrical and physical properties (Sabido et al. 2017b). Thus, lower inertias with higher velocities, shorter ECC-CON coupling time and greater power production were suggested to favour explosive muscle characteristics adaptations, whereas higher inertias with lower velocities were shown to call for greater work load (Martinez-Aranda and Fernandez-Gonzalo 2017) Thus, after a maximum CON action, higher moments of inertia are able to generate greater force productions and impulse in the system than smaller flywheels (Carroll et al. 2018). The energy produced in the system during this CON action is stored and maintained during the subsequent ECC action due to its inertial characteristics, and must be braked in a short and concentrated moment at the end of the ECC phase to reinforce the negative action (Maroto-Izquierdo et al. 2017b). By means of this approach, EO is generated in the system, and greater amounts of overload are achieved with higher inertial loads (Carroll et al. 2018). Notwithstanding, flywheel devices require a maximum CON action to generated EO only in the last third of the ECC action (Tesch et al. 2017). Moreover, the applicability of available flywheel hardware to functional training is limited due to flywheel exercise hardware traditionally developed following pre-existing uniaxial and bilateral weight-stack training machines (Maroto-Izquierdo et al. 2017a; Maroto-Izquierdo et al. 2017b).

Recently, different multifunctional electric-motor devices have been commercialized (Tinwala et al. 2017) aiming to offer solutions to some of the limitations of flywheel technology. These devices are potentially capable of generating EO in the entire ROM. Therefore, it is not necessary to reduce the active braking phase to obtain the overload, as it occurs with the traditional flywheel devices (Tinwala et al. 2017). In addition, other possibilities to modify the training stimulus while using electric-motor driven devices are changes in the specific CON and/or ECC intensity (no need for a maximum CON action), adjustments in the transition time between CON and ECC phases, and modifications in the ECC velocity, related to the CON velocity (Tinwala et al. 2017). Interestingly, active electric-motor devices completely neutralize the friction force and parasitic inertias, becoming *a priori* ideal inertial device from a mechanical perspective.

Given the current options to produce EO during iso-inertial RT and the belief that greater EO during iso-inertial exercise may promote larger adaptations, we designed a study to investigate the effects of iso-inertial training generated by an electric-motor device, which offers EO in the whole ROM, and compare such adaptations with conventional flywheel RT in a lower limb unilateral exercise. The aim of this study was to analyse whether increasing the EO in terms of ROM and/or velocity would induce different muscle adaptations than conventional flywheel EO training.

Methods

Participants

Forty sports science undergraduate students volunteered for the study (21.7 ± 3.4 years; 75.8 ± 9.8 kg; 177.1 ±5.4 cm). Participants were moderately active and healthy individuals, engaging in 6–8 h of recreational physical activity per week. They had no history of regular lower limb strength training and no previous muscle, joint or bone injury for the last 6 months. They were informed of the purposes and risks involved in the study before giving their informed written consent to participate. The Ethics Committee of the University of León approved the study protocols (ETICA-ULE-009-2018). All participants completed all the protocols, including two familiarization sessions, the prescribed training program, and the pre- and post-tests.

Training Program

Participants were randomly divided into 3 experimental training groups and 1 control group, which did not train. All participants included in an experimental group (n=30) completed 6-weeks (12 sessions) of an iso-inertial single-leg squat training program, using an electric-motor device (EX1 and EX2 groups) or a flywheel device (FW group) (figure 1). Volunteers trained 2 times per week with at least 48 hours of rest between sessions (Fernandez-Gonzalo et al. et al. 2014a). Following a standardized cycling warm-up, participants performed 4 sets of 7 maximal unilateral (dominant leg) coupled CON and ECC muscle actions in a single-leg squat position. Subjects were required to push with maximal effort through the entire CON action, which ranged from 70° of knee flexion to nearly full extension (0° = full knee extension). At the end of the CON action, the flywheel/motor strap rewound back, initiating the reversed ECC action. Before each session, the ROM was set up from 0º to 90º using a goniometer. So that in case of not stopping within the permitted range the device stopped the movement and notified it in the software. In the case of the flywheel device, subjects were instructed to resist gently during the first and second thirds of the ROM, and thereafter to apply maximal breaking force to stop the movement at about 70º of knee flexion. By means of this approach, EO is produced (Maroto-Izquierdo et al. 2017b; Tesch et al. 2017). An individual researcher was responsible for calibrating the ROM of each participant (i.e. length of cable used and distance from the vertical pulley to the platform) from 0º (i.e. full knee extension) to 90º employing a goniometer. In addition, the same researcher, indicated the knee angle in which they had to brake before each series and gave verbal information during the execution of each repetition. Besides, the electric-motor device is characterized by producing EO throughout the entire ROM, so it is not necessary to wait for the last third of movement to obtain EO (Tinwala et al. 2017). Therefore, the only instruction given to EX1 and EX2 participants was to stop the movement before reaching the end of the ROM. Participants were not allowed to use the other leg to produce force, positioning the non-training leg from the tibia to the foot's instep above a soft surface, at a fixed point, to avoid compensation (figure 1). Power was measured during each repetition (CON and ECC actions; SmartCoach™, Stockholm, Sweden), and real-time feedback was provided on a computer monitor. A strong verbal encouragement was given during all repetitions performed. All subjects were familiarized (2 sessions) with the exercise prior to the first training session. Subjects in the control group did not perform any strength-training program during the study period, as instructed.

FW participants (n=10) performed the exercise using a squat flywheel device (Kinetic Box (Kbox), Exxentric AB TM, Bromma, Sweden) (Sabido et al. 2017b), equipped with one 4.2-kg flywheel with a moment of inertia of 0.05 $kg{\cdot}m^{-2}$. EX1 (n=10) and EX2 (n=10) participants performed the same exercise, but in an electric-motor device (Exentrix, SmartCoach™, Stockholm, Sweden). This device was configured in flywheel mode using the iso-inertial settings in the device's software (Exentrix PC Interface - V2.4, SmartCoach™) and configured with a load of 37 inertial units for both EX groups. According to the manufacturer's instructions, one inertial unit is equivalent to a moment of inertia of 0.00134 $kg \cdot m^{-2}$, so the resulting moment of inertia was equivalent to the flywheel device (0.05 $kg \cdot m^{-2}$). In addition, the transition time between CON and ECC phase was the minimum permitted by the system. No different training loads were selected for the CON and ECC phases. However, the software for group EX2 was configured to perform the rewind of the cable (ECC action) at a 150% faster than the CON speed. Thus, the ECC speed was 1.5 times faster than groups EX1 and FW.

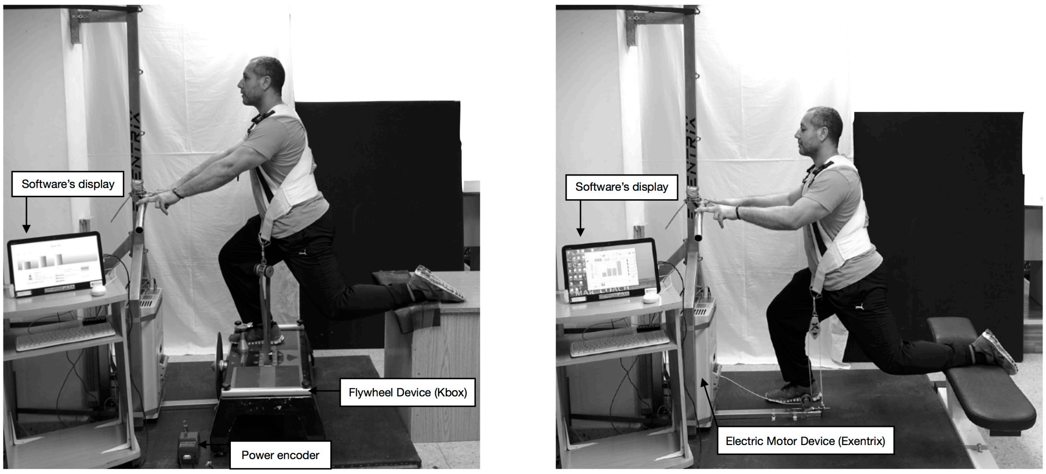

Figure 1. A. Single-leg squat exercise on the flywheel device. B: Single-leg squat exercise on the electric-motor device.

Testing Procedures

Dual energy X-ray absorptiometry analysis (DEXA)

DEXA was performed ~1 week before and after the training program, at the same time of day using a Lunar Prodigy® whole-body scan (GE Medical Systems, Madison, WI). A manual analysis was performed to estimate thigh lean mass (Encore® 2009 software, Lunar Corp., Madison, WI). Briefly, one rectangle mark was generated using the lower margin of the ischial tuberosities and the lower margin of the femoral condyles as thigh reference points. Lean mass was then calculated for the entire thigh. Subsequently, inside the span of the thigh rectangle a 6-cm perpendicular line was drawn from the distal to the proximal mark to establish three regions of interest (ROIs) of the thigh where lean muscle mass was estimated. Then, a 20 mm-thick slice was placed above the 6-cm distal vertical line (i.e. distal thigh ROI) (Fernandez-Gonzalo et al. 2014a). In addition, two other 20-mm slices were placed 6 (i.e. medial thigh ROI) and 12 cm (i.e. proximal thigh ROI) above the first slice. Finally, lean tissue mass estimation in both total thigh and the three slices created was calculated using Encore software.

Unilateral maximal dynamic strength (1-RM)

Twenty-four hours after the DEXA and jump tests, the unilateral 1-RM test was conducted on a 45º-inclined leg press device (Gerva-Sport, Madrid, Spain). Participants performed one repetition from 90° to full extension (180°) with a load corresponding to approximately 3-RM. The load was increased with 10 kg if the subject succeeded or decreased 5 kg if failed. Testing ended when subjects failed to overcome a given load in two successive trials. Unilateral 1-RM was achieved between 3 and 6 attempts, and trials were interspersed by 2-min recovery. Participants were asked to place the resting leg with the knee flexed and the foot propped on the ground. The 1-RM test was performed twice for each leg; 3–5 days before and 3–5 days after the training period.

Unilateral Muscle Power

Forty-eight hours after the 1-RM test muscle power test was performed, participants completed five sets of three unilateral repetitions from 90º-knee flexion to full extension (180º) in the leg-press described above, with 2-min recovery between sets. To avoid any use of the stretch-shortening cycle, each repetition started from a complete static position. Each set represented 40, 50, 60, 70, and 80 % of 1-RM load, and the order of the sets was individually randomized before testing and replicated at post-tests. Subjects were asked to perform the CON phase of each repetition as fast as possible. Mean power for each repetition was sampled at 1000 Hz using an encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L., Murcia, Spain) and the associated software (T-Force v. 2.28). The best repetition performed at each load was used for data analysis. The warm-up protocol described for the 1-RM test was also performed prior to the muscle power test.

Vertical jump performance

Vertical jump tests were carried out immediately after the DEXA analysis. Jump height was measured for countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) performed bilaterally and unilaterally in this order on a contact platform (Globus Ergotester®, Globus, Codogne, Italy) (Murtagh et al. 2017). A warm-up of 5-min cycling, 25 reps of high knee and 25 reps of butt kicks was performed. The SJ was performed from a 90°knee flexion with hands on the hips. For the CMJ, participants started in a standing straight position and were instructed to jump as high as possible with hands on the hips. The DJ consisted of dropping oneself from a box of 45 cm and then jump as high as possible straight after landing. Participants were asked to step off the platform and jumping after the first ground contact from a self-selected knee angle, maintaining the hands at the hips during the full test. Protocols were identical for bilateral and unilateral test. The three bilateral attempts were always completed first, followed by unilateral attempts. Jump height (and contact time for DJ) was recorded to the nearest 0.1 cm (0.05 s for contact time). Three trials, with 30-seconds of recovery in between, were allowed and the best result was included in the data analysis.

Statistical analyses

Statistical analyses were performed using SPSS v.20.0 (SPSS Inc. Chicago, IL). Results were expressed as mean ± SD. Data distribution was examined for normality using the Shapiro–Wilk test. A Mixed-model analysis of variance (group x time), followed by Bonferroni post hoc tests was used to investigate differences in variables measured. The effect size (ES) was calculated for interactions between groups using Cohen's guidelines. Threshold values for ES were >0.2 (small), >0.6 (large) and >2.0 (very large) (Hopkins et al. et al. 2009). The significance level was set to $p<0.05$.

Results

A significant group x time interaction was found in the ECC average peak power of each training session, where the EX2 group showed significant differences ($p<0.001$; ES range 3.5-6.8, figure 2) with respect to EX1 and FW groups. No further significant interactions were observed for the other variables analysed. In addition, there was a significant main effect of time for all functional and structural variables ($p<0.05$-.001, F range 6.0-77.2). However, the control group did not improve any of the variables measured.

There was a main effect of time ($p<0.001$) in the distal (F=47.3), medial (F=26.1) and proximal (F=24.8) ROIs measured and in the total thigh lean mass (F=48.9). EX2 ($p<0.001$, ES range 0.24-0.40) and FW groups ($p<0.001$, ES range 0.41-0.56) showed significant improvements in all measurements (table 1). The EX1 group showed significant gains at distal and medial portions ($p<0.05$, ES=0.35 and 0.21) and in total thigh mass ($p<0.01$, ES=0.23). Results from control group remained similar between pre- and post-measurement.

There was a significant main effect of time in the 1-RM load ($p<0.001$, F=77.2). Thus, between pre- and post-tests the 1-RM load increased 30.2% in EX1 ($p<0.001$; ES=1.49), 27.6% in EX2 ($p<0.001$; ES=1.39) and 22.4% in FW ($p<0.001$; ES=1.20) (table 1).

Across sessions (figure 2), CON average peak power increased 51% in EX1 [523.6 (±154) to 792.0 (±149) W; $p<0.001$, ES=1.77], 40% in EX2 [559.9 (±87) to 785.2 (±98) W; $p<0.01$, ES=2.43] and 52% in FW [468.0 (±118) to 712.0 (±180) W; $p<0.001$, ES=1.60]. The corresponding increases in ECC average peak power were 95% in EX1 [384.8 (±105) to 750.0 (±142) W; $p<0.001$, ES=2.92], 39% in EX2 [1217.0 (±168.7) to 1701.1 (±108.3) W; $p<0.001$, ES=3.41] and 95% in FW [512.8 (±223) to 997.8 (±254) w; $p<0.001$, ES=2.03]. The mean EO produced in terms of power (% above CON average peak power) was -13.3% in EX1, 114.1% in EX2 and 43.6% in FW. Mean EO produced in terms of force (% above CON force) was 17.2% for EX1 and 50.7% for EX2. No force measurements were recorded in the FW group during training.

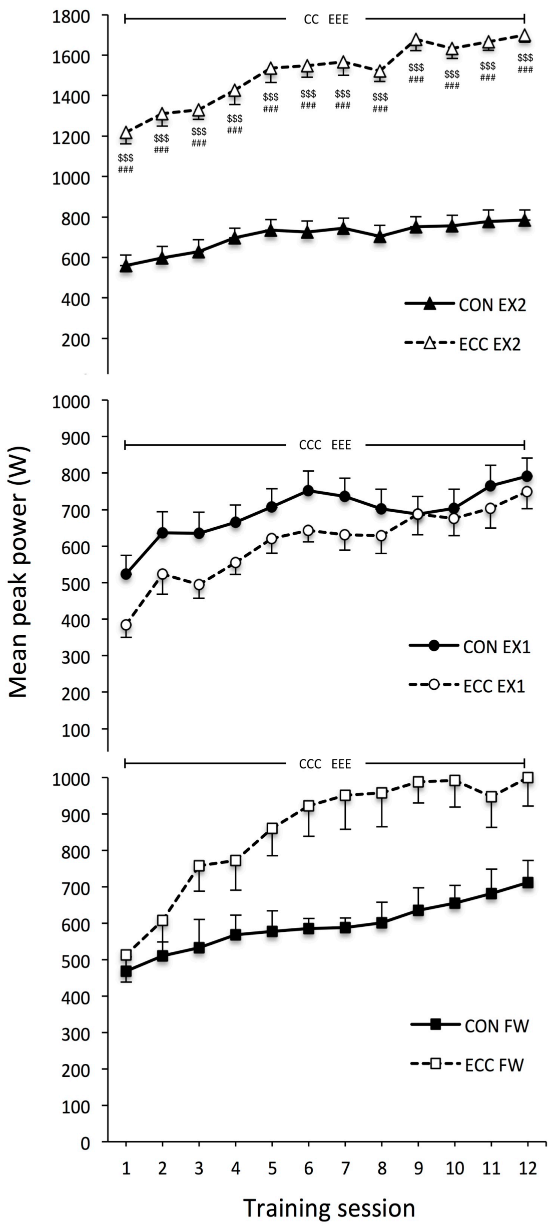

Figure 2. Mean concentric (CON) and eccentric (ECC) peak power (w) during each training session in all experimental groups (EX1, EX2 and FW). Significant effects of time (session 1 vs. session 12) (^{C} p<0.05; ^{CC} p<0.01; ^{CCC} p<0.001 for CON; ^{E} p<0.05; ^{EE} p<0.01; ^{EEE} p<0.001 for ECC). $^{\$}$ Significantly different form EX1 group, where $^{\$}$ p<0.05, $^{\$\$}$ p<0.01, and $^{\$\$\$}$ p<0.001. $^{\#}$ Significantly different from FW group, where $^{\#}$ p<0.05, $^{\#\#}$ p<0.01, and $^{\#\#\#}$ p<0.001.

Regarding mean power output, there was a significant main effect of time for all the loads tested (p<0.001, F range 21.4-57.4) (figure 3). Thus, EX1 experimented a significant (p<0.001) increase in all loads ranging from 14.2 to 21.1% (ES range 0.68–1.17). Similarly, the FW group showed gains in all loads measured, with an improvement of 15.8-21.7% in the loads 40 to 70% (p<0.001; ES range 0.75–0.91), and 15.3% at the 80% 1-RM (p<0.05; ES=0.62). Likewise, EX2 increased power output in all 1-RM percentages (9–10.8%, p<0.01, ES range 0.41–0.51), with the highest increase at 50% 1-RM (10.8%, p<0.001, ES=0.49) and at 80% 1-RM (16.8%, p<0.001, ES=0.79). Before training, maximal mean power was reached at the load corresponding to 60% of 1-RM by all training groups. Meanwhile, EX2 reached maximal mean power output at 80% of 1-RM after the training period.

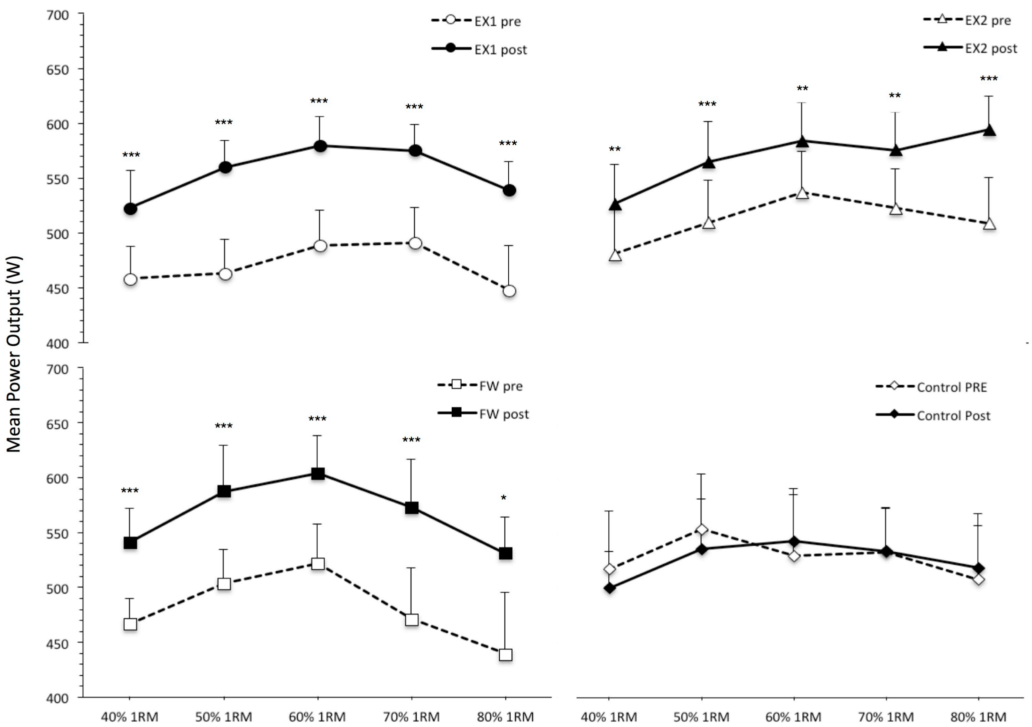

Figure 3. Mean leg press power (w) at different percentages of 1-RM before (pre) and after (post) training. * Significantly different from pre-training value, where * p<0.05, ** p<0.01 and *** p<0.001.

A significant time effect (p<0.05-.000, F range 6.0–51.5) was observed in CMJ, SJ, and DJ height in unilateral and bilateral tests (table 1). Regarding bilateral vertical jump height, the three training groups achieved significant improvements (p<0.05-.001; ES range 0.36–0.67). Regarding unilateral vertical jump height, FW (p<0.01-.001, ES range 0.73–1.33) and EX1 groups (p<0.05-.001; ES range 0.65–0.89) achieved significant improvements in all tests, while the EX2 group improved significantly the CMJ (p<0.05, ES=0.59) and the DJ (p<0.001, ES=0.81). In addition, EX1 and EX2 groups were the only ones that reduced the unilateral DJ contact time (p<0.001, ES=1.51 and 1.47, respectively).

Table 1. Distal, medial, proximal and total thigh muscle mass; unilateral maximal dynamic strength (1-RM); and vertical jump height and DJ contact time pre- and post-training.

	EX1 grupo					EX2 grupo					FW grupo					CONTROL grupo				
	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P	PRE	POST	Δ%	ES	P
Masa muscular																				
Distal (g)	189.0 ± 15.0	194.6 ± 17.4	2.9	0.35	*	194.9 ± 31.7	205.3 ± 34.8	5.4	0.31	***	186.7 ± 20	197.4 ± 18.2	5.7	0.56	***	200.3 ± 33.5	202.8 ± 36.2	1.3	0.07	
Medial (g)	309.3 ± 37.7	317.1 ± 36.1	2.5	0.21	*	324.2 ± 50.2	336.7 ± 55.8	3.9	0.24	***	305.3 ± 30.5	317.4 ± 25.6	4.0	0.43	***	328.3 ± 48.4	332.0 ± 50.0	1.1	0.07	
Proximal (g)	418.6 ± 38.5	425.8 ± 41.7	1.7	0.18		431.0 ± 51.7	452.2 ± 54.0	4.9	0.41	***	426.8 ± 37.8	441.1 ± 32.5	3.4	0.41	***	443.6 ± 59.4	444.8 ± 58.2	0.3	0.02	
Total (g)	6793.9 ± 758.3	6967.9 ± 776.2	3.4	0.30	**	6912.2 ± 974.9	7222 ± 1073.8	4.5	0.30	***	6549.2 ± 708.8	6881 ± 791.2	5.1	0.44	***	6783.0 ± 1102.9	6684.3 ± 995.1	-1.5	0.09	
Fuerza																				
1-RM (kg)	187.8 ± 36.7	244.4 ± 39.1	30.2	1.49	***	177.2 ± 41.8	226.1 ± 26.9	27.6	1.39	***	210.0 ± 34.7	256.1 ± 41.6	21.9	1.20	***	225.0 ± 40.3	225.7 ± 46.9	0.3	0.02	
Salto vertical UL																				
CMJ (cm)	21.6 ± 3.3	23.7 ± 3.2	9.8	0.65	*	21.8 ± 3.5	23.8 ± 3.3	9.1	0.59	*	21.1 ± 4.2	23.8 ± 3.1	12.8	0.73	**	23.8 ± 7.4	21.4 ± 5.3	-9.9	0.37	*
SJ (cm)	20.5 ± 3.6	22.8 ± 3.2	11.2	0.67	*	21.3 ± 3.8	22.7 ± 3.2	6.6	0.40		19.7 ± 3.8	23.1 ± 2.7	17.3	1.03	***	22.8 ± 7.9	20.8 ± 4.3	-8.8	0.31	
DJ (cm)	18.3 ± 4.4	21.6 ± 2.9	18.0	0.89	***	18.4 ± 4.4	21.4 ± 2.9	15.9	0.81	***	18.3 ± 2.6	21.5 ± 2.2	17.5	1.33	***	19.9 ± 4.1	18.9 ± 3.8	-5.0	0.25	
DJ CT (ms)	0.577 ± 0.16	0.386 ± 0.08	33.1	1.51	***	0.499 ± 0.12	0.364 ± 0.05	27.1	1.47	***	0.525 ± 0.10	0.463 ± 0.07	11.8	0.72		0.528 ± 0.07	0.524 ± 0.13	-0.8	0.04	
Salto vertical BL																				
CMJ (cm)	38.5 ± 4.3	40.6 ± 4.1	5.5	0.50	***	39.1 ± 6.4	42.2 ± 6.9	8.0	0.47	***	38.7 ± 6.9	41.3 ± 6.4	6.9	0.39	***	40.2 ± 4.6	39.6 ± 4.3	-1.6	0.13	
SJ (cm)	36.2 ± 3.9	38.6 ± 3.9	6.6	0.62	***	37.1 ± 5.2	39.7 ± 5.8	7.0	0.47	***	37.2 ± 5.6	39.1 ± 4.8	4.8	0.36	**	38.3 ± 4.7	38.6 ± 5.3	0.6	0.08	
DJ (cm)	35.7 ± 4.7	38.6 ± 5.2	8.4	0.59	*	36.7 ± 8.4	40.9 ± 8.4	11.3	0,5	***	35.6 ± 8.8	39.1 ± 5.8	9.5	0.47	**	38.2 ± 6.0	37.1 ± 5.4	-2.8	0.19	
DJ CT (ms)	0.502 ± 0.15	0.417 ± 0.08	16.9	0.71		0.451 ± 0.12	0.389 ± 0.08	13.9	0.61		0.458 ± 0.11	0.428 ± 0.10	6.7	0.29		0.488 ± 0.09	0.518 ± 0.09	6.0	0.33	

Abbreviation: 1-RM: One-Repetition Maximum; BL: Bilateral; CMJ: Countermovement Jump; DJ: Drop Jump; DJ CT: Drop Jump Contact Time; UL: Unilateral;. * Significantly different from pre-training value, where * $p<0.05$, ** $p<0.01$ and *** $p<0.001$.

Discussion

The aim of this study was to determine whether increasing the EO during iso-inertial resistance exercise training, in terms of ROM and/or velocity, would induce different muscle adaptations than conventional flywheel EO training. After 6-week training (12 sessions), the three experimental groups (EX1, EX2 and FW) showed comparable increases in maximum unilateral dynamic strength, unilateral muscle power at different loads, muscle hypertrophy, and both bilateral and unilateral vertical jump height. Therefore, it seems that the magnitude of EO offered by either flywheel or motor-driven iso-inertial RT does not have a major impact on the resistance exercise-induced muscle adaptations.

Based on our results, iso-inertial RT with EO performed in an electric-motor device is an effective resistance exercise method to induce functional and structural muscle adaptations in physically active men, without the need to perform a maximum braking action in the last third of the ROM. In addition, larger EO percentages may be achieved by increasing the speed of cable recoil in an electric-motor driven device (e.g. EX2 group). These results support previous data describing the effects produced by iso-inertial devices on skeletal muscle. Thus, five- to 15-week flywheel EO-RT programs of the lower limbs (bilaterally), have shown strong skeletal muscle adaptations (Maroto-Izquierdo et al. et al. 2017b), including gains in muscle mass (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. 2008; Seynnes et al. 2007), maximal voluntary contraction (Norrbrand et al. 2008; Seynnes et al. 2007; Tesch et al. 2017), 1-RM load (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a), ECC force (Hortobagyi et al. 2001), muscle power (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a), jump ability (de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a), running speed (de Hoyo et al. 2015b; Maroto-Izquierdo et al. 2017a), and electromyography activity (Norrbrand et al. 2011; Pozzo et al. 2006; Seynnes et al. 2007). Indeed, chronic exercise training employing non-gravitational iso-inertial technology produces early and vigorous neuromuscular adaptations, which appear to be more effective than those noted after traditional weight-training (Maroto-Izquierdo et al. 2017b; Tesch et al. 2017). The current study goes one step further, indicating that applying the EO over the entire ROM, by means of an electric-motor device, does not enhance the training-induced effects generated by a conventional inertial flywheel in which the EO is produced only in the last third of the ROM.

Moreover, this is the first study to analyse the EO generated by two different iso-inertial devices. Fernandez-Gonzalo et al. (2014a) and Sabido et al. (2017b) pinpointed that bilateral lower limb RT in an inertial device is capable of generating between 15-30% of EO (% above CON average peak power). According to others (Martinez-Aranda and Fernandez-Gonzalo 2017), iso-inertial technology devices, are capable of generating EO between 20 to 25% (% above CON peak force) in unilateral mono-articular exercises of the lower limb using an inertia of 0.05 kg·m^2 (i.e. knee extension). Our results show a slightly higher average EO in terms of average peak power (46%, with a range between 10 and 62% throughout the different training sessions in the FW group). This may be due to the differences in exercise type (Nunez et al. 2018), since the applied force is quite higher in the training leg in an unilateral multi-joint squat exercise than in one of the training legs in a bilateral training regime due to the bilateral deficit (Weir 1995). Regarding the EO generated in the groups that were trained with the electric-motor device, thus producing the force in the ECC during the whole ROM (EX1 and EX2), and taking as reference the FW group, the EO was higher in the EX2 group (114%, with a range between 105 and 123% in terms of average peak power; and 50.7%, with a range between 42.2 and 60.4% in terms of peak force throughout the different training sessions). However, the EX1 group only showed EO in relation to CON peak force (17.2%, with a range between 14.9 and 21.1% throughout the different training sessions). This could be due to the fact that EO was achieved through the entire ROM, and not only in the last third, as FW group, taking more time to slow down the movement, so ECC power production was lower. Consequently, although the EX1 group did not show EO in terms of average peak power, the overload in terms of peak force is similar to that demonstrated in flywheel devices by other authors (Martinez-Aranda and Fernandez-Gonzalo 2017). Therefore, our data seem to indicate that increasing the ECC speed is a good alternative to generate higher values of EO in terms of both average peak power and peak force throughout the entire ROM.

New training trends demand unilateral daily-life and sports specific exercises (Thompson 2017), in which several planes, muscle groups, and joints are involved at the same time, with a greater demand for stability and performing gestures similar to those that appear in sports practice (e.g. braking, changes of direction, throwing or striking) (Gonzalo-Skok et al. 2016). This is something that traditional flywheel hardware designed for single-plane exercise movements (e.g. knee extension exercise) does not allow. Yet, multifunctional flywheel devices do offer more possibilities in this area (e.g. Squat Flywheel device). Therefore, the exercise selected for this study was the single-leg squat, in order to combine the benefits of unilateral and specific training with those achieved by eccentric-overload flywheel training. In addition, the electric-motor device is multifunctional, allowing exercises practically in any plane of movement. However, since the motor-driven hardware did not allow to perform exercises requiring higher power than 1300 W, an unilateral exercise was selected to perform the training program with the maximum levels of strength and speed, yet within the device's range of power. Moreover, it has been recently shown that flywheel unilateral resistance training generates similar or greater adaptations than bilateral training regarding muscle mass, power, and sport-specific skills, such as running with a change of direction or vertical jump (Nunez et al. 2018). Gonzalo-Skok and coworkers (Gonzalo-Skok et al. 2016) suggested the incorporation of 1-limb exercises to any training routine, since most sports movements are performed unilaterally.

Regarding maximal dynamic strength, the three experimental groups showed important increases from pre- to post-tests. Previous studies have shown improvements between 12 and 25% in the same muscle groups trained with inertial devices (Fernandez-Gonzalo et al. 2014a; Maroto-Izquierdo et al. 2017a). Therefore, the current FW group (+22.4%) data is supported by previous results. Even without significant differences between groups, it seemed EX1 and EX2 groups showed slightly higher gains in 1-RM load (30.2% and 27.6%, respectively), than those shown by FW group as well as by other studies using inertial technology (Maroto-Izquierdo et al. 2017b; Tesch et al. 2017). This could be due to the fact that participants in EX1 and EX2 applied the braking force through the whole ROM of the ECC phase, although such hypothesis needs to be further validated.

EO-RT induces substantial gains in muscle power (Maroto-Izquierdo et al. 2017b). Fernandez-Gonzalo et al. (2014a) and Maroto-Izquierdo et al. (2017a) analysed the effects of flywheel RT on different percentages of the 1-RM (40-90% 1-RM load), showing increases in the range of 5-30%, which are similar to the results observed in the FW group of the current study. After 6 weeks of RT with an electric-motor device in iso-inertial mode, similar adaptations were observed in muscle power at different percentages of the 1-RM (40-80%) when the ECC velocity was not enhanced (EX1: 14.2-21%). However, these adaptations appeared to be slightly lower in the EX2 group (8.8-10.8%). Although, the higher EO produced by EX2 participants seemed to have a particular effect on the power produced at high loads, i.e. 80% of 1-RM (16.8%). Hence, it seems that muscle power adaptations do not only depend on the moment of inertia used (Martinez-Aranda and Fernandez-Gonzalo 2017; Sabido et al. 2017b) or the training velocity developed (Carroll et al. 2018), but also on the EO induced.

The training-induced power adaptations are also evident in the increments obtained in muscle power between sessions 1 and 12. Thus, iso-inertial training in a vertical plane appears to be an effective tool to increase power. Therefore, such training is recommended to increase vertical jump performance (Gonzalo-Skok et al. 2016; Maroto-Izquierdo et al. 2017b), as shown by the current data where all experimental groups improved vertical jump performance. In the case of the DJ, where the stretch-shortening cycle becomes a critical factor, EX1 and EX2 groups significantly reduced the contact time. This could potentially be explained by the similarity of the gesture between training and the jump test, and the emphasis on a short transition between ECC-CON actions in EX1 and EX2.

The efficacy of EO-RT to induce muscle hypertrophy has been well documented (Fernandez-Gonzalo et al. 2014a; Norrbrand et al. et al. 2008;

Tesch et al. et al. 2017). Throughout the scientific literature, flywheel devices have shown a great efficacy to induce gains in muscle volume/mass in young men and women (Fernandez-Gonzalo 2014a) and in well-trained athletes (Maroto-Izquierdo et al. 2017a). Such changes seem to be greater than those induced by other RT modalities (i.e. weight training) (Maroto-Izquierdo 2017b). The greater muscle mass plays an undisputed role in all adaptations related to muscle strength, power, and vertical jump (Maroto-Izquierdo et al. 2017b). The results showed by the FW group are in the same line as data from previous studies in which hypertrophy was measured by DXA (Fernandez-Gonzalo et al. 2014a). These results were also observed in the EX2 group. Although it has been demonstrated that muscle adaptations are greater when the ROM employed during training is larger (McMahon et al. 2014), and the working angle is an important factor to consider when iso-inertial RT is carried out (Maroto-Izquierdo et al. 2017b), no significant differences were observed between groups in the present work. The EX1 group showed a smaller effect size on muscle mass increases, which could be related to the magnitude of the EO. However, although results obtained through DEXA analysis are correlated with Magnetic Resonance Imaging and represents a valid approach to estimate muscle mass (Fernandez-Gonzalo et al. 2014a), we did not include any other architectural parameter among our variables. Furthermore, although time-under-tension and training-induced adaptations are similar between groups, the measurement of muscle activation during exercise could provide deeper insights into the comparison between different iso-iniertial devices. However, muscle activation during exercise (e.g. electromyography) has not been measured in this work. Therefore, one of the limitations of this study is the lack of inclusion of other physiological parameters to provide more information on the functional and structural adaptations found. Future research should include these neurophysiological parameters to deepen on the effects of iso-inertial training with different devices and the underpinning physiological mechanisms.

Conclusions

In summary, 6 weeks of RT with EO in physically active young men induced significant gains in strength, muscle power at different loads, vertical jump and lean tissue mass. The adaptations generated by an active electric-motor device, which produces EO throughout the entire ROM, were similar to those produced by a traditional flywheel device, where the EO occurs during the last part of the ROM. However, an electric-motor device allowed for modifications in the CON and ECC loads independently, as well as changes in the ECC speed with respect to the CON speed, which translated into higher EO. Therefore, the electric-motor devices have potential benefits for eccentrically reinforced training, functioning as an ideal inertial device without requiring a maximum CON action to generate EO. Such characteristic could be an interesting asset in clinical and sport performance environments.

CONCLUSIONS

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

CONCLUSIONS

The results obtained in our works and disseminated in the publications that constitute this doctoral thesis establish the following conclusions:

- FIRST CONCLUSION:

  Eccentric overload resistance training performed with non-gravity-dependent iso-inertial devices is an effective method leading to functional and structural changes in physically active young people and athletes.

- SECOND CONCLUSION:

  Brief episodes of eccentric overload, induced by maximum concentric actions with iso-inertial devices, performed at high intensity may generate greater increases in strength, muscle power, muscle mass and sport-specific performance tasks, such as vertical jump and running velocity, compared to traditional resistance training in both young physically active people and athletes.

- THIRD CONCLUSION:

  Six weeks of eccentric overload resistance training with flywheel devices led to significant enhancements in maximal dynamic strength, muscle power at different loads, vertical jump height, sprint time, agility, and muscle hypertrophy in professional athletes. In addition, muscle power, running speed and muscle size gains were higher compared to those induced by the same exercise performed in a weight-stack traditional machine at similar volume and intensity.

- FOURTH CONCLUSION:

  Six weeks of resistance training with eccentric overload generated by different iso-inertial devices in physically young males induced significant gains in strength, muscle power, vertical jump and lean tissue mass. The adaptations generated by an active electric-motor device were similar to those produced by a traditional flywheel device.

As a general conclusion, the different publications that constitute this doctoral thesis clearly enable us to establish eccentric overload resistance training is an effective method to develop muscle mass and increase neuromuscular performance (strength, power and speed) in athletes and physically active people. Six weeks of accentuated eccentric iso-inertial resistance training interventions led to significant gains in strength, muscle power at different intensities, vertical jump, running speed and muscle mass. Furthermore, these increases were larger than those found with other training methods (e.g. free-weight), not only in muscle mass size, but also in functional capacity. Therefore, new technologies which accentuate the eccentric action, such as electric-motors and flywheel devices, is an effective training method, which requires less mechanical work and constitute and easier way to apply overload than other traditional strength training methods. In addition, electric-motor devices seem to be interest in strength training, since they allow the prescription of a maximum (or submaximum) training loads during the eccentric action without the concentric strength limiting its potential. Finally, electric-motor devices have potential benefits for eccentrically reinforced training, functioning as an ideal inertial device without requiring a maximum concentric action to generate eccentric overload. Such characteristic could be an interesting asset in clinical and sport performance environments.

INTERNATIONAL CONFERENCE PRESENTATIONS AND FUTURE PUBLICATIONS

In addition, part of the most recent findings of this doctoral thesis have been published at some international conferences, and will constitute future publications aiming to:

- Examine muscle thickness (as an indicator of muscle hypertrophy), isokinetic torque and power at three different velocities in the rotator cuff, and throwing speed after short-term intervention of either pneumatic or flywheel training in professional handball players.
- Investigate the effects of three different unilateral iso-inertial resistance training protocols with eccentric-overload on changes in muscle mass and function of trained and contralateral non-trained legs.
- Determine and compare the effects of submaximal and supramaximal loads during eccentric overload resistance training on lower-limb neuromuscular performance, muscle mass and anabolic hormonal levels in physical active men.

Communication 1: Maroto-Izquierdo et al. (2018). Hypertrophic effects of iso-inertial effects on the shoulder muscles of professional handball players. 5th Congreso Internacional Ejercicio Físico y Salud. Sonora, Mexico.

Communication 2: Maroto-Izquierdo et al. (2018). Iso-inertial flywheel training and Pneumatic training effects on hypertrophy, strength and power of shoulder muscles in professional handball players. 6th National Strength & Conditioning Association (NSCA) International Conference. Madrid, Spain.

Communication 3: Maroto-Izquierdo et al. (2018). Effects of unilateral accentuated eccentric iso-inertial resistance training on muscle mass and function of the trained and non-trained contralateral legs. 11th International Conference on Strength Training (ICST). Perth, WA, Asutralia.

Communication 4: Maroto-Izquierdo et al. (2019). Functional and Structural effects of submaximal and supramaximal loads during eccentric-overload resistance training in the trained and contralateral legs. 24th European College of Sport Science (ECSS) Congress. Prague, Czech Republic.

Paper 4: Maroto-Izquierdo S, et al. (2019). Comparison of flywheel and pneumatic training on shoulder muscle hypertrophy, strength and power in professional handball players. Int J Sports Physiol Perform. Under Review.

Paper 5: Maroto-Izquierdo S, et al. (2019). Effects of unilateral accentuated eccentric iso-inertial resistance training on muscle mass and function of the trained and non-trained contralateral legs.

Paper 6: Maroto-Izquierdo S, et al. (2019). Functional and structural effects of submaximal and supramaximal loads during eccentric-overload resistance training.

REFERENCES

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

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REFERENCES

Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Halkjaer-Kristensen J, Dyhre-Poulsen P (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: effects of resistance training. *J Appl Physiol (1985)*, 89 (6): 2249-2257.

Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P (2002). Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *J Appl Physiol (1985)*, 92 (6): 2309-2318. doi:10.1152/japplphysiol.01185.2001

Aagaard P (2003). Training-induced changes in neural function. *Exerc Sport Sci Rev*, 31 (2): 61-67.

Abbott BC, Bigland B, Ritchie JM (1952). The physiological cost of negative work. *J Physiol*, 117 (3): 380-390.

Aboodarda SJ, Yusof A, Abu Osman NA, Thompson MW, Mokhtar AH (2013). Enhanced performance with elastic resistance during the eccentric phase of a countermovement jump. *Int J Sports Physiol Perform*, 8 (2): 181-187.

Albert MS, Hillegass E, Spiegel P (1994). Muscle torque changes caused by inertial exercise training. *J Orthop Sports Phys Ther*, 20 (5): 254-261. doi:10.2519/jospt.1994.20.5.254

Alcaraz PE, Romero-Arenas S, Vila H, Ferragut C (2011). Power-load curve in trained sprinters. *J Strength Cond Res*, 25 (11): 3045-3050. doi:10.1519/JSC.0b013e318212e1fa

Alegre LM, Ferri-Morales A, Rodriguez-Casares R, Aguado X (2014). Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. *Eur J Appl Physiol*, 114 (11): 2437-2446. doi:10.1007/s00421-014-2967-x

Alegre LM, Aguado X, Rojas-Martin D, Martin-Garcia M, Ara I, Csapo R (2015). Load-controlled moderate and high-intensity resistance training programs provoke similar strength gains in young women. *Muscle Nerve*, 51 (1): 92-101. doi:10.1002/mus.24271

Alkner BA, Berg HE, Kozlovskaya I, Sayenko D, Tesch P (2003). Effects of strength training, using a gravity-independent exercise system, performed during 110 days of simulated space station confinement. *Eur J Appl Physiol*, 90 44-49.

Alkner B, Tesch PA (2004a). Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest. *Acta Physiol Scand*, 181 345-357.

Alkner BA, Tesch P (2004b). Knee extensor and plantar flexor muscle size and function in response to 90 d bed rest with or without resistance exercise. *Eur J Appl Physiol*, 93 294-305.

Andersen JL, Aagaard P (2010). Effects of strength training on muscle fiber types and size; consequences for athletes training for high-intensity sport. *Scand J Med Sci Sports*, 20 (2): 32-38. doi:10.1111/j.1600-0838.2010.01196.x

Andersen LL, Aagaard P (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur J Appl Physiol*, 96 (1): 46-52. doi:10.1007/s00421-005-0070-z

Ando R, Nosaka K, Tomita A, Watanabe K, Blazevich AJ, Akima H (2018). Vastus intermedius vs vastus lateralis fascicle behaviors during maximal concentric and eccentric contractions. *Scand J Med Sci Sports*, 28 (3): 1018-1026. doi:10.1111/sms.13022

Arabatzi F, Kellis E (2012). Olympic weightlifting training causes different knee muscle-coactivation adaptations compared with traditional weight training. *J Strength Cond Res*, 26 (8): 2192-2201. doi:10.1519/JSC.0b013e31823b087a

Ashton RE, Tew GA, Aning JJ, Gilbert SE, Lewis L, Saxton JM (2018). Effects of short-term, medium-term and long-term resistance exercise training on cardiometabolic health outcomes in adults: systematic review with meta-analysis. *Br J Sports Med*, doi:10.1136/bjsports-2017-098970

Askling C, Karlsson J, Thorstensson A (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports*, 13 (4): 244-250.

Avrillon S, Jidovtseff B, Hug F, Guilhem G (2017). Influence of Isoinertial-Pneumatic Mixed Resistances on Force-Velocity Relationship. *Int J Sports Physiol Perform*, 12 (3): 385-392. doi:10.1123/ijspp.2016-0226

Azizi E, Roberts TJ (2014). Geared up to stretch: pennate muscle behavior during active lengthening. *J Exp Biol*, 217 (Pt 3): 376-381. doi:10.1242/jeb.094383

Baechle T, Earle RW (2008). *Essentials of strength training and conditioning.* Human Kinetics, Champaign, IL.

Bamey VS, Bamgerter BL (1961). Comparison of three programs of progressive resistance exercise. *Res Q*, 32 138-146.

Barry DW, Kohrt WM (2008). Exercise and the preservation of bone health. *J Cardiopulm Rehabil Prev*, 28 (3): 153-162. doi:10.1097/01.HCR.0000320065.50976.7c

Barstow IK, Bishop MD, Kaminski TW (2003). Is enhanced-eccentric resistance training superior to traditional training for increasing elbow flexor strength? *J Sports Sci Med*, 2 (2): 62-69.

Bauer P, Uebellacker F, Mitter B, Aigner AJ, Hasenoehrl T, Ristl R, Tschan R, Seitx, LB (2019). Combining higher-load and lower-load resistance training exercises: A systematic review and meta-analysis of findings from complex training studies. *J Sci Med Sport*. doi:10.1016/j.jsams.2019.01.006

Behm DG, Anderson KG (2006). The role of instability with resistance training. *J Strength Cond Res*, 20 (3): 716-722. doi:10.1519/R-18475.1

Behm DG, Muehlbauer T, Kibele A, Granacher U (2015). Effects of strength training using unstable surfaces on strength, power and balance performance across the lifespan: A systematic review and meta-analysis. *Sports Med*, 45 (12): 1645-1669. doi:10.1007/s40279-015-0384-x

Beltman JG, Sargeant AJ, van Mechelen W, de Haan A (2004). Voluntary activation level and muscle fiber recruitment of human quadriceps during lengthening contractions. *J Appl Physiol (1985)*, 97 (2): 619-626. doi:10.1152/japplphysiol.01202.2003

Berg HE, Tesch A (1994). A gravity-independent ergometer to be used for resistance training in space. *Aviat Space Environ Med*, 65 (8): 752-756.

Berg HE, Tesch A (1998). Force and power characteristics of a resistive exercise device for use in space. *Acta Astronaut*, 42 (1-8): 219-230.

Berger RA (1962a). Effect of varied weight training programs on strength. *Res Q*, 33: 168-181.

Berger RA (1962b). Optimum repetitions for the development of strength. *Res Q*, 33 :334-338.

Berger RA (1963). Comparative effects of three weight training programs. *Res Q*, 34: 396-398.

Berger RA (1966). Leg extension force at three different angles. *Res Q*, 37 (4): 560-562.

Bergstrom J (1962). Muscle electrolytes in man. *Scand J Clin Lab Invest*, 68 100-110.

Berning JM, Adams KJ, DeBeliso M, Sevene-Adams PG, Harris C, Stamford BA (2010). Effect of functional isometric squats on vertical jump in trained and untrained men. *J Strength Cond Res*, 24 (9): 2285-2289. doi:10.1519/JSC.0b013e3181e7ff9a

Berton R, Lixandrao ME, Pinto ESCM, Tricoli V (2018). Effects of weightlifting exercise, traditional resistance and plyometric training on countermovement jump performance: a meta-analysis. *J Sports Sci*, 36 (18): 2038-2044. doi:10.1080/02640414.2018.1434746

Blair SN, Kampert JB, Kohl HW, 3rd, Barlow CE, Macera CA, Paffenbarger RS, Jr., Gibbons LW (1996). Influences of cardiorespiratory fitness and other precursors on cardiovascular disease and all-cause mortality in men and women. *JAMA*, 276 (3): 205-210.

Blazevich AJ, Cannavan D, Coleman DR, Horne S (2007). Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985)*, 103 (5): 1565-1575. doi:10.1152/japplphysiol.00578.2007

Blazevich AJ, Horne S, Cannavan D, Coleman DR, Aagaard P (2008). Effect of contraction mode of slow-speed resistance training on the maximum rate of force development in the human quadriceps. *Muscle Nerve*, 38 (3): 1133-1146. doi:10.1002/mus.21021

Blazevich A (2017). *Sports Biomechanics. The Basics: Optimizing human performance.* Bloomsbury, London, UK

Bouchard C, Blair SN, Katzmarzyk PT (2015). Less sitting, more physical activity, or higher fitness? *Mayo Clin Proc*, 90 (11): 1533-1540. doi:10.1016/j.mayocp.2015.08.005

Bouleftour W et al. (2017). Bone shaft revascularization after marrow ablation is dramatically accelerated in BSP mice, along with faster hematopoietic recolonization. *J Cell Physiol*, 232 (9): 2528-2537. doi:10.1002/jcp.25630

Boyle M (2016). *New functional training for sports.* Human Kinetics, Australia

Braghin F, Basseti M, Crosio P, Locati D (2013). *Direct measurment of power on a gravity independent flywheel based ergometer*. In: *Special Topics in Structural Dynamics*, vol 6. Springer New York, pp 83-85

Brandenburg JP, Docherty D (2002). The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *J Strength Cond Res*, 16 (1): 25-32.

Bruseghini P et al. (2015). Effects of eight weeks of aerobic interval training and of isoinertial resistance training on risk factors of cardiometabolic diseases and exercise capacity in healthy elderly subjects. *Oncotarget*, 6 (19): 16998-17015. doi:10.18632/oncotarget.4031

Brzenczek-Owczarzak W, Naczk M, Arlet J, Forjasz J, Jedrzejczak T, Adach Z (2013). Estimation of the efficacy of inertial training in older women. *J Aging Phys Act*, 21 (4): 433-443.

Bullock N, Comfort P (2011). An investigation into the acute effects of depth jumps on maximal strength performance. *J Strength Cond Res*, 25 (11): 3137-3141. doi:10.1519/JSC.0b013e318212e224

Butler RJ, Crowell HP, Davis IM (2003). Lower extremity stiffness: implications for performance and injury. *Clin Biomech*, 18 (6): 511-517.

Carroll TJ, Selvanayagam VS, Riek S, Semmler JG (2011). Neural adaptations to strength training: moving beyond transcranial magnetic stimulation and reflex studies. *Acta Physiol (Oxf)*, 202 (2): 119-140. doi:10.1111/j.1748-1716.2011.02271.x

Carroll KM, Wagle JP, Sato K, Taber CB, Yoshida N, Bingham GE, Stone MH (2018). Characterising overload in inertial flywheel devices for use in exercise training. *Sports Biomech*, 1-12. doi:10.1080/14763141.2018.1433715

Caruso JF, Hernandez DA (2002). Net caloric cost of a 3-set flywheel ergometer resistance exercise paradigm. *J Strength Cond Res*, 16 (4): 567-572.

Caruso JF, Hernandez DA, Porter A, Schweikert T, Saito K, Cho M, De Garmo N, Nelson NM (2006). Integrated electromyography and performance outcomes to inertial resistance exercise. *J Strength Cond Res*, 20 (1): 151-156. doi:10.1519/R-17315.1

Caruso JF, Coday MA, Ramsey CA, Mclagan JR (2009). The impact of resistive exercise training on the relationship between anthropometry and jump-based power indices. *Isokinet Exerc Sci*, 17 (1): 41-50.

Channell BT, Barfield JP (2008). Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *J Strength Cond Res*, 22 (5): 1522-1527. doi:10.1519/JSC.0b013e318181a3d0

Chapman D, Newton M, Sacco P, Nosaka K (2006). Greater muscle damage induced by fast versus slow velocity eccentric exercise. *Int J Sports Med*, 27 (8): 591-598. doi:10.1055/s-2005-865920

Chelly MS, Fathloun M, Cherif N, Ben Amar M, Tabka Z, Van Praagh E (2009). Effects of a back squat training program on leg power, jump, and sprint performances in junior soccer players. *J Strength Cond Res*, 23 (8): 2241-2249. doi:10.1519/JSC.0b013e3181b86c40

Chelly MS, Ghenem MA, Abid K, Hermassi S, Tabka Z, Shephard RJ (2010). Effects of in-season short-term plyometric training program on leg power, jump- and sprint performance of soccer players. *J Strength Cond Res*, 24 (10): 2670-2676. doi:10.1519/JSC.0b013e3181e2728f

Chiu LZ, Salem GJ (2006). Comparison of joint kinetics during free weight and flywheel resistance exercise. *J Strength Cond Res*, 20 (3): 555-562. doi:10.1519/R-18245.1

Chui E (1950). The effect of systematic weight training on athletic power. *Res Q*, 21 188-194.

Chui E (1964). Effects of isometric and dynamic weight-training exercises upon strength and speed of movement. *Res Q*, 35 246-257.

Cirer-Sastre R, Beltran-Garrido JV, Corbi F (2017). Contralateral effects after unilateral strength training: a meta-analysis comparing training loads. *J Sports Sci Med*, 16 (2): 180-186.

Coburn JW, Malek, M.H. (ed) (2012) NSCA's essentials of personal training vol 2. Detroit.

Cohen J (1998). *Statistical power analysis for the behavioral sciences.*, (2nd ed.) edn. Erlbaum Associates, Hillsdale, NJ: L.

Colliander EB, Tesch PA (1990). Effects of eccentric and concentric muscle actions in resistance training. *Acta Physiol Scand*, 140 (1): 31-39. doi:10.1111/j.1748-1716.1990.tb08973.x

Coratella G, Schena F (2016). Eccentric resistance training increases and retains maximal strength, muscle endurance, and hypertrophy in trained men. *Appl Physiol Nutr Metab*, 41 (11): 1184-1189. doi:10.1139/apnm-2016-0321

Cormie P, McCaulley GO, McBride JM (2007). Power versus strength-power jump squat training: influence on the load-power relationship. *Med Sci Sports Exerc*, 39 (6): 996-1003. doi:10.1097/mss.0b013e3180408e0c

Cormie P, McBride JM, McCaulley GO (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *J Appl Biomech*, 24 (2): 112-120.

Cormie P, McGuigan MR, Newton RU (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Med Sci Sports Exerc*, 42 (9): 1731-1744. doi:10.1249/MSS.0b013e3181d392e8

Cuenca-Fernandez F, Lopez-Contreras G, Arellano R (2015). Effect on swimming start performance of two types of activation protocols: lunge and YoYo squat. *J Strength Cond Res*, 29 (3): 647-655. doi:10.1519/JSC.0000000000000696

Davies T, Orr R, Halaki M, Hackett D (2016). Effect of training leading to repetition failure on muscular strength: a systematic review and meta-analysis. *Sports Med*, 46 (4): 487-502. doi:10.1007/s40279-015-0451-3

de Hoyo M, de la Torre A, Paradas F, Sañudo B, Carrasco L, Mateo-Cortes J, Dominguez-Cobo S, Fernandes O, Gonzalo-Skok O (2015a). Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med*, 36 (4): 308-314. doi:10.1055/s-0034-1395521

de Hoyo M, Pozzo M, Sanudo B, Carrasco L, Gonzalo-Skok O, Dominguez-Cobo S, Moran-Camacho E (2015b). Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int J Sports Physiol Perform*, 10 (1): 46-52. doi:10.1123/ijspp.2013-0547

de Hoyo M, Sanudo B, Carrasco L, Dominguez-Cobo S, Mateo-Cortes J, Cadenas-Sanchez MM, Nimphius S (2015c). Effects of traditional versus horizontal inertial flywheel power training on common sport-related tasks. *J Hum Kinet*, 47 155-167. doi:10.1515/hukin-2015-0071

de Hoyo M, Sañudo B, Carrasco L, Mateo-Cortes J, Dominguez-Cobo S, Fernandes O, Del Ojo JJ, Gonzalo-Skok O (2016). Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. *J Sports Sci*, 34 (14): 1380-1387. doi:10.1080/02640414.2016.1157624

de Paula Simola RA, Harms N, Raeder C, Kellmann M, Meyer T, Pfeiffer M, Ferrauti A (2015). Assessment of neuromuscular function after different strength training protocols using tensiomyography. *J Strength Cond Res*, 29 (5): 1339-1348. doi:10.1519/JSC.0000000000000768

de Paula Simola RA, Harms N, Raeder C, Kellmann M, Meyer T, Pfeffer F, Ferrauti A (2016). Tensiomyography reliability and prediction of changes in muscle force following heavy eccentric strength exercise using muscle mechanical properties. *Sports Technol*, 1-9. doi:10.1080/19346182.2015.1117475

Del Valle A, Thomas CK (2005). Firing rates of motor units during strong dynamic contractions. *Muscle Nerve*, 32 (3): 316-325. doi:10.1002/mus.20371 deVries HA (1968). Efficiency of electrical activity as a physiological measure of the functional state of muscle tissue. *Am J Phys Med*, 47 10-22.

Dias CP, Toscan R, de Camargo M, Pereira EP, Griebler N, Baroni BM, Tiggemann CL (2015). Effects of eccentric-focused and conventional resistance training on strength and functional capacity of older adults. *Age (Dordr)*, 37 (5): 99. doi:10.1007/s11357-015-9838-1

Dimitriadis G, Mitrou P, Lambadiari V, Maratou E, Raptis SA (2011). Insulin effects in muscle and adipose tissue. *Diabetes Res Clin Pract*, 93 Suppl 1 S52-59. doi:10.1016/S0168-8227(11)70014-6

Dintiman GB (1964). Effects of various training programs on running speed. *Res Q*, 35 456-463.

Douglas J, Pearson S, Ross A, McGuigan M (2017a). Chronic adaptations to eccentric training: a systematic review. *Sports Med*, 47 (5): 917-941. doi:10.1007/s40279-016-0628-4

Douglas J, Pearson S, Ross A, McGuigan M (2017b). Eccentric exercise: physiological characteristics and acute responses. *Sports Med*, 47 (4): 663-675. doi:10.1007/s40279-016-0624-8

Douglas J, Pearson S, Ross A, McGuigan M (2018). Effects of accentuated eccentric loading on muscle properties, strength, power, and speed in resistance-trained rugby players. *J Strength Cond Res*, 32 (10): 2750-2761. doi:10.1519/JSC.0000000000002772

Duchateau J, Enoka RM (2016). Neural control of lengthening contractions. *J Exp Biol*, 219 (Pt 2): 197-204. doi:10.1242/jeb.123158

Duchateau J, Semmler JG, Enoka RM (2006). Training adaptations in the behavior of human motor units. *J Appl Physiol (1985)*, 101 (6): 1766-1775. doi:10.1152/japplphysiol.00543.2006

Duchateau J, Enoka RM (2008). Neural control of shortening and lengthening contractions: influence of task constraints. *J Physiol*, 586 (24): 5853-5864. doi:10.1113/jphysiol.2008.160747

Duchateau J, Baudry S (2014). Insights into the neural control of eccentric contractions. *J Appl Physiol*, 116 (11): 1418-1425. doi:10.1152/japplphysiol.00002.2013

Dudley GA, Tesch PA, Harris RT, Golden CL, Buchanan P (1991a). Influence of eccentric actions on the metabolic cost of resistance exercise. *Aviat Space Environ Med*, 62 (7): 678-682.

Dudley GA, Tesch PA, Miller BJ, Buchanan P (1991b). Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med*, 62 (6): 543-550.

Elkins MR, Moseley AM, Sherrington C, Herbert RD, Maher CG (2013). Growth in the physiotherapy evidence database (PEDro) and use of the PEDro scale. *Br J Sports Med*, 47 (4): 188-189. doi:10.1136/bjsports-2012-091804

Elmer S, Hahn S, McAllister P, Leong C, Martin J (2012). Improvements in multi-joint leg function following chronic eccentric exercise. *Scand J Med Sci Sports*, 22 (5): 653-661. doi:10.1111/j.1600-0838.2011.01291.x

Elmer SJ, Danvind J, Holmberg HC (2013). Development of a novel eccentric arm cycle ergometer for training the upper body. *Med Sci Sports Exerc*, 45 (1): 206-211. doi:10.1249/MSS.0b013e318269c79c

Eng CM, Azizi E, Roberts TJ (2018). Structural determinants of muscle gearing during dynamic contractions. *Integr Comp Biol*. doi:10.1093/icb/icy054

English KL, Loehr JA, Lee SM, Smith SM (2014). Early-phase musculoskeletal adaptations to different levels of eccentric resistance after 8 weeks of lower body training. *Eur J Appl Physiol*, 114 (11): 2263-2280. doi:10.1007/s00421-014-2951-5

Enoka RM (1995). Morphological features and activation patterns of motor units. *J Clin Neurophysiol*, 12 (6): 538-559.

Enoka RM (ed) (2002) Neuromechanics of human movement. . Human Kinetics, Champaign, IL

Fahey TD, Rolph R, Moungmee P, Nagel J, Mortara S (1976). Serum testosterone, body composition, and strength of young adults. *Med Sci Sports*, 8 31-34.

Falvo MJ, Sirevaag EJ, Rohrbaugh JW, Earhart GM (2010). Resistance training induces supraspinal adaptations: evidence from movement-related cortical potentials. *Eur J Appl Physiol*, 109 (5): 923-933.

doi:10.1007/s00421-010-1432-8

Fang Y, Siemionow V, Sahgal V, Xiong F, Yue GH (2001). Greater movement-related cortical potential during human eccentric versus concentric muscle contractions. *J Neurophysiol*, 86 (4): 1764-1772.

Fang Y, Siemionow V, Sahgal V, Xiong F, Yue GH (2004). Distinct brain activation patterns for human maximal voluntary eccentric and concentric muscle actions. *Brain Res*, 1023 (2): 200-212. doi:10.1016/j.brainres.2004.07.035

Farthing JP, Chilibeck PD (2003). The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *Eur J Appl Physiol*, 89 (6): 578-586. doi:10.1007/s00421-003-0842-2

Farup J et al. (2014). Whey protein hydrolysate augments tendon and muscle hypertrophy independent of resistance exercise contraction mode. *Scand J Med Sci Sports*, 24 (5): 788-798. doi:10.1111/sms.12083

Fernandez-Gonzalo R (2011). *Efectos del entrenamineto excéntrico sobre el daño muscular y la señalización intracelular del receptor tipo toll 4 (TLR4)*. Universidad de León.

Fernandez-Gonzalo R, Bresciani G, de Souza-Teixeira F, Hernandez-Murua JA, Jimenez-Jimenez R, Gonzalez-Gallego J, de Paz JA (2011). Effects of a 4-week eccentric training program on the repeated bout effect in young active women. *J Sports Sci Med*, 10 (4): 692-699.

Fernandez-Gonzalo R, Lundberg TR, Alvarez-Alvarez L, de Paz JA (2014a). Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *Eur J Appl Physiol*, 114 (5): 1075-1084. doi:10.1007/s00421-014-2836-7

Fernandez-Gonzalo R, Nissemark C, Aslund B, Tesch PA, Sojka P (2014b). Chronic stroke patients show early and robust improvements in muscle and functional performance in response to eccentric-overload flywheel resistance training: a pilot study. *J Neuroeng Rehabil*, 11: 150. doi:10.1186/1743-0003-11-150

Fernandez-Gonzalo R, Fernandez-Gonzalo S, Turon M, Prieto C, Tesch PA, Garcia-Carreira Mdel C (2016). Muscle, functional and cognitive adaptations after flywheel resistance training in stroke patients: a pilot randomized controlled trial. *J Neuroeng Rehabil*, 13: 37. doi:10.1186/s12984-016-0144-7

Fisher JP, Carlson L, Steele J (2016). The effects of muscle action, repetition duration, and loading strategies of a whole-body, progressive resistance training programme on muscular performance and body composition in trained males and females. *Appl Physiol Nutr Metab*, 41 (10): 1064-1070. doi:10.1139/apnm-2016-0180

Flanagan SD, Dunn-Lewis C, Comstock BA, Maresh CM, Volek JS, Denegar CR, Kraemer WJ (2012). Cortical activity during a highly-trained resistance exercise movement emphasizing force, power or volume. *Brain Sci*, 2 (4): 649-666. doi:10.3390/brainsci2040649

Fleck SJ, Falkel JE (1986). Value of resistance training for the reduction of sports injuries. *Sports Med*, 3 (1): 61-68. doi:10.2165/00007256-198603010-00006

Foure A, Nordez A, Cornu C (2013). Effects of eccentric training on mechanical properties of the plantar flexor muscle-tendon complex. *J Appl Physiol (1985)*, 114 (5): 523-537. doi:10.1152/japplphysiol.01313.2011

Franchi MV, Atherton PJ, Reeves ND, Flük M, Williams JP, Mitchel WK, Selby A, Beltran Valls RM, Narici VM (2014). Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol (Oxf)*, 210 (3): 642-654. doi:10.1111/apha.12225

Franchi MV, Wilkinson DJ, Quinlan JI, Mitchel WK, Lund JN, Williams JP, Reeves ND, Smith K, Atherton PJ, Narici VM (2015). Early structural remodeling and deuterium oxide-derived protein metabolic responses to eccentric and concentric loading in human skeletal muscle. *Physiol Rep*, 3 (11): doi:10.14814/phy2.12593

Franchi MV, Reeves ND, Narici MV (2017). Skeletal Muscle Remodeling in Response to Eccentric vs. Concentric Loading: Morphological, Molecular, and Metabolic Adaptations. *Front Physiol*, 8: 447. doi:10.3389/fphys.2017.00447

Freitas TT, Martinez-Rodriguez A, Calleja-Gonzalez J, Alcaraz PE (2017). Short-term adaptations following Complex Training in team-sports: A meta-analysis. *PLoS One*, 12 (6): e0180223. doi:10.1371/journal.pone.0180223

Friedmann-Bette B, Kinscherf R, Vorwald S, Müller H, Kucera K, Borisch S, Richter G, Bärtsch P, Billeter R (2004). Muscular adaptations to computer-guided strength training with eccentric overload. *Acta Physiol Scand*, 182 (1): 77-88. doi:10.1111/j.1365-201X.2004.01337.x

Friedmann-Bette B Bauer T, Kinscherf R, Vorwald S, Klute K, Bischoff D, Müller H, Weber MA, Metz J, Kauczor HU, Bärtsch P, Billeter R (2010). Effects of strength training with eccentric overload on muscle adaptation in male athletes. *Eur J Appl Physiol*, 108 (4): 821-836. doi:10.1007/s00421-009-1292-2

Frohm A, Halvorsen K, Thorstensson A (2005). A new device for controlled eccentric overloading in training and rehabilitation. *Eur J Appl Physiol*, 94 (1-2): 168-174. doi:10.1007/s00421-004-1298-8

Frost DM, Cronin J, Newton RU (2010). A biomechanical evaluation of resistance: fundamental concepts for training and sports performance. *Sports Med*, 40 (4): 303-326. doi:10.2165/11319420-000000000-00000

Fry AC (2004). The role of resistance exercise intensity on muscle fibre adaptations. *Sports Med*, 34 (10): 663-679. doi:10.2165/00007256-200434100-00004

Gabriel DA, Kamen G, Frost G (2006). Neural adaptations to resistive exercise: mechanisms and recommendations for training practices. *Sports Med*, 36 (2): 133-149. doi:10.2165/00007256-200636020-00004

Garber CE, Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, Nieman DC, Swain DP (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Med Sci Sports Exerc*, 43 (7): 1334-1359. doi:10.1249/MSS.0b013e318213fefb

Garcia-Hermoso A, Cavero-Redondo I, Ramirez-Velez R, Ruiz JR, Ortega FB, Lee DC, Martinez-Vizcaino V (2018). Muscular strength as a predictor of all-cause mortality in an apparently healthy population: a systematic review and meta-analysis of data from approximately 2 million men and women. *Arch Phys Med Rehabil*, 99 (10): 2100-2113 e2105. doi:10.1016/j.apmr.2018.01.008

Garcia-Lopez D (2006). *Efectos del entrenamiento excéntrico sobre el daño muscular, el estrés oxidativo y la activación del factor de transcripción nuclear Kappa-B inducidos por un ejercicio excéntrico agudo*. Universidad de León.

Garcia-Lopez D, Cuevas MJ, Almar M, Lima E, De Paz JA, Gonzalez-Gallego J (2007). Effects of eccentric exercise on NF-kappaB activation in blood mononuclear cells. *Med Sci Sports Exerc*, 39 (4): 653-664. doi:10.1249/mss.0b013e31802f04f6

Garcia-Lopez D (2008). *El Entrenamiento Excéntrico. Fundamentos y aplicaciones con población general y deportista.* In: Jiménez Gutiérrez A (ed) *Nuevas dimensiones en el entrenamiento de fuerza: aplicación de nuevos métodos, recursos y tecnologías*. INDE, Barcelona, España, pp 75-102

Garcia-Lopez D, Hernandez-Sanchez S, Martin E, Marin PJ, Zarzosa F, Herrero AJ (2014). Free-weight augmentation with elastic bands improves bench-press kinematics in professional rugby players. *J Strength Cond Res*, doi:10.1519/JSC.0000000000000374

Gillies EM, Putman CT, Bell GJ (2006). The effect of varying the time of concentric and eccentric muscle actions during resistance training on skeletal muscle adaptations in women. *Eur J Appl Physiol*, 97 (4): 443-453. doi:10.1007/s00421-006-0192-y

Gonzalez-Badillo JJ, Gorostiaga E (2002). *Fundamentos del entrenamiento de la fuerza. Aplicación al alto rendimiento deportivo.* vol 3rd Edition. INDE, Zaragoza, Spain.

Gonzalez-Badillo JJ, Sanchez-Medina L (2010). Movement velocity as a measure of loading intensity in resistance training. *Int J Sports Med*, 31 (5): 347-352.

Gonzalo-Skok O, Tous-Fajardo J, Valero-Campo C, Berzosa C, Bataller AV, Arjol-Serrano JL, Moras G, Mendez-Villanueva A (2016). Eccentric overload training in team-sports functional performance: constant bilateral vertical vs. variable unilateral multidirectional movements. *Int J Sports Physiol Perform*,1-23. doi:10.1123/ijspp.2016-0251

Goode AP, Reiman MP, Harris L, DeLisa L, Kauffman A, Beltramo D, Poole C, Ledbetter L, Taylor AB. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. *Br J Sports Med*, 49 (6): 349-356. doi:10.1136/bjsports-2014-093466

Gorostiaga EM, Granados C, Ibanez J, Izquierdo M (2005). Differences in physical fitness and throwing velocity among elite and amateur male handball players. *Int J Sports Med*, 26 (3): 225-232. doi:10.1055/s-2004-820974

Grabiner MD, Owings TM (1999). Effects of eccentrically and concentrically induced unilateral fatigue on the involved and uninvolved limbs. *J Electromyogr Kinesiol*, 9 (3): 185-189.

Green H, Goreham C, Ouyang J, Ball-Burnett M, Ranney D (1999). Regulation of fiber size, oxidative potential, and capillarization in human muscle by resistance exercise. *Am J Physiol*, 276 (2): R591-596. doi:10.1152/ajpregu.1999.276.2.R591

Gross M, Luthy F, Kroell J, Muller E, Hoppeler H, Vogt M (2010). Effects of eccentric cycle ergometry in alpine skiers. *Int J Sports Med*, 31 (8): 572-576. doi:10.1055/s-0030-1254082

Gual G, Fort-Vanmeerhaeghe A, Romero-Rodriguez D, Tesch PA (2015). Effects of in-season inertial resistance training with eccentric overload in a sports population at risk for patellar tendinopathy. *J Strength Cond Res*, doi:10.1519/JSC.0000000000001286

Guezennec Y, Leger L, Lhoste F, Aymonod M, Pesquies PC (1986). Hormone and metabolite response to weight-lifting training sessions. *Int J Sports Med*, 7 (2): 100-105. doi:10.1055/s-2008-1025742

Guilhem G, Cornu C, Guevel A (2010). Neuromuscular and muscle-tendon system adaptations to isotonic and isokinetic eccentric exercise. *Ann Phys Rehabil Med*, 53 (5): 319-341. doi:10.1016/j.rehab.2010.04.003

Guilhem G, Cornu C, Guevel A (2012). A methodologic approach for normalizing angular work and velocity during isotonic and isokinetic eccentric training. *J Athl Train*, 47 (2): 125-129.

Guilhem G, Cornu C, Maffiuletti NA, Guevel A (2013). Neuromuscular adaptations to isoload versus isokinetic eccentric resistance training. *Med Sci Sports Exerc*, 45 (2): 326-335. doi:10.1249/MSS.0b013e31826e7066

Hackett D, Davies T, Soomro N, Halaki M (2016). Olympic weightlifting training improves vertical jump height in sportspeople: a systematic review with meta-analysis. *Br J Sports Med*, 50 (14): 865-872. doi:10.1136/bjsports-2015-094951

Hahn D, Seiberl W, Schmidt S, Schweizer K, Schwirtz A (2010). Evidence of residual force enhancement for multi-joint leg extension. *J Biomech*, 43 (8): 1503-1508. doi:10.1016/j.jbiomech.2010.01.041

Hakkinen K, Komi PV, Alen M (1985a). Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand*, 125 (4): 587-600. doi:10.1111/j.1748-1716.1985.tb07759.x

Hakkinen K, Pakarinen A, Alen M, Komi PV (1985b). Serum hormones during prolonged training of neuromuscular performance. *Eur J Appl Physiol Occup Physiol*, 53 (4): 287-293.

Hakkinen K, Keskinen KL (1989). Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. *Eur J Appl Physiol Occup Physiol*, 59 (3): 215-220.

Hakkinen K, Kraemer WJ, Newton RU, Alen M (2001). Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. *Acta Physiol Scand*, 171 (1): 51-62. doi:10.1046/j.1365-201X.2001.00781.x

Hallal PC, Martins RC, Ramirez A (2014). The lancet physical activity observatory: promoting physical activity worldwide. *Lancet*, 384 (9942): 471-472. doi:10.1016/S0140-6736(14)61321-0

Hather BM, Tesch PA, Buchanan P, Dudley GA (1991). Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand*, 143 (2): 177-185. doi:10.1111/j.1748-1716.1991.tb09219.x

Hendy AM, Lamon S (2017). The cross-education phenomenon: brain and beyond. *Front Physiol*, 8 297. doi:10.3389/fphys.2017.00297

Herbert RD, Gandevia SC (1999). Twitch interpolation in human muscles: mechanisms and implications for measurement of voluntary activation. *J Neurophysiol*, 82 (5): 2271-2283. doi:10.1152/jn.1999.82.5.2271

Herzog W (2014). Mechanisms of enhanced force production in lengthening (eccentric) muscle contractions. *J Appl Physiol (1985)*, 116 (11): 1407-1417. doi:10.1152/japplphysiol.00069.2013

Herzog W, Powers K, Johnston K, Duvall M (2015). A new paradigm for muscle contraction. *Front Physiol*, 6 174. doi:10.3389/fphys.2015.00174

Herzog W, Schappacher G, DuVall M, Leonard TR, Herzog JA (2016). Residual force enhancement following eccentric contractions: a new mechanism involving titin. *Physiology,* 31 (4): 300-312. doi:10.1152/physiol.00049.2014

Hessel AL, Lindstedt SL, Nishikawa KC (2017). Physiological mechanisms of eccentric contraction and its applications: a role for the giant titin protein. *Front Physiol*, 8 70. doi:10.3389/fphys.2017.00070

Higbie EJ, Cureton KJ, Warren GL, 3rd, Prior BM (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J Appl Physiol*, 81 (5): 2173-2181.

Hoffman JR, Cooper J, Wendell M, Kang J (2004). Comparison of Olympic vs. traditional power lifting training programs in football players. *J Strength Cond Res*, 18 (1): 129-135.

Hollander DB et al. (2007). Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise. *J Strength Cond Res*, 21 (1): 34-40. doi:10.1519/R-18725.1

Hopkins WG, Marshall SW, Batterham AM, Hanin J (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 41 (1): 3-13. doi:10.1249/MSS.0b013e31818cb278

Hortobagyi T, Katch FI (1990). Eccentric and concentric torque-velocity relationships during arm flexion and extension. Influence of strength level. *Eur J Appl Physiol Occup Physiol*, 60 (5): 395-401.

Hortobagyi T, Barrier J, Beard D, Braspennincx J, Koens P, Devita P, Dempsey L, Lambert J. (1996a). Greater initial adaptations to submaximal muscle lengthening than maximal shortening. *J Appl Physiol (1985)*, 81 (4): 1677-1682. doi:10.1152/jappl.1996.81.4.1677

Hortobagyi T, Hill JP, Houmard JA, Fraser DD, Lambert NJ, Israel RG (1996b). Adaptive responses to muscle lengthening and shortening in humans. *J Appl Physiol*, 80 (3): 765-772.

Hortobagyi T, Lambert NJ, Hill JP (1997). Greater cross education following training with muscle lengthening than shortening. *Med Sci Sports Exerc*, 29 (1): 107-112.

Hortobagyi T, Dempsey L, Fraser D, Zheng D, Hamilton G, Lambert J, Dohm L (2000). Changes in muscle strength, muscle fibre size and myofibrillar gene expression after immobilization and retraining in humans. *J Physiol*, 524 Pt 1 293-304.

Hortobagyi T, DeVita P (2000). Favorable neuromuscular and cardiovascular responses to 7 days of exercise with an eccentric overload in elderly women. *J Gerontol A Biol Sci Med Sci*, 55 (8): B401-410.

Hortobagyi T, Devita P, Money J, Barrier J (2001). Effects of standard and eccentric overload strength training in young women. *Med Sci Sports Exerc*, 33 (7): 1206-1212.

Hortobagyi T, Money J, Zheng D, Dudek R, Fraser D, Dohm L (2002). Muscle adaptations to 7 days of exercise in young and older humans: Eccentric

Overload versus Standard Resistive Training. *J Aging Phys Act*, 10 290-305.

Hortobagyi T (2003). The positives of negatives: clinical implications of eccentric resistance exercise in old adults. *J Gerontol A Biol Sci Med Sci*, 58 (5): M417-418.

Hortobagyi T, DeVita P, LaStayo P (2009). Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *J Biomech*, 42 (7): 956-957. doi:10.1016/j.jbiomech.2008.12.024

Houtz S, Parrish A, Hellebrandt FA (1946). The influence of heavy resistance exercises on strength. *Physiother Rev*, 26 199-304.

Huxley AF, Hanson J (1954). Changes in the cross-striations of muscle during contraction and stretch and their structural interpretation. *Nature*, 173 973.

Huxley AF (1974). Review lecture: muscular contraction. *J Physiol*, 243 (1): 1-43.

Huxley AF (1998). Biological motors: energy storage in myosin molecules. *Curr Biol*, 8 (14): R485-488.

Hyldahl RD, Nelson B, XIn L, Welling T, Gorscost L, Hubal MJ, Chipkin S, Clarkson PM, Parcell AC (2015). Extracellular matrix remodeling and its contribution to protective adaptation following lengthening contractions in human muscle. *FASEB J*, 29 (7): 2894-2904. doi:10.1096/fj.14-266668

Hyldahl RD, Chen TC, Nosaka K (2017). Mechanisms and mediators of the skeletal muscle repeated bout effect. *Exerc Sport Sci Rev*, 45 (1): 24-33. doi:10.1249/JES.0000000000000095

Isner-Horobeti ME, Dufour SP, Vautravers P, Geny B, Coudeyre E, Richard R (2013). Eccentric exercise training: modalities, applications and perspectives. *Sports Med*, 43 (6): 483-512. doi:10.1007/s40279-013-0052-y

Izquierdo M et al. (2006a). Effect of loading on unintentional lifting velocity declines during single sets of repetitions to failure during upper and lower extremity muscle actions. *Int J Sports Med*, 27 (9): 718-724. doi:10.1055/s-2005-872825

Izquierdo M, Ibañez J, González-Badillo JJ, Häkkinen K, Ratamess NA, Kraemer WJ, French DN, Eslava J, Altadill A, Asiain X, Gorostiaga EM (2006b).

Differential effects of strength training leading to failure versus not to failure on hormonal responses, strength, and muscle power gains. *J Appl Physiol (1985)*, 100 (5): 1647-1656. doi:10.1152/japplphysiol.01400.2005

Jarvis MM, Graham-Smith P, Comfort P (2016). A methodological approach to quantifying plyometric intensity. *J Strength Cond Res*, 30 (9): 2522-2532. doi:10.1519/JSC.0000000000000518

Jimenez-Jimenez R, Cuevas MJ, Almar M, Lima E, Garcia-Lopez D, De Paz JA, Gonzalez-Gallego J (2008). Eccentric training impairs NF-kappaB activation and over-expression of inflammation-related genes induced by acute eccentric exercise in the elderly. *Mech Ageing Dev*, 129 (6): 313-321. doi:10.1016/j.mad.2008.02.007

Jimenez-Reyes P, Samozino P, Brughelli M, Morin JB (2016). Effectiveness of an individualized training based on force-velocity profiling during jumping. *Front Physiol*, 7 677. doi:10.3389/fphys.2016.00677

Jo E, Judelson DA, Brown LE, Coburn JW, Dabbs NC (2010). Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. *J Strength Cond Res*, 24 (2): 343-347. doi:10.1519/JSC.0b013e3181cc22a4

Kaminski TW, Wabbersen CV, Murphy RM (1998). Concentric versus enhanced eccentric hamstring strength training: clinical implications. *J Athl Train*, 33 (3): 216-221.

Kilgas MA, Elmer SJ (2017). Back to the future! Revisiting the physiological cost of negative work as a team-based activity for exercise physiology students. *Adv Physiol Educ*, 41 (1): 120-129. doi:10.1152/advan.00158.2016

Kingma JJ, de Knikker R, Wittink HM, Takken T (2007). Eccentric overload training in patients with chronic Achilles tendinopathy: a systematic review. *Br J Sports Med*, 41 (6): e3. doi:10.1136/bjsm.2006.030916

Kohl HW, Craig CL, Lambert EV, Inoue S, Alkandari JR, Leetongin G, Kahlmeier S (2012). The pandemic of physical inactivity: global action for public health. *Lancet*, 380 (9838): 294-305. doi:10.1016/S0140-6736(12)60898-8

Komi PV, Viitasalo JT (1976). Signal characteristics of EMG at different levels of muscle tension. *Acta Physiol Scand*, 96: 267-276.

Komi PV, Viitasalo JT, Rauramaa R, Vihko V (1978). Effect of isometric strength training of mechanical, electrical, and metabolic aspects of muscle function. *Eur J Appl Physiol Occup Physiol*, 40 (1): 45-55.

Komi PV (1984). Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. *Exerc Sport Sci Rev*, 12: 81-121.

Komi PV (1986). Training of muscle strength and power: interaction of neuromotoric, hypertrophic and mechanical factors. *Int J Sports Med*, 7 (1): 10-15.

Kraemer WJ, Ratamess NA (2004). Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc*, 36 (4): 674-688.

Kraemer WJ, Ratamess NA (2005). Hormonal responses and adaptations to resistance exercise and training. *Sports Med*, 35 (4): 339-361. doi:10.2165/00007256-200535040-00004

Kraemer WJ, Ratamess NA, Flanagan SD, Shurley JP, Todd JS, Todd TC (2017a). Understanding the science of resistance training: an evolutionary perspective. *Sports Med*, 47 (12): 2415-2435. doi:10.1007/s40279-017-0779-y

Kraemer WJ, Ratamess NA, Nindl BC (2017b). Recovery responses of testosterone, growth hormone, and IGF-1 after resistance exercise. *J Appl Physiol (1985)*, 122 (3): 549-558. doi:10.1152/japplphysiol.00599.2016

Kulig K, Powers CM, Shellock FG, Terk M (2001). The effects of eccentric velocity on activation of elbow flexors: evaluation by magnetic resonance imaging. *Med Sci Sports Exerc*, 33 (2): 196-200.

Lagally KM, Robertson RJ (2006). Construct validity of the OMNI resistance exercise scale. *J Strength Cond Res*, 20 (2): 252-256. doi:10.1519/R-17224.1

Lake J, Lauder M, Smith N, Shorter K (2012). A comparison of ballistic and nonballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. *J Appl Biomech*, 28 (4): 431-437.

Lauersen JB, Bertelsen DM, Andersen LB (2014). The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med*, 48 (11): 871-877. doi:10.1136/bjsports-2013-092538

Lee IM, Shiroma EJ, Lobelo F, Puska P, Blair SN, Katzmarzyk PT(2012). Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *Lancet*, 380 (9838): 219-229. doi:10.1016/S0140-6736(12)61031-9

Leeper A, Coday MA, Harikumar P, Caruso JF *Instrumentation of a high-speed inertial exercise device with load cell transducers*. In: 53rd International Instrumentation Symposium, 2007.

Leonard TR, Herzog W (2010). Regulation of muscle force in the absence of actin-myosin-based cross-bridge interaction. *Am J Physiol Cell Physiol*, 299 (1): C14-20. doi:10.1152/ajpcell.00049.2010

Linari M et al. (2000). A combined mechanical and X-ray diffraction study of stretch potentiation in single frog muscle fibres. *J Physiol*, 526 Pt 3 589-596.

Linari M, Bottinelli R, Pellegrino MA, Reconditi M, Reggiani C, Lombardi V (2004). The mechanism of the force response to stretch in human skinned muscle fibres with different myosin isoforms. *J Physiol*, 554 (Pt 2): 335-352. doi:10.1113/jphysiol.2003.051748

Lundberg TR, Fernandez-Gonzalo R, Gustafsson T, Tesch PA (2013). Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *J Appl Physiol*, 114 (1): 81-89. doi:10.1152/japplphysiol.01013.2012

Lundberg G, Fernandez-Gonzalo R, Tesch P (2014a). Exercise-induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol*, 116 611-620.

Lundberg TR, Fernandez-Gonzalo R, Tesch PA (2014b). Exercise induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol*. doi:10.1152/japplphysiol.01082.2013

Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J (2016). Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol*, 116 (6): 1091-1116. doi:10.1007/s00421-016-3346-6

Malliaras P et al. (2013). Patellar tendon adaptation in relation to load-intensity and contraction type. *J Biomech*, 46 (11): 1893-1899. doi:10.1016/j.jbiomech.2013.04.022

Manca A, Dragone D, Dvir Z, Deriu F (2017). Cross-education of muscular strength following unilateral resistance training: a meta-analysis. *Eur J Appl Physiol*, 117 (11): 2335-2354. doi:10.1007/s00421-017-3720-z

Manca A, Hortobagyi T, Rothwell J, Deriu F (2018). Neurophysiological adaptations in the untrained side in conjunction with cross-education of muscle strength: a systematic review and meta-analysis. *J Appl Physiol (1985)*, 124 (6): 1502-1518. doi:10.1152/japplphysiol.01016.2017

Maroto-izquierdo S, Garcia-Lopez D, de Paz JA (2017a). functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. *J Hum Kinet*, 60 133-143. doi:10.1515/hukin-2017-0096

Maroto-Izquierdo S, Garcia-Lopez D, Fernandez-Gonzalo R, Moreira OC, Gonzalez-Gallego J, de Paz JA (2017b). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport*, 20 (10): 943-951. doi:10.1016/j.jsams.2017.03.004

Maroto-Izquierdo S, Fernandez-Gonzalo R, Magdi HR, Manzano-Rodriguez S, Gonzalez-Gallego J, de Paz JA (2019). Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor. *Eur J Sport Sci*, 1-11. doi:10.1080/17461391.2019.1588920

Martinez-Aranda LM, Fernandez-Gonzalo R (2017). Effects of inertial setting on power, force, work, and eccentric overload during flywheel resistance exercise in women and men. *J Strength Cond Res*, 31 (6): 1653-1661. doi:10.1519/JSC.0000000000001635

Martyn-St James M, Carroll S (2006). Progressive high-intensity resistance training and bone mineral density changes among premenopausal women: evidence of discordant site-specific skeletal effects. *Sports Med*, 36 (8): 683-704. doi:10.2165/00007256-200636080-00005

Massuca LM, Fragoso I, Teles J (2014). Attributes of top elite team-handball players. *J Strength Cond Res*, 28 (1): 178-186. doi:10.1519/JSC.0b013e318295d50e

McCall GE, Byrnes WC, Dickinson A, Pattany PM, Fleck SJ (1996). Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. *J Appl Physiol (1985)*, 81 (5): 2004-2012.

McHugh MP, Tetro DT (2003). Changes in the relationship between joint angle and torque production associated with the repeated bout effect. *J Sports Sci*, 21 (11): 927-932. doi:10.1080/0264041031000140400

McLoda T, Murphy KM, Davison S (2003). Functional effects of inertial training of the upper extremity. *J Sport Rehabil*, 12 (3): 229-339.

McMahon GE, Morse CI, Burden A, Winwood K, Onambele GL (2014). Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. *J Strength Cond Res*, 28 (1): 245-255. doi:10.1519/JSC.0b013e318297143a

McMorris RO, Elkins EC (1954). A study of production and evaluation of muscular hypertrophy. *Arch Phys Med Rehabil*, 35 420-426.

Meckel Y, Atterbom H, Grodjinovsky A, Ben-Sira D, Rotstein A (1995). Physiological characteristics of female 100 metre sprinters of different performance levels. *J Sports Med Phys Fitness*, 35 (3): 169-175.

Meylan C, Cronin J, Nosaka K (2008). Isoinertial assessment of eccentric muscular strength. *Strength Cond J*, 30 (2): 56-64.

Meylan CM, Nosaka K, Green JP, Cronin JB (2010). Variability and influence of eccentric kinematics on unilateral vertical, horizontal, and lateral countermovement jump performance. *J Strength Cond Res*, 24 (3): 840-845. doi:10.1519/JSC.0b013e3181ae7961

Milner-Brown HS, Stein RB, Lee RG (1975). Synchronization of human motor units: possible roles of exercise and supraspinal reflexes. *Electroencephalogr Clin Neurophysiol*, 38 (3): 245-254.

Mina MA, Blazevich AJ, Giakas G, Seitz LB, Kay AD (2016). Chain-loaded variable resistance warm-up improves free-weight maximal back squat performance. *Eur J Sport Sci*, 16 (8): 932-939. doi:10.1080/17461391.2016.1199740

Mina MA, Blazevich AJ, Tsatalas T, Giakas G, Seitz LB, Kay AD (2019). Variable, but not free-weight, resistance back squat exercise potentiates jump performance following a comprehensive task-specific warm-up. *Scand J Med Sci Sports*, 29 (3): 380-392. doi:10.1111/sms.13341

Miyamoto N, Wakahara T, Ema R, Kawakami Y (2013). Further potentiation of dynamic muscle strength after resistance training. *Med Sci Sports Exerc*, 45 (7): 1323-1330. doi:10.1249/MSS.0b013e3182874c0e

Moher D et al. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev*, 4 1. doi:10.1186/2046-4053-4-1

Moir GL, Munford SN, Moroski LL, Davis SE (2018). The Effects of Ballistic and Nonballistic Bench Press on Mechanical Variables. *J Strength Cond Res*, 32 (12): 3333-3339. doi:10.1519/JSC.0000000000001835

Monajati A, Larumbe-Zabala E, Goss-Sampson M, Naclerio F (2018). Injury prevention programs based on flywheel vs. body weight resistance in recreational athletes. *J Strength Cond Res*. doi:10.1519/JSC.0000000000002878

Moore CA, Weiss LW, Schilling BK, Fry AC, Li Y (2007). Acute effects of augmented eccentric loading on jump squat performance. *J Strength Cond Res*, 21 (2): 372-377. doi:10.1519/R-18605.1

Murayama M, Nosaka K, Yoneda T, Minamitani K (2000). Changes in hardness of the human elbow flexor muscles after eccentric exercise. *Eur J Appl Physiol*, 82 (5-6): 361-367. doi:10.1007/s004210000242

Murtagh CF, Vanrenterghem J, O'Boyle A, Morgans R, Drust B, Erskine RM (2017). Unilateral jumps in different directions: a novel assessment of soccer-associated power? *J Sci Med Sport*, 20 (11): 1018-1023. doi:10.1016/j.jsams.2017.03.016

Naci H, Ioannidis JP (2015). Comparative effectiveness of exercise and drug interventions on mortality outcomes: metaepidemiological study. *Br J Sports Med*, 49 (21): 1414-1422. doi:10.1136/bjsports-2015-f5577rep

Naczk M, Naczk A, Brzenczek-Owczarzak W, Arlet J, Adach Z (2013). Impact of inertial training on strength and power performance in young active men. *J Strength Cond Res*, doi:10.1519/JSC.0b013e3182a993c2

Naczk M, Brzenczek-Owczarzak W, Arlet J, Naczk A, Adach Z (2014). Training effectiveness of the inertial training and measurement system. *J Hum Kinet*, 44 19-28. doi:10.2478/hukin-2014-0107

Naczk M, Naczk A, Brzenczek-Owczarzak W, Arlet J, Adach Z (2016). Efficacy of inertial training in elbow joint muscles: influence of different movement velocities. *J Sports Med Phys Fitness*, 56 (3): 223-231.

Naczk M, Lopacinski A, Brzenczek-Owczarzak W, Arlet J, Naczk A, Adach Z (2017). Influence of short-term inertial training on swimming performance in young swimmers. *Eur J Sport Sci*, 17 (4): 369-377. doi:10.1080/17461391.2016.1241304

Nardone A, Romano C, Schieppati M (1989). Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *J Physiol*, 409 451-471.

Nauman J, Nes BM, Zisko N, Revdal A, Myers J, Kaminsky LA, Wisloff U (2019). Personal Activity Intelligence (PAI): A new standard in activity tracking for obtaining a healthy cardiorespiratory fitness level and low cardiovascular risk. *Prog Cardiovasc Dis*, 62 (2): 179-185. doi:10.1016/j.pcad.2019.02.006

Neme Ide B, Alessandro Soares Nunes L, Brenzikofer R, Macedo DV (2013). Time course of muscle damage and inflammatory responses to resistance training with eccentric overload in trained individuals. *Mediators Inflamm*, 2013 204942. doi:10.1155/2013/204942

Newton RU, Murphy AJ, Humphries BJ, Wilson GJ, Kraemer WJ, Hakkinen K (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *Eur J Appl Physiol Occup Physiol*, 75 (4): 333-342. doi:10.1007/s004210050169

Newton MJ, Morgan GT, Sacco P, Chapman DW, Nosaka K (2008). Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *J Strength Cond Res*, 22 (2): 597-607. doi:10.1519/JSC.0b013e3181660003

Nilo Dos Santos WD, Gentil P, Lima de Araujo Ribeiro A, Vieira CA, Martins WR (2018). Effects of variable resistance training on maximal strength: a meta-analysis. *J Strength Cond Res*, 32 (11): e52-e55. doi:10.1519/JSC.0000000000002836

Norrbrand L, Fluckey JD, Pozzo M, Tesch PA (2008). Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur J Appl Physiol*, 102 (3): 271-281. doi:10.1007/s00421-007-0583-8

Norrbrand L, Pozzo M, Tesch PA (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. *Eur J Appl Physiol*, 110 (5): 997-1005. doi:10.1007/s00421-010-1575-7

Norrbrand L, Tous-Fajardo J, Vargas R, Tesch PA (2011). Quadriceps muscle use in the flywheel and barbell squat. *Aviat Space Environ Med*, 82 (1): 13-19.

Nosaka K, Sakamoto K, Newton M, Sacco P (2001). How long does the protective effect on eccentric exercise-induced muscle damage last? *Med Sci Sports Exerc*, 33 (9): 1490-1495.

Nosaka K (2018) Eccentric exercise as medicine. In 11th International Conference on Strength Training (ICST), Perth, WA, Australia,

Nunez FJ, Santalla A, Carrasquila I, Asian JA, Reina JI, Suarez-Arrones LJ (2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLoS One*, 13 (3): e0193841. doi:10.1371/journal.pone.0193841

O'Shea P (1966). Effects of selected weight training programs on the development of strength and muscle hypertrophy. *Res Q*, 37 (1): 95-102.

Ojasto T, Hakkinen K (2009). Effects of different accentuated eccentric load levels in eccentric-concentric actions on acute neuromuscular, maximal force, and power responses. *J Strength Cond Res*, 23 (3): 996-1004. doi:10.1519/JSC.0b013e3181a2b28e

Onambele GL, Maganaris CN, Mian OS, Tam E, Rejc E, McEwan IM, Narici MV (2008). Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *J Biomech*, 41 (15): 3133-3138. doi:10.1016/j.jbiomech.2008.09.004

Owerkowicz T, Cotter JA, Haddad F, Yu AM, Camilon ML, Hoang TN, Jimenez DJ, Kreitenberg A, Tesch PA, Caiozzo VJ, Adams GR (2016). Exercise responses to gravity-independent flywheel aerobic and resistance training. *Aerosp Med Hum Perform*, 87 (2): 93-101. doi:10.3357/AMHP.4229.2016

Paddon-Jones D, Leveritt M, Lonergan A, Abernethy P (2001). Adaptation to chronic eccentric exercise in humans: the influence of contraction velocity. *Eur J Appl Physiol*, 85 (5): 466-471. doi:10.1007/s004210100467

Pascoe DD, Costill DL, Fink WJ, Robergs RA, Zachwieja JJ (1993). Glycogen resynthesis in skeletal muscle following resistive exercise. *Med Sci Sports Exerc*, 25 (3): 349-354.

Paulsen G, Crameri R, Benestad HB, Fjeld JG, Morkrid L, Hallen J, Raastad T (2010). Time course of leukocyte accumulation in human muscle after eccentric exercise. *Med Sci Sports Exerc*, 42 (1): 75-85. doi:10.1249/MSS.0b013e3181ac7adb

Pauole K, Madole K, Garhammer J, Lacourse M, Rozenek R (2000). Reliability and Validity of the T-Test as a Measure of Agility, Leg Power, and Leg Speed in College-Aged Men and Women. *J Strength Cond Res*, 14 (4): 443-450.

Pearson SJ, Harridge SD, Grieve DW, Young A, Woledge RC (2001). A variable inertial system for measuring the contractile properties of human muscle. *Med Sci Sports Exerc*, 33 (12): 2072-2076.

Pearson SJ, Hussain SR (2014). Region-specific tendon properties and patellar tendinopathy: a wider understanding. *Sports Med*, 44 (8): 1101-1112. doi:10.1007/s40279-014-0201-y

Penailillo L, Blazevich A, Numazawa H, Nosaka K (2013). Metabolic and muscle damage profiles of concentric versus repeated eccentric cycling. *Med Sci Sports Exerc*, 45 (9): 1773-1781. doi:10.1249/MSS.0b013e31828f8a73

Penailillo L, Blazevich AJ, Nosaka K (2015). Muscle fascicle behavior during eccentric cycling and its relation to muscle soreness. *Med Sci Sports Exerc*, 47 (4): 708-717. doi:10.1249/MSS.0000000000000473

Perez-Gomez J, Calbet JA (2013). Training methods to improve vertical jump performance. *J Sports Med Phys Fitness*, 53 (4): 339-357.

Peterson MD, Rhea MR, Alvar BA (2005). Applications of the dose-response for muscular strength development: a review of meta-analytic efficacy and reliability for designing training prescription. *J Strength Cond Res*, 19 (4): 950-958. doi:10.1519/R-16874.1

Piercy KL, Troiano RP (2018). Physical Activity Guidelines for Americans From the US Department of Health and Human Services. *Circ Cardiovasc Qual Outcomes*, 11 (11): e005263. doi:10.1161/CIRCOUTCOMES.118.005263

Piercy KL (2018). The physical activity guidelines for Americans. *JAMA*, 320 (19): 2020-2028. doi:10.1001/jama.2018.14854

Pinniger GJ, Steele JR, Thorstensson A, Cresswell AG (2000). Tension regulation during lengthening and shortening actions of the human soleus muscle. *Eur J Appl Physiol*, 81 (5): 375-383. doi:10.1007/s004210050057

Pozzo M, Alkner B, Norrbrand L, Farina D, Tesch PA (2006). Muscle-fiber conduction velocity during concentric and eccentric actions on a flywheel exercise device. *Muscle Nerve*, 34 (2): 169-177. doi:10.1002/mus.20574

Proske U, Allen TJ (2005). Damage to skeletal muscle from eccentric exercise. *Exerc Sport Sci Rev*, 33 (2): 98-104.

Raastad T, Glomsheller T, Bjoro T, Hallen J (2003). Recovery of skeletal muscle contractility and hormonal responses to strength exercise after two weeks of high-volume strength training. *Scand J Med Sci Sports*, 13 (3): 159-168.

Ramirez Varela A, Pratt M, Borges C, Hallal PC (2016) 1st Physical Activity Almanac: The Global Observatory for Physical Activity - GoPA! International Society for Physical Activity and Health (ISPAH).

Rassier DE, Leite FS, Nocella M, Cornachione AS, Colombini B, Bagni MA (2015). Non-crossbridge forces in activated striated muscles: a titin dependent mechanism of regulation? *J Muscle Res Cell Motil*, 36 (1): 37-45. doi:10.1007/s10974-014-9397-6

Raue U, Terpstra B, Williamson DL, Gallagher PM, Trappe SW (2005). Effects of short-term concentric vs. eccentric resistance training on single muscle fiber MHC distribution in humans. *Int J Sports Med*, 26 (5): 339-343. doi:10.1055/s-2004-821041

Reeves ND, Maganaris CN, Longo S, Narici MV (2009). Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol*, 94 (7): 825-833. doi:10.1113/expphysiol.2009.046599

Riebe D, Franklin BA, Thompson PD, Garber CE, Whitfield GP, Magal M, Pescatello LS (2015). Updating ACSM's Recommendations for Exercise Preparticipation Health Screening. *Med Sci Sports Exerc*, 47 (11): 2473-2479. doi:10.1249/MSS.0000000000000664

Rittweger J, Frost HM, Schiessl H, Ohshima H, Alkner B, Tesch P, Felsenberg D (2005). Muscle atrophy and bone loss after 90 days' bed rest and the effects of flywheel resistive exercise and pamidronate: results from the LTBR study. *Bone*, 36 (6): 1019-1029. doi:10.1016/j.bone.2004.11.014

Rittweger J, Felsenberg D, Maganaris C, Ferretti JL (2007). Vertical jump performance after 90 days bed rest with and without flywheel resistive exercise, including a 180 days follow-up. *Eur J Appl Physiol*, 100 (4): 427-436. doi:10.1007/s00421-007-0443-6

Roig M, Shadgan B, Reid WD (2008). Eccentric exercise in patients with chronic health conditions: a systematic review. *Physiother Can*, 60 (2): 146-160. doi:10.3138/physio.60.2.146

Roig M, O'Brien K, Kirk G, Murray R, McKinnon P, Shadgan B, Reid WD (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med*, 43 (8): 556-568. doi:10.1136/bjsm.2008.051417

Roig M, Macintyre DL, Eng JJ, Narici MV, Maganaris CN, Reid WD (2010). Preservation of eccentric strength in older adults: Evidence, mechanisms and implications for training and rehabilitation. *Exp Gerontol*, 45 (6): 400-409. doi:10.1016/j.exger.2010.03.008

Romero-Rodriguez D, Gual G, Tesch PA (2011). Efficacy of an inertial resistance training paradigm in the treatment of patellar tendinopathy in athletes: a case-series study. *Phys Ther Sport*, 12 (1): 43-48. doi:10.1016/j.ptsp.2010.10.003

Ruttley TM, Colosky PE, Jr., James SP (2001). A gravity-independent constant force resistive exercise unit. *Biomed Sci Instrum*, 37 87-93.

Sabido R, Hernandez-Davo JL, Botella J, Navarro A, Tous-Fajardo J (2017a). Effects of adding a weekly eccentric-overload training session on strength and athletic performance in team-handball players. *Eur J Sport Sci*, 17 (5): 530-538. doi:10.1080/17461391.2017.1282046

Sabido R, Hernandez-Davo JL, Pereyra-Gerber GT (2017b). Influence of different inertial loads on basic training variables during the flywheel squat exercise. *Int J Sports Physiol Perform*,1-30. doi:10.1123/ijspp.2017-0282

Saeterbakken AH, van den Tillaar R, Seiler S (2011). Effect of core stability training on throwing velocity in female handball players. *J Strength Cond Res*, 25 (3): 712-718. doi:10.1519/JSC.0b013e3181cc227e

Saeterbakken AH, Andersen V, van den Tillaar R (2016). Comparison of kinematics and muscle activation in free-weight back squat with and without elastic bands. *J Strength Cond Res*, 30 (4): 945-952. doi:10.1519/JSC.0000000000001178

Sanz-Lopez F, Martinez-Amat A, Hita-Contreras F, Valero-Campo C, Berzosa C (2016). Thermographic assessment of eccentric overload training within three days of a running session. *J Strength Cond Res*, 30 (2): 504-511. doi:10.1519/JSC.0000000000001071

Sarmiento S, Rodriguez-Matoso D, Henráquez del Pino Y, Álvarez-Piñera L, García-Manso JM, Rodríguez-Ruiz D (2014). Effects of flywheel resistance training for gait improvement in female Alzheimer's patients. *Ciencia, Cultura y Deporte*, 25 (9):

Schiaffino S, Dyar KA, Ciciliot S, Blaauw B, Sandri M (2013). Mechanisms regulating skeletal muscle growth and atrophy. *FEBS J*, 280 (17): 4294-4314. doi:10.1111/febs.12253

Schoenfeld BJ (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res*, 24 (10): 2857-2872. doi:10.1519/JSC.0b013e3181e840f3

Schoenfeld BJ (2012). Does exercise-induced muscle damage play a role in skeletal muscle hypertrophy? *J Strength Cond Res*, 26 (5): 1441-1453. doi:10.1519/JSC.0b013e31824f207e

Schoenfeld BJ (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Med*, 43 (3): 179-194. doi:10.1007/s40279-013-0017-1

Schoenfeld BJ, Ogborn DI, Krieger JW (2015). Effect of repetition duration during resistance training on muscle hypertrophy: a systematic review and meta-analysis. *Sports Med*, 45 (4): 577-585. doi:10.1007/s40279-015-0304-0

Schoenfeld BJ, Ogborn D, Krieger JW (2016a). Effects of resistance training frequency on measures of muscle hypertrophy: a systematic review and meta-analysis. *Sports Med*, 46 (11): 1689-1697. doi:10.1007/s40279-016-0543-8

Schoenfeld BJ, Wilson JM, Lowery RP, Krieger JW (2016b). Muscular adaptations in low- versus high-load resistance training: A meta-analysis. *Eur J Sport Sci*, 16 (1): 1-10. doi:10.1080/17461391.2014.989922

Schoenfeld BJ, Grgic J, Ogborn D, Krieger JW (2017a). Strength and hypertrophy adaptations between low- vs. high-load resistance training: A systematic review and meta-analysis. *J Strength Cond Res*, 31 (12): 3508-3523. doi:10.1519/JSC.0000000000002200

Schoenfeld BJ, Ogborn D, Vigotsky AD, Franchi M, Krieger JW (2017b). Hypertrophic effects of concentric versus eccentric muscle actions: A systematic review and meta-analysis. *J Strength Cond Res*, doi:10.1519/JSC.0000000000001983

Schoenfeld BJ, Grgic J (2018). Eccentric overload training: a viable strategy to enhance muscle hypertrophy? *Strength Cond J*, 40 (2): 78-81.

Schoenfeld BJ, Grgic J, Krieger J (2018). How many times per week should a muscle be trained to maximize muscle hypertrophy? A systematic review and meta-analysis of studies examining the effects of resistance training frequency. *J Sports Sci*,1-10. doi:10.1080/02640414.2018.1555906

Schoenfeld BJ, Grgic J (2019). Does Training to failure maximize muscle hypertrophy? *Strength Cond J*, doi:10.1519/SSC.0000000000000473

Scripture EW, Smith TL, E.M. B (1894). On the education of muscular control and power. *Yale Psychol Lib*, 2 114-119.

Scudese E, Willardson JM, Simao R, Senna G, Freitas de Salles B, Miranda H (2013). The effect of rest interval length on repetition consistency and perceived exertion during near maximal loaded bench press sets. *J Strength Cond Res*, doi:10.1519/JSC.0b013e3182a953ca

Sekiguchi H, Kimura T, Yamanaka K, Nakazawa K (2001). Lower excitability of the corticospinal tract to transcranial magnetic stimulation during lengthening contractions in human elbow flexors. *Neurosci Lett*, 312 (2): 83-86.

Semmler JG (2002). Motor unit synchronization and neuromuscular performance. *Exerc Sport Sci Rev*, 30 (1): 8-14.

Senna G, Willardson JM, de Salles BF, Scudese E, Carneiro F, Palma A, Simao R (2011). The effect of rest interval length on multi and single-joint exercise performance and perceived exertion. *J Strength Cond Res*, 25 (11): 3157-3162. doi:10.1519/JSC.0b013e318212e23b

Seynnes OR, de Boer M, Narici MV (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol*, 102 (1): 368-373. doi:10.1152/japplphysiol.00789.2006

Shamseer L, Moher D, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *BMJ*, 349 g7647. doi:10.1136/bmj.g7647

Sheppard J, Newton R, McGuigan M (2007). The effect of accentuated eccentric load on jump kinetics in high-performance volleyball players. *Int J Sports Sci Coach*, 2 (3): 267-273.

Sheppard JM, Young K (2010). Using additional eccentric loads to increase concentric performance in the bench press trhow. *J Strength Cond Res,* 24 (10): 2853-2856.

Sherrington C (1929). Ferrier lecture: some functional problems attaching to convergence. *Proc R Soc Lond B Biol Sci*, 105 332-362.

Silbernagel KG, Thomee R, Thomee P, Karlsson J (2001). Eccentric overload training for patients with chronic Achilles tendon pain. A randomised controlled study with reliability testing of the evaluation methods. *Scand J Med Sci Sports*, 11 (4): 197-206.

Soria-Gila MA, Chirosa IJ, Bautista IJ, Baena S, Chirosa LJ (2015). Effects of variable resistance training on maximal strength: A meta-analysis. *J Strength Cond Res*, 29 (11): 3260-3270. doi:10.1519/JSC.0000000000000971

Souron R, Nosaka K, Jubeau M (2018). Changes in central and peripheral neuromuscular fatigue indices after concentric versus eccentric contractions of the knee extensors. *Eur J Appl Physiol*, 118 (4): 805-816. doi:10.1007/s00421-018-3816-0

Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, Newton RU (2014). Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. *J Strength Cond Res*, 28 (9): 2415-2423. doi:10.1519/JSC.0000000000000547

Staron RS, Leonardi MJ, Karapondo DL, Malicky ES, Falkel JE, Hagerman FC, Hikida RS (1991). Strength and skeletal muscle adaptations in heavy-resistance-trained women after detraining and retraining. *J Appl Physiol (1985)*, 70 (2): 631-640. doi:10.1152/jappl.1991.70.2.631

Staron RS et al. (1994). Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *J Appl Physiol (1985)*, 76 (3): 1247-1255. doi:10.1152/jappl.1994.76.3.1247

Steinhaus A (1932). Physiology at the service of physical education: muscle hypertrophy. *J Health Phys Ed*, 3 (2): 36-37.

Stone MH, Collins D, Plisk S, Haff GG (2000). Training principles: Evaluation of modes and methods of resistance training. *Strength Cond J*, 22 (3): 65-76.

Stone M, Plisk S, Collins D (2002). Training principles. Evaluation of modes and methods of resistance training: A coaching perspective. *Sports Biomech*, 1 (1): 79-103. doi:10.1080/14763140208522788

Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, Hartman M (2004). The importance of isometric maximum strength and peak rate-of-force development in sprint cycling. *J Strength Cond Res*, 18 (4): 878-884. doi:10.1519/14874.1

Suchomel TJ, Nimphius S, Stone MH (2016a). The importance of muscular strength in athletic performance. *Sports Med*, 46 (10): 1419-1449. doi:10.1007/s40279-016-0486-0

Suchomel TJ, Sato K, DeWeese BH, Ebben WP, Stone MH (2016b). Potentiation effects of half-squats performed in a ballistic or nonballistic manner. *J Strength Cond Res*, 30 (6): 1652-1660. doi:10.1519/JSC.0000000000001251

Suchomel TJ, Sato K, DeWeese BH, Ebben WP, Stone MH (2016c). Potentiation following ballistic and nonballistic complexes: the effect of strength level. *J Strength Cond Res*, 30 (7): 1825-1833. doi:10.1519/JSC.0000000000001288

Suchomel TJ, Comfort P, Lake JP (2017). Enhancing the force-velocity profile of athletes using weightlifting derivatives. *Strength Cond J*, 39 (1): 10-20. doi:10.1519/SSC.0000000000000275

Suchomel TJ, Nimphius S, Bellon CR, Stone MH (2018). The importance of muscular strength: training considerations. *Sports Med*, 48 (4): 765-785. doi:10.1007/s40279-018-0862-z

Tee JC, Bosch AN, Lambert MI (2007). Metabolic consequences of exercise-induced muscle damage. *Sports Med*, 37 (10): 827-836. doi:10.2165/00007256-200737100-00001

Terada T, Friesen A, Chahal BS, Bell GJ, McCargar LJ, Boule NG (2013). Feasibility and preliminary efficacy of high intensity interval training in type 2 diabetes. *Diabetes Res Clin Pract*, 99 (2): 120-129. doi:10.1016/j.diabres.2012.10.019

Tesch PA, Thorsson A, Colliander EB (1990). Effects of eccentric and concentric resistance training on skeletal muscle substrates, enzyme activities and capillary supply. *Acta Physiol Scand*, 140 (4): 575-580. doi:10.1111/j.1748-1716.1990.tb09035.x

Tesch PA, Ekberg A, Lindquist DM, Trieschmann JT (2004a). Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. *Acta Physiol Scand*, 180 (1): 89-98. doi:10.1046/j.0001-6772.2003.01225.x

Tesch PA, Trieschmann JT, Ekberg A (2004b). Hypertrophy of chronically unloaded muscle subjected to resistance exercise. *J Appl Physiol*, 96 (4): 1451-1458. doi:10.1152/japplphysiol.01051.2003

Tesch PA, Fernandez-Gonzalo R, Lundberg TR (2017). Clinical applications of iso-inertial, eccentric-overload (YoYo) resistance exercise. *Front Physiol*, 8 241. doi:10.3389/fphys.2017.00241

Thompson WR (2017). Worldwide survey of fitness trends for 2018: the CREP Edition. *ACSM's Health Fit J*, 21 (6): 10-19. doi:10.1249/FIT.0000000000000341

Tinwala F, Cronin J, Haemmerle E, Ross A (2017). Eccentric strength training: a review of the available technology. *Strength Cond J*, 39 (1): 32-47. doi:10.1519/SSC.0000000000000262

Toigo M, Boutellier U (2006). New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. *Eur J Appl Physiol*, 97 (6): 643-663. doi:10.1007/s00421-006-0238-1

Toji H, Kaneko M (2004). Effect of multiple-load training on the force-velocity relationship. *J Strength Cond Res*, 18 (4): 792-795. doi:10.1519/13933.1

Tous-Fajardo J, Maldonado RA, Quintana JM, Pozzo M, Tesch PA (2006). The flywheel leg-curl machine: offering eccentric overload for hamstring development. *Int J Sports Physiol Perform*, 1 (3): 293-298.

Tous-Fajardo J, Gonzalo-Skok O, Arjol-Serrano JL, Tesch P (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *Int J Sports Physiol Perform*, 11 (1): 66-73. doi:10.1123/ijspp.2015-0010

Trappe S, Trappe T, Gallagher P, Harber M, Alkner B, Tesch P (2004). Human single muscle fibre function with 84 day bed-rest and resistance exercise. *J Physiol*, 557 (Pt 2): 501-513. doi:10.1113/jphysiol.2004.062166

Tremblay MS, Gonzalez SA, Katzmarzyk PT, Onywera VO, Reilly JJ, Tomkinson G, Active Healthy Kids Global A (2015). Physical activity report cards: Active healthy kids global alliance and the lancet physical activity observatory. *J Phys Act Health*, 12 (3): 297-298. doi:10.1123/jpah.2015-0184

Tricoli V, Lamas L, Carnevale R, Ugrinowitsch C (2005). Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *J Strength Cond Res*, 19 (2): 433-437. doi:10.1519/R-14083.1

Van Cutsem M, Duchateau J, Hainaut K (1998). Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol*, 513 (Pt 1) 295-305.

Vescovi JD, Binkley HM, Kerksick CM, Committee NE (2004). Sports performance graduate program interest and need survey: a brief report from the NSCA Education Committee. *J Strength Cond Res*, 18 (2): 383-387. doi:10.1519/1533-4287(2004)18<383:SPGPIA>2.0.CO;2

Vissing K et al. (2008). Muscle adaptations to plyometric vs. resistance training in untrained young men. *J Strength Cond Res*, 22 (6): 1799-1810. doi:10.1519/JSC.0b013e318185f673

Vogt M, Hoppeler HH (2014). Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *J Appl Physiol (1985)*, 116 (11): 1446-1454. doi:10.1152/japplphysiol.00146.2013

Wagle JP, Taber CB, Cunanan AJ, Bingham GE, Carroll KM, DeWeese BH, Sato K, Stone MH (2017). Accentuated eccentric loading for training and performance: a review. *Sports Med*, 47 (12): 2473-2495. doi:10.1007/s40279-017-0755-6

Walker S, Blazevich AJ, Haff GG, Tufano JJ, Newton RU, Hakkinen K (2016). Greater strength gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. *Front Physiol*, 7 149. doi:10.3389/fphys.2016.00149

Walker S, Hakkinen K, Haff GG, Blazevich AJ, Newton RU (2017). Acute elevations in serum hormones are attenuated after chronic training with traditional isoinertial but not accentuated eccentric loads in strength-trained men. *Physiol Rep*, 5 (7): doi:10.14814/phy2.13241

Weir JP, Housh DJ, Housh TJ, Weir LL (1995). The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *J Orthop Sports Phys Ther*, 22 (5): 207-215. doi:10.2519/jospt.1995.22.5.207

Wernbom M, Augustsson J, Thomee R (2007). The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports Med*, 37 (3): 225-264. doi:10.2165/00007256-200737030-00004

Wilkin BM (1952). The effect of weight training on speed of movement. *Res Q*, 23 361-369.

Willardson JM, Burkett LN (2006). The effect of rest interval length on bench press performance with heavy vs. light loads. *J Strength Cond Res*, 20 (2): 396-399. doi:10.1519/R-17735.1

Yamauchi J, Nakayama S, Ishii N (2009). Effects of bodyweight-based exercise training on muscle functions of leg multi-joint movement in elderly individuals. *Geriatr Gerontol Int*, 9 (3): 262-269. doi:10.1111/j.1447-0594.2009.00530.x

Yarrow JF, Borsa PA, Borst SE, Sitren HS, Stevens BR, White LJ (2007). Neuroendocrine responses to an acute bout of eccentric-enhanced resistance exercise. *Med Sci Sports Exerc*, 39 (6): 941-947. doi:10.1097/mss.0b013e318043a249

Yarrow JF, Borsa PA, Borst SE, Sitren HS, Stevens BR, White LJ (2008). Early-phase neuroendocrine responses and strength adaptations following eccentric-enhanced resistance training. *J Strength Cond Res*, 22 (4): 1205-1214. doi:10.1519/JSC.0b013e31816eb4a0

ANNEXED

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

The original publications of the studies that constitute this doctoral thesis are indicated below.

PUBLICATION 1

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

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Review

Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis

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Hypertrophy

ABSTRACT

Objectives: The purpose of this meta-analysis was to examine the effect of flywheel (FW) resistance training with Eccentric Overload (FW-EOT) on muscle size and functional capacities (i.e. strength and power) in athletes and healthy subjects, and to compare FW-induced adaptations with those triggered by traditional resistance exercise interventions.
Design: A systematic review and meta-analysis of randomised controlled trials.
Methods: A search of electronic databases [PubMed, MEDLINE (SportDiscus), Web of Science, Scopus and PEDro] was conducted to identify all publications employing FW-EOT up to April 30, 2016. Outcomes were analyzed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A total of 9 studies with 276 subjects and 92 effect sizes met the inclusion criteria and were included in the statistical analyses.
Results: The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49–0.76) with a significant ($p < 0.001$) Z overall effect of 9.17. No significant heterogeneity (p value = 0.78) was found. The meta-analysis showed significant differences between FW-EOT vs. conventional resistance training in concentric and eccentric strength, muscle power, muscle hypertrophy, vertical jump height and running speed, favoring FW-EOT.
Conclusions: This meta-analysis provides evidence supporting the superiority of FW-EOT, compared with traditional weight-stack exercise, to promote skeletal muscle adaptations in terms of strength, power and size in healthy subjects and athletes.

1. Introduction

Eccentric (ECC) training has been extensively studied in the scientific literature.[1] In comparison with concentric (CON) exercise, isolated ECC actions are characterized by producing higher peaks of force[2] with lower muscle activation[3,4] and metabolic cost,[5] as well as higher solicitation of Type IIx fibers,[6] increased cross-education effect[7] and greater cortical activity.[8] Furthermore, despite producing high levels of muscle damage and soreness after the initial bout,[9] ECC-based resistance exercise training has been associated with effective muscle damage prevention mechanisms,[10–12] earlier increments in muscle mass when compared with CON[13,14] and improved jumping performance.[10,15] Thereby, ECC actions seem to optimize the efficacy of training.[16,17]

The ability to produce force in the CON phase limits the load/weight to be used during training. As a result, and given the higher force production capacity of skeletal muscle during ECC actions, the loads used during traditional free weights or weight-stack exercise are sub-optimal during the ECC phase of the movement.[2,18] However, optimization of resistance training using a strictly ECC regime is rather complex and technically difficult to apply.[19] In addition, ECC actions are rarely isolated in real-life situations, and usually appear during the stretch-shortening cycle, inducing a greater contribution of the elastic components in the muscle-tendon unit; the stretch-shortening cycle increases the potential to produce force in the subsequent CON action due

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to increased storage and use of elastic energy.[17] Several methods have been designed and proposed to offer an eccentric overload (EO) during resistance training, such as (1) controlling and adjusting the time/velocity of CON and ECC movement during resistance training[20,21]; (2) using third-party assistance or devices for moving/rising the load during the CON phase[10–12]; and (3) employing isokinetic dynamometers.[22]

Devices created to isolate or overload the ECC phase of the muscle action have emerged as an alternative method that may produce greater muscle adaptations, and therefore have been developed and/or tested for rehabilitation and performance purposes. The iso-inertial devices were originally designed by Berg & Tesch[23] in 1994 to counteract the deleterious effect of microgravity on skeletal muscle. Such technology presents one of the most-used exercise paradigms to produce EO during resistance training. The iso-inertial devices more frequently employed are “The Flywheel Exercise Device”,[23,24] “VersaPulley”,[25] and “Inertial Training and Measurement System”.[26] These iso-inertial devices use the flywheel (FW) principle to produce unlimited resistance during the entire range of motion. During the CON phase the force applied unwinds a cord/strap connected to the shaft with the FW, which starts to rotate and store energy. Kinetic energy will increase as a function of the rotational speed. Once the CON action is completed, the cord/strap rewinds and the trainee must resist the pull of the FW by performing a braking, ECC muscle action. By using appropriate technique, i.e. resisting the inertial force gently during the first third of the ECC action, and then applying maximal effort to stop the movement at the end of the range of motion, EO can be produced in force/power values.[24,27] Then, the next CON action is immediately initiated.

The effects of inertial training using FW devices have been extensively investigated over the past 20 years. The majority of studies assessed the effects of eccentric overload training (EOT) on lower body muscle mass in healthy and active subjects. These studies employed a mean workload of 4 sets of 7 maximum repetitions during 5–15 weeks. Results indicate that EOT employing FW technology induce gains of 5–13% in muscle mass,[28–31] 11–39% in maximal voluntary contraction,[28–30] 12–25% in 1 repetition maximum (1 RM),[31,32] 21–90% in ECC force,[19,23,33] 10–33% in muscle power,[32,34] 6–15% in jump ability,[32,34,35] 2–10% in running speed[32,35,36] and up to 35% in electromyography activity.[29,37,38] Despite EOT being associated with a high magnitude of muscle damage and inflammatory responses during the initial phase of training, a significant attenuation of these processes occur shortly after,[31] indicating no counterproductive effects on muscle. Additionally, these devices have been shown very effective in counteracting the decrements in muscle mass and strength during weightlessness,[39–41] as well as improving muscle function, balance, gait and functional performance in elderly[42,43] and stroke patients.[44,45]

While there has been an increase use of these technology and a significant amount of research comparing the effectiveness of eccentric overload flywheel resistance training (FW-EOT) with traditional weight-stack exercise programs, there is no systematic review that summarizes the results of such studies, and adequately assess their scientific rigor. When confronting with a task of this magnitude, there are inherent methodological limitations, such as the difficulty to isolate or enhance the ECC phase from the CON,[1] and the diversity of devices employed to generate EO. To circumvent these limitations, we performed a systematic review including only training studies using FW technology to generate the EO vs. traditional free-weight or weight-stack training. Therefore, the purpose of the current review and meta-analysis was to systematically review the literature on randomised clinical trials examining the effects of FW-EOT, and how the intervention affects functional and structural muscle adaptations among athletes and healthy subjects, and to perform a quantitatively comparison of FW-EOT vs. traditional resistance exercise training in inducing gains in muscle mass, force and power.

2. Methods

This systematic review was designed following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P).[46,47] The PRISMA-P statement includes 26 points, grouped in 17 kinds of items checklist and it is designed to be used as a basis for reporting systematic review of randomised trials. A review protocol was not registered for this review.

A systematic, computerized search of the literature in PubMed, Web of Science (including Web of Science and MEDLINE results), Scopus, SportDiscus and PEDro was conducted by an independent researcher with controlled vocabulary and keywords related to eccentric training, eccentric overload training and flywheel training. Our search time frame was restricted to 22 years (1 January 1994 to 30 April 2016); 1994 was chosen because research on FW technology began that year.[23] We developed our search strategy based on the lack of reviews and meta-analysis about FW-EOT.[1,48] To do this, the search strategy used by previous reviews in the field of resistance training was employed.[48] The search language was restricted to English, and a filter containing Medical Subject Headings (MeSH) terms was applied. First, a general search including the terms “eccentric training”, “eccentric exercise”, “negative work” was performed. A more specific search included the terms of “eccentric-overload”, “eccentric-overload training”, “inertial training”, “inertial exercise”, “isoinertial training”, “flywheel”, “flywheel resistance”, “gravity-independent” and “enhanced-eccentric”. These terms were chosen because they have been traditionally used to describe this training methodology. The results of this specific search were then combined with the following terms: “device”, “strength”, “force”, “power”, “hypertrophy” and “muscle mass”.

The reference list of all selected publications was verified to retrieve relevant publications that were not identified by the computerized search. References of selected and included original articles, abstracts and available conference proceedings were also searched, including publications, posters, abstracts or conference proceedings. To identify relevant articles, titles and abstracts of all selected publication after the first search were analyzed looking for training methods where the ECC phase was overloaded or reinforced. In the specific search, in addition to the identified citations of the first search, titles and abstracts of all recognized publications were examined in detail. Full-text papers were recovered if the abstract provided insufficient information to establish eligibility or if the article abstract had passed the first eligibility review.

All articles examining FW-EOT were eligible for full-text review. An article was eligible for study inclusion if it met all of the following criteria:

1. The original article was a randomised controlled trial (RCT) or clinical controlled trial (CCT) published in peer-reviewed journals.
2. The article reported on athletes or physical active subjects of either sex who had completed an EOT protocol during at least 4 weeks with a minimum training frequency of 2 days per week.
3. The study described healthy subjects without a history of injury in the trained limb.
4. The manuscript included a FW-EOT intervention and a control or alternative intervention group, comparing training adaptations in strength and/or power, and/or muscle mass.

An article was excluded if:

1. Had subjects with any pathology or included subjects with existing, or under treatment for, musculoskeletal injuries in the trained limb.
2. Did not have the minimum requirements regarding in the training protocol (e.g, duration or frequency).
3. Reports focused on elderly above the age of 60 years.
4. Were not written in English.

All criteria were independently applied by two reviewers to the full text of the articles that passed the eligibility screening of titles and abstracts. Any disagreement was resolved by discussion.

Two investigators independently performed quality assessments of the included studies, and disagreements were resolved during a consensus meeting by a third part. The methodological quality of individual studies was assessed using the Physiotherapy Evidence Database (PEDro) scale.[49] Results from individual study analysis of quality were used to identify common areas of methodological weaknesses across studies. PEDro uses 11 criteria, and reviewed studies were awarded one point for each criterion that was clearly satisfied, for a potential maximum value of 11 points. Criteria included:

1. Eligibility criteria reported.
2. Random assignment.
3. Concealed allocation.
4. Groups similar at baseline regarding most important prognostic indicator.
5. Blinding of participants.
6. Blinding of therapists who administered the therapy.
7. Blinding of assessors who measured key outcome.
8. Measures of at least one key outcome were obtained from more than 85% of initial participants.
9. All participants received treatment or control condition as allocated.
10. Results of between-group statistical comparisons are reported.
11. Study provides point measures and measures of variability for at least one key outcome.

Although PEDro does not provide specific instructions to classify studies according to the score obtained, we have used the criteria established by others.[1,16] Thus, a study was considered of high quality when the score was greater than 5, of moderate quality when the score was 5 or 4, and of low quality when the study was scored 3 or less.

The meta-analysis was conducted using to RevMan 5.3 (The Nordic Cochrane Centre, The Cochrane Collaboration, Copenhagen 2012. Free to download at http://tech.cochrane.org/revman/download) to determine the efficacy of FW-EOT in increasing strength, power and muscle mass, as well as jump ability and speed. Data were pooled in different subgroups according to five physical variables: Strength (CON, ECC or both), muscle power (isotonic or isokinetic conditions only in CON movements), hypertrophy (increases in muscle size, volume or thickness in muscle groups subjected to training), jump ability (CMJ height) and speed. Outcomes were analysed as continuous outcomes using a random effects model to calculate a standardized mean difference (SMD) and 95% CI. A p value less than 0.05 indicated a statistical significance for an overall effect, and a p value less than 0.1 indicated statistical significance for heterogeneity between studies. When the articles selected did not provide sufficient data for the analysis, authors were contacted to obtain relevant data. Studies were not included in the meta-analyses if summary statistics of means, standard deviations and number of participants allocated in each group were not available.

3. Results

Fig. 1 shows a flow chart with the different phases of the search and selection of the studies included in the review. The initial search of electronic databases identified 264 titles, of which 171 were rejected for duplication issues. Four titles/articles[32,50–52] were identified through manual search. Thus, 97 titles were identified, but 48 of them were rejected because they did not meet the intervention criteria: 20 studies of bed rest, descriptive studies, 6 studies of elderly, 5 studies with chronic patients, 2 studies of post-activation potentiation, and 3 studies with other intervention methodology. From a total of 49 abstracts that were screened, 24 were excluded because they had insufficient requirements regarding the training protocol, and 4 studies were excluded for lack of comparison between groups. Twenty-one full texts were reviewed, but only 9 studies satisfied the inclusion criteria to be considered for this review.[26,28,30,32,34–36,52,53] The main reasons for exclusion were: lack of control group (n = 4), lack of information (n = 2), combination FW-EOT with other training methodology (n = 2), and different mechanism to produce EO (n = 4).

The mean methodological quality of the studies in PEDro scale was 7 ± 0.5, out of 11, with scores ranging from 6 to 8. All studies were categorized as high quality. The most common flaws were the lack of blinding of participants, therapists and assessors. It should be considered however, that blinding of participants in these studies is a difficult requisite to satisfy. Inter-rater reliability was significantly high (ICC = 0.98).

The main characteristics of the studies included in the review regarding participants, interventions and results are illustrated in Table 1. After adjusting for dropouts, the total number of participants in the studies included was 276. Of these 276 participants, 165 performed FW-EOT. The rest (n = 111) served as controls or performed resistance training without EO. Demographic data were provided for all studies; the estimated mean age of the experimental and control groups were 25.8 ± 8.5 and 23.2 ± 10.6, respectively. The distribution of sex among studies was not proportional, with only one study including female subjects,[28] with a total of 3 women and 273 men in both the experimental and control groups.

Training interventions ranged from 4 to 10 weeks with a mean frequency of 2.33 ± 0.72 sessions per week, with a mean total of 14 ± 2 sessions per study. The total number of sets (3–6) and repetitions (6–8) per session differed across studies. Inertial Training and Measurement System (ITMS) studies used a training load of 15–20 s per set (between 8 and 11 repetitions).[26,34,52] All studies employed FW devices to produce EO. Exercise devices employed were FW leg press,[32] YoYo squat,[35] Multi-Gym FW,[31] FW supine leg curl[35,36] and FW prone leg extension device.[28,30,50,53,54] Also, three studies employed ITMS.[26,34,52] The muscle groups trained were knee extensors,[28,30,34,50,53,54] knee flexors[36] or both.[31,32,35] Also, two studies of upper limb targeting shoulder abductors[26] and elbow flexors and extensors[52] were included. In the flywheel devices, the workload is provided by the inertia of a rotating mass, which in turns depends on its geometrical and physical properties, and may vary depending on the total number of flywheels installed.[28,50] The most common moment of inertial employed was between 0.07 and 0.145 $kg\,m^2$.[28,30,32,53] Given the fact that muscles are capable of achieving higher absolute forces when contracting eccentrically as compared with concentrically,[1] it is important to quantify the intensity of the training during FW exercise. In most of the studies[28,30,32,35,36,53] subjects were asked to push with maximal effort through the entire CON action. At the end of this CON action, the FW strap winds back due to inertial forces, which initiate the

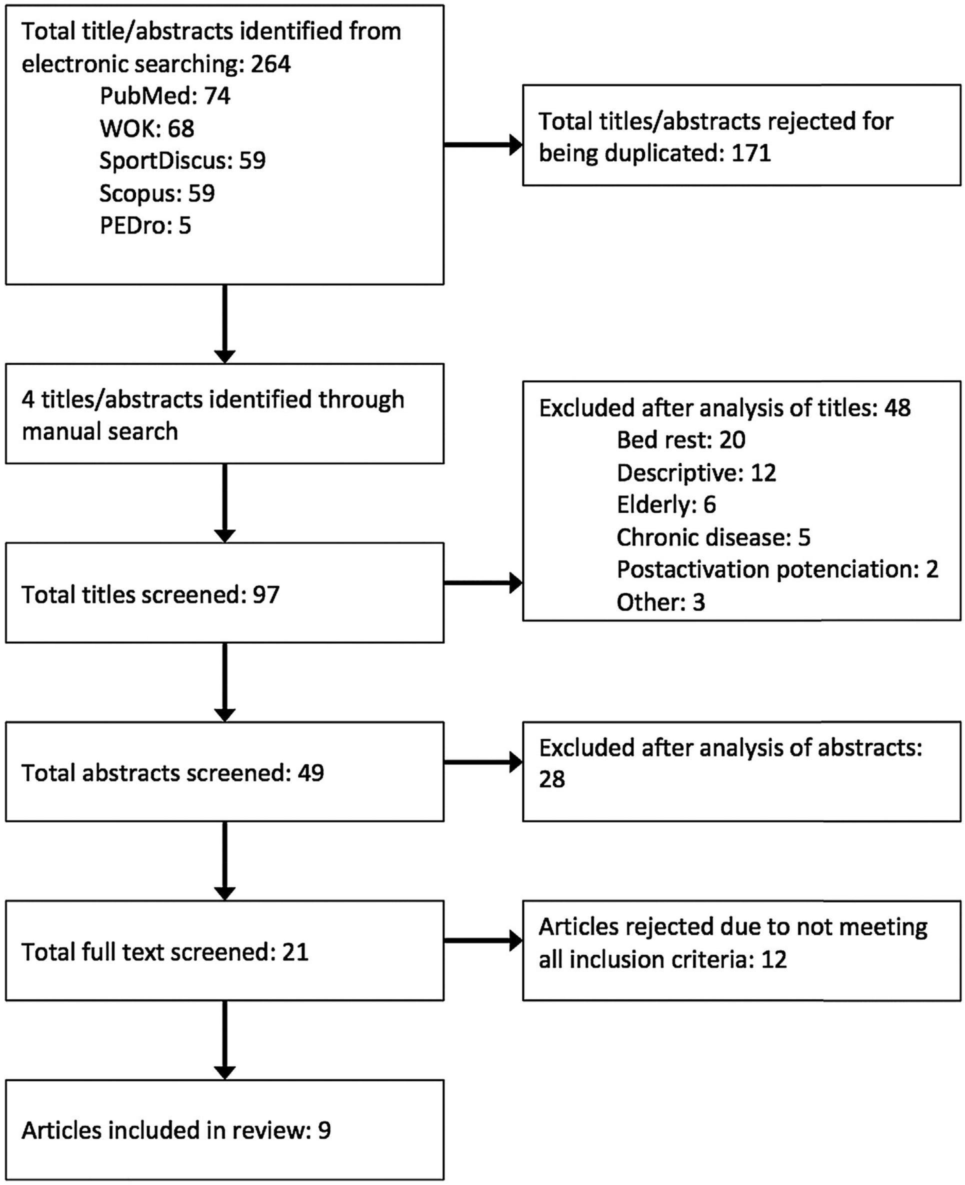

Fig. 1. Flow chart illustrating the different phases of the search and selection of the studies included in the review (PRISMA).

reversed ECC action. During the first third of the ECC action, subjects were instructed to resist gently, and thereafter to apply maximal breaking force to stop the movement. Then, the next CON action was instantly initiated. In these studies, CON and ECC power during training was assessed with an encoder or by means of rate perceived exertion.[32] Some studies adjusted the inertia to the higher CON power output.[35] Only one study failed to use any methodology to quantify the load during training.[36]

Individual main effect analysis, overall pooled estimate and measures of heterogeneity are illustrated in Fig. 2. This figure depicts SMD and 95% CI of the included studies for strength, muscle power, muscle hypertrophy, jump height and running speed adaptations following EOT. The overall pooled estimate from the main effects analysis was 0.63 (95% CI 0.49–0.76) with a significant ($p < 0.001$) Z overall effect of 9.17. No significant heterogeneity (heterogeneity p value = 0.78) was found.

Meta-analyses of subgroups demonstrated significance differences in training-induced adaptations favouring FW-EOT vs. control group in both CON and ECC strength (SMD 0.66; 95% CI 0.44–0.89), muscle power (SMD 0.8; 95% CI 0.53–1.07), muscle hypertrophy (SMD 0.57; 95% CI 0.25–0.9), vertical jump performance (SMD 0.46; 95% CI 0.09–0.83) and running speed (SMD 0.41; 95% CI 0.0–0.82) (Fig. 2).

4. Discussion

This is the first systematic review that analyses the efficacy of eccentric overload flywheel resistance training as a method to improve strength, muscle power and muscle mass. In addition, the statistical approach employed, allows comparing the efficacy of FW-EOT vs. traditional resistance exercise training in eliciting functional and structural muscle adaptations in athletes and healthy subjects. The search performed yielded 9 studies that met the inclusion criteria.[26,28,30,32,34–36,52,53] Using data from these sources, strong effects towards higher gains after FW training compared with other methodologies, in terms of force, muscle power and hypertrophy, as well as jump ability and speed were found. The heterogeneity among studies in the subgroup analysis reported in the current investigation was mainly caused by the different methods of evaluation employed in each investigation. Interestingly, the

Table 1
Characteristics of the studies included.

Study	Participants[a]	Muscle group	Interventions	Results[b]
Askling et al.[36]	30 male field soccer athletes from 2 Swedish premier league teams	Knee flexors	Exp (n = 15), additional training: leg curl FW device 10 weeks (16 sessions) 4 sets of 8 reps/session	Significant increases in CON and ECC peak torque and running speed in exp. No training effects in control group. No difference between groups
de Hoyo et al.[35]	33 junior soccer players (under 17 to under 19)	Knee extensors and flexors	Exp (n = 18): Half-squat and leg curl FW device 10 weeks (15 sessions) 3–5 sets of 6 reps/session	Significant increases in CMJ and running speed in exp. No differences in control group
Maroto-Izquierdo et al.[32]	29 professional handball players	Knee extensors and flexors	Exp (n = 15): Leg press FW device 6 weeks (15 sessions) 4 sets of 7 reps/session	Exp showed significant increases in 1 RM, muscle power in all % of 1 RM, SJ and CMJ, running speed, agility T-test and muscle mass. Control showed smaller training effect in 1 RM, SJ and running speed
Naczk et al.[34]	58 male physical education students	Knee extensors	2 training groups: T0 (no additional load) and T10 (10 kg additional load). 2 control groups ITMS 5 weeks (15 sessions) 3 sets of 15 s/set	Significant increases in muscle force, muscle power, CMJ, SJ and muscle mass No significant differences between training groups
Naczk et al.[26]	46 male physical education students	Shoulder abductors	Exp (n = 33) divided in 3 groups: T0 (no additional load), T5 (5 kg additional load) and T10 (10 kg additional load) ITMS 4 weeks (12 sessions) 3 sets of 20 s/set	All groups showed significant training effects in torque and power No significant differences between training groups
Naczk et al.[52]	38 male physical education students	Elbow flexors and extensors	Exp (n = 20) divided in 2 groups: TF (7.5 rad s^{-1}) and TS (5.76 rad s^{-1}) ITMS 5 weeks (15 sessions) 3 sets of 15 s/set. Flexion and extension, right and left arms worked separately	Greater improvements in elbow flexor force and power in TF than in TS Elbow extensor force and power increased significantly only in TF
Norrbrand et al.[30]	15 men (mean age 39)	Knee extensors	5 weeks (12 sessions) Exp (n = 7). Seated knee extension FW device 4 sets of 7 reps/session Control (n = 8). Standard seated weight stack machine 4 sets of 7 RM/session	QF volume improved significantly in both groups, greater gains in exp
Norrbrand et al.[53]	17 men (mean age 39)	Knee extensors	Same protocol than Norrbrand et al.[30]	Both groups improved significantly MVC and strength. Higher EMG activity in ECC in exp
Tesch et al.[28]	10 middle-age (30–53 year) men and women	Knee extensors	Unilateral (left) leg extension exercise in a seated knee extension FW device 5 weeks (12 sessions) 4 sets of 7 reps/session	CON and ECC strength, maximal isometric strength and QF volume increased significantly

% 1 RM, percentage repetition maximum; AE, aerobic exercise; CMJ, countermovement jump; CSA, cross-sectional area; con, concentric; ecc, eccentric; Ext, experimental group; MVC, maximal voluntary contraction; QF, quadriceps; RE, resistance exercise; RF, rectus femoris; SJ, squat jump; TF, faster training group; TS, slower training group; VL, vastus lateralis; VI, vastus intermedius.

[a] Number of participants at the end of the studies.

[b] Only results for the outcomes of interest are provided.

only studies assessing FW-EOT adaptations in the upper limbs were the ones reporting the largest effect sizes (ES between 0.52 and 1.75) of all investigations analyzed.[26,52]

During traditional CON-ECC resistance exercise performed at maximal intensity, the ECC phase is clearly under-loaded (e.g. about 40–50%).[55] Multiple studies using different protocols have shown the critical role of the ECC muscle action to improve contractile characteristics and muscle size in humans.[3,55,56] Therefore, it seems reasonable to believe that applying eccentric overload during resistance exercise could increase force production capability.[19] Indeed, studies employing eccentric overload training by means of inertial gravity-independent devices (i.e. FW), show robust increments in force production.[27,31,33,35] The current systematic review confirm these data, showing that resistance training offering brief episodes of EO employing FW devices, is associated with significantly greater improvements in maximal dynamic strength when compared to traditional resistance exercise programs. These results are supported by Fernandez-Gonzalo et al.,[31] who reported increases of 25% in maximal dynamic strength in both men (ES = 1.78) and women (ES = 0.62). Furthermore, those studies assessing both CON and ECC force, showed larger increments in ECC than CON force.[36,51] Also, Martinez-Aranda and Fernandez-Gonzalo have

Study or Subgroup	Eccentric Overload Mean	SD	Total	Weight training Mean	SD	Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
1.1.1 Strength								
Norrbrand et al. (2010)	47	128	9	29	152.9	8	2.0%	0.12 [−0.83, 1.08]
Tesch et al. (2004)	50	269	10	5	226	10	2.3%	0.17 [−0.71, 1.05]
Maroto-Izquierdo et al. (2016)	31.6	60.81	15	19.1	53.13	14	3.4%	0.21 [−0.52, 0.94]
Naczk et al. (2016) ext TS	8	20.16	10	0	25.64	9	2.2%	0.33 [−0.57, 1.24]
Naczk et al. (2014) T5	9.99	24.04	11	2.35	12.81	13	2.7%	0.39 [−0.42, 1.21]
Askling et al. (2003) CON	20	33.42	15	3	31	15	3.4%	0.51 [−0.22, 1.24]
Naczk et al. (2014) T10	11.99	22.13	11	2.35	12.81	13	2.7%	0.53 [−0.29, 1.35]
Naczk et al. (2014) T0	13.62	23.17	11	2.35	12.81	13	2.7%	0.60 [−0.23, 1.42]
Naczk et al. (2016) flex TS	17	17.47	10	0	32.18	9	2.1%	0.64 [−0.29, 1.57]
Naczk et al. (2016) ext TF	14	26.11	10	−2	20.64	9	2.1%	0.65 [−0.28, 1.57]
Askling et al. (2003) ECC	28	32.56	15	−2	34	15	3.2%	0.88 [0.12, 1.63]
Naczk et al. (2016) flex TF	34	25.66	10	1	24.16	9	1.8%	1.26 [0.26, 2.27]
Naczk et al. (2013) T10	53	29.86	18	4	26.96	10	2.2%	1.65 [0.74, 2.55]
Naczk et al. (2013) T0	47	25.18	19	−5	37.9	11	2.4%	1.67 [0.80, 2.54]
Subtotal (95% CI)			**174**			**158**	**35.0%**	**0.66 [0.44, 0.89]**
Heterogeneity: Chi² = 16.48, df = 13 (P = 0.22); I² = 21%								
Test for overall effect: Z = 5.73 (P < 0.00001)								
1.1.2 Muscle Power								
Naczk et al. (2016) ext TS	12	41.24	10	−6	53.07	9	2.2%	0.36 [−0.55, 1.27]
Naczk et al. (2014) T10	18.75	41.28	11	3.02	30.57	13	2.7%	0.42 [−0.39, 1.24]
Naczk et al. (2014) T5	27.28	54.48	11	3.02	30.57	13	2.7%	0.54 [−0.28, 1.36]
Naczk et al. (2016) flex TS	19	26.38	10	−11	70.52	9	2.1%	0.55 [−0.37, 1.47]
Naczk et al. (2014) T0	26.81	48.23	11	3.02	30.57	13	2.7%	0.58 [−0.24, 1.40]
Naczk et al. (2016) ext TF	30	60.02	10	−15	46.33	9	2.0%	0.80 [−0.15, 1.74]
Maroto-Izquierdo et al. (2016)	129.24	76.13	15	57.46	67.16	14	3.0%	0.97 [0.19, 1.75]
Naczk et al. (2016) flex TF	59	66.8	10	−3	51.77	9	1.9%	0.98 [0.02, 1.95]
Naczk et al. (2013) T0	102	75.04	19	−8	84.02	11	2.6%	1.37 [0.54, 2.20]
Naczk et al. (2013) T10	100	73.62	18	−5	73.75	10	2.4%	1.38 [0.52, 2.25]
Subtotal (95% CI)			**125**			**110**	**24.3%**	**0.80 [0.53, 1.07]**
Heterogeneity: Chi² = 6.49, df = 9 (P = 0.69); I² = 0%								
Test for overall effect: Z = 5.75 (P < 0.00001)								
1.1.3 Hypertrophy								
Norrbrand et al. (2008)	80	315.16	7	42	526.93	8	1.7%	0.08 [−0.93, 1.10]
Tesch et al. (2004)	71	421	10	−13	387	10	2.3%	0.20 [−0.68, 1.08]
Naczk et al. (2016) TS	0.4	0.72	10	0	0.72	9	2.1%	0.53 [−0.39, 1.45]
Naczk et al. (2013) T0	3.66	5.14	19	0.56	4.95	11	3.1%	0.59 [−0.17, 1.35]
Naczk et al. (2016) TF	0.46	0.72	10	0	0.72	9	2.1%	0.61 [−0.32, 1.54]
Naczk et al. (2013) T10	4.99	6.86	18	0.56	4.95	10	2.8%	0.69 [−0.11, 1.48]
Maroto-Izquierdo et al. (2016)	6.2	5.1	15	1.2	4.24	14	2.9%	1.03 [0.25, 1.82]
Subtotal (95% CI)			**89**			**71**	**17.2%**	**0.57 [0.25, 0.90]**
Heterogeneity: Chi² = 3.02, df = 6 (P = 0.81); I² = 0%								
Test for overall effect: Z = 3.47 (P = 0.0005)								
1.1.4 Jump								
Maroto-Izquierdo et al. (2016)	3.49	7.89	15	1.12	5.84	14	3.3%	0.33 [−0.40, 1.06]
Naczk et al. (2013) T0	6.81	19.08	19	−0.43	8.12	11	3.2%	0.44 [−0.31, 1.19]
Naczk et al. (2013) T10	3.15	6.62	18	−0.43	8.12	10	2.9%	0.48 [−0.30, 1.27]
De Hoyo et al. (2015)	2.6	5.87	18	−0.6	4.67	15	3.7%	0.58 [−0.12, 1.28]
Subtotal (95% CI)			**70**			**50**	**13.1%**	**0.46 [0.09, 0.83]**
Heterogeneity: Chi² = 0.24, df = 3 (P = 0.97); I² = 0%								
Test for overall effect: Z = 2.44 (P = 0.01)								
1.1.5 Speed								
De Hoyo et al. (2015)	0.04	0.184	18	−0.01	0.17	15	3.8%	0.27 [−0.41, 0.96]
Askling et al. (2003)	0.08	0.215	15	0	0.141	15	3.4%	0.43 [−0.30, 1.15]
Maroto-Izquierdo et al. (2016)	0.38	0.361	15	0.19	0.306	14	3.2%	0.55 [−0.19, 1.29]
Subtotal (95% CI)			**48**			**44**	**10.5%**	**0.41 [−0.00, 0.82]**
Heterogeneity: Chi² = 0.29, df = 2 (P = 0.87); I² = 0%								
Test for overall effect: Z = 1.94 (P = 0.05)								
Total (95% CI)			**506**			**433**	**100.0%**	**0.63 [0.49, 0.76]**
Heterogeneity: Chi² = 30.06, df = 37 (P = 0.78); I² = 0%								
Test for overall effect: Z = 9.17 (P < 0.00001)								
Test for subgroup differences: Chi² = 3.54, df = 4 (P = 0.47), I² = 0%								

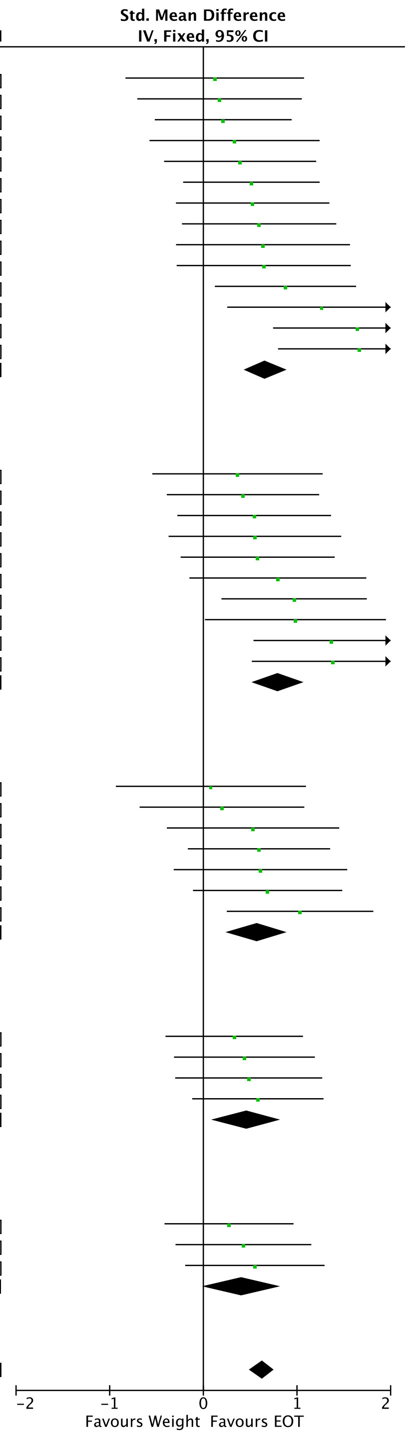

Fig. 2. Forest plot with meta-analysis of standardized mean difference showing comparison of eccentric overload training versus control/weight training on strength (N), muscle power (W), muscle hypertrophy (cm³, mm or kg), jump height (cm) and running speed (s).

recently shown that the EO produced in terms of force/torque during FW exercise (% above CON) is ~25% for both men and women.[57] This EO seems to be maintained over the duration of the training period. In addition, anecdotal data seem to indicate that the use of lower inertia[26,34] or high movement velocity[52] during FW training may induce greater force gains. However, this hypothesis needs to be tested in future investigations.

Originally, FW devices were created to counteract the muscle mass and strength losses during space-like, microgravity situations.[39–41,58,59] Thus, the efficacy of FW training to reduce the muscle atrophy and neuromuscular deconditioning during unloading has been analyzed in multiple occasions during the last 15 years, eliminating or greatly reducing loss in muscle mass during long term bed rest studies,[39–41,58] and even increasing muscle volume during unilateral lower limb suspension.[41] The results of the current meta-analyses indicate that not only FW-EOT is effective in increasing muscle mass, but also that is more potent than traditional resistance training in inducing hypertrophy adaptations ($p < 0.001$). The high variability in the effect size of the different studies in terms of muscle hypertrophy after EOT employing FW vs. traditional resistance exercise training could be partly explained by the different methods used to evaluate changes in muscle mass. While some studies used bioelectrical impedance[34,52] or ultrasonography,[32] only 2 studies employed magnetic resonance imaging,[28,30] which is considered the "gold-standard" for muscle mass assessment.[1] Thus, even though all studies showed benefits on muscle mass, magnetic resonance imaging studies were those showing the lower effect (ES = 0.23–0.34). In addition to the studies included in the meta-analysis, two additional investigations[29,31] reported significant gains in muscle mass in young subjects after FW-EOT employing magnetic resonance imaging and DXA, respectively. Interestingly, it seems that adding aerobic exercise 6 h[50] or 15 min[51] prior to FW-EOT elicits even greater muscle hypertrophy (ES = 0.57 and 0.27, respectively) than FW-EOT alone (ES = 0.31 and 0.14, respectively). Finally, the largest effect of FW-EOT training in muscle mass were found in a study describing FW-induced adaptations in well-trained athletes (ES = 0.6 in FW-EOT group versus ES = 0.38 in weight training group).[32] Indeed, the EO produced during FW training is generally greater in athletes with experience in FW training, highlighting the importance of an appropriate technique to maximize the benefits of this training paradigm.[27] In addition, a proper technique during FW training may impact the working angle, where the main gains in strength and muscle mass occur.[60,61] This is an important factor to consider in future studies because muscle mass gains are greater when the ROM employed during training is longer.[62]

The greatest overall effect of subgroups analysis was found for the variable "muscle power" (Z = 5.75; $p < 0.001$. SMD 0.8 W; 95% CI 0.53–1.07). Thus, regardless of the specific exercise device or muscle group analysed, FW-EOT induced very robust adaptations in terms of muscle power, which are greater than those seen after traditional resistance exercise training. Apart from the studies included in the meta-analysis, the first investigation assessing FW-induced adaptations in muscle power at different loads (i.e. 40–80% of 1 RM) was Fernandez-Gonzalo et al.,[31] who interestingly, showed that power increments at high percentages of 1 RM were greater for men than women. Expanding on these data, FW-EOT induced power gains at high loads (70–90%) of 1 RM in athletes.[32] These major improvements in muscle power may be explained by the particular characteristics of the FW training to induce EO, since the EO is usually applied in the last portion of the range of motion during the ECC action. That is, the EO is produced mainly at a joint angle close to 70° during leg press[32] and elbow flexion exercise,[52] or at 90° during knee extension,[28,30,34,53] just before the subsequent CON action is initiated. This exercise technique would maximize the stretch shortening cycle, allowing for greater production of force during the first part of the CON action,[32] and therefore, a higher velocity during the entire movement (i.e. increased power).

The significant improvements in vertical jump after FW training corroborate the efficacy of this training model to induce positive power adaptations in healthy and well-trained subjects. Thus, the articles included in the current meta-analysis indicate that vertical jump improvements induced by FW-EOT are higher than traditional resistance training, as long as the jump modality used to assess jumping ability includes an eccentric phase (i.e. a counter movement jump, CMJ). Of note however, De Hoyo et al.[63] showed that under specific circumstances, i.e. FW exercise (VersaPulley device) performed in the horizontal plane vs. free weights using guided (vertical) squat exercise, gains in jumping height were lower for FW than traditional training (ES = 0.4 and 0.9, respectively). Therefore, vertical FW training is recommended to increase jumping ability.

The selection of running speed as an outcome in this meta-analysis is based on the fact that it is an important performance factor in many sports, and it is usually related with vertical jump and multi-joint strength training. Although the findings in this variable showed the lowest significance of all outcomes analysed ($p < 0.05$), FW-EOT training appeared more effective to improve running speed than traditional resistance training[32,35,36] (ES between 0.3 and 1.45 in FW-EOT groups and −0.08 and 0.55 in control groups). These results are supported by Tous-Fajardo et al.,[64] not included in the meta-analysis, who showed greater improvements in soccer-specific performance tasks such as change of direction and linear running speed, after a combined FW-EOT and vibration training protocol vs. conventional training (plyometric, speed and weight-loaded training). Adding to this, from a molecular perspective, it seems EOT favours increments of mRNA levels of genes preferentially expressed in fast glycolytic fibers, ultimately inducing a faster muscle phenotype. Such changes may help the muscle to become better suited for explosive, high-speed actions.[65]

5. Conclusion

Although free weights and weight-stack machines are the most popular modes of resistance training, the results of this systematic review indicate that brief episodes of eccentric overload induced by flywheel devices, and performed at high intensity are associated with greater improvements in both concentric and eccentric force, muscle power and muscle hypertrophy in healthy and well-trained subjects. In addition, eccentric overload training appeared to be more effective than traditional resistance exercise in promoting increases in capacities highly related to athletic performance, such as vertical jump height and running speed. The efficacy of eccentric overload flywheel training to promote functional and structural adaptations is possibly mediated by the capacity to achieve higher forces during the eccentric muscle action, which maximizes the stretch-shortening cycle and thus, the capacity to produce greater force in the subsequent concentric action. However, these gains could even be greater considering the possibilities offered by FW technology. Thus, it appears at high speed and with light moments of inertia is the most effective training protocol to induced muscle adaptations employing FW. Finally, muscle power is the training outcome that experienced the greatest increase after a period of FW-EOT in healthy subjects and athletes. Future studies should analyse FW resistance training with eccentric overload programs using and comparing different training devices, volumes, intensities and exercise modes to fine-tune FW training routines.

Practical implications

Iso-inertial flywheel resistance exercise, a technology originally developed to combat muscle deconditioning during spaceflight, is a powerful tool to induce muscle force and power increments, as well as muscle hypertrophy in healthy subjects and athletes.

The available scientific literature indicates flywheel resistance exercise, calling for brief episodes of eccentric overload, triggers significantly greater skeletal muscle adaptations (i.e. strength, power and muscle mass) compared to traditional, gravity-dependent resistance exercise paradigms.

Eccentric overload flywheel resistance exercise boosts performance-related abilities (i.e. jump height and running speed). The magnitude of these adaptations is greater than those reported after weight-stack or free weight resistance training, which highlights the efficacy of iso-inertial exercise training.

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References

1. Roig M, O'Brien K, Kirk G et al. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med* 2009; 43(8):556–568.
2. Hollander DB, Kraemer RR, Kilpatrick MW et al. Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise. *J Strength Cond Res* 2007; 21(1):34–40.
3. Hortobagyi T, Hill JP, Houmard JA et al. Adaptive responses to muscle lengthening and shortening in humans. *J Appl Physiol* 1996; 80(3):765–772.
4. Higbie EJ, Cureton KJ, Warren 3rd GL et al. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J Appl Physiol* 1996; 81(5):2173–2181.
5. Dudley GA, Tesch PA, Harris RT et al. Influence of eccentric actions on the metabolic cost of resistance exercise. *Aviat Space Environ Med* 1991; 62(7):678–682.
6. Duchateau J, Baudry S. Insights into the neural control of eccentric contractions. *J Appl Physiol* 2014; 116(11):1418–1425.
7. Hortobagyi T, Lambert NJ, Hill JP. Greater cross education following training with muscle lengthening than shortening. *Med Sci Sports Exerc* 1997; 29(1):107–112.
8. Fang Y, Siemionow V, Sahgal V et al. Greater movement-related cortical potential during human eccentric versus concentric muscle contractions. *J Neurophysiol* 2001; 86(4):1764–1772.
9. Paulsen G, Crameri R, Benestad HB et al. Time course of leukocyte accumulation in human muscle after eccentric exercise. *Med Sci Sports Exerc* 2010; 42(1):75–85.
10. Garcia-Lopez D, Cuevas MJ, Almar M et al. Effects of eccentric exercise on NF-kappaB activation in blood mononuclear cells. *Med Sci Sports Exerc* 2007; 39(4):653–664.
11. Jimenez-Jimenez R, Cuevas MJ, Almar M et al. Eccentric training impairs NF-kappaB activation and over-expression of inflammation-related genes induced by acute eccentric exercise in the elderly. *Mech Ageing Dev* 2008; 129(6):313–321.
12. Fernandez-Gonzalo R, Bresciani G, de Souza-Teixeira F et al. Effects of a 4-week eccentric training program on the repeated bout effect in young active women. *J Sports Sci Med* 2011; 10(4):692–699.
13. Farthing JP, Chilibeck PD. The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *Eur J Appl Physiol* 2003; 89(6):578–586.
14. Franchi MV, Atherton PJ, Reeves ND et al. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol (Oxf)* 2014; 210(3):642–654.
15. Meylan CM, Nosaka K, Green JP et al. Variability and influence of eccentric kinematics on unilateral vertical, horizontal, and lateral countermovement jump performance. *J Strength Cond Res* 2010; 24(3):840–845.
16. Roig M, Shadgan B, Reid WD. Eccentric exercise in patients with chronic health conditions: a systematic review. *Physiother Can* 2008; 60(2):146–160.
17. Meylan C, Cronin J, Nosaka K. Isoinertial assessment of eccentric muscular strength. *Strength Cond J* 2008; 30(2):56–64.
18. Hortobagyi T. The positives of negatives: clinical implications of eccentric resistance exercise in old adults. *J Gerontol A Biol Sci Med Sci* 2003; 58(5):M417–M418.
19. Hortobagyi T, Devita P, Money J et al. Effects of standard and eccentric overload strength training in young women. *Med Sci Sports Exerc* 2001; 33(7):1206–1212.
20. Gillies EM, Putman CT, Bell GJ. The effect of varying the time of concentric and eccentric muscle actions during resistance training on skeletal muscle adaptations in women. *Eur J Appl Physiol* 2006; 97(4):443–453.
21. Dias CP, Toscan R, de Camargo M et al. Effects of eccentric-focused and conventional resistance training on strength and functional capacity of older adults. *Age (Dordrecht)* 2015; 37(5):99.
22. Guilhem G, Cornu C, Maffiuletti NA et al. Neuromuscular adaptations to isoload versus isokinetic eccentric resistance training. *Med Sci Sports Exerc* 2013; 45(2):326–335.
23. Berg HE, Tesch A. A gravity-independent ergometer to be used for resistance training in space. *Aviat Space Environ Med* 1994; 65(8):752–756.
24. Berg HE, Tesch A. Force and power characteristics of a resistive exercise device for use in space. *Acta Astronaut* 1998; 42(1–8):219–230.
25. Chiu LZ, Salem GJ. Comparison of joint kinetics during free weight and flywheel resistance exercise. *J Strength Cond Res* 2006; 20(3):555–562.
26. Naczk M, Brzenczek-Owczarzak W, Arlet J et al. Training effectiveness of the inertial training and measurement system. *J Hum Kinet* 2014; 44:19–28.
27. Tous-Fajardo J, Maldonado RA, Quintana JM et al. The flywheel leg-curl machine: offering eccentric overload for hamstring development. *Int J Sports Physiol Perform* 2006; 1(3):293–298.
28. Tesch PA, Ekberg A, Lindquist DM et al. Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. *Acta Physiol Scand* 2004; 180(1):89–98.
29. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol* 2007; 102(1):368–373.
30. Norrbrand L, Fluckey JD, Pozzo M et al. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur J Appl Physiol* 2008; 102(3):271–281.
31. Fernandez-Gonzalo R, Lundberg TR, Alvarez-Alvarez L et al. Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *Eur J Appl Physiol* 2014; 114(5):1075–1084.
32. Maroto-Izquierdo S, Garcia-Lopez D, De Paz Fernandez JA. Functional and muscle-size effects of flywheel resistance training with eccentric overload in professional handball players. *J Hum Kinet* 2016 (in press).
33. Romero-Rodriguez D, Gual G, Tesch PA. Efficacy of an inertial resistance training paradigm in the treatment of patellar tendinopathy in athletes: a case-series study. *Phys Ther Sport* 2011; 12(1):43–48.
34. Naczk M, Naczk A, Brzenczek-Owczarzak W et al. Impact of inertial training on strength and power performance in young active men. *J Strength Cond Res* 2013 (Epub ahead of Print).
35. de Hoyo M, Pozzo M, Sanudo B et al. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int J Sports Physiol Perform* 2015; 10(1):46–52.
36. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports* 2003; 13(4):244–250.
37. Norrbrand L, Tous-Fajardo J, Vargas R et al. Quadriceps muscle use in the flywheel and barbell squat. *Aviat Space Environ Med* 2011; 82(1):13–19.
38. Pozzo M, Alkner B, Norrbrand L et al. Muscle-fiber conduction velocity during concentric and eccentric actions on a flywheel exercise device. *Muscle Nerve* 2006; 34(2):169–177.
39. Rittweger J, Frost HM, Schiessl H et al. Muscle atrophy and bone loss after 90 days' bed rest and the effects of flywheel resistive exercise and pamidronate: results from the LTBR study. *Bone* 2005; 36(6):1019–1029.
40. Alkner BA, Tesch P. Knee extensor and plantar flexor muscle size and function in response to 90 d bed rest with or without resistance exercise. *Eur J Appl Physiol* 2004; 93:294–305.
41. Tesch PA, Trieschmann JT, Ekberg A. Hypertrophy of chronically unloaded muscle subjected to resistance exercise. *J Appl Physiol* 2004; 96(4):1451–1458.
42. Onambele GL, Maganaris CN, Mian OS et al. Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *J Biomech* 2008; 41(15):3133–3138.
43. Brzenczek-Owczarzak W, Naczk M, Arlet J et al. Estimation of the efficacy of inertial training in older women. *J Aging Phys Act* 2013; 21(4):433–443.
44. Fernandez-Gonzalo R, Nissemark C, Aslund B et al. Chronic stroke patients show early and robust improvements in muscle and functional performance in response to eccentric-overload flywheel resistance training: a pilot study. *J Neuroeng Rehabil* 2014; 11:150.
45. Fernandez-Gonzalo R, Fernandez-Gonzalo S, Turon M et al. Muscle, functional and cognitive adaptations after flywheel resistance training in stroke patients: a pilot randomized controlled trial. *J Neuroeng Rehabil* 2016; 13:37.
46. Shamseer L, Moher D, Clarke M et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *BMJ* 2015; 349:g7647.
47. Moher D, Shamseer L, Clarke M et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev* 2015; 4:1.
48. Goode AP, Reiman MP, Harris L et al. Eccentric training for prevention of hamstring injuries may depend on intervention compliance: a systematic review and meta-analysis. *Br J Sports Med* 2015; 49(6):349–356.
49. Elkins MR, Moseley AM, Sherrington C et al. Growth in the Physiotherapy Evidence Database (PEDro) and use of the PEDro scale. *Br J Sports Med* 2013; 47(4):188–189.
50. Lundberg TR, Fernandez-Gonzalo R, Gustafsson T et al. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *J Appl Physiol* 2013; 114(1):81–89.
51. Lundberg G, Fernandez-Gonzalo R, Tesch P. Exercise-induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol* 2014; 116:611–620.
52. Naczk M, Naczk A, Brzenczek-Owczarzak W et al. Efficacy of inertial training in elbow joint muscles: influence of different movement velocities. *J Sports Med Phys Fitness* 2016; 56(3):223–231.
53. Norrbrand L, Pozzo M, Tesch PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. *Eur J Appl Physiol* 2010; 110(5):997–1005.
54. Lundberg TR, Fernandez-Gonzalo R, Tesch PA. Exercise induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol* 2014; 116(6):611–620.
55. Dudley GA, Tesch PA, Miller BJ et al. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med* 1991; 62(6):543–550.
56. Hather BM, Tesch PA, Buchanan P et al. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand* 1991; 143(2):177–185.
57. Martinez-Aranda LM, Fernandez-Gonzalo R. Effects of inertial setting on power, force, work and eccentric overload during flywheel resistance exercise in women and men. *J Strength Cond Res* 2016 (Epub ahead of Print).
58. Alkner B, Tesch PA. Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest. *Acta Physiol Scand* 2004; 181:345–357.
59. Alkner BA, Berg HE, Kozlovskaya I et al. Effects of strength training, using a gravity-independent exercise system, performed during 110 days of simulated space station confinement. *Eur J Appl Physiol* 2003; 90:44–49.
60. Bloomquist K, Langberg H, Karlsen S et al. Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *Eur J Appl Physiol* 2013; 113(8):2133–2142.

61. Noorkoiv M, Nosaka K, Blazevich AJ. Neuromuscular adaptations associated with knee joint angle-specific force change. *Med Sci Sports Exerc* 2014; 46(8):1525–1537.
62. McMahon GE, Morse CI, Burden A et al. Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. *J Strength Cond Res* 2014; 28(1):245–255.
63. de Hoyo M, Sanudo B, Carrasco L et al. Effects of traditional versus horizontal inertial flywheel power training on common sport-related tasks. *J Hum Kinet* 2015; 47:155–167.
64. Tous-Fajardo J, Gonzalo-Skok O, Arjol-Serrano JL et al. Change of direction speed in soccer players is enhanced by functional inertial eccentric overload and vibration training. *Int J Sports Physiol Perform* 2016; 11:66–73.
65. Friedmann-Bette B, Bauer T, Kinscherf R et al. Effects of strength training with eccentric overload on muscle adaptation in male athletes. *Eur J Appl Physiol* 2010; 108(4):821–836.

PUBLICATION 2

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

Sergio Maroto Izquierdo

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Section III – Sports Training

DE GRUYTER OPEN

Functional and Muscle-Size Effects of Flywheel Resistance Training with Eccentric-Overload in Professional Handball Players

by

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The aim of the study was to analyse the effects of 6 week (15 sessions) flywheel resistance training with eccentric-overload (FRTEO) on different functional and anatomical variables in professional handball players. Twenty-nine athletes were recruited and randomly divided into two groups. The experimental group (EXP, n = 15) carried out 15 sessions of FRTEO in the leg-press exercise, with 4 sets of 7 repetitions at a maximum-concentric effort. The control group (CON, n = 14) performed the same number of training sessions including 4 sets of 7 maximum repetitions (7RM) using a weight-stack leg-press machine. The results which were measured included maximal dynamic strength (1RM), muscle power at different submaximal loads (PO), vertical jump height (CMJ and SJ), 20 m sprint time (20 m), T-test time (T-test), and Vastus-Lateralis muscle (VL) thickness. The results of the EXP group showed a substantially better improvement (p < 0.05-0.001) in PO, CMJ, 20 m, T-test and VL, compared to the CON group. Moreover, athletes from the EXP group showed significant improvements concerning all the variables measured: 1RM (ES = 0.72), PO (ES = 0.42 - 0.83), CMJ (ES = 0.61), SJ (ES = 0.54), 20 m (ES = 1.45), T-test (ES = 1.44), and VL (ES = 0.63 - 1.64). Since handball requires repeated short, explosive effort such as accelerations and decelerations during sprints with changes of direction, these results suggest that FRTEO affects functional and anatomical changes in a way which improves performance in well-trained professional handball players.

Key words: *muscle power, hypertrophy, iso-inertial, sport performance.*

Introduction

Muscle strength and power are critical in competitive team sports as these abilities are the basis of specific actions that determine performance (i.e. throwing, jumping, running and hitting). In these sport modalities, that include handball, players are required to repeatedly carry out short, explosive efforts such as accelerations and decelerations during sprints with changes of direction. Handball involves high-intensity short duration exercise, requiring a well-developed aerobic fitness, speed and strength (Massuca et al., 2014). Therefore, new training methods are continuously being sought to improve the ability of skeletal muscles to develop explosive strength (Perez-Gomez et al., 2013). Common exercises for explosive-strength improvement include plyometrics, ballistic exercises and weightlifting (i.e. power snatch).

As an alternative to these traditional methods, inertial-resistance training emerges as a paradigm that can be applied through different systems, such as flywheel devices. Flywheel devices provide a gravity-independent stimulus (Alkner et al., 2003; Trappe et al., 2004) that in addition to causing greater muscle activation (Caruso et al., 2006; Norrbrand et al., 2010) allows

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for brief episodes of eccentric-overload (EO) (Berg et al., 1994; Tesch et al., 2004). Given the general consensus which exists regarding the importance of eccentric action in resistance training, induced hypertrophy (Hather et al., 1991) and strength gains (Dudley et al., 1991), the main application of flywheel-resistance training with eccentric-overload (FRTEO) is to develop muscle mass (Fernandez-Gonzalo et al., 2014a; Norrbrand et al., 2008; Seynnes et al., 2007; Tesch et al., 2004), and specially to avoid muscle atrophy caused by weightlessness situations (Alkner et al., 2003, 2004; Rittweger et al., 2007). These benefits have also been observed in people with chronic diseases that involve functional impairment (i.e. strokes and multiple sclerosis) (Fernandez-Gonzalo et al., 2014b), and in the elderly (Brzenczek-Owczarzak et al., 2013; Hortobagyi et al., 2009).

Specifically in competitive sport, FRTEO-related research has been focused on the prevention and treatment of injuries (Askling et al., 2003; de Hoyo et al., 2015a; Romero-Rodriguez et al., 2011) and as a part of warm-up routines (de Hoyo et al., 2014). Much less is known about the effects of FRTEO on athletic performance and muscle hypertrophy in well-trained athletes. De Hoyo and co-workers have recently reported significant improvements in vertical jump height, sprint time (10 m and 20 m) (de Hoyo et al., 2015a) and kinetic variables during changes of direction (de Hoyo et al., 2016) after 10 week FRTEO carried out by junior soccer players. These results reinforce the input of Askling et al. (2003). In addition, Tous-Fajardo et al. (2016) suggested that iso-inertial EO in combination with vibration training performed once a week could serve as a viable adjunct to improve performance tasks specific to soccer such as changes of direction and linear speed abilities. Naczk et al. (2013, 2014, 2016) have also observed significant improvements in muscle power in healthy active men, although these benefits have not been demonstrated in athletes. To the best of our knowledge, no studies have analyzed the FRTEO chronic effects on handball players.

Therefore, the aim of this study was to analyse the effects of 6 week FRTEO on maximal dynamic strength and power output at different submaximal loads, vertical jump height, sprint time, agility and muscle thickness in professional handball players. These effects were compared to those induced by traditional in-season weight training. We hypothesized that FRTEO would lead to a higher increase in all functional, structural and dependent variables that were analysed.

Methods

A randomized controlled study was designed to compare the effects of FRTEO with those induced by traditional weight training in a group of professional handball players. Twenty-nine athletes completed six weeks (15 sessions) of resistance training with the leg-press exercise. Participants were randomly divided into 2 groups: an experimental group (EXP, n = 15), which carried out the leg press on a FRTEO basis, and a control group (CON, n = 14), which performed a similar program (volume and intensity) using a traditional weight-stack machine. Each week included 2-3 sessions consisting of 4 sets of 7 repetitions performed at maximal concentric effort. Before and after the training program, athletes came to the lab on four occasions separated by a minimum of 24 h. The first test session was used in order to collect descriptive data and to familiarize the players from the EXP group with the flywheel leg-press device. Vastus-Lateralis muscle thickness was also measured during this first experimental session. The 1RM test was carried out during the second test session. The third session was used to measure maximal power output with different loads. The last test session was focused on measuring vertical jump height, 20 m sprint time and T-test time.

Participants

Twenty-nine professional male handball players were recruited from the same handball club (*Club Balonmano Atlético Valladolid*), which played in the first division of the Spanish handball league (ASOBAL). The biometric data and characteristics of the participants are presented in Table 1. Their regular weekly exercise practice consisted of 4 handball sessions (~9 h), 3 sessions including strength/power exercises, 3 on-track specific physical training sessions (changes of direction and plyometric exercises) and 1 competitive match (at the weekends). The participants were highly experienced with free-weight resistance exercises, but none of them had previously used flywheel devices. Before giving their written informed consent to participate, athletes were informed of the purposes, benefits and risks involved in the study, being aware that they could terminate their participation in the study at any time. The study protocol was approved by the Ethics Committee of the University of León, and conformed to the standards set by the Declaration of Helsinki.

Concerning the annual periodization, the study was carried out during the beginning of the second round of the first division of the Spanish handball league (January to February). The main exclusion criteria used for this study were to have had a lower limb joint injury in the 6 months prior to the study (Fernandez-Gonzalo et al., 2014a), and/or severe lower limb muscle injury (strains for more than 27 days) in the previous 2 months (de Hoyo et al., 2014). Athletes who suffered an injury during the experimental phase of the study were excluded, as well as participants who did not follow the prescribed training program or players that did not carry out the exercises correctly. None of the participants were excluded from the study. Moreover, athletes were not allowed to change their sleeping, eating, and drinking habits throughout their participation in the study.

Measures

Maximal Dynamic Strength

The 1RM leg-press was assessed using a previously established protocol (Fernandez-Gonzalo et al., 2014a). A 45° leg press device (Ortus Fitness S.L., Valencia, Spain) was used. Briefly, after a warm-up on the leg press, participants attempted to lift a progressively increased load, with 3 min of rest allowed between attempts. The 1RM value was obtained using as few attempts as possible (5 attempts maximum). To consider a repetition as valid, a knee full extension (180º) had to be reached, starting from a 90º knee flexion.

Power Output

The same leg press device employed in 1RM testing was used to measure maximal concentric power output (PO) at different intensities (50, 60, 70, 80 and 90% of 1RM). For each load, participants completed a set of 3 repetitions from 90° knee flexion to full extension (180°) with a 3 min recovery between sets. To avoid any use of the stretch-shortening cycle, each repetition started from a complete static position, at 90º knee flexion. Players were requested to perform the concentric phase of each repetition as fast as possible. Power for each repetition was sampled at 100 Hz using a rotary encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L., Murcia, Spain) and the associated software (T-Force v. 2.28). The repetition with the highest mean power at each load was used for further analysis. The order of tested intensities was randomized without replacement. Participants were aware of the percentage and amount of weight they were using. For the post-training evaluation, the same order was used as in the pre-training session.

Vertical Jump

Countermovement jump (CMJ) and squat jump (SJ) heights were assessed using a contact platform (ChronoJump, BoscoSystem, Barcelona, Spain) and the associated software (ChronoJump 1.5.0). Participants performed three attempts of each vertical jump, trying to jump as high as possible with their hands on the hips. For the SJ, the eccentric phase was eliminated, starting from a standardized position with a 90° knee flexion. The CMJ started from a standing position without any pause between the eccentric and concentric phase. The knee flexion angle was self-selected. A 30 s active recovery was allowed between following attempts. The highest value of the SJ and CMJ was selected for further analysis.

Speed and Agility

20 m sprint time and T-test time were measured using photocells (ChronoJump, BoscoSystem, Barcelona, Spain) and the associated software (ChronoJump 1.5.0). The 20 m sprint test consisted of a maximal intensity straight sprint between two photocell gates separated by 20 m from a standing position. The T-test was administered using the protocol outlined by Pauole et al. (2000) with minor modifications. The measurement of time started when players passed the electronic sensors, and stopped the instant the participants crossed the sensor plane again. Three trials were performed for each test, with a 2 min active recovery period between attempts. All assessments were performed on a competition parquet surface and players wore handball-specific shoes. The fastest trial was used for statistical analysis.

Vastus Lateralis muscle thickness

The thickness of the Vastus Lateralis (VL) of the right leg of all participants was estimated using a previously described protocol (Alegre et al., 2014, 2015). VL muscle was measured in vivo by B-mode ultrasonography (MyLab™50, Esaote, Genoa, Italy) with a 5 cm, 12 MHz linear array probe, which was coated in water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. Before measurements, the subjects were laid on a couch for 15 min to allow osmotic fluids to shift. During measurements, the participants were laid in a supine position with their knees fully extended and muscles relaxed. The images for the measurements of muscle thickness were recorded at 25, 50 and 75% distance between the greater trochanter and lateral condyle of the femur (VL25, VL50 and VL75, respectively), with the ultrasound probe placed on the transversal plane and perpendicular to the skin. VL muscle thickness was determined by measuring the perpendicular distance between the medial and lateral limits of the muscle with ultrasound software (MyLab™ Desk, Esaote, Genoa, Italy) before and after the training intervention. In order to increase the reliability of the obtained data, the measuring points were marked daily on the skin with indelible ink and muscle architecture images from before and after the intervention were compared.

Procedures

Participants performed a lower-limb resistance-training program based on the leg press exercise. The training program lasted 6 weeks, and included 2 (weeks 1, 3, 5) or 3 (weeks 2, 4, 6) sessions per week, with at least 48 hours between sessions (Fernandez-Gonzalo et al., 2014a; Norrbrand et al., 2008). Each session included 4 sets of 7 repetitions, with a 3 min recovery period between sets. Each training session started with a warm-up consisting of 5 min cycling and 2 sets of 10 non-maximal repetitions in specific leg press exercises. The flywheel device (Leg Press, Inc YoYo Technology, Stockholm, Sweden) used by the EXP group was equipped with two 6.5 kg flywheels (45 cm diameter) with moment inertia of 0.145 $kg \cdot m^2$ (Figure 1).

FRTEO performed by the EXP group consisted of accelerating/braking flywheels through the extension-flexion of the knees and hips, as previously described (Fernandez-Gonzalo et al., 2014a). Briefly, each repetition consisted of a maximum concentric action of thrust on the platform where the feet were placed, rotating the wheels. Participants were asked to push with maximal effort through the entire concentric action, which ranged from 70° knee flexion to near full extension. At the end of this concentric action, the flywheel strap wound back due to inertial forces, which initiated the reversed eccentric action. During the first third of the eccentric action, participants were instructed to resist gently, and thereafter, to apply maximal breaking force to stop the movement at about 70° knee flexion (Fernandez-Gonzalo et al., 2014a). By means of this approach, EO was produced (Norrbrand et al., 2010; Romero-Rodriguez et al., 2011; Tesch et al., 2004).

The CON group carried out leg presses on a traditional weight-stack machine (Ortus Fitness S.L., Valencia, Spain). They performed the same training volume with a load equivalent to 7 repetitions maximum (7RM) for each set. Participants were instructed to perform the concentric phase of each repetition at maximal velocity. At the end of each set, the participants were asked to rate their perceived exertion according to a resistance-training specific scale (OMNI scale) (Lagally et al., 2006). The athletes were accustomed to the OMNI scale, as strength and conditioning staff used it regularly during pre-season and in-season workouts. Research personnel provided strong verbal encouragement during all repetitions performed by players from both groups.

Statistical Analysis

Statistical analysis was performed with SPSS v.20.0 (SPSS Inc., IBM, USA). The data is presented as mean ± SEM. Data distribution was checked for normality using the Shapiro–Wilk test. VL thickness, 1RM, power at different loads, SJ, CMJ, 20 m sprint time and T-test time were examined using a two-way ANOVA. The 2 factors considered were experimental condition (EXP vs. CON) and time (PRE vs. POST). When a significant interaction was found, post hoc comparisons with Bonferroni adjustment were employed. The effect size (ES) of training was calculated for paired variables (Cohen, 1998). Cohen suggested ES of 0.2, 0.5, 0.8 and 1.3 to represent small, moderate, large and very large effects, respectively. Practical relevance was defined as an ES > 0.8 (Hopkins et al., 2009). The significance level was set at $p < 0.05$.

Results

Participants from both groups completed all the designed training sessions. Perceived exertion reported after the training sets was similar in the EXP and CON groups. Table 2 displays maximal dynamic strength (1RM), power output, vertical jump, sprint time and agility results.

Maximal Dynamic Strength

A significant time effect was observed ($F_{1,29} = 33.71$). Thus, the EXP (12.2%, $p < 0.001$; ES = 0.72) and CON (7.9%, $p < 0.01$; ES = 0.49) groups showed a significant increase in 1RM value. No significant condition or condition x time main effects were observed.

Power Output

Regarding PO, there was a significant time effect for all the loads tested: PO50 ($F_{1,29} = 10.247$; $p < 0.01$), PO60 ($F_{1,29} = 7.576$; $p < 0.05$), PO70 ($F_{1,29} = 13.344$; $p < 0.01$), PO80 ($F_{1,29} = 10.454$; $p < 0.01$) and PO90 ($F_{1,29} = 5.195$; $p < 0.05$). Although no significant condition or condition x time main effects were observed, only the EXP players showed significant changes in PO, with increases ranging from 10 to 21.6% (ES = 0.42 – 0.83).

Vertical Jump

A significant time effect was observed in SJ ($F_{1,29} = 26.233$; $p < 0.001$), with significant increases showed by the CON ($p < 0.05$, ES = 0.36) and EXP ($p < 0.001$; ES = 0.54) groups. No significant condition or condition x time main effects were observed.

Results regarding the CMJ indicated a significant time ($F_{1,29} = 28.452$; $p < 0.001$), condition ($F_{1,29} = 5.513$; $p < 0.05$) and condition x time ($F_{1,29} = 5.691$; $p < 0.05$) main effects. Thus, only the EXP participants enhanced their CMJ value after the training period ($p < 0.001$; ES = 0.61). Post-hoc analysis pointed out that the CMJ value after the training period was significantly higher in the EXP group in comparison to the CON group ($p < 0.05$).

Speed and Agility

Significant time ($F_{1,29} = 58.417$; $p < 0.001$) and condition x time ($F_{1,29} = 6.503$; $p < 0.05$) main effects were observed concerning the 20 m sprint time. Post-hoc analysis revealed that both groups significantly reduced their sprint time (EXP: $p < 0.01$, ES = 1.45; CON: $p < 0.01$, ES = 0.85), with a larger reduction in the EXP group.

Results regarding T-test time showed significant time ($F_{1,29} = 26.345$; $p < 0.001$), condition ($F_{1,29} = 5.226$; $p < 0.05$) and condition x time ($F_{1,29} = 5.713$; $p < 0.05$) main effects. Thus, only the EXP participants significantly reduced their T-test time value after the training period ($p < 0.001$; ES = 1.44). Moreover, post-hoc analysis pointed out that the T-test time after the training period was significantly higher in the EXP group in comparison to the CON group ($p < 0.05$).

Vastus-Lateralis muscle thickness

Results regarding Vastus-Lateralis muscle thickness are displayed in Figure 2.

A significant time effect was observed concerning VL25 ($F_{1,29} = 22.801$; $p < 0.001$), VL50 ($F_{1,29} = 168.772$; $p < 0.001$) and VL75 ($F_{1,29} = 39.229$; $p < 0.001$). Likewise, data showed a significant interaction condition x time effect for VL25 ($F_{1,29} = 15.028$; $p < 0.01$), VL50 ($F_{1,29} = 74.665$; $p < 0.001$) and VL75 ($F_{1,29} = 9.651$; $p < 0.01$). Thus, the EXP participants showed a significant VL hypertrophy at proximal ($p < 0.001$; ES = 1.61), medial ($p < 0.001$; ES = 1.64) and distal ($p < 0.001$; ES = 0.63) levels. Although athletes from the CON group also showed a significant increase in muscle thickness at media (VL50, $p < 0.05$; ES = 0.39) and distal (VL75, $p < 0.05$; ES = 0.15) measurements, the VL muscle hypertrophy experienced by the EXP participants was significantly higher ($p < 0.001$-0.01) than that showed by the CON group at all measurement levels (VL25, VL50 and VL75).

Table 1

Descriptive data of the participants, Mean ± SEM

	Age (y)	Body height (cm)	Body mass (kg)	Body mass index (kg/m²)
Experimental Group	19.8 ± 1	186 ± 8	82.3 ± 3.3	23.7 ± 0.6
Control Group	23.8 ± 1.6	184 ± 1	85.6 ± 3.7	25.2 ± 0.9

Table 2

1RM, PO at different loads, SJ, CMJ, 20 m and T-test results before and after the training period for the EXP and CON groups. Values are mean ± SEM

	EXPERIMENTAL			CONTROL		
	Pre	Post	Δ%	Pre	Post	Δ%
1RM (kg)	258.7 ± 9.5	290.3 ± 12.5	12.2	242.9 ±	262 ± 9.1 *	7.9
PO50 (w)	835.1 ± 30.4	943.1 ± 59 **	12.9	894.2 ±	943.4 ± 47.4	5.5
PO60 (w)	918 ± 39.2	1009.5 ± 67.4	10	908.3 ±	954.9 ± 45.1	5.1
PO70 (w)	916.8 ± 38.6	1030.4 ± 65.4	12.4	922.5 ±	982.7 ± 37.6	6.5
PO80 (w)	840.2 ± 38.7	1005.8 ± 68.7	19.7	886.2 ±	948.4 ± 34.8	7
PO90 (w)	777.4 ± 42	944.9 ± 70*	21.6	871.9 ± 41	941 ± 42.7	7.9
SJ (cm)	33.4 ± 1.5	36.7 ± 1.5 ***	9.6	31.5 ± 1.2	32.9 ± 0.8 *	4.5
CMJ (cm)	35.7 ± 1.3	39.2 ± 1.5 ***	9.8	33 ± 1.2	34.1 ± 0.9	3.4
20m (s)	3.7 ± 0.1	3.3 ± 0.1 ***	-10	3.6 ± 0.1	3.5 ± 0.1 **	-5.1
T-test (s)	9.2 ± 0.1	8.6 ± 0.1 ***	-7	9.5 ± 0.2	9.1 ± 0.1	-4.4

Abbreviations: 1RM, maximal dynamic strength; PO, power output; PO50-90 maximal concentric power output (PO) at different intensities (50, 60, 70, 80 and 90% of 1RM); SJ, squat jump; CMJ, countermovement jump; 20 m, 20 m sprint time.
** Significantly different from pre-training value, where *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.*
$ Significantly different from CON group value, where $p < 0.05 and $$p < 0.01.

Figure 1

Iso-inertial device used in the FRTEO program.

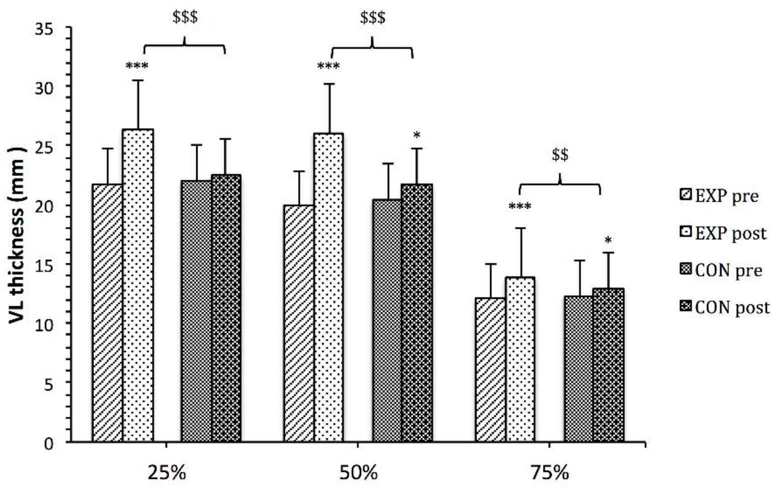

Figure 2

*Vastus Lateralis thickness at proximal (25%), medial (50%) and distal (75%) measurements before and after the training program for both, experimental (EXP) and control (CON) groups. * Significantly different from pre-training value, where *p < 0.05 and ***p < 0.001. $ Significantly different from CON group value, where $p < 0.05 and $$$p < 0.001.*

Discussion

In addition to technical and tactical game skills, performance in handball is related to power, strength, speed and agility (Massuca et al., 2014). Therefore, training approaches that lead to improvements in those abilities should be taken into account by coaches as well as strength and conditioning specialists focused on handball performance. To the best of our knowledge, this is the first study comparing functional and structural effects of a flywheel resistance-training program with eccentric-overload (FRTEO) to those induced by a traditional weight-training program, in professional handball players. The main finding pointed out by the results is that 6 week FRTEO including 15 sessions with 4 sets of 7 repetitions performed at maximal concentric intensity using the leg press exercise induced significant improvements in maximal dynamic strength (1RM), maximal power at different loads, vertical jump height, 20 m sprint time and T-test time. Moreover, FRTEO induced significant hypertrophy in Vastus-Lateralis muscle at proximal (VL25), medium (VL50) and distal (VL75) levels. All these positive effects were significantly higher than those showed by subjects who carried out a similar (volume and perceived effort) training program on a conventional leg/press weight/stack machine.

During traditional concentric-eccentric resistance exercise performed at maximal intensity, the eccentric phase is clearly under-loaded (e.g. about 40-50%) which has been shown in several studies (Dudley et al., 1991; Hather et al., 1991). These studies used a variety of experimental manipulation and demonstrated the role of eccentric contractions to improve contractile characteristics and muscle size in humans. It makes sense to apply eccentric-overloads during resistance training in order to increase neuromuscular adaptations (Hortobagyi et al., 2001). Specific literature includes research studies in which this EO is applied through an iso-inertial gravity-independent stimulus, with positive results concerning structural (Alkner et al., 2003, 2004; Tesch et al., 2004) and functional adaptations (de Hoyo et al., 2015a; Fernandez-Gonzalo et al., 2014a; Romero-Rodriguez et al., 2011) when applied to different populations, mainly recreationally trained subjects or physical education students. Our results point out that applying FRTEO can significantly increase the 1RM value in well-trained handball players, although this improvement is similar to that obtained after a traditional weight training program. Although the participants of the EXP group were exposed to EO, the 1RM test carried out was similar in nature to training performed by the CON group. After a similar 6 week FRTEO study (Fernandez-Gonzalo et al., 2014a) which was also carried out with the leg press exercise, a group of physical education students increased the 1RM value by 25%. As the participants in our study were professional handball players and thus well-trained athletes, the lower increase observed in maximal dynamic strength of the athletes compared to the students could be due to the initial physical ability of the athletes before the study.

The significant improvements concerning PO at different intensities (50, 60, 70, 80 and 90% of 1RM) after FRTEO carried out by the EXP participants are in line with previous studies. Moreover, Fernandez-Gonzalo and co-workers (2014a) also observed significant increases in muscle power at loads equivalent to 60, 70 and 80% of the 1RM after similar FRTEO. Furthermore, after analysing a sample of students, Naczk et al. (2013, 2014, 2016) showed significant muscle power improvements in lower and upper limbs. However, our study is the first to demonstrate the positive effects of FRTEO on increasing muscle power at high percentages of 1RM in athletes. Interestingly, participants from the CON group did not increase their PO at any load, even though the training stimulus could be considered more similar in nature to that found during the PO test. These major improvements in muscle power may be explained by the particular characteristics of flywheel training to induce EO, since the eccentric EO is usually applied in the last portion of the range of motion during the eccentric action. That is, EO is produced mainly at a joint angle close to 70º during the leg press just before the subsequent concentric action is initiated. This exercise technique would maximize the stretch shortening cycle, allowing for greater production of force during the first part of the concentric action, and therefore, a higher velocity during the entire movement (i.e. increased power).

PO results together with vertical jump (SJ and CMJ) and significant improvements observed in the EXP group indicate that FRTEO appears to be an effective tool to increase muscle power in well-trained handball players. Although a similar training program carried out by physical education students did not induce any significant increases in SJ or CMJ (Fernandez-Gonzalo et al., 2014a), a study focused on elite soccer players indicated significant gains in CMJ height after 10week FRTEO (de Hoyo et al., 2015a). The significant interaction condition x time showed by our results in regard to CMJ height could suggest that vertical jump improvements induced by FRTEO are higher in comparison with those induced by traditional resistance training when the jump modality includes an eccentric phase (i.e. CMJ). Since leg power has been suggested as an essential component for elite handball players (Massuca et al., 2014), these results could support the inclusion of FRTEO in handball training routines. In a recent study, de Hoyo et al. (2015b) showed that under specific circumstances, i.e. FW exercise performed in the horizontal plane vs. free weights using a guided (vertical) squat exercise, the gains in jumping height were lower for FW compared to traditional training.

As quickness and agility are characteristics of elite handball players (Massuca et al., 2014), the present results concerning 20 m sprints and T-tests indicate that FRTEO is a useful training approach producing performance-related adaptations. These adaptations are relevant given the importance of the decelerating phases in the sprinting technique, either in a linear or in a change-of-direction approach. Efficient eccentric activation timing and force production of the quadriceps and hamstring muscle groups are necessary during the stance phase in order to provide better elastic energy absorption and storage for impulse during take-off. In the same line, De Hoyo and co-workers (2015a, 2016) showed significant improvements in kinetic variables, changes of direction and 20 m sprints time after 10 week FRTEO carried out with half squat and leg curl flywheel devices by junior elite soccer players. Similar to linear-sprint results, and probably more representative in terms of performance, our data pointed out a significant improvement in the change-of-direction test, such as the T-test. These results are in line with Tous-Fajardo et al. (2016) who suggested that flywheel training performed once a week could serve as a viable adjunct to improve performance tasks specific to soccer.

Greater muscle mass is often an advantageous characteristic in sports, as in team handball, where speed and explosiveness are the essence of the sport (Massuca et al., 2014). Our results indicate that the significant increase in Vastus-Lateralis muscle thickness achieved after the FRTEO program was significantly higher than that induced by a traditional weight training program. The efficacy of FRTEO to induce muscle hypertrophy has been well documented (Fernandez-Gonzalo et al., 2014a; Norrbrand et al., 2008; Tesch et al., 2004). After a similar FRTEO training program, physical education students also showed significant hypertrophy of the thigh muscles (Fernandez-Gonzalo et al., 2014a). In a similar line, Norrbrand et al. (2008) observed a significant increase in quadriceps muscle volume after 5 week FRTEO carried out by untrained men in leg-extension exercises. At a physiological level, the enhanced eccentric load apparently led to a subtly faster gene expression pattern, inducing a faster muscle phenotype plus associated adaptations that make a muscle better suited for fast, explosive movements (Friedmann-Bette et al., 2010). However, since the mechanism of hypertrophy is not yet completely understood, future studies should delve into these potential pathways, helping us to understand the underlying mechanism of the high hypertrophic role of FRTEO.

In summary, 6-week FRTEO with 2-3 sessions a week, including 4 sets of 7 repetitions of the leg-press exercise performed at maximum concentric intensity induces significant improvements in maximal dynamic strength, power output at different loads, vertical jump height, sprint time, agility and muscle thickness in professional handball players. The adaptations regarding muscle power at different submaximal loads, countermovement jump, 20 m sprint time, T-test time and muscle thickness of the Vastus Lateralis were significantly larger than those observed after a similar (volume and intensity) resistance training program carried out with a traditional weight-stack leg press machine and including a similar volume and perceived effort. Therefore, the EO applied through a flywheel device seems to be a useful tool inducing functional and anatomical adaptations related with performance in well-trained handball players. Future studies should analyze FRTEO programs using different training volumes and exercises in order to reinforce these results.

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References

Alegre LM, Aguado X, Rojas-Martin D, Martin-Garcia M, Ara I, Csapo R. Load-controlled moderate and high-intensity resistance training programs provoke similar strength gains in young women. *Muscle Nerve,* 2015; 51(1): 92-101

Alegre LM, Ferri-Morales A, Rodriguez-Casares R, Aguado X. Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture. *Eur J Appl Physiol,* 2014; 114(11): 2437-2446

Alkner B, Tesch PA. Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest. *Acta Physiol Scand,* 2004; 181: 345-357

Alkner BA, Berg HE, Kozlovskaya I, Sayenko D, Tesch P. Effects of strength training, using a gravity-independent exercise system, performed during 110 days of simulated space station confinement. *Eur J Appl Physiol,* 2003; 90: 44-49

Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sports,* 2003; 13(4): 244-250

Berg HE, Tesch A. A gravity-independent ergometer to be used for resistance training in space. *Aviat Space Environ Med,* 1994; 65(8): 752-756

Brzenczek-Owczarzak W, Naczk M, Arlet J, Forjasz J, Jedrzejczak T, Adach Z. Estimation of the efficacy of inertial training in older women. *J Aging Phys Act,* 2013; 21(4): 433-443

Caruso JF, Hernandez DA, Porter A, Schweikert T, Saito K, Cho M, De Garmo N, Nelson NM. Integrated electromyography and performance outcomes to inertial resistance exercise. *J Strength Cond Res,* 2006; 20(1): 151-156

Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* (2nd ed.). Hillsdale, NJ: L.: Erlbaum Associates; 1998

de Hoyo M, de la Torre A, Pradas F, Sanudo B, Carrasco L, Mateo-Cortes J, Dominguez-Cobo S, Fernandes O, Gonzalo-Skok O. Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med,* 2014; 36(4): 308-314

de Hoyo M, Pozzo M, Sanudo B, Carrasco L, Gonzalo-Skok O, Dominguez-Cobo S, Moran-Camacho E. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int J Sports Physiol Perform,* 2015a; 10(1): 46-52

de Hoyo M, Sanudo B, Carrasco L, Dominguez-Cobo S, Mateo-Cortes J, Cadenas-Sanchez MM, Nimphius S. Effects of traditional versus horizontal inertial flywheel power training on common sport-related tasks. *J Hum Kinet,* 2015b; 47: 155-167

de Hoyo M, Sanudo B, Carrasco L, Mateo-Cortes J, Dominguez-Cobo S, Fernandes O, Del Ojo JJ, Gonzalo-Skok O. Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. *J Sports Sci,* 2016; 34(14): 1380-1387

Dudley GA, Tesch PA, Miller BJ, Buchanan P. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med,* 1991; 62(6): 543-550

Fernandez-Gonzalo R, Lundberg TR, Alvarez-Alvarez L, de Paz JA. Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *Eur J Appl Physiol,* 2014a; 114(5): 1075-1084

Fernandez-Gonzalo R, Nissemark C, Aslund B, Tesch PA, Sojka P. Chronic stroke patients show early and robust improvements in muscle and functional performance in response to eccentric-overload flywheel resistance training: a pilot study. *J Neuroeng Rehabil,* 2014b; 11: 150

Friedmann-Bette B, Bauer T, Kinscherf R, Vorwald S, Klute K, Bischoff D, Muller H, Weber MA, Metz J, Kauczor HU, Bartsch P, Billeter R. Effects of strength training with eccentric overload on muscle adaptation in male athletes. *Eur J Appl Physiol,* 2010; 108(4): 821-836

Hather BM, Tesch PA, Buchanan P, Dudley GA. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol Scand,* 1991; 143(2): 177-185

Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc,* 2009; 41(1): 3-13

Hortobagyi T, DeVita P, LaStayo P. Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *J Biomech,* 2009; 42(7): 956; author reply 957

Hortobagyi T, Devita P, Money J, Barrier J. Effects of standard and eccentric overload strength training in young women. *Med Sci Sports Exerc,* 2001; 33(7): 1206-1212

Lagally KM, Robertson RJ. Construct validity of the OMNI resistance exercise scale. *J Strength Cond Res,* 2006; 20(2): 252-256

Massuca LM, Fragoso I, Teles J. Attributes of top elite team-handball players. *J Strength Cond Res,* 2014; 28(1): 178-186

Naczk M, Brzenczek-Owczarzak W, Arlet J, Naczk A, Adach Z. Training effectiveness of the inertial training and measurement system. *J Hum Kinet,* 2014; 44: 19-28

Naczk M, Naczk A, Brzenczek-Owczarzak W, Arlet J, Adach Z. Impact of inertial training on strength and power performance in young active men. *J Strength Cond Res,* 2013; [Epub ahead of print]

Naczk M, Naczk A, Brzenczek-Owczarzak W, Arlet J, Adach Z. Efficacy of inertial training in elbow joint muscles: influence of different movement velocities. *J Sports Med Phys Fitness,* 2016; 56(3): 223-231

Norrbrand L, Fluckey JD, Pozzo M, Tesch PA. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur J Appl Physiol,* 2008; 102(3): 271-281

Norrbrand L, Pozzo M, Tesch PA. Flywheel resistance training calls for greater eccentric muscle activation than weight training. *Eur J Appl Physiol,* 2010; 110(5): 997-1005

Pauole K, Madole K, Garhammer J, Lacourse M, Rozenek R. Reliability and Validity of the T-Test as a Measure of Agility, Leg Power, and Leg Speed in College-Aged Men and Women. *J Strength Cond Res,* 2000; 14(4): 443-450

Perez-Gomez J, Calbet JA. Training methods to improve vertical jump performance. *J Sports Med Phys Fitness,* 2013; 53(4): 339-357

Rittweger J, Felsenberg D, Maganaris C, Ferretti JL. Vertical jump performance after 90 days bed rest with and without flywheel resistive exercise, including a 180 days follow-up. *Eur J Appl Physiol,* 2007; 100(4): 427-436

Romero-Rodriguez D, Gual G, Tesch PA. Efficacy of an inertial resistance training paradigm in the treatment of patellar tendinopathy in athletes: a case-series study. *Phys Ther Sport,* 2011; 12(1): 43-48

Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol,* 2007; 102(1): 368-373

Tesch PA, Ekberg A, Lindquist DM, Trieschmann JT. Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. *Acta Physiol Scand,* 2004; 180: 89-98

Tesch PA, Ekberg A, Lindquist DM, Trieschmann JT. Muscle hypertrophy following 5-week resistance training using a non-gravity-dependent exercise system. *Acta Physiol Scand,* 2004; 180(1): 89-98

Tous-Fajardo J, Gonzalo-Skok O, Arjol-Serrano JL, Tesch P. Enhancing Change-of-Direction Speed in Soccer Players by Functional Inertial Eccentric Overload and Vibration Training. *Int J Sports Physiol Perform,* 2016; 11(1): 66-73

Trappe S, Trappe T, Gallagher P, Harber M, Alkner B, Tesch P. Human single muscle fibre function with 84 day bed-rest and resistance exercise. *J Physiol,* 2004; 557(Pt 2): 501-513

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PUBLICATION 3

Functional and structural effects of eccentric-overload resistance training in athletes and physical active people

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ORIGINAL ARTICLE

Comparison of the musculoskeletal effects of different iso-inertial resistance training modalities: Flywheel vs. electric-motor

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Abstract
This study aimed to analyse whether increasing the eccentric overload (EO) during resistance training, in terms of range of motion and/or velocity using an electric-motor device, would induce different muscle adaptations than conventional flywheel-EO resistance training. Forty physically active university students (21.7 ± 3.4 years) were randomly placed into one of the three training groups (EX1, EX2, FW) and a control group without training ($n = 10$ per group). Participants in the training groups completed 12 sessions (4 sets of 7 repetitions) of iso-inertial single-leg squat training over 6 weeks for the dominant leg. Resistance was generated either by an electric-motor device at two different velocities for the eccentric phase; 100% (EX1) or 150% (EX2) of concentric speed, or by a conventional flywheel device (FW). Thigh lean tissue mass, unilateral leg press one-repetition maximum (1-RM), unilateral muscle power at different percentages of the 1-RM and bilateral/unilateral vertical jump were assessed before and after the 6-week training. There were significant ($p < 0.05$–0.001) main effects of time in the 3 training groups, indicating increased thigh lean tissue mass (2.5–5.8%), 1-RM load (22.4–30.2%), vertical jump performance (9.1–32.9%) and muscle power (8.8–21.7%), without differences across experimental groups. Participants in the control group did not improve any of the variables measured. In addition, EX2 showed greater gains in eccentric average peak power during training than EX1 and FW ($p < 0.001$). Despite the different EO offered, 6 weeks of resistance training using flywheel or electric-motor devices induced similar significant gains in muscle mass, strength, muscle power and vertical jump.

Keywords: *Eccentric overload, strength, muscle power, hypertrophy, range of motion*

Highlights

- 12 sessions (4 sets of 7 repetitions) of iso-inertial RT in physically active young men induces significant skeletal muscle mass and performance adaptations.
- Eccentric-overload application over the entire ROM or over the last part of the ROM led to similar training-induced effects.
- Electric-motor devices have potential benefits for accentuated eccentric training, functioning as an ideal inertial device without requiring a maximum CON action to generate eccentric-overload, and allowing the achievement of larger percentages of eccentric-overload by increasing the eccentric velocity with respect to the concentric.
- Higher eccentric-overload percentages seems to be related with greater increases in muscle size, while lower eccentric-overload percentages seems to be related with greater increases in muscle power.

Introduction

The potential benefits of isolated or overloaded eccentric (ECC) resistance exercise, compared with concentric (CON) or conventional CON-ECC exercise regimens, have been widely studied (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Roig et al., 2009). Among different technologies allowing for eccentric overload (EO), iso-inertial flywheel resistance exercise is one of the most utilized exercise paradigms with established efficacy in different scenarios such as injury prevention/rehabilitation (de Hoyo et al., 2015; Gual, Fort-Vanmeerhaeghe, Romero-Rodriguez, & Tesch, 2016; Monajati, Larumbe-Zabala, Goss-Sampson, &

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Naclerio, 2018) and performance (de Hoyo, de la Torre et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017; Naczk et al., 2017; Sabido, Hernandez-Davo, Botella, Navarro, & Tous-Fajardo, 2017). Furthermore, iso-inertial flywheel resistance exercise has been suggested to improve muscle function, and functionality in elderly subjects (Brzenczek-Owczarzak et al., 2013) and stroke patients (Fernandez-Gonzalo et al., 2016). Originally designed to counteract the deleterious effect of microgravity on skeletal muscle (Tesch, Fernandez-Gonzalo, & Lundberg, 2017), the superiority of flywheel-EO resistance training (RT) over weight-stack RT (i.e. guided resistance exercise machines) to promote functional and structural adaptations in terms of strength, power, muscle size, running speed, and jump ability in healthy subjects and athletes has been demonstrated (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). It appears that the greater overall load and mechanical stress placed on the muscle, caused by the maximal nature of the CON action during the entire range of motion (ROM), as well as the EO in the last portion of the ECC action, are responsible for the stronger physiological responses and training-induced musculoskeletal adaptations of flywheel RT vs. traditional gravity-dependent protocols (Tesch et al., 2017).

The different protocols that can be employed using flywheel RT are characterized by the different moment of inertia of the flywheel, which in turn is a function of its geometrical and physical properties (Sabido, Hernandez-Davo, & Pereyra-Gerber, 2018). Thus, lower inertias with higher velocities, shorter ECC-CON coupling time and greater power production were suggested to favour explosive muscle characteristics adaptations, whereas higher inertias with lower velocities were shown to call for greater work load (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2018). Thus, after a maximum CON action, higher moments of inertia are able to generate greater force productions and impulse in the system than smaller flywheels (Carroll et al., 2018). The energy produced in the system during this CON action is stored and maintained during the subsequent ECC action due to its inertial characteristics, and must be braked in a short and concentrated moment at the end of the ECC phase to reinforce the negative action (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). By means of this approach, EO is generated in the system, and greater amounts of overload are achieved with higher inertial loads (Carroll et al., 2018). Notwithstanding, flywheel devices require a maximum CON action to generated EO only in the last third of the ECC action (Tesch et al., 2017). Moreover, the applicability of available flywheel hardware to functional training is limited due to flywheel exercise hardware traditionally developed following pre-existing uniaxial and bilateral weight-stack training machines (Maroto-Izquierdo, Garcia-Lopez, & de Paz 2017; Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017).

Recently, different multifunctional electric-motor devices have been commercialized (Tinwala, Cronin, Haemmerle, & Ross, 2017) aiming to offer solutions to some of the limitations of flywheel technology. These devices are potentially capable of generating EO in the entire ROM. Therefore, it is not necessary to reduce the active braking phase to obtain the overload, as it occurs with the traditional flywheel devices (Tinwala et al., 2017). In addition, other possibilities to modify the training stimulus while using electric-motor driven devices are changes in the specific CON and/or ECC intensity (no need for a maximum CON action), adjustments in the transition time between CON and ECC phases, and modifications in the ECC velocity, related to the CON velocity (Tinwala et al., 2017). Interestingly, active electric-motor devices completely neutralize the friction force and parasitic inertias, becoming *a priori* ideal inertial device from a mechanical perspective.

Given the current options to produce EO during iso-inertial RT and the belief that greater EO during iso-inertial exercise may promote larger adaptations, we designed a study to investigate the effects of iso-inertial training generated by an electric-motor device, which offers EO in the whole ROM, and compare such adaptations with conventional flywheel RT in a lower limb unilateral exercise. The aim of this study was to analyse whether increasing the EO in terms of ROM and/or velocity would induce different muscle adaptations than conventional flywheel EO training.

Methods

Participants

Forty sports science undergraduate students volunteered for the study (21.7 ± 3.4 years; 75.8 ± 9.8 kg; 177.1 ± 5.4 cm). Participants were moderately active and healthy individuals, engaging in 6–8 h of recreational physical activity per week. They had no history of regular lower limb strength training and no previous muscle, joint or bone injury for the last 6 months. They were informed of the purposes and risks involved in the study before giving their informed written consent to participate. The Ethics Committee of the University of León approved the

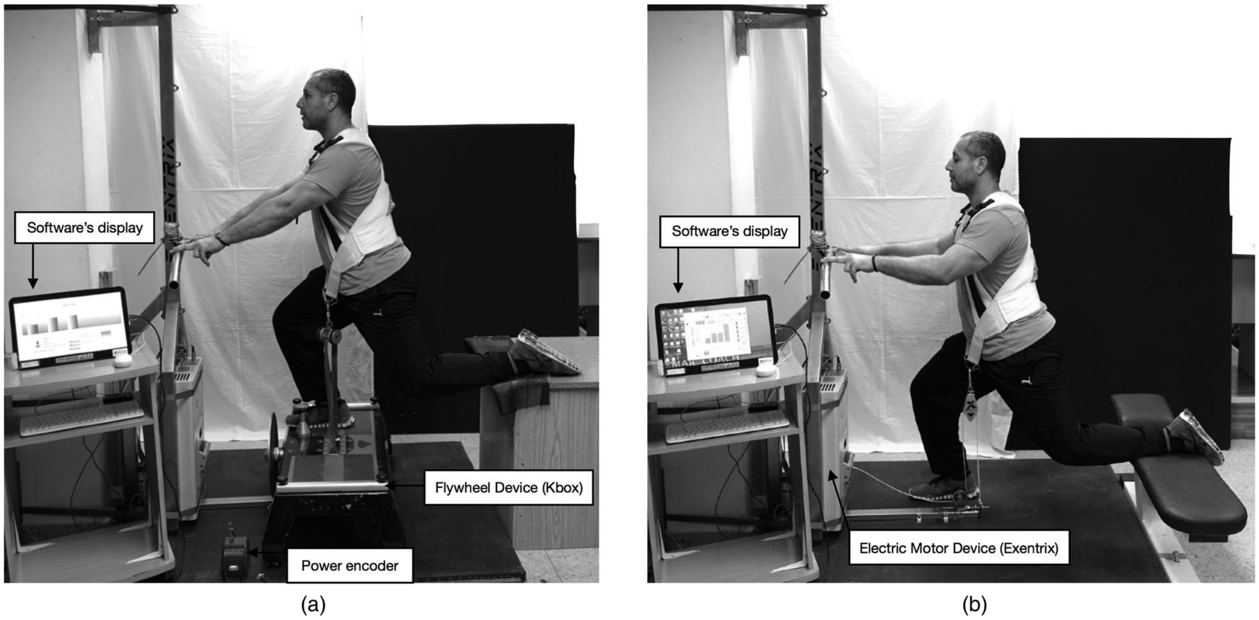

Figure 1. A. Single-leg squat exercise on the flywheel device. B: Single-leg squat exercise on the electric-motor device.

study protocols (ETICA-ULE-009-2018). All participants completed all the protocols, including two familiarization sessions, the prescribed training programme, and the pre- and post-tests.

Training program

Participants were randomly divided into 3 experimental training groups and 1 control group, which did not train. All participants included in an experimental group ($n = 30$) completed 6-weeks (12 sessions) of an iso-inertial single-leg squat training programme, using an electric-motor device (EX1 and EX2 groups) or a flywheel device (FW group) (Figure 1). Volunteers trained 2 times per week with at least 48 h of rest between sessions (Fernandez-Gonzalo, Lundberg, Alvarez-Alvarez, & de Paz, 2014). Following a standardized cycling warm-up, participants performed 4 sets of 7 maximal unilateral (dominant leg) coupled CON and ECC muscle actions in a single-leg squat position. Subjects were required to push with maximal effort through the entire CON action, which ranged from 70° of knee flexion to nearly full extension (0° = full knee extension). At the end of the CON action, the flywheel/motor strap rewound back, initiating the reversed ECC action. Before each session, the ROM was set up from 0° to 90° using a goniometer. So that in case of not stopping within the permitted range the device stopped the movement and notified it in the software. In the case of the flywheel device, subjects were instructed to resist gently during the first and second thirds of the ROM, and thereafter to apply maximal breaking force to stop the movement at about 70° of knee flexion. By means of this approach, EO is produced (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). An individual researcher was responsible for calibrating the ROM of each participant (i.e. length of cable used and distance from the vertical pulley to the platform) from 0° (i.e. full knee extension) to 90° employing a goniometer. In addition, the same researcher, indicated the knee angle in which they had to brake before each series and gave verbal information during the execution of each repetition. Besides, the electric-motor device is characterized by producing EO throughout the entire ROM, so it is not necessary to wait for the last third of movement to obtain EO (Tinwala et al., 2017). Therefore, the only instruction given to EX1 and EX2 participants was to stop the movement before reaching the end of the ROM. Participants were not allowed to use the other leg to produce force, positioning the non-training leg from the tibia to the foot's instep above a soft surface, at a fixed point, to avoid compensation (Figure 1). Power was measured during each repetition (CON and ECC actions; SmartCoach™, Stockholm, Sweden), and real-time feedback was provided on a computer monitor. A strong verbal encouragement was given during all repetitions performed. All subjects were familiarized (2 sessions) with the exercise prior to the first training session. Subjects in the control group did not perform any strength-training programme during the study period, as instructed.

FW participants ($n = 10$) performed the exercise using a squat flywheel device (Kinetic Box (Kbox), Exxentric AB TM, Bromma, Sweden) (Sabido et al., 2018), equipped with one 4.2-kg flywheel with a moment of inertia of 0.05 kg·m^{-2}. EX1 ($n = 10$) and EX2 ($n = 10$) participants performed the same exercise, but in an electric-motor device (Exentrix, SmartCoach™, Stockholm, Sweden). This device was configured in flywheel mode using the iso-inertial settings in the device's software (Exentrix PC Interface – V2.4, SmartCoach™) and configured with a load of 37 inertial units for both EX groups. According to the manufacturer's instructions, one inertial unit is equivalent to a moment of inertia of 0.00134 kg·m^{-2}, so the resulting moment of inertia was equivalent to the flywheel device (0.05 kg·m^{-2}). In addition, the transition time between CON and ECC phase was the minimum permitted by the system. No different training loads were selected for the CON and ECC phases. However, the software for group EX2 was configured to perform the rewind of the cable (ECC action) at a 150% faster than the CON speed. Thus, the ECC speed was 1.5 times faster than groups EX1 and FW.

Testing procedures

Dual energy X-ray absorptiometry analysis (DEXA). DEXA was performed ~1 week before and after the training programme, at the same time of day using a Lunar Prodigy® whole-body scan (GE Medical Systems, Madison, WI). A manual analysis was performed to estimate thigh lean mass (Encore® 2009 software, Lunar Corp., Madison, WI). Briefly, one rectangle mark was generated using the lower margin of the ischial tuberosities and the lower margin of the femoral condyles as thigh reference points. Lean mass was then calculated for the entire thigh. Subsequently, inside the span of the thigh rectangle a 6-cm perpendicular line was drawn from the distal to the proximal mark to establish three regions of interest (ROIs) of the thigh where lean muscle mass was estimated. Then, a 20 mm-thick slice was placed above the 6-cm distal vertical line (i.e. distal thigh ROI) (Fernandez-Gonzalo et al., 2014). In addition, two other 20-mm slices were placed 6 (i.e. medial thigh ROI) and 12 cm (i.e. proximal thigh ROI) above the first slice. Finally, lean tissue mass estimation in both total thigh and the three slices created was calculated using Encore software.

Unilateral maximal dynamic strength (1-RM). Twenty-four hours after the DEXA and jump tests, the unilateral 1-RM test was conducted on a 45°-inclined leg press device (Gerva-Sport, Madrid, Spain). Participants performed one repetition from 90° to full extension (180°) with a load corresponding to approximately 3-RM. The load was increased with 10 kg if the subject succeeded or decreased 5 kg if failed. Testing ended when subjects failed to overcome a given load in two successive trials. Unilateral 1-RM was achieved between 3 and 6 attempts, and trials were interspersed by 2-min recovery. Participants were asked to place the resting leg with the knee flexed and the foot propped on the ground. The 1-RM test was performed twice for each leg; 3–5 days before and 3–5 days after the training period.

Unilateral muscle power. Forty-eight hours after the 1-RM test muscle power test was performed, participants completed five sets of three unilateral repetitions from 90°-knee flexion to full extension (180°) in the leg-press described above, with 2-min recovery between sets. To avoid any use of the stretch-shortening cycle, each repetition started from a complete static position. Each set represented 40, 50, 60, 70, and 80% of 1-RM load, and the order of the sets was individually randomized before testing and replicated at post-tests. Subjects were asked to perform the CON phase of each repetition as fast as possible. Mean power for each repetition was sampled at 1000 Hz using an encoder (T-FORCE Dynamic Measurement System, Ergotech Consulting S.L., Murcia, Spain) and the associated software (T-Force v. 2.28). The best repetition performed at each load was used for data analysis. The warm-up protocol described for the 1-RM test was also performed prior to the muscle power test.

Vertical jump performance. Vertical jump tests were carried out immediately after the DEXA analysis. Jump height was measured for countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) performed bilaterally and unilaterally in this order on a contact platform (Globus Ergotester®, Globus, Codogne, Italy) (Murtagh et al., 2017). A warm-up of 5-min cycling, 25 reps of high knee and 25 reps of butt kicks was performed. The SJ was performed from a 90°knee flexion with hands on the hips. For the CMJ, participants started in a standing straight position and were instructed to jump as high as possible with hands on the hips. The DJ consisted of dropping oneself from a box of 45 cm and then jump as high as possible straight after landing. Participants were asked to step off the platform and jumping after the first ground contact from a self-selected knee angle, maintaining the hands at the hips during the full test. Protocols were identical for bilateral and unilateral test. The three bilateral attempts were always completed first, followed by unilateral attempts. Jump height (and contact time for DJ) was recorded to the nearest 0.1 cm (0.05 s for contact time). Three trials, with 30-seconds of recovery in between, were allowed and the best result was included in the data analysis.

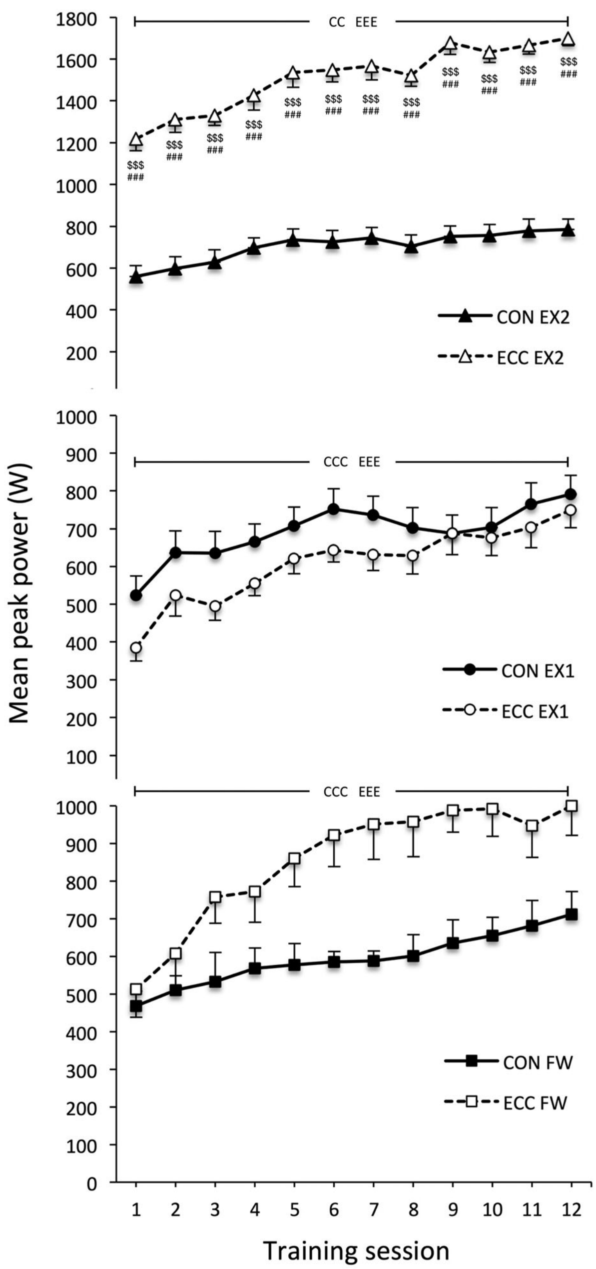

Figure 2. Mean concentric (CON) and eccentric (ECC) peak power (w) during each training session in all experimental groups (EX1, EX2 and FW). Significant effects of time (session 1 vs. session 12) (^{C} $p < 0.05$; ^{CC} $p < 0.01$; ^{CCC} $p < 0.001$ for CON; ^{E} $p < 0.05$; ^{EE} $p < 0.01$; ^{EEE} $p < 0.001$ for ECC). $^{\$}$ Significantly different form EX1 group, where $^{\$}$ $p < 0.05$, $^{\$\$}$ $p < 0.01$, and $^{\$\$\$}$ $p < 0.001$. $^{\#}$ Significantly different from FW group, where $^{\#}$ $p <$ 0.05, $^{\#\#}$ $p < 0.01$, and $^{\#\#\#}$ $p < 0.001$.

Statistical analyses

Statistical analyses were performed using SPSS v.20.0 (SPSS Inc. Chicago, IL). Results were expressed as mean ± SD. Data distribution was examined for normality using the Shapiro–Wilk test. A Mixed-model analysis of variance (group x time), followed by Bonferroni post hoc tests was used to investigate differences in variables measured. The effect size (ES) was calculated for interactions between groups using Cohen's guidelines. Threshold values for ES were >0.2 (small), >0.6 (large) and >2.0 (very large) (Hopkins, Marshall, Batterham, & Hanin, 2009). The significance level was set to $p < 0.05$.

Results

A significant group x time interaction was found in the ECC average peak power of each training session, where the EX2 group showed significant differences ($p < 0.001$; ES range 3.5–6.8, Figure 2) with respect to EX1 and FW groups. No further significant interactions were observed for the other variables analysed. In addition, there was a significant main effect of time for all functional and structural variables ($p < 0.05$–.001, F range 6.0–77.2). However, the control group did not improve any of the variables measured.

There was a main effect of time ($p < 0.001$) in the distal ($F = 47.3$), medial ($F = 26.1$) and proximal ($F = 24.8$) ROIs measured and in the total thigh lean mass ($F = 48.9$). EX2 ($p < 0.001$, ES range 0.24–0.40) and FW groups ($p < 0.001$, ES range 0.41–0.56) showed significant improvements in all measurements (Table I). The EX1 group showed significant gains at distal and medial portions ($p <$ 0.05, ES = 0.35 and 0.21) and in total thigh mass ($p < 0.01$, ES = 0.23). Results from control group remained similar between pre- and post-measurement.

There was a significant main effect of time in the 1-RM load ($p < 0.001$, $F = 77.2$). Thus, between pre- and post-tests the 1-RM load increased 30.2% in EX1 ($p < 0.001$; ES = 1.49), 27.6% in EX2 ($p <$ 0.001; ES = 1.39) and 22.4% in FW ($p < 0.001$; ES = 1.20) (Table I).

Across sessions (Figure 2), CON average peak power increased 51% in EX1 [523.6 (±154) to 792.0 (±149) W; $p < 0.001$, ES = 1.77], 40% in EX2 [559.9 (±87) to 785.2 (±98) W; $p < 0.01$, ES = 2.43] and 52% in FW [468.0 (±118) to 712.0

Table I. Distal, medial, proximal and total thigh muscle mass; unilateral maximal dynamic strength (1-RM); and vertical jump height and DJ contact time pre- and post-training

	EX1 group					EX2 group					FW group					CONTROL group				
	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*	PRE	POST	Δ%	ES	*P*
Muscle thigh																				
Distal (g)	189.0 ± 15.0	194.6 ± 17.4	2.9	0.35	*	194.9 ± 31.7	205.3 ± 34.8	5.4	0.31	***	186.7 ± 20	197.4 ± 18.2	5.7	0.56	***	200.3 ± 33.5	202.8 ± 36.2	1.3	0.07	
Medial (g)	309.3 ± 37.7	317.1 ± 36.1	2.5	0.21	*	324.2 ± 50.2	336.7 ± 55.8	3.9	0.24	***	305.3 ± 30.5	317.4 ± 25.6	4.0	0.43	***	328.3 ± 48.4	332.0 ± 50.0	1.1	0.07	
Proximal (g)	418.6 ± 38.5	425.8 ± 41.7	1.7	0.18		431.0 ± 51.7	452.2 ± 54.0	4.9	0.41	***	426.8 ± 37.8	441.1 ± 32.5	3.4	0.41	***	443.6 ± 59.4	444.8 ± 58.2	0.3	0.02	
Total (g)	6793.9 ± 758.3	6967.9 ± 776.2	3.4	0.30	**	6912.2 ± 974.9	7222 ± 1073.8	4.5	0.30	***	6549.2 ± 708.8	6881 ± 791.2	5.1	0.44	***	6783.0 ± 1102.9	6684.3 ± 995.1	−1.5	0.09	
Strength																				
1-RM load (kg)	187.8 ± 36.7	244.4 ± 39.1	30.2	1.49	***	177.2 ± 41.8	226.1 ± 26.9	27.6	1.39	***	210.0 ± 34.7	256.1 ± 41.6	21.9	1.20	***	225.0 ± 40.3	225.7 ± 46.9	0.3	0.02	
UL Vertical Jump																				
CMJ (cm)	21.6 ± 3.3	23.7 ± 3.2	9.8	0.65	*	21.8 ± 3.5	23.8 ± 3.3	9.1	0.59	*	21.1 ± 4.2	23.8 ± 3.1	12.8	0.73	**	23.8 ± 7.4	21.4 ± 5.3	−9.9	0.37	*
SJ (cm)	20.5 ± 3.6	22.8 ± 3.2	11.2	0.67	*	21.3 ± 3.8	22.7 ± 3.2	6.6	0.40		19.7 ± 3.8	23.1 ± 2.7	17.3	1.03	***	22.8 ± 7.9	20.8 ± 4.3	−8.8	0.31	
DJ (cm)	18.3 ± 4.4	21.6 ± 2.9	18.0	0.89	***	18.4 ± 4.4	21.4 ± 2.9	15.9	0.81	***	18.3 ± 2.6	21.5 ± 2.2	17.5	1.33	***	19.9 ± 4.1	18.9 ± 3.8	−5.0	0.25	
DJ CT (ms)	0.577 ± 0.16	0.386 ± 0.08	33.1	1.51	***	0.499 ± 0.12	0.364 ± 0.05	27.1	1.47	***	0.525 ± 0.10	0.463 ± 0.07	11.8	0.72		0.528 ± 0.07	0.524 ± 0.13	−0.8	0.04	
BL Vertical Jump																				
CMJ (cm)	38.5 ± 4.3	40.6 ± 4.1	5.5	0.50	***	39.1 ± 6.4	42.2 ± 6.9	8.0	0.47	***	38.7 ± 6.9	41.3 ± 6.4	6.9	0.39	***	40.2 ± 4.6	39.6 ± 4.3	−1.6	0.13	
SJ (cm)	36.2 ± 3.9	38.6 ± 3.9	6.6	0.62	***	37.1 ± 5.2	39.7 ± 5.8	7.0	0.47	***	37.2 ± 5.6	39.1 ± 4.8	4.8	0.36	**	38.3 ± 4.7	38.6 ± 5.3	0.6	0.08	
DJ (cm)	35.7 ± 4.7	38.6 ± 5.2	8.4	0.59	*	36.7 ± 8.4	40.9 ± 8.4	11.3	0,5	***	35.6 ± 8.8	39.1 ± 5.8	9.5	0.47	**	38.2 ± 6.0	37.1 ± 5.4	−2.8	0.19	
DJ CT (ms)	0.502 ± 0.15	0.417 ± 0.08	16.9	0.71		0.451 ± 0.12	0.389 ± 0.08	13.9	0.61		0.458 ± 0.11	0.428 ± 0.10	6.7	0.29		0.488 ± 0.09	0.518 ± 0.09	6.0	0.33	

Abbreviation: 1-RM: One-Repetition Maximum; BL: Bilateral; CMJ: Countermovement Jump; DJ: Drop Jump; DJ CT: Drop Jump Contact Time; UL: Unilateral; *Significantly different from pre-training value, where $^{*}p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$.

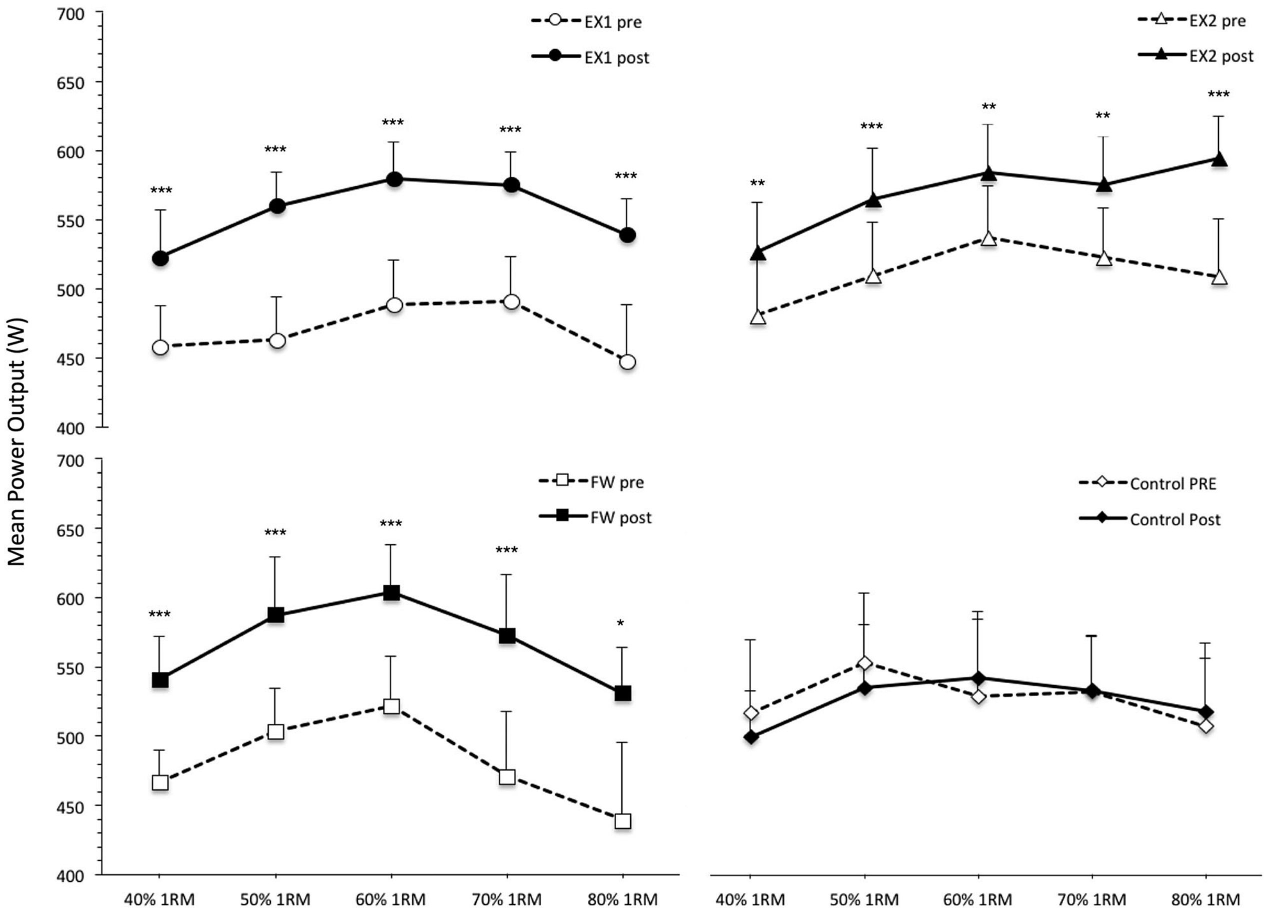

Figure 3. Mean leg press power (w) at different percentages of 1-RM before (pre) and after (post) training. * Significantly different from pre-training value, where * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

(±180) W; $p < 0.001$, ES = 1.60]. The corresponding increases in ECC average peak power were 95% in EX1 [384.8 (±105) to 750.0 (±142) W; $p < 0.001$, ES = 2.92], 39% in EX2 [1217.0 (±168.7) to 1701.1 (±108.3) W; $p < 0.001$, ES = 3.41] and 95% in FW [512.8 (±223) to 997.8 (±254) w; $p < 0.001$, ES = 2.03]. The mean EO produced in terms of power (% above CON average peak power) was −13.3% in EX1, 114.1% in EX2 and 43.6% in FW. Mean EO produced in terms of force (% above CON force) was 17.2% for EX1 and 50.7% for EX2. No force measurements were recorded in the FW group during training.

Regarding mean power output, there was a significant main effect of time for all the loads tested ($p <$ 0.001, F range 21.4–57.4) (Figure 3). Thus, EX1 experimented a significant ($p < 0.001$) increase in all loads ranging from 14.2–21.1% (ES range 0.68–1.17). Similarly, the FW group showed gains in all loads measured, with an improvement of 15.8–21.7% in the loads 40–70% ($p < 0.001$; ES range 0.75–0.91), and 15.3% at the 80% 1-RM ($p < 0.05$; ES = 0.62). Likewise, EX2 increased power output in all 1-RM percentages (9–10.8%, $p < 0.01$, ES range 0.41–0.51), with the highest increase at 50% 1-RM (10.8%, $p < 0.001$, ES = 0.49) and at 80% 1-RM (16.8%, $p < 0.001$, ES = 0.79). Before training, maximal mean power was reached at the load corresponding to 60% of 1-RM by all training groups. Meanwhile, EX2 reached maximal mean power output at 80% of 1-RM after the training period.

A significant time effect ($p < 0.05$–.000, F range 6.0–51.5) was observed in CMJ, SJ, and DJ height in unilateral and bilateral tests (Table I). Regarding bilateral vertical jump height, the three training groups achieved significant improvements ($p <$ 0.05–.001; ES range 0.36–0.67). Regarding unilateral vertical jump height, FW ($p < 0.01$–.001, ES range 0.73–1.33) and EX1 groups ($p < 0.05$–.001; ES range 0.65–0.89) achieved significant improvements in all tests, while the EX2 group improved significantly the CMJ ($p < 0.05$, ES = 0.59) and the DJ ($p < 0.001$, ES = 0.81). In addition, EX1 and EX2 groups were the only ones that reduced the unilateral DJ contact time ($p < 0.001$, ES = 1.51 and 1.47, respectively).

Discussion

The aim of this study was to determine whether increasing the EO during iso-inertial resistance exercise training, in terms of ROM and/or velocity, would induce different muscle adaptations than conventional flywheel EO training. After 6-week training (12 sessions), the three experimental groups (EX1, EX2 and FW) showed comparable increases in maximum unilateral dynamic strength, unilateral muscle power at different loads, muscle hypertrophy, and both bilateral and unilateral vertical jump height. Therefore, it seems that the magnitude of EO offered by either flywheel or motor-driven iso-inertial RT does not have a major impact on the resistance exercise-induced muscle adaptations.

Based on our results, iso-inertial RT with EO performed in an electric-motor device is an effective resistance exercise method to induce functional and structural muscle adaptations in physically active men, without the need to perform a maximum braking action in the last third of the ROM. In addition, larger EO percentages may be achieved by increasing the speed of cable recoil in an electric-motor driven device (e.g. EX2 group). These results support previous data describing the effects produced by iso-inertial devices on skeletal muscle. Thus, five- to 15-week flywheel EO-RT programmes of the lower limbs (bilaterally), have shown strong skeletal muscle adaptations (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017), including gains in muscle mass (Norrbrand, Fluckey, Pozzo, & Tesch, 2008; Seynnes, de Boer, & Narici, 2007), maximal voluntary contraction (Norrbrand et al., 2008; Seynnes et al., 2007; Tesch et al., 2017), 1-RM load (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), ECC force (Hortobagyi, Devita, Money, & Barrier, 2001), muscle power (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), jump ability (de Hoyo, Pozzo et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), running speed (de Hoyo, Pozzo et al., 2015; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017), and electromyography activity (Norrbrand, Tous-Fajardo, Vargas, & Tesch, 2011; Pozzo, Alkner, Norrbrand, Farina, & Tesch, 2006). Indeed, chronic exercise training employing non-gravitational iso-inertial technology produces early and vigorous neuromuscular adaptations, which appear to be more effective than those noted after traditional weight-training (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). The current study goes one step further, indicating that applying the EO over the entire ROM, by means of an electric-motor device, does not enhance the training-induced effects generated by a conventional inertial flywheel in which the EO is produced only in the last third of the ROM.

Moreover, this is the first study to analyse the EO generated by two different iso-inertial devices. Fernandez-Gonzalo et al. (Fernandez-Gonzalo et al., 2014) and Sabido et al. (Sabido et al., 2018) pinpointed that bilateral lower limb RT in an inertial device is capable of generating between 15 and 30% of EO (% above CON average peak power). According to others (Martinez-Aranda & Fernandez-Gonzalo, 2017), iso-inertial technology devices, are capable of generating EO between 20 and 25% (% above CON peak force) in unilateral mono-articular exercises of the lower limb using an inertia of 0.05 $kg{\cdot}m^2$ (i.e. knee extension). Our results show a slightly higher average EO in terms of average peak power (46%, with a range between 10 and 62% throughout the different training sessions in the FW group). This may be due to the differences in exercise type (Nunez et al., 2018), since the applied force is quite higher in the training leg in an unilateral multi-joint squat exercise than in one of the training legs in a bilateral training regime due to the bilateral deficit (Weir, Housh, Housh, & Weir, 1995). Regarding the EO generated in the groups that were trained with the electric-motor device, thus producing the force in the ECC during the whole ROM (EX1 and EX2), and taking as reference the FW group, the EO was higher in the EX2 group (114%, with a range between 105 and 123% in terms of average peak power; and 50.7%, with a range between 42.2 and 60.4% in terms of peak force throughout the different training sessions). However, the EX1 group only showed EO in relation to CON peak force (17.2%, with a range between 14.9 and 21.1% throughout the different training sessions). This could be due to the fact that EO was achieved through the entire ROM, and not only in the last third, as FW group, taking more time to slow down the movement, so ECC power production was lower. Consequently, although the EX1 group did not show EO in terms of average peak power, the overload in terms of peak force is similar to that demonstrated in flywheel devices by other authors (Martinez-Aranda & Fernandez-Gonzalo, 2017). Therefore, our data seem to indicate that increasing the ECC speed is a good alternative to generate higher values of EO in terms of both average peak power and peak force throughout the entire ROM.

New training trends demand unilateral daily-life and sports specific exercises (Thompson, 2017), in which several planes, muscle groups, and joints are involved at the same time, with a greater demand for stability and performing gestures similar to those that appear in sports practice (e.g. braking, changes of direction, throwing or striking) (Gonzalo-Skok et al., 2017). This is something that traditional flywheel hardware designed for single-plane exercise movements (e.g. knee extension exercise) does not allow. Yet, multifunctional flywheel devices do offer more possibilities in this area (e.g. Squat Flywheel device). Therefore, the exercise selected for this study was the single-leg squat, in order to combine the benefits of unilateral and specific training with those achieved by eccentric-overload flywheel training. In addition, the electric-motor device is multifunctional, allowing exercises practically in any plane of movement. However, since the motor-driven hardware did not allow to perform exercises requiring higher power than 1300 W, an unilateral exercise was selected to perform the training programme with the maximum levels of strength and speed, yet within the device's range of power. Moreover, it has been recently shown that flywheel unilateral resistance training generates similar or greater adaptations than bilateral training regarding muscle mass, power, and sport-specific skills, such as running with a change of direction or vertical jump (Nunez et al., 2018). Gonzalo-Skok and coworkers (Gonzalo-Skok et al., 2017) suggested the incorporation of 1-limb exercises to any training routine, since most sports movements are performed unilaterally.

Regarding maximal dynamic strength, the three experimental groups showed important increases from pre- to post-tests. Previous studies have shown improvements between 12 and 25% in the same muscle groups trained with inertial devices (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017). Therefore, the current FW group (+22.4%) data is supported by previous results. Even without significant differences between groups, it seemed EX1 and EX2 groups showed slightly higher gains in 1-RM load (30.2% and 27.6%, respectively), than those shown by FW group as well as by other studies using inertial technology (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017; Tesch et al., 2017). This could be due to the fact that participants in EX1 and EX2 applied the braking force through the whole ROM of the ECC phase, although such hypothesis needs to be further validated.

EO-RT induces substantial gains in muscle power (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). Fernandez-Gonzalo et al. (2014) and Maroto-Izquierdo et al. (Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017) analysed the effects of flywheel RT on different percentages of the 1-RM (40–90% 1-RM load), showing increases in the range of 5–30%, which are similar to the results observed in the FW group of the current study. After 6 weeks of RT with an electric-motor device in iso-inertial mode, similar adaptations were observed in muscle power at different percentages of the 1-RM (40–80%) when the ECC velocity was not enhanced (EX1: 14.2–21%). However, these adaptations appeared to be slightly lower in the EX2 group (8.8–10.8%). Although, the higher EO produced by EX2 participants seemed to have a particular effect on the power produced at high loads, i.e. 80% of 1-RM (16.8%). Hence, it seems that muscle power adaptations do not only depend on the moment of inertia used (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2018) or the training velocity developed (Carroll et al., 2018), but also on the EO induced.

The training-induced power adaptations are also evident in the increments obtained in muscle power between sessions 1 and 12. Thus, iso-inertial training in a vertical plane appears to be an effective tool to increase power. Therefore, such training is recommended to increase vertical jump performance (Gonzalo-Skok et al., 2017), as shown by the current data where all experimental groups improved vertical jump performance. In the case of the DJ, where the stretch-shortening cycle becomes a critical factor, EX1 and EX2 groups significantly reduced the contact time. This could potentially be explained by the similarity of the gesture between training and the jump test, and the emphasis on a short transition between ECC-CON actions in EX1 and EX2.

The efficacy of EO-RT to induce muscle hypertrophy has been well documented (Norrbrand et al., 2008; Tesch et al., 2017). Throughout the scientific literature, flywheel devices have shown a great efficacy to induce gains in muscle volume/mass in young men and women (Fernandez-Gonzalo et al., 2014) and in well-trained athletes (Maroto-Izquierdo, Garcia-Lopez, & de Paz, 2017). Such changes seem to be greater than those induced by other RT modalities (i.e. weight training) (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). The greater muscle mass plays an undisputed role in all adaptations related to muscle strength, power, and vertical jump (Maroto-Izquierdo, Garcia-Lopez, Fernandez-Gonzalo et al., 2017). The results showed by the FW group are in the same line as data from previous studies in which hypertrophy was measured by DEXA (Fernandez-Gonzalo et al., 2014). These results were also observed in the EX2 group. Although it has been demonstrated that muscle adaptations are greater when the ROM employed during training is larger (McMahon, Morse, Burden, Winwood, & Onambele, 2014), and the working angle is an important factor to consider when iso-inertial RT is carried out (Maroto-Izquierdo, Garcia-Lopez, Fernandez-

Gonzalo et al., 2017), no significant differences were observed between groups in the present work. The EX1 group showed a smaller effect size on muscle mass increases, which could be related to the magnitude of the EO. However, although results obtained through DEXA analysis are correlated with Magnetic Resonance Imaging and represents a valid approach to estimate muscle mass (Fernandez-Gonzalo et al., 2014), we did not include any other architectural parameter among our variables. Furthermore, although time-under-tension and training-induced adaptations are similar between groups, the measurement of muscle activation during exercise could provide deeper insights into the comparison between different iso-iniertial devices. However, muscle activation during exercise (e.g. electromyography) has not been measured in this work. Therefore, one of the limitations of this study is the lack of inclusion of other physiological parameters to provide more information on the functional and structural adaptations found. Future research should include these neurophysiological parameters to deepen on the effects of iso-inertial training with different devices and the underpinning physiological mechanisms.

Conclusions

In summary, 6 weeks of RT with EO in physically active young men induced significant gains in strength, muscle power at different loads, vertical jump and lean tissue mass. The adaptations generated by an active electric-motor device, which produces EO throughout the entire ROM, were similar to those produced by a traditional flywheel device, where the EO occurs during the last part of the ROM. However, an electric-motor device allowed for modifications in the CON and ECC loads independently, as well as changes in the ECC speed with respect to the CON speed, which translated into higher EO. Therefore, the electric-motor devices have potential benefits for eccentrically reinforced training, functioning as an ideal inertial device without requiring a maximum CON action to generate EO. Such characteristic could be an interesting asset in clinical and sport performance environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Brzenczek-Owczarzak, W., Naczk, M., Arlet, J., Forjasz, J., Jedrzejczak, T., & Adach, Z. (2013). Estimation of the efficacy of inertial training in older women. *Journal of Aging and Physical Activity*, *21*(4), 433–443. doi:10.1123/japa.21.4.433

Carroll, K. M., Wagle, J. P., Sato, K., Taber, C. B., Yoshida, N., Bingham, G. E., & Stone, M. H. (2018). Characterising overload in inertial flywheel devices for use in exercise training. *Sports Biomechanics*, 1–12. doi:10.1080/14763141.2018.1433715

de Hoyo, M., de la Torre, A., Pradas, F., Sanudo, B., Carrasco, L., Mateo-Cortes, J., & Gonzalo-Skok, O. (2015). Effects of eccentric overload bout on change of direction and performance in soccer players. *International Journal of Sports Medicine*, *36*(4), 308–314. doi:10.1055/s-0034-1395521

de Hoyo, M., Pozzo, M., Sanudo, B., Carrasco, L., Gonzalo-Skok, O., Dominguez-Cobo, S., & Moran-Camacho, E. (2015). Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *International Journal of Sports Physiology and Performance*, *10*(1), 46–52. doi:10.1123/ijspp.2013-0547

Fernandez-Gonzalo, R., Fernandez-Gonzalo, S., Turon, M., Prieto, C., Tesch, P. A., & Garcia-Carreira Mdel, C. (2016). Muscle, functional and cognitive adaptations after flywheel resistance training in stroke patients: A pilot randomized controlled trial. *Journal of NeuroEngineering and Rehabilitation*, *13*(37), doi:10.1186/s12984-016-0144-7

Fernandez-Gonzalo, R., Lundberg, T. R., Alvarez-Alvarez, L., & de Paz, J. A. (2014). Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *European Journal of Applied Physiology*, *114*(5), 1075–1084. doi:10.1007/s00421-014-2836-7

Gonzalo-Skok, O., Tous-Fajardo, J., Valero-Campo, C., Berzosa, C., Bataller, A. V., Arjol-Serrano, J. L., & Mendez-Villanueva, A. (2017). Eccentric overload training in team-sports functional performance: Constant bilateral vertical vs. variable unilateral multidirectional movements. *International Journal of Sports Physiology and Performance*, *12*(7), 951–958. doi:10.1123/ijspp.2016-0251

Gual, G., Fort-Vanmeerhaeghe, A., Romero-Rodriguez, D., & Tesch, P. A. (2016). Effects of in-season inertial resistance training with eccentric overload in a sports population at risk for patellar tendinopathy. *Journal of Strength and Conditioning Research*, *30*(7), 1834–1842. doi:10.1519/JSC.0000000000001286

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. doi:10.1249/MSS.0b013e31818cb278

Hortobagyi, T., Devita, P., Money, J., & Barrier, J. (2001). Effects of standard and eccentric overload strength training in young women. *Medicine & Science in Sports & Exercise*, *33*(7), 1206–1212.

Maroto-Izquierdo, S., Garcia-Lopez, D., & de Paz, J. A. (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball Players. *Journal of Human Kinetics*, *60*, 133–143. doi:10.1515/hukin-2017-0096

Maroto-Izquierdo, S., Garcia-Lopez, D., Fernandez-Gonzalo, R., Moreira, O. C., Gonzalez-Gallego, J., & de Paz, J. A. (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, *20*(10), 943–951. doi:10.1016/j.jsams.2017.03.004

Martinez-Aranda, L. M., & Fernandez-Gonzalo, R. (2017). Effects of inertial setting on power, force, work, and eccentric overload during flywheel resistance exercise in women and men. *Journal of Strength and Conditioning Research*, *31*(6), 1653–1661. doi:10.1519/JSC.0000000000001635

McMahon, G. E., Morse, C. I., Burden, A., Winwood, K., & Onambele, G. L. (2014). Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. *Journal of Strength and Conditioning Research*, *28*(1), 245–255. doi:10.1519/JSC.0b013e318297143a

Monajati, A., Larumbe-Zabala, E., Goss-Sampson, M., & Naclerio, F. (2018). Injury prevention programs based on flywheel vs. body weight resistance in recreational athletes. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000002878

Murtagh, C. F., Vanrenterghem, J., O'Boyle, A., Morgans, R., Drust, B., & Erskine, R. M. (2017). Unilateral jumps in different directions: A novel assessment of soccer-associated power? *Journal of Science and Medicine in Sport*, *20*(11), 1018–1023. doi:10.1016/j.jsams.2017.03.016

Naczk, M., Lopacinski, A., Brzenczek-Owczarzak, W., Arlet, J., Naczk, A., & Adach, Z. (2017). Influence of short-term inertial training on swimming performance in young swimmers. *European Journal of Sport Science*, *17*(4), 369–377. doi:10.1080/17461391.2016.1241304

Norrbrand, L., Fluckey, J. D., Pozzo, M., & Tesch, P. A. (2008). Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *European Journal of Applied Physiology*, *102*(3), 271–281. doi:10.1007/s00421-007-0583-8

Norrbrand, L., Tous-Fajardo, J., Vargas, R., & Tesch, P. A. (2011). Quadriceps muscle use in the flywheel and barbell squat. *Aviation, Space, and Environmental Medicine*, *82*(1), 13–19. doi:10.3357/ASEM.2867.2011

Nunez, F. J., Santalla, A., Carrasquila, I., Asian, J. A., Reina, J. I., & Suarez-Arrones, L. J. (2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLoS One*, *13*(3), e0193841. doi:10.1371/journal.pone.0193841

Pozzo, M., Alkner, B., Norrbrand, L., Farina, D., & Tesch, P. A. (2006). Muscle-fiber conduction velocity during concentric and eccentric actions on a flywheel exercise device. *Muscle & Nerve*, *34*(2), 169–177. doi:10.1002/mus.20574

Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B., & Reid, W. D. (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *43*(8), 556–568. doi:10.1136/bjsm.2008.051417

Sabido, R., Hernandez-Davo, J. L., Botella, J., Navarro, A., & Tous-Fajardo, J. (2017). Effects of adding a weekly eccentric-overload training session on strength and athletic performance in team-handball players. *European Journal of Sport Science*, *17*(5), 530–538. doi:10.1080/17461391.2017.1282046

Sabido, R., Hernandez-Davo, J. L., & Pereyra-Gerber, G. T. (2018). Influence of different inertial loads on basic training variables during the flywheel squat exercise. *International Journal of Sports Physiology and Performance*, *13*(4), 482–489. doi:10.1123/ijspp.2017-0282

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *Journal of Applied Physiology*, *102*(1), 368–373. doi:10.1152/japplphysiol.00789.2006

Tesch, P. A., Fernandez-Gonzalo, R., & Lundberg, T. R. (2017). Clinical applications of iso-inertial, eccentric-overload (YoYo) resistance exercise. *Frontiers in Physiology*, *8*, 241. doi:10.3389/fphys.2017.00241

Thompson, W. R. (2017). Worldwide survey of fitness trends for 2018: The CREP edition. *ACSM's Health & Fitness Journal*, *21*(6), 10–19. doi:10.1249/FIT.0000000000000341

Tinwala, F., Cronin, J., Haemmerle, E., & Ross, A. (2017). Eccentric strength training: A review of the available technology. *Strength & Conditioning Journal*, *39*(1), 32–47. doi:10.1519/SSC.0000000000000262

Weir, J. P., Housh, D. J., Housh, T. J., & Weir, L. L. (1995). The effect of unilateral eccentric weight training and detraining on joint angle specificity, cross-training, and the bilateral deficit. *The Journal of Orthopaedic and Sports Physical Therapy*, *22*(5), 207–215. doi:10.2519/jospt.1995.22.5.207

La presente tesis doctoral profundiza en el análisis de los efectos inducidos por el entrenamiento por sobrecarga excéntrica con medios no gravitacionales sobre las capacidades neuromusculares y estructurales de deportistas y jóvenes físicamente activos. Y compara los cambios en la fuerza, potencia y masa muscular producidos por diferentes medios de entrenamiento de fuerza.

This doctoral thesis provides profound insights into functional and structural changes after eccentric-overload resistance training with non-gravity-dependent devices on neuromuscular performance and muscle mass in athletes and physically active people. In addition to comparing the training-induced effects on strength power muscle mass with other training methods.

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