Universitat de Girona

PHYSICAL PERFORMANCE AND HAMSTRING INJURY RISK FACTORS DURING THE OFF-SEASON PERIOD IN FOOTBALLERS: INERTIAL FLYWHEEL VERSUS GRAVITY-DEPENDENT RESISTANCE TRAINING METHODS

Jordi Vicens Bordas

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Physical performance and hamstring injury risk factors during the off-season period in footballers

Inertial flywheel versus gravity-dependent resistance training methods

DOCTORAL
THESIS

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Jordi Vicens Bordas

2021

Thesis to obtain the degree of: "Doctor of the University of Girona"

Doctorate Program of Molecular Biology, Biomedicine and Health

Directors:	Tutor:
Azahara Fort-Vanmeerhaeghe, PhD	Elisabeth Pinart Nadal, Professor, BI
Kristian Thorborg, PhD, PT	

Of course, if one ignores contradictory observations, one can claim to have an “elegant” or “robust” theory. But it isn’t science

Halton Christian Arp

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Thesis supervision certificate

Azahara Fort-Vanmeerhaeghe, of Blanquerna University

I DECLARE:

That the present thesis, entitled **Physical performance and hamstring injury risk factors during the off-season period in footballers,** and presented by Jordi Vicens Bordas to obtain a doctoral degree, is a compendium of publications, and has been completed under my supervision.

For all intents and purposes, I hereby sign this document.

Azahara Fort-Vanmeerhaeghe
PhD Supervisor

Barcelona, 15 December 2020

Thesis supervision certificate

Professor Kristian Thorborg, of University of Copenhagen

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For all intents and purposes, I hereby sign this document.

Prof. Kristian Thorborg
PhD Supervisor

Copenhagen, 18 December 2020

List of publications

The present Doctoral Thesis is based on the following publications, which are detailed below and referred to in the text with their Roman numerals:

I. Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses
Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Bandholm T, Thorborg K.
J Sci Med Sport. 2018 Jan, 21(1): 75-83. doi: 10.1016/j.jsams.2017.10.006.
Journal Impact Factor (2018) – 3.623

II. Letter to the Editor: Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review with meta-analyses
Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Bandholm T, Thorborg K.
J Sci Med Sport. 2018 Jan, 21(1): 2-3. doi: 10.1016/j.jsams.2017.09.001.
Journal Impact Factor (2018) – 3.623

III. Eccentric hamstring strength is associated with age and duration of previous hamstring injury in male soccer players
Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Clausen MB, Bandholm T, Opar D, Shield A, Thorborg K.
Int J Sports Phys Ther. 2020 Apr;15(2):246-253. doi: 10.26603/ijspt20200246
Journal Impact Factor – n/a

IV. Performance changes during the off-season period in football players – effects of age and previous hamstring injury
Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Casals M, Bandholm T, Ishoi L, Opar D, Shield A, Thorborg K.
J Sports Sci. 2020 Jul 13; 1-11. doi: 10.1080/02640414.2020.1792160
Journal Impact Factor (2019) – 2.720

V. Intervention protocol: Performance improvements after a short-term off-season training program in semi-professional footballers: the design of a randomized controlled trial. A comparison of inertial flywheel and gravity-dependent resistance training methods.
Vicens-Bordas J, Fort-Vanmeerhaeghe A.
Open Science Framework 2020 Nov. doi: 10.17605/OSF.IO/G8YBQ
Journal Impact Factor – n/a

List of communications

I. **Vicens-Bordas J. (2018)**. Eccentric hamstring strength is influenced by age and duration of previous injury in football players. XXVII Isokinetic Medical Group Conference – Football Medicine Outcomes - Are we winning? Barcelona, Spain, June.

II. **Vicens-Bordas J. (2020)** Eccentric hamstring strength and sprinting performance changes during the off-season in Spanish footballers. IOC World Conference on prevention of injury & illness in sport. Monaco, France, March. Abstract published at British Journal of Sports Medicine; Vol. 54, Suppl 1, A78. doi:10.1136/bjsports-2020-IOCAbstracts.185

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List of abbreviations

BFlh: biceps femoris long head

CI: confidence interval

CMJ: countermovement jump

COD: Change of direction

CV: coefficient of variation

DJ: drop jump

ES: effect size

FW: inertial flywheel

GPS: global positioning system

HSI: hamstring strain injury

HSR: high-speed running

ICC: intraclass correlation coefficient

MRI: magnetic resonance imaging

MVIC: maximum voluntary isometric contraction

NHE: Nordic hamstring exercise

RCT: randomized controlled trial

RFD: rate of force development

RM: repetition maximum

RPE: rating of perceived exertion

RSA: repeated-sprint ability

SJ: squat jump

SMD: standardized mean difference

VO_{2max}: maximum aerobic capacity

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Abstract

The physical demands (high-intensity running and sprinting) of football match play place footballers at increased risk of hamstring strain injuries. Some of the negative effects of a hamstring strain injury such as neuromuscular deficits and a decrease in performance are already known. While previous injury and age are known risk factors for future hamstring injuries, their relationship with the changes in eccentric hamstring strength and performance during the off-season in semi-professional and amateur footballers have not been studied thoroughly. Moreover, a variety of resistance training interventions aiming at improving physical performance and strength are available in the literature, with inertial flywheel resistance training arising lately and providing promising results. However, its superiority against gravity-dependent interventions on physical performance and strength variables is not scientifically available at the moment. The thesis aimed to firstly compare the use of inertial flywheel with gravity-dependent resistance training for improving physical performance and thigh muscle strength and, secondly, to test how previous injury, age and the off-season period affects physical performance and eccentric hamstring strength in semi-professional and amateur footballers.

Five publications (a systematic review with meta-analyses, a letter to the editor, a cross-sectional study, a longitudinal observational study and the design of a randomised controlled trial with an intervention protocol) were developed as the main body of the thesis. The systematic review with meta-analyses (Publication I) included 7 studies (three randomised and four non-randomised controlled trials), that compared inertial flywheel against gravity-dependent training interventions. The two observational studies included semi-professional and amateur footballers. The cross-sectional study (Publication III) included a cohort of 284 footballers from 17 teams (4th-6th tiers) and assessed their eccentric hamstring strength at the beginning of the pre-season. The longitudinal observational study (Publication IV) included 74 semi-professional (3rd-4th tier, n = 28) and amateur (5th-8th tier, n = 46) male footballers which were assessed at the beginning and end of the off-season summer period on selected physical performance measures (sprint, change of direction performance and eccentric hamstring strength). The intervention protocol (Publication V) consists of a randomized pre-mid-post parallel-group trial, including semi-professional footballers, divided into two intervention groups, the inertial flywheel resistance and the gravity-dependent resistance groups. Players will be assessed for sprint, repeated-sprint ability, change of direction and jumping performances and hamstring strength. Participants will perform three supervised sessions a week during the last three weeks of the off-season period, and one supervised session a week during the pre-season (4 weeks). Both groups will perform the same volume, frequency and duration of interventions, including gym-based strength and power sessions, on-field sprinting, COD and plyometrics sessions.

The results from the systematic review and meta-analyses (Publication I) showed no difference between the inertial flywheel or the gravity-dependent interventions in the changes in muscle strength for RCTs (SMD = -0.05; 95%CI -0.51 to 0.40; p = 0.82) or non-RCTs (SMD= 0.02; 95%CI -0.45 to 0.49; p=0.93; I2=0%; and SMD= 0.03; 95%CI -0.43 to 0.50; p=0.88; I2=0%). Meta-analyses on other primary outcomes more related to performance, such as muscle power or rate of force development, could not be performed due to lack of data. The main objections from the Letter to the Editor (Publication II) against the publication were 1) the lack of a protocol registration; 2) the inclusion of six, out of nine, studies that do not compare inertial flywheel against gravity-dependent interventions, but against no training; 3) the inclusion of one non-published study. In the pre-season study cohort (Publication III), age had a negative association with preseason eccentric hamstring strength with a 0.9% reduction per year. Players with a previous hamstring injury duration of more than three weeks (n = 27) had 13% lower preseason eccentric hamstring strength compared to players without previous hamstring injury or a hamstring injury of less than 3 weeks. In the longitudinal off-season study (Publication IV), small to medium increases in sprint times were observed at 5 m (d = 0.26, p = 0.057), 10 m (d = 0.42, p < 0.001) and 30 m (d = 0.64, p < 0.001) at the end of the off-season. Small (d = -0.23, p = 0.033) improvements were observed for change of direction performance (lower time), and no changes in eccentric hamstring strength (d = 0.10, p = 0.317) at the end of the off-season. The changes in the outcomes were not affected by age ($p = 0.449$ to 0.928), previous hamstring injury ($p = 0.109$ to 0.995) or off-season length ($p = 0.148$ to 0.927).

To conclude, given the available literature, inertial flywheel resistance training is not superior to gravity-dependent resistance training on enhancing muscle strength (maximum isometric voluntary contraction). There was not enough evidence to analyse other strength variables (concentric, eccentric or RFD), muscular adaptations or performance outcomes (sprint, jump or COD) at the moment of the meta-analyses. However, recent evidence in team-sport athletes shows interesting results regarding strength and performance adaptations. While an update of the meta-analysis could provide a clearer picture, it could be hypothesised that similar strength but greater performance adaptations (mainly COD and jumping) are present in favour of inertial flywheel interventions. Semi-professional and amateur footballers with a previous hamstring injury of more than three weeks present lower eccentric hamstring strength at the beginning of preseason. Moreover, increasing age is associated with lower eccentric hamstring strength at the beginning of preseason in amateur footballers. Semi-professional and amateur footballers showed impaired sprint performance after the off-season period, independent of age, previous hamstring injury and length of the off-season. Such decrements in sprint performance are not related to the changes in eccentric hamstring strength, which is not altered after the off-season period. Instead, a small improvement during the change of direction test seems to be present after the off-season period.

Ideally, practitioners should monitor the physical performance and strength profiles of the players, trying to personalize part of the off-season training of the players. However, this scenario in a semi-professional or amateur squat of 20-24 players is unlikely. Even though our results showed no decrements in eccentric hamstring strength, the off-season is a great period (without sport-specific demands) to improve such aspect which is related to performance and injury risk reduction. Hence, practitioners are advised to prescribe some sort of strength and conditioning preparation (targeting strength, aerobic and anaerobic conditioning, and also general and sport-specific abilities) before the start of pre-season. Additionally, a greater emphasis should be placed on older players and players with a previous hamstring injury of longer duration, which are more prone to present eccentric hamstring weaknesses. Those weaknesses can be improved through consistent resistance training practices, either using inertial flywheel exercises or gravity-dependent exercises with an emphasis on eccentric actions.

Keywords: soccer, performance, eccentric strength, pre-season, off-season, inertial flywheel

Resum

Les demandes condicionals (carreres a alta intensitat i esprints) que realitzen els futbolistes en un partit es relacionen amb un increment del risc de patir lesions de la musculatura isquiosural. Alguns dels efectes negatius relacionats amb les lesions de la musculatura isquiosural són els dèficits neuromusculars i la reducció del rendiment físic. A més, la història de lesió i l'edat són factors de risc per futures lesions d'aquesta musculatura, tot i que la seva relació amb la força excèntrica i el rendiment físic durant el període transitori en futbolistes semiprofessionals i amateurs no s'ha estudiat detalladament. En l'actualitat, existeixen diferents mètodes d'entrenament per poder millorar el rendiment físic i la força en futbolistes, on l'entrenament amb màquines inercials està donant resultats interessants. Tot i això, encara no hi ha evidència científica de la superioritat de l'entrenament amb màquines inercials comparat amb l'entrenament amb mètodes gravitacionals clàssics. Els objectius de la tesi són primer de tot, comparar l'ús de l'entrenament amb màquines inercials amb l'entrenament amb mètodes gravitacionals per la millora del rendiment físic i la força; i segon, avaluar si la lesió prèvia, l'edat i el període transitori afecten el rendiment físic i la força excèntrica isquiosural i en futbolistes semiprofessionals i amateurs.

Cinc publicacions (una revisió sistemàtica amb meta-anàlisis, una carta a l'editor, dos estudis observacionals –un transversal i un longitudinal–, i el disseny d'un estudi aleatoritzat amb el protocol d'intervenció) s'han desenvolupat com a cos principal de la tesi. La revisió sistemàtica amb meta-anàlisis (Publicació I) inclou 7 estudis (tres assaigs clínics aleatoritzats i quatre no aleatoritzats), on es compara l'entrenament de força utilitzant màquines inercials o bé mètodes gravitacionals. Els dos estudis observacionals han inclòs futbolistes semiprofessionals i amateurs. L'estudi transversal (Publicació III) inclou una cohort de 284 jugadors de 17 equips (3a divisió – 2a catalana) on s'analitza la força excèntrica isquiosural al començament de la pretemporada. En l'estudi observacional longitudinal (Publicació IV) s'inclouen 74 futbolistes semiprofessionals (2ª B i 3ª divisió, n = 28) i amateurs (1ª – 4ª catalana) on es compara el rendiment en l'esprint, el canvi de direcció i la força excèntrica isquiosural entre l'inici i el final del període transitori. El protocol d'intervenció (Publicació V) és un estudi aleatoritzat pre-mid-post que inclou futbolistes semiprofessionals dividits en dos grups d'intervenció, el grup d'entrenament inercial i el gravitacional. S'avaluarà el rendiment en l'esprint, la capacitat de repetir esprints, el canvi de direcció i el salt, i també la força de la musculatura isquiosural. Els jugadors realitzaran tres entrenaments supervisats durant les tres últimes setmanes del període transitori, i una sessió supervisada durant la pretemporada (4 setmanes). Els dos grups realitzaran el mateix volum, freqüència i durada de les intervencions, incloent-hi el treball de força i potència al gimnàs, i el treball d'esprint, COD i pliometria al camp.

Els resultats de la revisió sistemàtica amb meta-anàlisis (Publicació I) demostren que no hi ha diferència en les millores de força entre l'entrenament amb màquines inercials o l'entrenament amb mètodes gravitacionals en estudis aleatoritzats (SMD = -0.05; 95%CI -0.51 a 0.40; p = 0.82) o no aleatoritzats (SMD= 0.02; 95%CI -0.45 a 0.49; p=0.93; I2=0%; i SMD= 0.03; 95%CI -0.43 a 0.50; p=0.88; I2=0%). Altres mesures de rendiment com poden ser la potència muscular o la producció de força per unitat de temps, no van poder-se meta-analitzar. Les objeccions més importants exposades a la Carta a l'Editor (Publicació II) són: 1) la falta de registre del protocol; 2) la inclusió de sis estudis (d'un total de nou), que no comparen intervencions amb màquines inercials amb intervencions gravitacionals, sinó que comparen amb no entrenament; 3) la inclusió d'un article no publicat. En l'estudi transversal de la pretemporada (Publicació III), s'ha trobat que l'edat té una associació negativa (0.9% de reducció per any) amb la força excèntrica isquiosural a l'inici de la pretemporada. Els jugadors amb una lesió de la musculatura isquiosural de més de tres setmanes durant la temporada anterior (n = 27) presenten un 13% menys de força excèntrica isquiosural, en comparació amb els jugadors que no van patir lesió o una lesió de menys de tres setmanes. En l'estudi observacional longitudinal del període transitori (Publicació IV), els temps de l'esprint augmenten als 5 m (d = 0.26, p = 0.057), 10 m (d = 0.42, p < 0.001) i 30 m (d = 0.64, p < 0.001) al final del període transitori. En canvi, el rendiment (menor temps) en el test de canvi de direcció es veu millorat (d = -0.23, p = 0.033) i la força excèntrica isquiosural no canvia (d = 0.10, p = 0.317) al final del període transitori. Aquests canvis en el rendiment no es veuen afectats per l'edat (p = 0.449 a 0.928), per la història prèvia de lesió isquiosural (p = 0.109 a 0.995) ni per la durada del període transitori (p = 0.148 a 0.927).

En el present treball, podem concloure que amb l'evidència que hi ha fins al dia d'avui, l'entrenament inercial no és superior a l'entrenament gravitacional en la millora de la força isomètrica màxima. A més a més, actualment encara no hi ha estudis suficients per poder comparar els efectes de l'entrenament inercial amb l'entrenament gravitacional amb altres variables relacionades amb la força (concèntrica, excèntrica, potència o producció de força per unitat de temps), altres adaptacions musculars o rendiment condicional (esprint, canvi de direcció o salt). Tot i això, recentment s'han trobat resultats interessants pel que fa a la millora de força i el rendiment en jugadors d'esports d'equip. Abans de fer una actualització del meta-anàlisis, es podria suggerir que hi ha millores similars a nivell de força, però millors guanys de rendiment (sobretot COD i salts) a favor de l'entrenament amb màquines inercials. Els futbolistes semiprofessionals i amateurs amb una història de lesió isquiosural de més de tres setmanes durant la temporada anterior presenten menys força excèntrica isquiosural al començament de la pretemporada. A més a més, els futbolistes de més edat també presenten una menor força excèntrica isquiosural. Pel que fa als canvis durant el període transitori, els futbolistes presenten una disminució del rendiment de l'esprint, que no és dependent de l'edat, ni de la història prèvia de lesió isquiosural ni tampoc de la llargada del període transitori. Aquesta disminució del rendiment de l'esprint no està relacionada amb els canvis en la força excèntrica isquiosural, que no es veu afectada durant aquest període. En canvi, sembla haver-hi una petita millora en el rendiment durant el canvi de direcció.

En un context ideal, els preparadors físics haurien de mesurar els perfils de rendiment físic i força dels jugadors de futbol, per poder-los personalitzar l'entrenament durant el període transitori. Malauradament, aquesta situació no és realista en un equip de futbol semiprofessional o amateur, amb 20-24 jugadors. Tot i que els resultats d'aquesta tesi han demostrat que no hi ha pèrdua de força excèntrica en la musculatura isquiosural, el període transitori és un moment ideal (sense demandes de competició) per poder millorar aquest aspecte, ja que està relacionat amb el rendiment físic i un menor risc de lesió. Per tant, els preparadors físics haurien de programar entrenaments de preparació física (buscant adaptacions de força, resistència aeròbica i anaeròbica, i habilitats generals i específiques de l'esport) abans del començament de la pretemporada. A més a més, els preparadors físics haurien de prioritzar el treball amb els jugadors de més edat i jugadors amb una lesió isquiosural de més de tres setmanes, ja que tenen més probabilitats de presentar menys força excèntrica de la musculatura isquiosural. Aquests dèficits de força es poden millorar a través d'entrenaments de força regulars, sigui utilitzant màquines inercials o bé mètodes gravitacionals emfatitzant les accions excèntriques.

Paraules clau: futbol, rendiment, força excèntrica, pretemporada, període transitori, iso-inercial

Resumen

Las demandas condicionales (carreras a alta intensidad y esprints) que realizan los futbolistas en un partido, se relacionan con un incremento del riesgo de sufrir lesiones de la musculatura isquiosural. Algunos de los efectos negativos relacionados con las lesiones de la musculatura isquiosural son los déficits neuromusculares y la reducción del rendimiento. Además, la historia de lesión y la edad son factores de riesgo por futuras lesiones isquiosurals, a pesar de que su relación con la fuerza excéntrica y el rendimiento durante el período transitorio en futbolistas semi-profesionales y amateurs no se ha estudiado en detalle. En la actualidad, existen diferentes métodos de entrenamiento para poder mejorar el rendimiento físico y la fuerza en futbolistas, donde el entrenamiento con máquinas inerciales está dando resultados interesantes. Aun así, hoy en día no existe evidencia científica respecto a la superioridad del entrenamiento con máquinas inerciales comparado con el entrenamiento utilizando métodos gravitacionales. Los objetivos de la tesis son, primero, comparar el uso del entrenamiento con máquinas inerciales con el entrenamiento con métodos gravitacionales para la mejora del rendimiento físico y la fuerza; y segundo, evaluar si la lesión previa, la edad y el período transitorio afectan el rendimiento físico y la fuerza excéntrica isquiosural en futbolistas semi-profesionales y amateurs.

Cinco publicaciones (una revisión sistemática con meta-análisis, una carta al editor, dos estudios observacionales –uno transversal y un longitudinal–, y el diseño de un estudio aleatorizado con el protocolo de intervención) se han desarrollado como cuerpo principal de la tesis. La revisión sistemática con meta-análisis (Publicación I) incluye 7 estudios (tres ensayos clínicos aleatorizados y cuatro no aleatorizados), donde comparan el entrenamiento utilizando máquinas inerciales con un entrenamiento gravitacional. Los dos estudios observacionales han incluido futbolistas semi-profesionales y amateurs. El estudio transversal (Publicación III) incluye una cohorte de 284 jugadores de 17 equipos (3ª división – 2ª catalana) donde se analiza la fuerza excéntrica isquiosural a comienzos de la pretemporada. En el estudio observacional longitudinal (Publicación IV) se incluyen 74 futbolistas semi-profesionales (2ª B y 3ªdivisión, n = 28) y amateurs (1ª – 4ª catalana) donde se evalúa el rendimiento en el esprint, el cambio de dirección y la fuerza excéntrica isquiosural al inicio y final del período transitorio. El protocolo de intervención (Publicación V) es un estudio aleatorizado pre-mid-post que incluye futbolistas semi-professionales divididos en dos grupos de intervención, el grupo de entrenamiento inercial y el gravitacional. Se evaluará el rendimiento en el esprint, la capacidad de repetir esprints, el cambio de dirección y el salto, y también la fuerza de la musculatura isquiosural. Los jugadores realizarán tres entrenamientos supervisados durante las tres últimas semanas del período transitorio, y una sesión supervisada durante la pretemporada (4 semanas). Los dos grupos realizarán el mismo volumen, frecuencia y duración de las intervenciones, incluyendo trabajo de fuerza y potencia en el gimnasio, y trabajo de esprint, COD y pliometría en el campo.

Los resultados de la revisión sistemática con meta-análisis (Publicación I) demuestran que no hay diferencia en las mejoras de fuerza entre el entrenamiento con máquinas inerciales o el entrenamiento con métodos gravitacionales en estudios aleatorizados (SMD = -0.05; 95%CI -0.51 a 0.40; p = 0.82) o no aleatorizados (SMD= 0.02; 95%CI -0.45 a 0.49; p=0.93; I2=0%; y SMD= 0.03; 95%CI -0.43 a 0.50; p=0.88; I2=0%). Otras medidas de rendimiento como pueden ser la potencia muscular o la producción de fuerza por unidad de tiempo, no se pudieron meta-analizar. Las objeciones más importantes expuestas a la Carta al Editor (Publicación II) son: 1) la falta de registro del protocolo; 2) la inclusión de seis estudios (de un total de nueve), donde no comparan intervenciones con máquinas inerciales con intervenciones gravitacionales, sino que comparan el no entrenamiento; 3) la inclusión de un artículo no publicado. En el estudio transversal de la pretemporada (Publicación III), se ha encontrado que la edad tiene una asociación negativa (0.9% de reducción por año) con la fuerza excéntrica isquiosural al inicio de la pretemporada. Los jugadores con una lesión en la musculatura isquiosural durante la temporada anterior con una duración de más de tres semanas (n = 27) presentan un 13% menos de fuerza excéntrica isquiosural, en comparación con los jugadores que no sufrieron lesión o una lesión de menos de tres semanas. En el estudio observacional longitudinal del período transitorio (Publicación IV), los tiempos del esprint aumentan a los 5 m (d = 0.26, p = 0.057), 10 m (d = 0.42, p < 0.001) y 30 m (d = 0.64, p < 0.001) al final del período transitorio. En cambio, el rendimiento (menor tiempo) en la prueba de cambio de dirección se ve mejorado (d = -0.23, p = 0.033) y la fuerza excéntrica isquiosural no cambia (d = 0.10, p = 0.317) al final del período transitorio. Estos cambios en el rendimiento no se ven afectados por la edad (p = 0.449 a 0.928), por la historia previa de lesión isquiosural (p = 0.109 a 0.995) ni por la duración del período transitorio (p = 0.148 a 0.927).

En el presente trabajo, podemos concluir que con la evidencia que hay hasta día de hoy, el entrenamiento inercial no es superior al entrenamiento gravitacional en la mejora de la fuerza isométrica máxima. Además, actualmente no hay estudios suficientes para poder comparar los efectos del entrenamiento inercial con el gravitacional para otras variables relacionadas con la fuerza (concéntrica, excéntrica, potencia o producción de fuerza por unidad de tiempo), otras adaptaciones musculares o rendimiento condicional (esprint, cambio de dirección o salto). A pesar de esto, recientemente se han encontrado resultados interesantes en cuanto a la superioridad en el rendimiento en jugadores de deportes de equipo. Antes de hacer una actualización del metaanálisis, se podría sugerir que hay mejoras similares por lo que hace a variables de fuerza, pero mejor rendimiento (sobretodo COD y saltos) a favor del entrenamiento con máquinas inerciales. Los futbolistas semi-profesionales y amateurs con una historia de lesión isquiosural de más de tres semanas durante la temporada anterior presentan menos fuerza excéntrica isquiosural a comienzos de la pretemporada. Además, los futbolistas de más edad también presentan menos fuerza excéntrica isquiosural. En cuanto a los cambios de rendimiento durante el período transitorio, los futbolistas presentan una disminución del rendimiento en el esprint, que no es dependiente de la edad, ni de la historia previa de lesión isquiosural, ni tampoco de la duración del período transitorio. Esta disminución del rendimiento del esprint no está relacionada con los cambios en la fuerza excéntrica isquiosural, que no se ve afectada durante este período. En cambio, parece haber una pequeña mejora en el rendimiento del cambio de dirección.

En un contexto ideal, los preparadores físicos deberían medir los perfiles de rendimiento físico y fuerza de los jugadores, para poder personalizar el entrenamiento durante el período transitorio. Por desgracia, esta situación no es muy realista en un equipo de fútbol semi-profesional o amateur, con 20-24 jugadores en plantilla. Aunque los resultados de esta tesis han demostrado que no hay pérdida de fuerza excéntrica en la musculatura isquiosural, el período transitorio es un momento ideal (sin demandas competitivas) para poder mejorar este aspecto, ya que va relacionado con el rendimiento físico y un menor riesgo de lesión. Por lo tanto, los preparadores físicos deberían programar entrenamientos (buscando adaptaciones de fuerza, resistencia aeróbica y anaeróbica, y habilidades generales y específicas del deporte) antes de empezar la pretemporada. Además, los preparadores físicos deberían priorizar el trabajo con los jugadores de mayor edad y los jugadores con un historial de lesión en la musculatura isquiosural de más de tres semanas, ya que tienen más opciones de presentar menos fuerza excéntrica en dicha musculatura. Estos déficits de fuerza pueden mejorarse a través de entrenamientos de fuerza regulares, ya sea utilizando máquinas inerciales o gravitacionales enfatizando las acciones excéntricas.

Palabras clave: futbol, rendimiento, fuerza excéntrica, pretemporada, período transitorio, iso-inercial

PREFACE

Motivation of the study

I could not start this thesis without summarizing my "biased" background, to understand the early steps in my professional and academic career. When I was a teenager (not so long ago…), I loved sports, especially playing football. I was certain I wanted to study Physical Education (the only related profession I knew was teaching PE in secondary education). Sometimes, mainly during holidays, when I could not practice football with the team, I started wondering which was the best way to keep in shape during this period and maintain physical performance. I thought the aerobic condition was the "important" physical capacity in football, so I used to go for a run. A few years later (2007), I started studying Sports Sciences and Physical Education at INEFC Barcelona and I realized there was life outside teaching Physical Education. I didn't know Sports Scientists or Strength and Conditioning Coaches even existed as a profession, before. During the degree, I developed a lot of skills, improved my knowledge of sports sciences, and also understood football is not only aerobic. However, it was not until finishing the degree, that I realized I wanted to become a Strength and Conditioning Coach. During my last undergraduate academic year, and also during the first year as a post-graduate, professor Francisco "Paco" Seirul·lo crossed my path to plant his seeds.

The complexity under every sentence Paco articulated was tremendous. I only understood a portion of what he was saying, even nowadays I don't grasp everything of what he describes. When analysing football performance or any team-sport performance, professor Seirul·lo has promoted and embraced, during the last 40 years, the use of the complex dynamic systems theory for the development and optimisation of footballers, contemplating the importance of the "non-linear" reality and the chaos from a highly variable and dynamic context. While this is contemplated by some practitioners, it is difficult for science to "prove" it. Considering the conditioning structure, which is the "part of the puzzle" most widely developed by strength and conditioning and fitness coaches nowadays, Dr Julio Tous and Dr Gerard Moras collaborated on developing my foundations around "Strength is the driver of performance". But I realised that to develop myself, I needed to improve my researching skills and also my English. So, I decided to move to the UK (2012), Middlesbrough-Darlington to be concise, where I had to travel to Newcastle College to study English (what a challenge, like, right?), and my English definitely got ~~worse~~ better. Then I moved to Cardiff where I performed the MSc in Strength and Conditioning at Cardiff Metropolitan University (thanks to Dr Jeremy Moody, Dr Rob Meyers, Dr Rhodri Lloyd and Dr Peter O'Donoghue) and I had the privilege to be involved with Cardiff City FC as a Sports Science intern (thanks Callum, Mike, Ben, Alun, Kristian, Martyn and René).

Back to Girona (2014), I started working at Sportclinic, with Ernest, Albert and Lluis. Lluis Sala has been the most influential man on me, professionally wise. He helped me to close the loop, with his broad experience (skiing, rugby, football, tennis and other individual sports) helped me put in practice all the knowledge acquired to improve athletes' performance. We spent two years working shoulder by shoulder. Because of his experience and a similar way of understanding performance, I can consider him one of my mentors! And Ernest, we have been working on our PhDs' also shoulder by shoulder, what a journey, I hope it does not end here! Not only the involvement in the private clinic working individually with athletes, but the experience with football teams such UE Llagostera, Girona FC "B" and CF Peralada, and also all the academic pathway up until this PhD, has helped me evolve as a practitioner.

While this thesis will have a look at some of the physical aspects of football performance, mainly on the strength component and how this relates to performance in footballers, it needs to be highlighted that it will try to give just some answers to the puzzle.

And, hopefully, this is just the beginning of the game.

CHAPTER 1

Introduction

APPROACH TO THE SPORT, FOOTBALL

> The beginning of knowledge
> is the discovery of something
> we do not understand
>
> **Frank Herbert**

Football is one of the most popular team sports in the world (Dvorak et al., 2000), and the most popular in Spain with 806.172 licenses, including male and female football players of all age groups in 2017 (Spanish Football Federation, 2017). More precisely, the Catalan region had 126.612 licenses, from which 423 were professional and 20.368 amateurs at the senior level in 2017 (Spanish Football Federation, 2017).

Considering this two-level classification, with professional football (salaried licensed players) on the one hand, and amateur football players (part-time or non-salaried, licensed players) on the other; makes it difficult to classify the intermediate levels with part-time salaried (semi-professional or high-level amateur) football players which are common in European football (Fitzharris et al., 2017; Loose et al., 2019; van Beijsterveldt et al., 2014). Those types of players are normally engaged in work or education in addition to playing football, involving a high frequency of training sessions (3 to 5, and a game). While some could think that the division played could be a decent way of categorisation, considering most of the 1st division and 2nd leagues in European football are professional (AEPFL, 2005) however, depending on the country, due to a diversity of factors (culture, development and economical status or policies), not all the leagues are equal. And the same happens with semi-professional football, in which a fourth division team from one country could be as professional as a second division team from another country or vice-versa, as can be seen in Table 1. One information that could help classify the level of footballers could be the number of training sessions per week, the number and type of qualified staff in the team, medical and training equipment, budget of the club, as suggested by Loose et al. (2019) (Loose et al., 2019), but certainly, the specific context of each country may differ and such information could understand the football level of the teams and players.

Football physical performance

Football match-play characteristics include a variety of distances covered at different intensities (walk, jog, run fast and sprint), in combination with other movements such as tackling, jumping and changes of direction (including acceleration and deceleration strategies) integrated alongside technical skills (see Figure 1) (Bloomfield et al., 2007; Di Salvo et al., 2007). Importantly, professional football is becoming more technically and physically demanding during the last decade (Barnes et al., 2014; Bradley et al., 2016; Bush et al., 2015), with players experiencing an increase in high-intensity actions during matches (Barnes et al., 2014) such as straight sprinting (Faude et al., 2012) and changes of direction (COD) (Ade et al., 2016; Bloomfield et al., 2007), with sprinting being the most frequent action preceding goal situations (Faude et al., 2012).

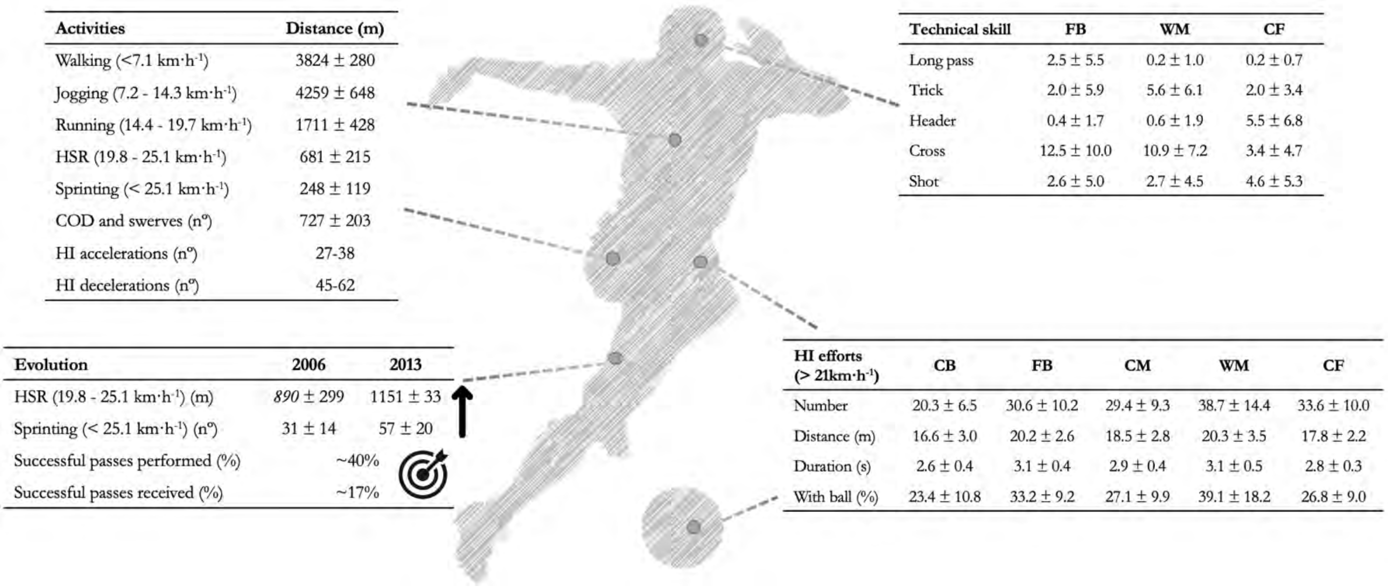
Considering the relevance of COD in football (Ade et al., 2016; Bloomfield et al., 2007; de Hoyo et al., 2018; Sonderegger et al., 2016), the analysis of accelerations and decelerations using global positioning systems (GPS) is rising interest among the sports research community lately. Tierney and colleagues (Tierney et al., 2016) provided some data on high-intensity ($> 2\ \mathrm{m \cdot s^{-2}}$) accelerations (27 to 38) and decelerations (45 to 62) during match play across different positions and systems played, showing greater decelerations compared to accelerations. A recent systematic review with meta-analyses revealed that most of the team-sports analysed (football, rugby codes, Australian football, American football and hockey) are biased to greater high-intensity decelerations compared to accelerations (SMD = -0.88, 95%CI -1.12 – -0.64), with football being the sport with greater effects (SMD = -1.74, 95%CI -2.21 – -1.28) and American football is the only exception (SMD = 1.26, 95%CI 1.06 – 1.43), and (Harper et al., 2019). While acceleration and deceleration data seems essential to obtain the football physical demands and loads, it should be highlighted that starting velocity should be considered to not to under-estimate (actions with high initial running speed) or over-estimate (actions with low initial running speed) some of the actions (Sonderegger et al., 2016).

Table 1. Professional, semi-professional and amateur tier-specific classification in Spain, United Kingdom and Germany.

	SPAIN			UNITED KINGDOM			GERMANY		
Tier	Division / League	Groups	Teams	Division / League	Groups	Teams	Division / League	Groups	Teams
1st	La Liga	1	20	Premier League	1	20	Bundesliga	1	18
2nd	La Liga 2	1	20	Championship	1	24	2. Bundesliga	1	18
3rd	Segunda División "B"	4	80	League One	1	24	3. Liga	1	20
4th	Tercera División	18	360	League Two	1	24	1st regional division	5	73
5th	1st regional division	36	592	National League	1	24	2nd regional division	14	241
6th	2nd regional division	68	n/a	National League N/S	2	44	3rd regional division	34	594
7th	3rd regional division	96		1st regional – Premier division	4	88	4th regional division	n/a	n/a
8th	4th regional division	78		2nd regional division – Division one	7	140	5th - 11th regional divisions	n/a	n/a
9th	5th regional division	6		3rd regional division	14	281			
10th				4th regional division	20	384			
11th				5th - 14th regional divisions	n/a	n/a			

Data extracted from each football federation.

Contemplating the complexity of football match-play, practitioners are nowadays trying to adopt an integrated approach to contextualize match physical performance to better understand the game (Ade et al., 2016; Bradley & Ade, 2018; Paul et al., 2015). Football players' performance is influenced not only by players level (professional vs amateur) or position (forward, midfielder, defender) but also other contextual factors and situational variables such as team playing style, playing opposition, match status or competition period, possession or non-possession of the ball, just to name a few (Ade et al., 2016; Bradley & Ade, 2018; Casamichana et al., 2019; Castellano et al., 2011; De Paula Simola et al., 2015; Paul et al., 2015). Inline to that, while high-intensity running, accelerations and decelerations tend to decrease from the first half to the second half (Akenhead et al., 2013; Bradley & Noakes, 2013; Mohr et al., 2003; Rampinini, Impellizzeri, et al., 2009), it seems that such decrements could be overestimated if not taking into account effective match-play or game interruption, which are normally higher during the last phases of the game (Linke et al., 2018). All these factors show the difficulties of analysing the complex game of football.



Activities	Distance (m)
Walking (<7.1 $km \cdot h^{-1}$)	3824 ± 280
Jogging (7.2 - 14.3 $km \cdot h^{-1}$)	4259 ± 648
Running (14.4 - 19.7 $km \cdot h^{-1}$)	1711 ± 428
HSR (19.8 - 25.1 $km \cdot h^{-1}$)	681 ± 215
Sprinting (< 25.1 $km \cdot h^{-1}$)	248 ± 119
COD and swerves (nº)	727 ± 203
HI accelerations (nº)	27-38
HI decelerations (nº)	45-62

Evolution	2006	2013
HSR (19.8 - 25.1 $km \cdot h^{-1}$) (m)	*890* ± 299	1151 ± 33
Sprinting (< 25.1 $km \cdot h^{-1}$) (nº)	31 ± 14	57 ± 20
Successful passes performed (%)	~40%	
Successful passes received (%)	~17%	

Technical skill	FB	WM	CF
Long pass	2.5 ± 5.5	0.2 ± 1.0	0.2 ± 0.7
Trick	2.0 ± 5.9	5.6 ± 6.1	2.0 ± 3.4
Header	0.4 ± 1.7	0.6 ± 1.9	5.5 ± 6.8
Cross	12.5 ± 10.0	10.9 ± 7.2	3.4 ± 4.7
Shot	2.6 ± 5.0	2.7 ± 4.5	4.6 ± 5.3

HI efforts (> 21$km \cdot h^{-1}$)	CB	FB	CM	WM	CF
Number	20.3 ± 6.5	30.6 ± 10.2	29.4 ± 9.3	38.7 ± 14.4	33.6 ± 10.0
Distance (m)	16.6 ± 3.0	20.2 ± 2.6	18.5 ± 2.8	20.3 ± 3.5	17.8 ± 2.2
Duration (s)	2.6 ± 0.4	3.1 ± 0.4	2.9 ± 0.4	3.1 ± 0.5	2.8 ± 0.3
With ball (%)	23.4 ± 10.8	33.2 ± 9.2	27.1 ± 9.9	39.1 ± 18.2	26.8 ± 9.0

Figure 1. Match demands in professional football (author's elaboration).
CB = centre back; CM = centre midfielder; CF = centre forward; COD = change of direction; FB = full-back; HI = high-intensity; HSR = high-speed running; WM = wide midfielder. Data extracted from Bloomfield et al., 2007; Bradley et al., 2013; Barnes et al., 2014; Ade et al., 2016; Tierney et al., 2016.

Semi-professional and amateur football match-play physical demands are scarcely researched (Casamichana et al., 2012; Castellano & Casamichana, 2013; Castillo-Rodríguez et al., 2020), with no direct comparisons between professional, semi-professional and amateur categories. Some evidence exists comparing professional divisions (Bradley et al., 2013; Di Salvo et al., 2012), with teams from lower tiers (2nd and 3rd) seem to cover greater distances at higher intensities (750-899 m) compared to the top tier (693-727 m; ES = 0.4-1.0), accompanied to lower performance in technical indicators (ES = 0.3-0.6). Again, those results highlight the complexity of the sport and the importance of taking other factors into account (technical ability, team formation or playing style) and develop an integrated approach when looking at the physical performance (Bradley et al., 2013; Paul et al., 2015). Instead, amateur players possess similar VO_{2max} (56-58 $ml \cdot kg^{-1} \cdot min^{-1}$) than professional players, but reduced repeated-sprint ability performance (RSA_{mean} 7.17 vs 7.41; d = 1.3) and worse physiological responses to high-intensity demands (d = 1.06 to 1.48; [La-] [HCO_3-] [H+] $mmol \cdot l^{-1}$ and RPE) (Rampinini, Sassi, et al., 2009). Moreover, the Yo-Yo IR2 was discriminant between elite (tier 1; 41% higher performance) and sub-elite (tier 3) Danish and Norwegian football players (Ingebrigtsen et al., 2012). Amateurs performed less high-intensity and sprinting distances

(259-427 m and 175-314 m, respectively) compared to professionals (282-473 m and 202-355 m, respectively) during small-sided games (2v2 and 3v3), with the worst technical performance (greater loss of ball possessions and lower successful passes) (Dellal et al., 2011). When looking at neuromuscular factors such as strength and power production, greater 10 m but not 30 m sprint times seem to differentiate between professional and amateur French footballers (Cometti et al., 2001). Professional soccer players showed greater eccentric hamstring strength than amateurs during isokinetic testing (Cometti et al., 2001); and greater eccentric hamstring strength during the NHE than division 4 footballers (441N vs 336N) (Buchheit et al., 2016). Also, youth professional footballers showed greater maximal isometric strength, rate of force development, 10 m sprint and jumping ability (SJ and DJ) than sub-elite and recreational youth footballers (Gissis et al., 2006). Surprisingly though, amateurs presented greater eccentric knee extensor strength and no differences were present between professional and amateur players on jumping abilities (Cometti et al., 2001). Hence, it seems reasonable to infer that similar match demands are going to be observed in semi-professional games with high-intensity distances (above 21 $km \cdot h^{-1}$) and efforts (high-intensity accelerations and decelerations), with even lower high-intensity efforts covered in amateur games.

Therefore, semi-professional and amateur footballers may possess a greater potential to get in shape and could be interpreted as an opportunity for fitness and strength and conditioning coaches to improve footballer's physical performance, considering it as a differentiating factor from semi-professional to professional. However, improving physical performance will not directly translate to playing at higher football levels since a footballer all-around performance will be dictated by the combination of technical and tactical factors, among others, which may be more important when a certain level of physical performance is achieved.

Football injuries

The injury incidence rates in male adult football (including professional and amateur) are one of the highest of all sports, with up to 35.5 injuries per 1000 match hours and 7.6 injuries per 1000 training hours (Junge & Dvorak, 2004). One of the largest studies in European professional football (the UEFA injury study) showed a match injury incidence of 27.5/1000h, and a training injury incidence of 4.1/1000h (Ekstrand et al., 2011a). Incidences in Spanish professional football (2nd Division) were 38.8 injuries per 1000 match hours and 3.8 injuries per 1000 training hours (Noya Salces et al., 2014) which were similar to Dutch professional football (32.8/1000 match hours and 2.8/1000h training hours) (Stubbe et al., 2015). When looking at semi-professional or amateur football cohorts (Table 2, Figure 2), injury incidences for a match (12.1 to 32.2/1000h) and training (2.7 to 4.8/1000h) are also documented in the last decade (Engebretsen et al., 2010; Fitzharris et al., 2017; Loose et al., 2019; van Beijsterveldt et al., 2014). The wide differences in incidence rates indicate the considerable peculiarities of the different contexts (Junge & Dvorak, 2004). Not only the players level (professional, semi-professional and amateur), but the football season ("summer season" vs "autumn-spring season") and the climate seem to affect the injury incidence (Waldén et al., 2013). Therefore, the risk of injury should be investigated for each specific context and football subpopulation.

When comparing professionals to semi-professionals, the last seems to be more prevalent to injury, considering 79% of the players became injured during one season (Loose et al., 2019). In the Dutch cohorts, while there was no difference between amateurs and professionals in injury prevalence (around 60%), amateurs presented more moderate (RR 0.51, 95%CI 0.40-0.65) and severe (RR 0.34, 95%CI 0.24-0.48) injuries, higher recurrence of injuries (RR 0.36, 95%CI 0.22-0.59) and also more complaints after returning to play and competition (31.3% vs 13.4%; $p < 0.001$) compared to professional football players in the Dutch cohort (van Beijsterveldt et al., 2015). Instead, professionals presented more overuse (26.9% vs 19.3%; $p = 0.02$) and minimal injuries (van Beijsterveldt et al., 2015).

Table 2. Training and match injury incidence in semi-professional or amateur football studies.

Study	**Level (Tier)**	**Country**	**Season**	**N players (teams)**	**Injuries (% injured players)**	**Injury incidence / 1000h**	**Hamstring injuries, (% muscle strains)**
Loose et al., 2019	Semi-pro (4-7)	Germany	2015-16	1130 (62)	2630 (79%)	Training: 4.5 (n/a) Match: 27.1 (n/a)	n/a
Fitzharris et al., 2017	Semi-pro (2)	Ireland	2014	140 (6)	152 (31%)	Training: 4.8 (95%CI 2.2 to 7.7) Match: 23.1 (95%CI 15.2 to 31.3)	31 (41%) posterior thigh
van Beijsterveld et al., 2014	Amateur (n/a)	Netherlands	2009-10	456 (23)	424 (60%)	Training: 3.9 (95%CI 3.3 to 4.7) Match: 20.4 (95%CI 18.1 to 23.1)	65 (39%) posterior thigh 42 (25%) anterior thigh
Sousa, Rebelo & Brito, 2013 *	Amateur (4-5)	Portugal	2010-11	231 (11)	213 (59%)	Training: 2.4 (95%CI 1.8 to 3.0) Match: 32.2 (95%CI 23.1 to 41.3)	39 (75%) whole thigh #
Engebretsen et al., 2010	Semi-pro / amateur (2-4)	Norway	2004	508 (31)	505 (56%)	Training: 2.7 (95%CI 2.4 to 3.1) Match: 12.1 (95%CI 10.5 to 13.7)	76 (n/a)

Notes: *study analysed injuries on artificial turf; #number of injuries of the whole thigh (including posterior and anterior thigh); $ The study used a different system to register injuries which makes it not comparable to other studies; n/a: not applicable.

A snapshot on hamstrings

In semi-professional and amateur football, as in professional, lower extremities are the most affected body part (85 to 92% of all injuries) (Ekstrand et al., 2011b; van Beijsterveldt et al., 2014), with the ankle (18.2-20.4%), the posterior thigh (15.3-20.4%) and the knee (11.1-15.1%) being the most commonly injured body parts (Figure 2) (Fitzharris et al., 2017; van Beijsterveldt et al., 2014). When considering muscle injuries alone, the hamstrings injuries account the 37% of all muscle injuries in professional (Ekstrand et al., 2011b) and 39-41% in semi-professional and amateur football (Fitzharris et al., 2017; van Beijsterveldt et al., 2014).

The most common hamstring strain injury (HSI) mechanism (91% non-contact) is running at high intensities (~60%), with stretching (<20%) and kicking, passing and twisting/turning (each ~5%) being also reported in football(Woods et al., 2004). Hence, most of the research is focused on the understanding of sprinting related HSIs. One of the biomechanical determinants of HSIs is related to the high peak forces and much negative work produced by the hamstring muscle group at the end of the swing phase achieved at high sprinting velocities (above 6.8-7m·s^{-1}) (Schache et al., 2012). Moreover, HSIs present high recurrence rates (12-33%) (Ekstrand et al., 2016; Hägglund, Waldén, Magnusson, et al., 2013; Waldén et al., 2009) which have not improved in the last few years, even though the considerable amount of research in this area (de Visser et al., 2012; Fyfe et al., 2013; Green et al., 2020; Opar et al., 2012). These high recurrence rates are suggested to be due to insufficient rehabilitation and/or a rushed return-to-play following an HSI, and those seem to be inversely related to the level of play (Hägglund et al., 2016) being amateur football players more prone to injury recurrences (van Beijsterveldt et al., 2015). Reducing the risk of a first time hamstring injury, but more importantly, the injury recurrence is a key priority due to the more extensive rehabilitation and costs associated with the consequent injury (Ekstrand et al., 2011b; Freckleton & Pizzari, 2013; van Beijsterveldt et al., 2013).

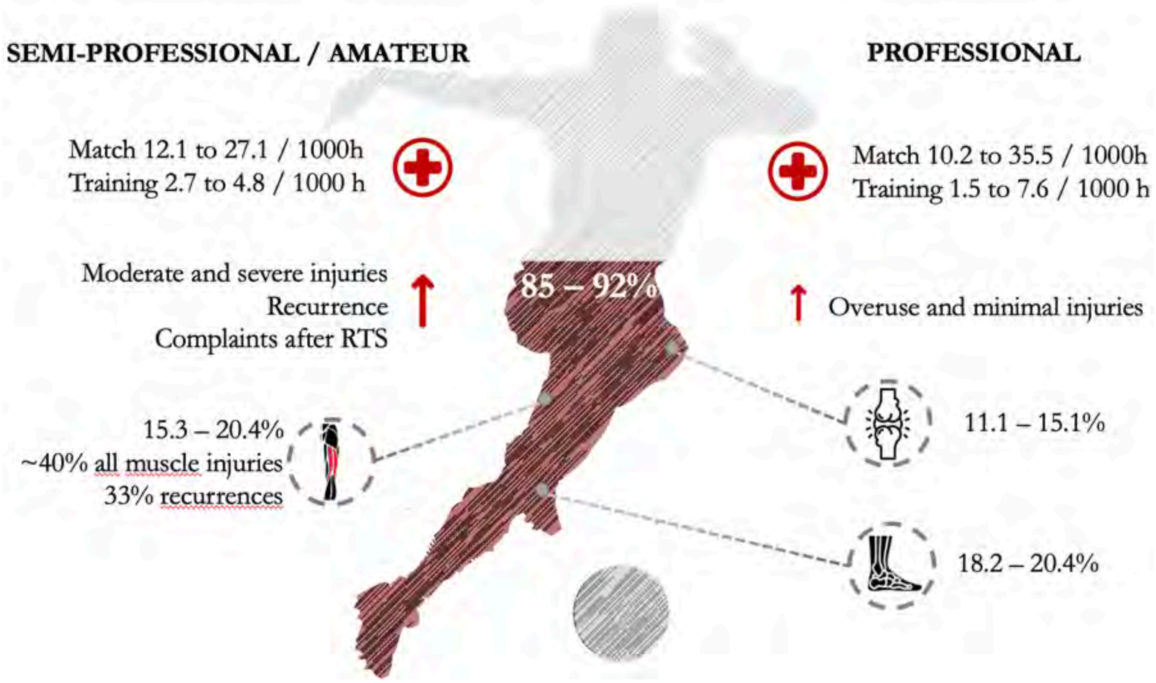


Figure 2. Injuries in semi-professional, amateur and professional football (author's elaboration).

Even though the sports science and medicine communities are highly aware of this problematic (Mendiguchia et al., 2012; van der Horst et al., 2017), HSIs have been increasing 4% annually in professional football for the last decade (Ekstrand et al., 2016). However, when adjusting the incidence rates with the increasing high-intensity demands of the game, injuries seem to be decreasing (around 20%) (Buchheit et al., 2018). Some researchers will argue practitioners from elite clubs do not implement proven strategies (Bahr et al., 2015), but a recent survey demonstrated elite clubs try to adapt the evidence to their context by implementing eccentric exercises, and the monitoring of sprinting and high speed running loads (McCall et al., 2020) to tackle the hamstring problematic (Buckthorpe et al., 2019). While the injury economic burden may be a problem for professional football (Ekstrand, 2013; Hickey et al., 2014), it may not be as important in semi-professional or amateur football, considering the economic constraints. However, this does not mean semi-professional or amateur football players do not need to take care of their "hamstring health", pondering the unquantifiable psycho-social costs of HSIs and reinjuries (Jansen et al., 2019; van Mechelen et al., 1992).

In order to analyse and prevent the sport-related injuries, van Mechelen and colleagues (1992) provided the "sequence of prevention" (van Mechelen et al., 1992), which involves an analysis and magnitude of the injury "problem", the analysis of the aetiology (injury mechanism and risk factors), the implementation of an intervention and the effectiveness of the intervention. This cycle has been revised and evolved to more complex, ecological, comprehensive and multifactorial approaches for injury prevention (Bittencourt et al., 2016; Hulme & Finch, 2015; O'Brien et al., 2019). For researchers, while the analysis of single risk factors could start explaining some injuries, the need to look for interactions between other factors (confounders, moderators and mediators) seems crucial. Hence, a need for abandoning these univariable injury risk detection practices (Hulme & Finch, 2015) and use a more complex systems paradigm seems crucial for improving the sport sciences and medicine community.

Risk factors for hamstring injuries

Understanding the risk factors associated with hamstring strain injuries (see Table 3) is a fundamental component for injury prevention, return to training and competition (post-injury) and load management during the season. Such a multifactorial risk factor approach should be complemented with a multifactorial intervention to tackle the problem. Risk factors could be divided into internal risk factors (athlete), or external risk factors (environment). Internal risk factors can then be divided by modifiable (physical fitness, strength, flexibility, body mass, among others) and non-modifiable (age, previous injury, gender and ethnicity). Considering all these factors act simultaneously on the athlete, the risk an athlete to get injured varies over time as individual intrinsic and extrinsic risk factors change (Bittencourt et al., 2016; Hulme & Finch, 2015; O'Brien et al., 2019).

Considering the impossibility of practitioners to intervene on non-modifiable risk factors but the ability to intervene on the modifiable ones, it seems interesting to analyse possible relationships between non-modifiable and modifiable risk factors. The present work will try to analyse the relationship between age, previous hamstring injury and eccentric hamstring strength in football but also provide a wider view on which non-modifiable and modifiable factors could be related to future hamstring injuries (Table 3). For comprehensive reviews on hamstring injury risk factors see (de Visser et al., 2012; Freckleton & Pizzari, 2013; Green et al., 2020; Opar et al., 2012; Pizzari et al., 2020).

Non-modifiable risk factors for hamstring injuries

Age (Green et al., 2020; Henderson et al., 2010; Van Dyk et al., 2017; Woods et al., 2004) and **previous hamstring injury** (Opar et al., 2012) have often been linked to future HSIs. Professional football players older than 23 years have been reported to be at an elevated risk of sustaining an HSI (Woods et al., 2004) and each year of age has been reported to increase the risk of sustaining an HSI up to 1.8-fold (OR; 95% CI 1.2 to 2.7) in English Premier League football players (Henderson et al., 2010). While the mechanism behind this apparent effect of age on injury risk is not clear, it could be, at least in part, due to age-related changes in hamstring strength. However, the impact of age on eccentric hamstring strength has not previously been investigated in football players at any level.

Previous HSI is the non-modifiable risk factor with greater odds for a future HSI, with several studies supporting this finding. In addition, the results from a recent meta-analysis that players with a history of an HSI are almost 3 times at greater risk (RR 2.7, 95%CI 2.4 to 3.1) or those with a recent HSI being almost 5 times at greater risk (RR 4.8, 95%CI 3.5 to 6.6) than players without (Green et al., 2020). Players with previous HSI may present persistent biceps femoris long head muscle atrophy (Croisier, 2004), and neuromuscular inhibition (Opar et al., 2012). This may limit adaptations during the rehabilitation process and thereby increase the risk of re-injuries (Opar et al., 2012), due to persistent inadequate muscle structure and/or function.

Considering the interactions between modifiable and non-modifiable risk factors, the training history and habits of individual athletes may therefore moderate players' risk of injury (Gabbett, 2016). In line with this, players with a previous HSI and older age, combined with low levels of eccentric hamstring strength, were at increased risk of sustaining a future HSI (Timmins et al., 2016).

Table 3. Hamstring injury risk factors.

Intrinsic		Extrinsic
Non-modifiable	Modifiable	
Age	Hamstrings muscle group	Environment
	Isometric strength	Non-specific (weather or field condition)
Previous injury	Concentric strength	Specific (uncertainty of football actions)
Hamstring	Eccentric strength	
Calf	Between-limb asymmetries	Playing position
ACL	Hamstring-quadriceps ratios	Match and training running exposures
	Fatigability	
Ethnicity	Muscle architecture	Workload
		Match vs training
	Flexibility, range of motion	Pre-season vs in-season
	Hip, knee and ankle	Acute vs chronic sprint and HSR distances
	Lower-limb strength and power	
	Sprint related abilities	
	Sprint F-v profile	
	Repeated-sprint ability	
	Lumbo-pelvic motor control	
	Sprint technique	

Modifiable risk factors for hamstring injuries

Decreased hamstring strength or strength imbalances have been considered a risk factor for a long time ago (Burkett et al. 1970, cited in Opar et al., 2012), however evidence on prospective studies is mixed (Green et al., 2020; Timmins et al., 2016; Van Dyk et al., 2017). Even though some contradictions between studies is present, the weight of the evidence would suggest that hamstring strength testing, and eccentric hamstring strength, in particular, is an important consideration when screening injury risk in athletes (Green et al., 2020; Lee et al., 2018). Strength testing is further discussed in section "Testing physical performance, strength and power".

As cited previously, the most common hamstring injury mechanism is during sprinting, where high peak forces and much negative work (eccentric actions) are exhibited at the end of the swing phase above $7 m\cdot s^{-1}$ (Schache et al., 2012). Also, since eccentric activation and strength deficits remain present despite apparently successful rehabilitation and return to pre-injury levels of training and match play (Bourne et al., 2016), it seems reasonable to focus on improving eccentric strength, as an important part of the puzzle, when analysing the risk of future HSIs (Buckthorpe et al., 2019). While intense eccentric hamstring strength interventions have been effective at reducing the risk of primary HSIs (Arnason et al., 2007; Petersen et al., 2011), the positive effect on HSIs of higher eccentric strength in players with previous HSIs and older in age (Timmins et al., 2016) emphasises the importance of testing and working on this capacity.

Between-limb asymmetries are considered important to be detected, not only for decreasing the risk of future injuries but for performance improvements (Newton et al., 2006). Some of the rationales behind this reliy on that the weaker side (10-15% difference) seems to have a reduced ability to perform and an elevated risk of injury (C. Bishop et al., 2018). However, up to date, there is no convincing evidence showing that greater asymmetries or imbalances are associated with increased risk of future HSIs in football (Croisier et al., 2008; Dauty et al., 2018; Fousekis et al., 2011; Henderson et al., 2010; Timmins et al., 2016; Van Dyk et al., 2017).

Strength endurance and muscle fatigability are also regarded as important factors when analysing injury risk. Hamstring and calves' strains seem to be more frequent at the later moments of the halves in both professional (Ekstrand et al., 2011a, 2011b) and amateur football (Fitzharris et al., 2017; Sousa et al., 2013), with the latest showing greater injuries during the 2nd half (Fitzharris et al., 2017; Sousa et al., 2013), with the last 15 minutes of the match with the greatest amount of injuries (Fitzharris et al., 2017; Sousa et al., 2013). This could be related to the match demands since a decrease in the high-intensity running are experienced by the players by the end of the game. Some authors attribute neuromuscular fatigue to possibly play a role in HSI prevention, since a reduction in muscular strength in the hamstring muscle group was present during a game, (Greig & Siegler, 2009) after and 24h following a match (Wollin et al., 2017), but recovered at 48h (Wollin et al., 2017). Match-congestion periods were also related to greater hamstring injuries in professional footballers (Bengtsson et al., 2013; Dellal et al., 2015; Dupont et al., 2010). In addition, hamstring endurance capacity was related to future HSI (Schuermans et al., 2016) and identified previously injured legs (Lord et al., 2018, 2019).

Muscle architecture shows promising evidence placing players with longer fascicles (biceps femoris long head) at reduced risk of future hamstring injuries (Timmins et al., 2016). **Range of motion, flexibility or mobility** in the hip, knee and even the ankle complexes have been regarded to put the athletes at increased risk of hamstring injuries. However, the majority of tests measuring range of motion, flexibility or mobility do not show a relationship with future hamstring injuries (Pizzari et al., 2020). Considering football players may not require outstanding flexibility or mobility levels for performing properly, it is generally accepted that a minimum level may be required to perform effectively.

Improved **lower-limb strength and power** could be linked to a reduction of injuries. For instance, higher strength (3RM) during the trap-bar deadlift were a moderator for lower-body injuries in hurling players (Malone et al., 2019). Similarly, footballers with greater strength (4RM) during a squat, showed less muscle damage (CK levels) following matches, which could be linked to a decreased injury risk (Owen et al., 2015). **Sprint related abilities** (sprinting ability or repeated-sprint ability) could also be linked to hamstring injuries. Higher sprint performance (10 m) and higher repeated-sprint ability (RSA, less total time) have been moderators for lower-body injuries in hurling players (Malone et al., 2019). Moreover, specific changes in the force-velocity profiles during sprinting, such as reduced theoretical maximal force (F_0) production, has been also suggested to affect the risk of future hamstring injuries (Mendiguchia et al., 2014, 2016). Therefore, while no strong evidence is present at the moment, it could be hypothesised that footballers, with reduced strength, power, sprint and RSA performance could be placed at higher risk of injury.

Also, **running technique** (Schuermans, Van Tiggelen, et al., 2017) and **lumbopelvic strength or control** (Schuermans, Danneels, et al., 2017) have been regarded as possible risk factors for hamstring injuries, but showing weak and scarce evidence supporting its relationship at the moment. While running technique and lumbopelvic strength or control may lack evidence for hamstring injury prevention, they seem paramount for improving sprinting performance.

Risk factors are temporal (they vary over time) (Bittencourt et al., 2016), with **training and match loads** affecting the risk factors throughout the season, screening tests performed in just one time-point (i.e. pre-season testing) may not provide much information, since they are not able to predict injuries nowadays (Ruddy et al., 2019; Verhagen et al., 2018). Instead, if screening tests could be repeated along the season (Esmaeili et al., 2018), controlling for the mediators (training load) and moderators (physical abilities and performance) (Malone et al., 2019), that would suppose a better way to analyse the evolving and dynamic risk of injury. Also, it would help to assess the effectiveness of the proposed interventions, with the aim to better support the players. Hence, training and match loads are considered external risk factors, with **high-intensity running** (above ~20km·h^{-1}) or **sprinting** (above ~25 km·h^{-1}; or 80% maximum velocity) **loads** are gaining some attention lately as possible risk factors for HSIs (Duhig et al., 2016; Malone et al., 2019; Malone, Owen, et al., 2017; Malone, Roe, et al., 2017; Ruddy et al., 2016). Even though the training load is part of the environment (season period, team/coach playing style, training drills) and not the athlete, high-intensity running, and sprinting could be considered modifiable risk factors, since the training content can be modified, by exposing the players to greater or lower sprinting or high-intensity running demands. Those physical demands are also highly related to the playing position, on top of other factors (as discussed in section "Football physical performance"), then practitioners must be aware of those factors when dealing with training and match high-intensity running and sprinting loads.

Reduced performance after a hamstring injury

After an HSI, players experience a decrease in acceleration performance at the return to play (Mendiguchia et al., 2014) and higher drop in speed with repeated-sprint ability test (Røksund et al., 2017), but also a decrease in strength and muscle activation in the hamstring muscle group (Maniar et al., 2016). Those deficits in muscle activation and strength during eccentric actions remain present despite apparently successful rehabilitation and return to pre-injury levels of training and match play (Bourne et al., 2016). Recently, Higashihara and colleagues showed that previously injured athletes also show deficits in the BFlh activity during the late swing phase during sprinting (Higashihara et al., 2019). Interestingly, previously injured elite Australian footballers showed fewer improvements compared to non-injured (13.9 N vs 54.6 N, respectively) after an eccentric-biased intervention (minimum 1x week) in eccentric hamstring strength during the pre-season period (Opar et al., 2015a). Those results are supported with the long term deficits in voluntary activation during maximal eccentric ($d = -2.70$) but not concentric ($d = -0.61$) muscle actions were found in previously injured players (Buhmann et al., 2020) with important implications for hamstring re-injuries (Fyfe et al., 2013). Taken all the evidence together, both the short and long-term neuromuscular and performance impairments experienced by the athletes need to be detected by practitioners to implement some remediation strategies.

The off-season period

In Spanish semi-professional and amateur football, the average season lasts approximately 10-11 months (July-August to May-June) and the off-season period lasts about 4-8 weeks (May to August) depending on the division played. Most of professional footballers will consider the off-season break as a need to recover from the high physical and psychological demands of the competitive period (Silva et al., 2016). While this could be the same in semi-professional football players, amateurs may not, considering the lower demands during the competitive period. A complete cessation or near absence of training stimuli during the off-season leads to a partial or complete loss of some training-induced adaptations (Inigo Mujika & Padilla, 2000), which may not be the most appropriate action for football players (Silva et al., 2016).

There are evidence showing detraining effects (Table 4), as reduced sprinting (1-3%) (Caldwell & Peters, 2009; Koundourakis et al., 2014; Nakamura et al., 2012; Requena et al., 2017), change of direction (2%) (Caldwell & Peters, 2009) and jumping (5-7%) (Caldwell & Peters, 2009; Koundourakis et al., 2014; Requena et al., 2017) performances, reduced cardiorespiratory capacity (3-15%) (Caldwell & Peters, 2009; Koundourakis et al., 2014; Nakamura et al., 2012; Requena et al., 2017) and increased body fat percentage (4-19%) (Caldwell & Peters, 2009; Carling & Orhant, 2010; Koundourakis et al., 2014; Requena et al., 2017) after the off-season period in male amateur and professional football players. However, as suggested by Silva et al. (2016) some players may get involved in sports activities and voluntary non-periodized training and even some may follow a specific training program in order to minimise such negative adaptations. While some of the interventions could not maintain physical performance during the off-season (Koundourakis et al., 2014; Nakamura et al., 2012), promising evidence (including aerobic and strength and power-type sessions) showed no decrements in sprinting or jumping performances in elite football players (Requena et al., 2017). Moreover, the inclusion of strength or aerobic exercises during the off-season seems to have some merit in avoiding deconditioning. The inclusion of high-intensity interval (HIIT) sessions every two weeks maintained cardiorespiratory capacity in Norwegian footballers (2nd – 3rd tiers) (Slettaløkken & Rønnestad, 2014). However, players performed other activities (strength, football, running, other) which were not standardized and could confound the results of the study.

Considering the short pre-season period (4-6 weeks), with a high frequency of training sessions and rapid increases in training loads, players are already exposed to a high injury risk profile (Woods et al., 2002). The percentage of muscle strains in the lower limb muscle groups vary between pre-season and in-season. The quadriceps muscle group (≈ 30% vs ≈ 15%) and Achilles-tendon related (3.5 vs 1 injuries/week) injuries are a major problem during pre-season compared to in-season (Woods et al., 2002). Instead, hamstring injuries are less frequent during pre-season compared to in-season (≈ 25% vs ≈ 40%), and adductor injuries remained similar between periods (22-23%) (Woods et al., 2002).

Contemplating all the available evidence, none of the studies has analysed how hamstring strength is affected during this period, considering the importance of a well-developed hamstring musculature from a performance and injury risk reduction point of view (Bourne, Timmins, et al., 2017; Bourne et al., 2020a).

Table 4. Studies analysing off-season physical performance changes.

Study	**Population** **N; age ± SD**	**Study design**	**Outcomes**	**Results**
Caldwell et al., 2009	Semi-professional footballers (Tier 6, UK) 13 males 24 ± 4 years	Observational 5 times tested during a full season Testing at the end of season 1 (April) and beginning of season 2 (July)	CMJ (cm) 15 m sprint (s) Illinois agility test (s) VO_{2max}(mL·kg^{-1}·min^{-1}) Body fat (%) Flexibility (cm)	Detrimental off-season effects were present in all the performance variables (CMJ ES = -083; 15 m sprint ES = 0.84; agility ES = 0.64; VO_{2max} ES = -1.26) between the end of season and start of preseason.
Nakamura et al., 2012	Semi-professional (Tier 3, n = 13) and amateur (n = 16) footballers (Japan) 29 males 23 ± 2 years	Intervention Control (n = 5), Running group (n = 13), Plyometric group (n = 11) Off-season period: 3 weeks Training: 2 sessions of 45 min/week for 3 weeks	5-10-20 m sprint (s) YoYoIR2 performance (m)	All groups showed decrements in sprint and YoYoIR2 performances. The 3-week training interventions (running or plyometric) had no effect on sprint or aerobic performance.
Slettalokken et al., 2014	Semi-professional footballers (Tiers 2-3, Norway) 17 males 18 – 26 years	Intervention 6 weeks off-season, 1 session every 2nd week (HIIT 0.5, n = 8), or 1 session a week (HIIT 1, n = 9). Including other voluntary activities (strength, soccer, running. Other) Off-season testing from the end of season 1 to beginning of season 2	20 m shuttle run (m) VO_{2max} (mL·kg^{-1}·min^{-1})	This study suggests that adding 1 HIT session every second week to normal off-season activity is sufficient for maintaining VO_{2max}. However, it seems that this training frequency or even when it is doubled to 1 session per week is not enough for maintaining performance during shuttle run tests, which is regarded as a more soccer-specific than the V_ O2max test.
Koundourakis et al., 2014	Professional footballers (Tier 1, Greece) 55 males	Intervention Team A (n = 23), Team B (n = 22) Off-season testing from the end of season 1 (mid-May) to beginning of season 2 (July)	SJ and CMJ (cm) 10-20 m sprint (s) VO_{2max} (mL·kg^{-1}·min^{-1})	Medium to large detraining effects (d = 0.52 to 1.04) on all performance variables were observed for both teams. Low intensity running do not help maintain jumping or sprinting

	25 ± 5 years	6 weeks off-season: 2 weeks off and 4 weeks performing low intensity running (50-60% VO_{2max})		performance, neither aerobic capacity in professional footballers.
Requena et al., 2017	Professional footballers (Tier 1, Spain) 19 males 26 ± 3 years	Intervention 3 times tested during a full season Off-season testing from the end of season 1 to beginning of season 2 6-7 weeks off-season: 2-3 weeks off and 4 weeks performing strength, power and running sessions	CMJ (cm) 15-30 m sprint (s) Maximal aerobic speed ($V_{Vam\text{-}Eval}$)	No detrimental effects ($d < 0.2$, $p > 0.05$) were observed for CMJ or 15-30 m sprint performance during the off-season. Instead, $V_{Vam\text{-}Eval}$ was reduced ($d = -0.66$) after the off-season period. The off-season training intervention was enough to maintain sprint and jumping capacity in elite footballers.
Jiménez-Reyes et al., 2020	Professional footballers (Tier 1, Spain) 21 males 27 ± 3 years	Observational 6 times tested during a full season Off-season testing from the end of season 1 (May) to mid-pre-season 2 (August)	30 m sprint (F-v profile) 10 m sprint (s)	10 m sprint performance, F0, Pmax and Rfpeak were higher during the in-season than at the end or beginning of the season. Maximal running velocity was similar in all periods of the season.

*Effect sizes were calculated using the Cohen's d. CMJ: counter-movement jump; F-v: force-velocity; F_0, maximum theoretical force; HIIT: high-intensity interval training; Pmax: maximal mechanical power output; Rfpeak: peak ratio of force; SJ: squat jump; VO_{2max}: maximum aerobic capacity

TESTING PHYSICAL PERFORMANCE

> You can have data without information, but you cannot have information without data
>
> **Daniel Keys Moran**

Testing can help athletes know where they stand, see their evolution along the time, help in program designing, compare results following injury, increasing performance and athlete longevity (Newton et al., 2008). Moreover, in practice, testing can provide live feedback for the athlete which in turn can increase motivation during training and greater performance adaptations (Randell et al., 2011; Weakley et al., 2019).

Measurement considerations – Is that result useful?

Considering the sport needs analysis is already accomplished, several points need to be taken into account when deciding the tests to be implemented such as validity, reliability, sensitivity, specificity and feasibility of the test (Atkinson & Nevill, 1998; Hopkins, 2000).

Validity refers to the ability of the test to measure what it is purported to measure in a reliable way (Atkinson & Nevill, 1998). Reliability refers to the ability to reproduce (repeat) the test measures in recurrent trials on the same individuals, providing minimal measurement error (Atkinson & Nevill, 1998). Better reliability means better precision of single measurements and better tracking of changes in research or real-world settings. When measuring athletes, the true value is hidden by the error of the measurement, which researchers and practitioners want to minimise. Examples of reliability measures are the intraclass correlation coefficient (ICC), coefficient of variation (CV%), standard error of measurement (SEM) or typical error of measurement (TEM) and 95% limits of agreement (LoA) (Hopkins, 2000). Sensitivity refers to the ability to detect an important or worthwhile change between testing sessions, which is very related to reliability. Familiarisation and standardisation procedures will help reduce the error of the measurements and hence increase the reliability of the measures. Specificity refers to the ability of the test to assess key performance components (related to the sport) accurately (Newton et al., 2008). It will be related to the sport analysed and the aim of the test. Finally, the feasibility of the test is related to its practicality and limitations. Some of the questions related to feasibility could be: is the test easy, or not, to undertake, administer and score? How long does it take to test the players? Is the data easy to interpret? Every practitioner should be able to answer those questions before starting to collect data and the context of each practitioner may allow very different answers. Practitioners should perform reliability measures for the testing within their group of interest. In the following paragraphs, some of those aspects will be evaluated for different types of tests.

Physical performance

Testing will be part of the screening and monitoring process. While GPS, accelerometers, and heart rate monitors will probably be used for the monitoring of specific training and match demands, the use of radar guns, timing gates, photoelectric cells, force platforms, isokinetic devices, load cells, video cameras, among others is going to be used for screening and testing physical qualities more analytically. Some of those tests will focus on biomechanical outcomes assessing the strength, power and performance (sprint, COD and jump); or focus on physiological outcomes ($VO_{2\,Max}$, heart rate or lactate concentration) assessing aerobic (continuous or intermittent tests (30:15 IFT, Yo-Yo IRT)) and anaerobic capacity (RSA tests), the latter not being within the scope of this thesis.

Sprint, change of direction and jump testing

Sprint performance is normally assessed using timing gates or radar guns. While the gold standard is the fully automated system; timing gates, radar guns, and also GPS units seem to be valid and reliable if used properly (Haugen & Buchheit, 2016). Considering the short sprint distances involved in football, 20-30 m have been regarded as an adequate distance to be tested, ideally with split times. Lately, the force-velocity-power continuum/spectrum has been developed for sprinting and jumping

(Jiménez-Reyes et al., 2018), which are increasing in popularity since it can be validly and reliably analysed by practitioners using video analysis.

COD performance is normally assessed using timing gates, to measure the total time involved in a COD test. It should be noted that a wide variety of COD tests exist, with no gold standard for assessing this ability. The COD tests selected should be linked to the demands of the sport analysed. Considering football COD actions involve turns from 0 to 180º (Bloomfield et al., 2007), tests analysing such COD are considered valid. However, no gold standard test for analysing COD exists (Nimphius et al., 2016). When analysing COD, normally tests analyse the time to perform a COD task, using timing gates. However, if practitioners would like to analyse COD performance, the distance involved in the whole COD test could interfere with the interpretation of the results and should be taken into account. Therefore, force plates integrated with 3D cameras can also be used for understanding the COD kinetics and kinematics in order to analyse specific COD ability, exclusive for lab settings.

When assessing jump performance, multiple tests are available in the literature, with the options of jumping bilaterally or unilaterally, and in the three different planes of motion (vertically, horizontally, laterally). Moreover, a variety of options exist in every plane, such as squat jump, countermovement jump, depth jump, multiple vertical jumps for the vertical jumping performance; broad jump, triple jump for distance, for horizontal jumping performance; and lateral hops or jumps for lateral jumping performance. The use of unilateral jump tests seems interesting since it provides an idea of dominant and non-dominant limbs when performing the test, which could help inform future training strategies for performance and injury risk reduction. Normally, vertical jump tests which are the most broadly used, are assessed using contact mats, while the gold standard technology for assessing jump performance is the force plate. However, the use of force plates is normally exclusive for research labs or high-performance settings. With the need for reducing the gap between research and practice, new technology is being developed in order to provide reliable and valid data to follow the process. Recently, a video-based analysis using a mobile phone app has been validated for measuring sprint (Romero-Franco et al., 2017), jump (Balsalobre-Fernández et al., 2015) and COD (Balsalobre-Fernández et al., 2019) times, which helps to close the gap between laboratory and field-testing setups.

Looking at the wider and complex picture of football performance, after discussing the importance of physical performance, in a football team sometimes the most physically developed footballer may not be the most proficient, considering technical, tactical, psychological aspects will directly affect footballers' performance. Just because the physical aspects may be the easiest to objectivate, does not mean they are the most important and the only ones to consider.

Thigh muscle strength testing

Strength and power can be assessed via dynamic or isometric measurements. One of the difficulties when analysing the literature relies on that strength can be measured in very different ways. Three phases of the muscle action (concentric, isometric, eccentric) can be assessed, which can be presented as strength or torque (absolute or relative). Different exercises, monoarticular (knee or hip dominant) or biarticular, can be also analysed. Then, different devices are available, such as isokinetic dynamometers, handheld dynamometers, force plates, load cells and linear or rotational encoders. Even though isokinetic dynamometers are the gold standard for measuring strength, in the context of football, the use of field-based (hand-held dynamometry, force plates, load cells) devices seems more suitable, also contemplating the high cost and the lab-based setting of isokinetic dynamometers.

Examples of **isometric assessments** for the lower limb could be the isometric mid-thigh pull or the isometric squat, both being measured with a force plate, or a strain gauge. One of the advantages of isometric testing is that allows for the analysis of force-time characteristics such as

RFD and impulse, which can provide a more comprehensive description of an athlete's power production ability. Other devices that allow us to perform isometric assessments are hand-held dynamometers and isokinetic dynamometers. Normally though, single-joint exercises are tested when testing using those devices which may be a limitation for performance testing and are more used in physiotherapy and rehabilitation settings. Specific tests for the hamstring muscle group could be performed using a force plate (Matinlauri et al., 2017; McCall et al., 2015), strain gauges (Hickey et al., 2017; Wollin et al., 2016), hand-held dynamometer (Kelln et al., 2008; Reurink et al., 2016) (depending on the exercise selected) or even an isokinetic dynamometer (Croisier et al., 2008; Fousekis et al., 2011; Green et al., 2018; Van Dyk et al., 2017) as shown in Table 5. Normally, force plates or strain gauges or fixated dynamometers may provide less error than hand-held dynamometry considering the practitioner/evaluator technique will affect measurement error during hand-held dynamometry assessments.

Examples of **dynamic assessments** could be 1RM or multiple repetitions (3-10RMs) testing using free weights (squat, deadlift, bench press or bench pull). While most of the sporting actions contain dynamic movements, the specificity of such tests could be considered high. However, testing maximal strength (1RM) may exhibit some drawbacks for young or inexperienced athletes, placing maximal repetitions testing with lighter weights (3-10RMs) as a more feasible choice. Weight-stack machines could also be a choice to measure dynamic strength, however, single-joint exercises provide less specificity to sports performance, which may be used for rehabilitation rather than performance. Some of the strengths when testing 1RM or RMs are that no specific technology, but only the free weights are needed to test strength in this manner.

Isokinetic dynamometry can also assess concentric-eccentric muscle actions and is normally used to measure asymmetries and lower limb rations on the knee joint. As introduced earlier, isokinetic dynamometry even though is considered the gold standard at measuring strength, its poor predictive validity at detecting future HSI (Green et al., 2018), its minimal relationship on sprint performance measures (Cronin & Hansen, 2005; Morin et al., 2015), on top of its unfeasibility (high costs and lab-based) renders its use in everyday practice. Recently, a field-based and time-efficient device have been developed to measure eccentric hamstring strength during the Nordic hamstring exercise (NHE) (Opar et al., 2013), which is increasing in popularity in the field and has already been used in numerous studies in football (Markovic et al., 2020; Suarez-Arrones et al., 2019; Timmins et al., 2016). During the NHE, the force exerted against the load cells seems to be related to the athlete body mass and size, and not only to the ability to generate eccentric hamstring strength (Buchheit et al., 2016; Markovic et al., 2020; Roe et al., 2018). There are several ways of overcoming such limitation, as normalizing strength to body mass (N/kg) (Roe et al., 2018), torque (N·m/kg) (Markovic et al., 2020) or allometric scaling (Buchheit et al., 2016). Also, another option to overcome such limitation could be to perform maximal trials by adding external load (holding the weight plate 5-25kg on the chest) to test maximal strength(Presland et al., 2018). However, it is possible that testing only the knee flexor strength may not be specific enough to high-intensity running and that more specific strength tests would better reflect injury risk. Other hamstring testing alternatives have been developed, which can be seen in Table 5.

Finally, considering most sports involve dynamic and explosive movements (jumping, sprinting, striking or kicking), the measurement of force, velocity and power during more specific movements is widely used for athlete testing in performance settings. Squatting or jumping exercises are normally tested using force plates, linear or rotational position transducers, and accelerometers in order to obtain the power output. Some testing examples could be the bilateral or unilateral squat using smith machines, the jump squat (with loads), counter-movement jump (with loads), or different types of jumps without loads. If using a force plate or a strain gauge, the rate of force development can also be obtained from dynamic movements which is more related to athletic performance as discussed earlier.

Table 5. Hamstring testing setups

Study	**Muscle action**	**Modality**	**Device**	**Exercise**
McCall et al., 2015	Isometric knee flexion + hip extension	Unilateral	Force plate	90° hip flexion – 90° knee flexion – supine 30° knee flexion – supine
Matinlauri et al., 2017	Isometric knee flexion + hip extension	Unilateral	Force plate	90° hip flexion – 20° knee flexion Standing, hands on wall and hands on chest
Wollin, Purdam & Drew, 2016	Isometric knee flexion	Unilateral	Load cell	45° hip flexion – 30° knee flexion – prone
Hickey et al., 2017	Isometric knee flexion	Unilateral	Load cell	0° hip flexion – 0° knee flexion lying supine 45° hip flexion – 45° knee flexion lying supine 90° hip flexion – 90° knee flexion lying supine
Hickey et al., 2017	Eccentric knee flexion	Unilateral / bilateral	Load cell	Eccentric slider – supine
Hickey et al., 2017	Dynamic hip extension	Unilateral / bilateral	Load cell	Hamstring bridge – supine
Green, Bourne & Pizzari, 2018; Van Dyk et al., 2017; Fousekis et al., 2011; Croisier et al., 2008	Eccentric and concentric knee flexion	Unilateral	Isokinetic dynamometry	85-90° hip flexion – sitting Eccentric 30 to 120°/s Concentric 60 to 300°/s
Timmins et al., 2016; Van Dyk et al., 2017	Eccentric and isometric knee flexion	Unilateral / bilateral	Load cells	Hip neutral (0°) – prone
Kelln et al., 2008; Reurink et al., 2016	Isometric knee flexion or hip extension	Unilateral	Handheld dynamometry	Hip neutral (0°) – Knee flexion 15° - prone Hip neutral (0°) – Knee flexion 90° - prone
Tous-Fajardo et al., 2006	Dynamic knee flexion	Bilateral	Load cell and linear encoder	Inertial flywheel leg curl, hip flexion 40° - prone
Suárez-Arrones et al., 2020	Dynamic knee flexion and hip extension	Unilateral	Rotary encoder	Inertial flywheel leg curl, hip flexion 40° - prone Inertial flywheel hip extension, supine

With the use of inertial flywheel devices, strain gauges and linear or rotational encoders can be used to measure the force, velocity or power output of an exercise. The cylinder-shaped device will provide the same force as the cylinder is constant, instead, with the cone-shaped device the force can vary by modifying the distance of the wrapping position, providing different speed/force ratios (Moras & Vázquez-Guerrero, 2015). While most of the research has studied the squat exercise, some authors have investigated more specific exercises such as the forward lunge (Sabido et al., 2017), lateral squat (Raya-González et al., 2020) using cylinder-based devices, showing good reliability scores. One advantage of using cone-shaped devices is the possibility of assessing more specific multidirectional movements (COD and deceleration abilities) (Madruga-Parera et al., 2019), crucial for team sports and football players, with an accentuated eccentric action. Hence, the possibility to test using such devices is appealing due to its specificity, however, the reliability of such measures needs to be studied yet. When looking at the hamstring muscle group assessments using inertial flywheel devices, some research is available looking at the leg curl exercise using a cylinder-based device (Suarez-Arrones et al., 2020; Tous-Fajardo et al., 2006), or the hamstring back kick using the cone-shaped device (Suarez-Arrones et al., 2020).

THE POWER OF STRENGTH

> Not everything that can be counted
> counts, and not everything that
> counts can be counted
>
> **William Bruce Cameron**

In biomechanics, muscular strength has been defined as the ability to generate force to overcome inertia or load (Siff, 2008). Force, using Newton's second law of motion (Force = Mass * Acceleration), can be described as the change in motion of an object that is directly proportional to the forces produced upon it. Hence, the greater the forces, the greater the acceleration and velocity. From a performance standpoint, the power output, which is a surrogate of force and velocity (Power = Force * Velocity) is also used as a measure of performance in different sports (Cormie et al., 2011; Stone et al., 2003).

Many of factors affect football players' physical performance, with muscular strength being one of those (Suchomel et al., 2016), which can be improved through regular resistance training exposure (see section "Resistance training interventions"). When examining injury prevention strategies, muscular strength is also considered valuable (Lauersen et al., 2014, 2018). As introduced by Tous (2017) and Moras (2017), while force and power outputs could be closely related to physical performance, mainly in individual sports; in team sports, the need to continuously perform multidirectional and varying powerful actions, within the context of the game (perception-action, intentions), makes it more difficult to justify such relationships. From that standpoint, the inclusion of variable (movement types, movement planes, unilateral or bilateral, including or not perturbations) and powerful specific actions during training, may better prepare the players to cope with the competition demands while also decreasing the risk of injury.

Strength related to performance

Most actions in football involve exerting high forces against gravity, in order to manipulate the players' body mass (sprinting, COD, jumping) or in combination with the opponents' body mass (duels, blocking) (Suchomel et al., 2016). While some researchers and practitioners may think "the greater the strength and hypertrophy, the better", this not necessarily applies, considering some "weak" players can express great performances (Siff, 2008). Then, "the right amount of force at the right time" seems imperative for performance (Siff, 2008). Hence, the rate of force development (RFD) and consequently the mechanical power, should be considered two of the most important characteristics with concerning football performance (Suchomel et al., 2016). Some researchers and practitioners have proposed that the ability to repeat powerful actions, also known as repeated-power ability (Gonzalo-Skok et al., 2016) could be one of the most important aspects of a footballers' performance. Such powerful actions will include both general motor skills such as high-intensity running, sprinting and high-intensity accelerations, decelerations and COD or jumping; and specific motor skills such as passing, dribbling, kicking or duelling.

As introduced earlier, **sprinting** is one of the most important aspects of football performance, even though in professional football matches players may not reach maximum velocities regularly (Buchheit et al., 2020), sprint acceleration performance over short distances is common (Sonderegger et al., 2016). The mechanical determinants of greater sprinting ability are different between the acceleration and top velocity phases. The vertical force production is important for greater top velocities (Weyand et al., 2000), instead, horizontal force production generated from hip extensor and knee flexor muscles being important for the acceleration phase (Higashihara et al., 2010; Morin et al., 2015). Also, the early rate of torque development (0-100ms) in the hamstring muscle group (Ishøi, Aagaard, et al., 2018) and the players' technical ability to apply the force in the forward direction (Morin et al., 2015) are important aspects when looking for sprinting acceleration performance. Stronger footballers (back squat 1RM and 5RM) demonstrated greater sprint performances (5 m to 30 m) than their weaker counterparts (Comfort et al., 2014; Wisløff et al., 2004). Interestingly, there seems to be a relationship between increments in lower-body strength and sprinting performance in athletes (Seitz et al., 2014). When looking at associations between maximal isometric muscle actions and performance, it is more difficult to find relationships, probably due to the lack of specificity of the testing procedures (monoarticular and open-chain exercises) (Requena et al., 2009). Importantly, the power output during the squat exercise was more related to sprinting performance than maximal strength in semi-professional footballers (Requena et al., 2009). Similarly, in a group of elite athletes, the greater sprinting performance was more related to lower limb maximal power outputs during the half squat and jump squat rather than maximal strength (Loturco, Suchomel, et al., 2019). Moreover, the ability to repeat sprinting actions without complete recovery, also known as repeated-sprint ability (RSA), can also be considered an important physical capacity in football. RSA performance is more related to physiological rather than biomechanical characteristics, which is not the aim of this thesis. Hence, readers are referred to the work of Girard and colleagues for more information on RSA (D. Bishop et al., 2011; Girard et al., 2011). However, most of the sprints in football are not very long (<30 m), and most of the powerful actions include multi-directional accelerations and decelerations and COD, probably the football performance could be better described as repeated power ability as introduced earlier.

COD performance is described as the ability to decelerate, reverse or change movement direction and accelerate again (Jones et al., 2009). COD performance could be included in the concept of "agility"(Nimphius et al., 2018; Sheppard & Young, 2006; Young et al., 2015), which require perception and action, with different neuromuscular strategies used in non-planned, reactive movements compared to a more "closed" planned movements (Brughelli et al., 2008; Spiteri, Newton, & Nimphius, 2015). The dynamic nature of football will require the players to percept and act upon multiple stimuli, where pre-planned actions are not found. However, as sprint and jumping performance, the mechanical determinants of greater COD performance need to be understood, with most of the tests in the literature investigated pre-planned COD movements. COD performance is influenced by both deceleration and acceleration abilities, which are linked to other physical qualities such as muscle strength and power (Brughelli et al., 2008; Paul et al., 2016). The available research highlights the importance of eccentric strength (braking phase), isometric strength (plant phase) and concentric strength (propulsive phase) to permit rapid deceleration and subsequent reacceleration (Chaouachi et al., 2012; Dos'Santos et al., 2017; Spiteri, Newton, Binetti, et al., 2015). Not only physical attributes condition COD performance but also technical attributes (body lean posture, foot placement and stride adjustment) that will be modified depending on the approaching velocity and COD angle (Buchheit et al., 2012; Dos'Santos et al., 2018). The greater relative horizontal and vertical braking and propulsive forces have been identified as determinants of superior COD performance (Dos'Santos et al., 2017) during the ultimate foot contact (plant phase) and the penultimate foot contact has (braking phase). Research has normally focused on the final foot contact (plant phase) as a determinant of COD performance, only recently looking at the importance of penultimate foot contact (braking phase) on COD performance (Dos'Santos et al., 2017).

Jumping is not one of the most important aspects of a footballer physical performance. However, footballers need to jump for headers during the match, with certain constraints and specific technique (adapted to the ball trajectory, intention, and opponent). Jumping performance, which could be interpreted as lower-body power, is strongly related to the net impulse created by the athlete (measured using force plates). The shape and magnitude of the impulse will be determined by the force-time characteristics of each individual and will be affected by strength and power (Cormie et al., 2009). Greater jumping abilities from stronger athletes may be related to better technique and better stretch-shortening cycle mechanics (Cormie et al., 2009). Normally, jumping is tested using bilateral or unilateral jumps, predominantly vertically. It must be highlighted though that jumping actions in football are generally preceded by a run-up, which may need greater unilateral strength and lower limb coordination (Requena et al., 2014). Specific tests have been developed and provided weak to moderate relationships with traditional standing jumps (squat jump, counter-movement jump, drop jump), which could provide important insights into more specific football jumping performance (Requena et al., 2014).

Strength related to future hamstring injuries

As introduced earlier, decreased neuromuscular qualities could be related to hamstring injuries. Players with increased athletic abilities such as muscular strength, anaerobic power, aerobic capacity, speed or repeated-sprint ability seem to place them at a reduced risk of injuries (Lehance et al., 2009; Malone et al., 2019; Malone, Roe, et al., 2017). Considering this, a number of studies have analysed the role of injury prevention programs (including strength, stretching, proprioception exercises or multicomponent programs) on reducing the sports' injury risk (Lauersen et al., 2014). Strength training reduced sports injuries to less than

1/3 and overuse injuries by half, with stretching showing no beneficial effect (Lauersen et al., 2014). While injury prevention strategies should embrace a holistic approach (with a thorough analysis of injury risk factors), with a myriad of interventions (strength, stretching, load management, recovery and sleep or psychological stress management), it seems that the strength component is a must (Lauersen et al., 2014, 2018). One of the multi-modal prevention programs used in football is the FIFA 11+ (Bizzini & Dvorak, 2015), which is shown to prevent injuries if compliance is high (Goode et al., 2015; Silvers-Granelli et al., 2018). One of the exercises included in the FIFA 11+ protocol is the Nordic hamstring exercise (Mjolsnes et al., 2004; Petersen et al., 2011), which is the one with the highest evidence for hamstring injury prevention (Al Attar et al., 2017), reducing by half the rate of hamstring injuries (Van Dyk et al., 2019). After such interventions, the increases in eccentric hamstring strength, on top of other structural adaptations (fascicle length and pennation angle), may be related to the reduction in first time or recurrent HSIs (Bourne, Timmins, et al., 2017). The reasoning for including eccentrically-biased exercises lies in the findings that the muscle damage occurs due to high mechanical strains when acting eccentrically (Lieber & Friden, 1993), and the hamstring muscle group produces high peak forces and much negative work at the end of the swing phase at high sprinting velocities (above $7\text{m}\cdot\text{s}^{-1}$) (Schache et al., 2012), on top of the negative adaptations (eccentrically-biased) discussed in section "Reduced performance after a hamstring injury".

Resistance training interventions

Resistance training, also known as strength or weight training, is becoming more popular and widely used nowadays by a large number of people with a diversity of aims and goals (Lloyd et al., 2014; Ratamess et al., 2009). In sport, resistance training interventions should pursue a twofold objective, to increase strength, power and athletic performance (Suchomel et al., 2016) and also to reduce the risk of injuries (Bourne, Timmins, et al., 2017; Lauersen et al., 2014, 2018).

Several resistance training methods, including a variety of gravity-dependent exercises (traditional, ballistic, plyometrics, Olympic-lifting or weight-lifting exercises), have been proved effective at improving physical performance in professional football players (Brito et al., 2014; Faude et al., 2013; Loturco et al., 2013, 2017; Silva et al., 2015). In the last decade, a considerable amount of research has focused on the use of inertial flywheel resistance training, which offers an alternative method for improving strength, power and athletic performance (de Hoyo et al., 2014; Núñez et al., 2018; Suarez-Arrones et al., 2018; Tous-Fajardo et al., 2016). Considering the specificity of the exercises (in regard to force and power production), the frontal plane of movement (squatting, jumping) is normally over-emphasised when using gravity-dependent exercises. However, due to sport-specificity, exercises trying to develop force and power through the sagittal (sprinting) or transversal (shuffling, changing direction) planes are gaining attention nowadays. For instance, some inertial flywheel devices allow practitioners to prescribe exercises with more specific force application (horizontal orientation) and a higher degree of correspondence (more sport-specific) to multi-directional movements.

When designing a training program, the principles of progression, specificity and variability should be present in order to adapt to the player training response, and probably the use of one single exercise or training method is not the way to go. Then, the following considerations should be present when planning and programming the interventions (optimisation or coadjuvant sessions) in order to improve players performance (sprinting, jumping and COD) and reduce injury risk: movement patterns (general or sport-specific actions), methods of training, loads and velocities, the temporal organization in the microcycle or session. The benefits of strength and power training are unquestionable, but studies comparing flywheel inertial with gravity-dependent resistance training methods are limited. While studies looking at the effects of single exercise interventions on strength, performance and injury prevention are needed, in order to draw direct relationships between dose-response, it may lack ecological validity for strength and conditioning practitioners. In the following sub-sections, we will discuss the use of gravity-dependent and inertial flywheel resistance training options available.

Inertial flywheel interventions

Inertial flywheel (FW) devices were firstly introduced by Berg and Tesch in the early 90s (Berg & Tesch, 1994), with the intention to prepare space travellers exposed to non-gravity environments (Berg & Tesch, 1998; Tesch et al., 2017), due to its particular inertial loading mechanism. In 2003, Askling and colleagues used for the first time the leg-curl device in professional football players(Askling et al., 2003). Since then (see Figure 3), FW resistance training has been used in detrained populations (Rodrigo Fernandez-Gonzalo et al., 2014), disabled populations (Rodrigo Fernandez-Gonzalo, Fernandez-Gonzalo, et al., 2016), healthy adults (Caruso et al., 2005; de Hoyo, Sañudo, et al., 2015; Norrbrand et al., 2008, 2010), with a special interest for the sports science community in the last 5 years in amateur, semi-professional and professional athletes (Caruso et al., 2008; de Hoyo et al., 2014; de Hoyo, Pozzo, et al., 2015; Gonzalo-Skok, Tous-Fajardo, Valero-Campo, et al., 2017; Tous-Fajardo et al., 2016), being effective in injury prevention (Askling et al., 2003; de Hoyo, Pozzo, et al., 2015) and rehabilitation (Romero-Rodriguez et al., 2011).

FW devices allow for maximal dynamic muscle actions, involving the stretch-shortening cycle, which is of particular interest for performance enhancement. The loading paradigm during FW exercises is that the force generated during the concentric action needs to be reversed during the last third of the eccentric action (Berg & Tesch, 1994). Hence, FW devices allow short periods of greater eccentric than concentric forces, provided maximal effort and the appropriate technique are employed (Norrbrand et al., 2008; Tous-Fajardo et al., 2006). Instead of the kilograms used in gravity-dependent exercises to control for intensity, the inertia used during the FW resistance exercise will alter the force, power and work relationship, affecting also the use of the stretch-shortening cycle during the coupled concentric-eccentric actions (Martinez-Aranda & Fernandez-Gonzalo, 2017). Finally, compared to isotonic loading (e.g. gravity-dependent), inertial loading provides accommodated resistance, which permits the players to provide maximal forces from the very first repetition with force and consequently power declining throughout the set (Norrbrand, 2010).

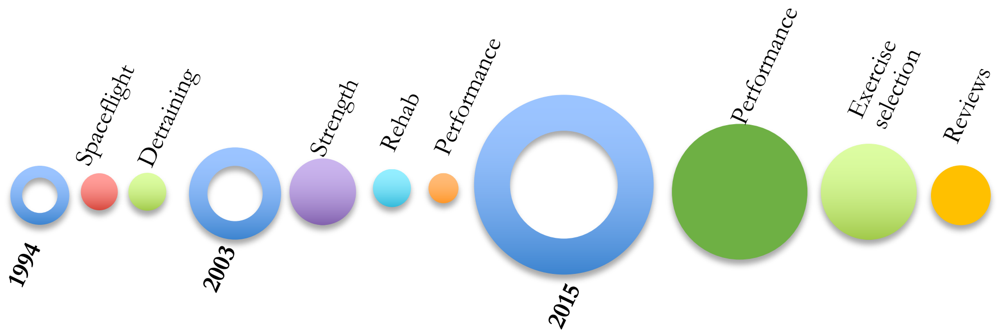


Figure 3. Research topics using inertial flywheel devices – timeline (author's elaboration).

Table 6. Intervention studies in soccer players using inertial flywheel resistance methods.

Study	Population N; age ± SD	Group 1: Exercises (equipment)	Group 2: Exercises (equipment)	Outcomes	Results
Askling et al., 2003	Professional footballers RCT Intervention = 15 males 24 ± 2.6 years Control = 15 males 26 ± 3.6 years	Intervention Pre-season, 16 sessions (10 weeks) 4x8reps leg curl exercise (Yoyo Technology Inc, Sweden)	Control Normal football training	Peak torque CON and ECC (Nm) 30 m sprint times (s)	Between-group analyses showed greater peak torque CON and ECC, and greater 30 m sprint performance in intervention group
De Hoyo et al., 2015	Professional academy footballers Non-RCT Intervention = 18 males 18 ± 1 years Control = 15 males 17 ± 1 years	Intervention In-season, 18 sessions in total (10 weeks) 3-6 x 6reps (0.11 kg·m²) Squat and leg curl exercises (Yoyo Technology Inc, Sweden)	Control Normal football training	CMJ (cm) 10 m flying sprint (s) 20 m sprint (s) Injury data	Between-group analyses showed greater effects in CMJ and 10 m flying sprint in favour of the intervention group.
De Hoyo et al., 2016	Professional academy footballers Non-RCT Intervention = 17 males Control = 17 males 17.0 ± 1.0 years	Intervention In-season, 18 sessions in total (10 weeks) 3-6 x 6reps @peak power output Squat and leg curl exercises (Yoyo Technology Inc, Sweden)	Control Normal football training	Side-step cutting kinetics Cross-over cutting kinetics	Greater improvements for the intervention group in contact time and breaking time during side-step cutting. Greater improvements in relative peak braking force and relative breaking impulse during crossover cutting.

Tous-Fajardo et al., 2016	Academy footballers Non-RCT Intervention 1 = 12 males Intervention 2 = 12 males 17 ± 0.5 years	Eccentric-vibration group In-season, 11 sessions (11 weeks) 2 x 6-10reps 8 exercises (lateral squats, backward lunges, hamstring kicks, reverse wood chops, unilateral squat in vibration platform, Nordic-hamstring, side-bridge, partner resisted adductions and abductions) Cylinder-shape (Yoyo Technology Inc, Sweden; Inertia 0.11 kg·m²) Cone-shaped (Versa-Pulley, Costa Mesa, CA; Inertia 0.27 kg·m²)	Free weight group In-season, 11 sessions (11 weeks) 2 x 6-10reps 9 exercises (lunges, 10 m skipping, 10 m sprint, half-squats, CMJ, 10 m sprint, calf raises, calf reactive jumps and jumps heading ball)	10 m sprint (s) 30 m sprint (s) RSA (s) COD - V-cut test (s) CMJ (cm) 5-repeated jumps (cm, W·kg^{-1})	Within-group analyses showed improvements in COD (ES = 1.22) and average power during 5-repeated jumps (ES = 0.44) for the eccentric-vibration group. Large decrements in 10 m and 30 m performance (ES = -0.87 – -1.22) were observed for the free weight group, and no changes for the eccentric-vibration group. Between-group analyses showed greater results in 10 m and 30 m sprint performance, V-cut test performance and 5-repeated jump performance in favour of the eccentric-vibration group.
Gonzalo-Skok et al., 2017	Semi-professional and amateur team-sport players RCT Intervention 1 = 24 males Intervention 2 = 24 males 20.5 ± 2.0 years	Pre- and in-season, 16 sessions (8 weeks) Cone-shaped (Versa-Pulley, Costa Mesa, CA; Inertia 0.27 kg·m²) Bilateral-vertical group 6 x 6-10reps 1 exercise, squat	Unilateral-multidirectional group 1 x 6-10reps 6 exercises: backward lunges, defensive-like shuffling steps, side-step, crossover cutting, lateral crossover cutting and lateral squat	25 m sprint (s) COD tests (s) V-cut test (s) CMJ (cm) Unilateral vertical, horizontal and lateral jumps (cm)	Whithin-group analyses showed improvements in all the outcomes in both groups. Between-group comparisons showed better results in lateral jumps (ES=0.21), left leg horizontal jump (ES = 0.35) and 10-m COD with right leg (ES = 0.42) in VUMD than in CBV.
Otero-Esquina et al., 2017	Professional academy footballers Non-RCT Intervention 1 = 12 males Intervention 2 = 12 males Control = 12 males	Intervention 1 In-season, 1 session/week 2-3 x 4-6reps Leg curl (Yoyo Technology Inc, Sweden, 0.11 kg·m²) 2-3 x 4-6reps Full-back squat (olympic bar) @40-55% 1RM 1 x 3-6reps plyometric exercise 3-5 x 20 m resisted sprint @20% BM	Intervention 2 In-season, 2 sessions/week	CMJ (cm, W) 10-20 m sprint (s) COD test (s)	Improvements in CMJ (ES = 0.39 - 0.81) in both intervention groups. Improvements in COD (ES = 0.70-0.81) in intervention and control groups. Sprint improvements (ES = 0.43-0.52) only in intervention 2. Between-group: Likely greater performance in sprint for intervention 2.

	17.0 ± 1.0 years				
Núñez et al., 2018	Team-sport players Non-RCT Intervention 1 = 14 males 22.8 ± 2.6 years Intervention 2 = 13 males 22.6 ± 2.7 years	Unilateral group 12 sessions (6 weeks) 4x7reps (0.05 kg·m^2) lunge (Exxentrix kBox, Sweden)	Bilateral group 12 sessions (6 weeks) 4x7reps (0.10 kg·m^2) squat (Exxentrix kBox, Sweden)	CMJ (s) 10 m sprint (s) COD 90º (s) COD 180º (s) Mean power (W/kg)	Within-groups analyses showed improvements in COD 90º performance (s) and mean power (w/kg) in unilateral and bilateral groups. No difference between-groups.
Suárez-Arrones et al., 2018	Professional footballers Intervention = 14 males 17.5 ± 0.8 years No control	Intervention Pre- and in season, 27 weeks Familiarization (3 weeks) Progression phase 1 (5 weeks) Progression phase 2 (19 weeks) 2 sessions/week Combination of inertial and gravity-dependent exercises		40 m sprint (s) Mean propulsive power at 30kg and 40kg (W)	Within-group analyses showed greater mean propulsive power (30 and 40kg), and decreased sprint times at post-test
Coratella et al., 2019	Semi-professional (4th tier) footballers RCT Intervention 1 = 20 males Intervention 2 = 20 males 23 ± 4 years	Inertial flywheel In-season, 8 sessions (8 weeks) 4-6 x 8 reps (Inertias 0.025 to 0.1 kg·m^2) Squat exercise, inertial flywheel (YoYo squat, nHance, Stockholm, Sweden)	Gravity-dependent In-season, 8 sessions (8 weeks Week 1: 3 x 8 reps (70% 1RM) Weeks 2-6: 4 x 4 reps (>85% 1RM) Squat exercise, Olympic bar (Technogym, Cenesa, Italy)	COD (s) 10 m and 30 m sprint (s) SJ and CMJ (cm) Squat 1RM (kg·BM^{-1}) Hamstrings and quadriceps peak torque (N·m) H_{ecc}:Q_{conc} ratio (a.u.)	Whithin-group analyses showed improvements in SJ, CMJ, 1RM, quadriceps and hamstrings peak torque for both groups. Only improvemets in COD tests and H_{ecc}:Q_{conc} for the FW group. Between-group comparisons showed better results in COD tests, eccentric quadriceps peak torque and H_{ecc}:Q_{conc} ratio for the FW group. Only the GD group showed better results at concentric quadriceps peak torque.

Sagelv et al., 2020	Recreationally active (5^{th} and 6^{th} tiers) footballers RCT Intervention 1 = 13 males 23 ± 3 years Intervention 2 = 13 males 23 ± 2 years Control = 12 25 ± 2 years	Inertial flywheel Pre-season, 6 sessions (6 weeks) 3-4 x 4-6 reps (Inertia 0.11 kg·m^2) Squat exercise, inertial flywheel (D11 full, Desmotec, Biella, Italy)	Gravity-dependent In-season, 8 sessions (8 weeks 4-6 x 8reps (80% 1RM) Barbell free weight Squat exercise	10 m sprint (s) CMJ (cm) Squat 1RM (kg; kg ·$kg^{-0.67}$)	Within-group analyses showed improvements in 10 m sprint (2%, d = -0.96 to -0.97), CMJ (8-9%, d = 1.54 to 1.70) and squat 1RM (17-46%, d = 3.13 to 3.17) for both intervention groups. Control group showed no changes in any of the variables. Between-group comparisons showed better results in squat 1RM for the GD group at post-test compared to the FW group (d = 3.43). Both interventions showed better results than the control group in all the outcomes (large to very large effects).
		Control: normal training			

a.u.: arbitrary units; BM: body mass; CMJ: counter-movement jump; COD: change of direction; CON: concentric; ECC: eccentric; F-v: force-velocity; ES: effect size; F_0, maximum theoretical force; Hecc:Qconc: knee functional ratio; RM: repetition maximum; RSA: repeated-sprint ability; SJ: squat jump

Most of the research up to 2015 was related to the "cylinder-shaped" FW devices, while in the last 5 years investigations including the cone-shaped devices started arising. The aforementioned paragraphs were related to cylinder-shaped FW devices, which seems to produce greater forces due to their mechanics compared to the cone-shaped FW device (Núñez et al., 2020). Some of the lower-body exercises that can be performed using the cylinder-shaped FW "closed chain" device is the squat (and some of its variants such as lateral and frontal lunges and split squat), deadlift and calf raise (Figure 4). Also, some of the "open chain" devices available in the market are the leg extension or the leg curl devices (Figure 4). While the difference in eccentric overload production between exercises (open vs closed chain or mono-articular vs multi-articular) has not been studied yet, it is suggested the technique involved during those exercises affects the production of an eccentric overload, hence the desired training adaptations (Tous-Fajardo et al., 2006). Moreover, the inclusion of more complex movements may increase movement variability, which could be interesting from a performance perspective (Fernández-Valdés et al., 2020). The cone-shaped device, with a horizontal direction of the force production, offers practitioners the option to include sport-specific actions in multiple planes of direction (Figure 5) (Gonzalo-Skok, Tous-Fajardo, Valero-Campo, et al., 2017), with promising results showing greater improvements in COD performance when compared to gravity-dependent interventions, in football (Tous-Fajardo et al., 2016) or handball (Madruga-Parera et al., 2020) players.

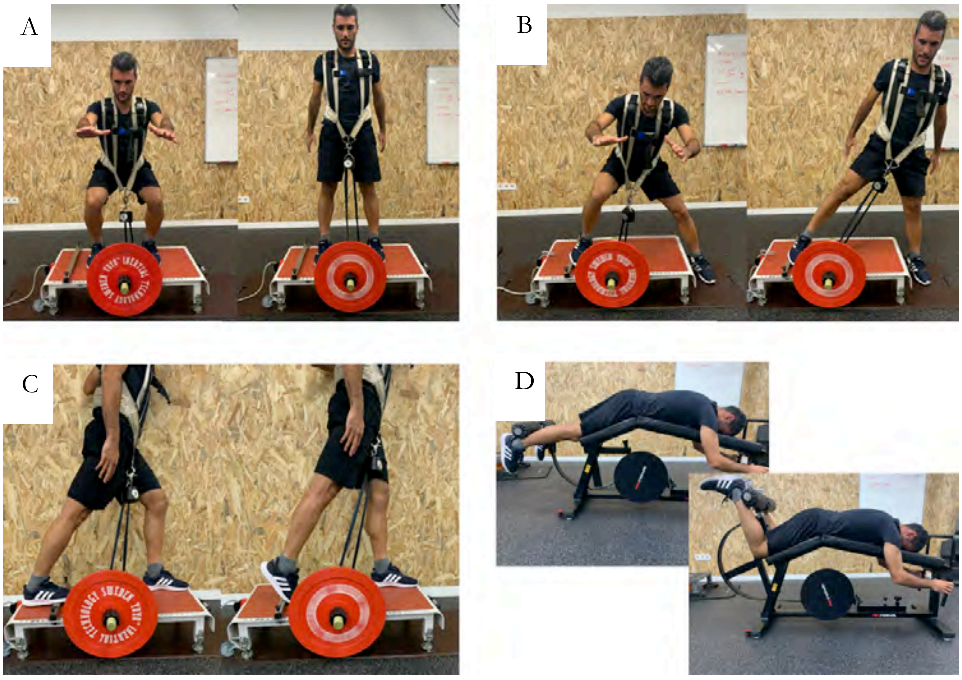


Figure 4. Examples of inertial flywheel exercises using a cylinder-shaped device (author's elaboration). A: squat; B: lateral lunge; C: unilateral calf raises; D: leg curl.

It has been shown that a combination of different FW exercises (Gonzalo-Skok, Tous-Fajardo, Valero-Campo, et al., 2017) or a combination of FW exercises with superimposed vibration enhances cutting performance in footballers (Tous-Fajardo et al., 2016). A summary of FW resistance training interventions in footballers is available in Table 6. Most of the studies analyse the squat exercise or its variants (Coratella et al., 2019; Núñez et al., 2018), mainly for performance improvements, with little attention for hamstring specific exercises being placed (Askling et al., 2003; de Hoyo, Pozzo, et al., 2015; Otero-Esquina et al., 2017). However, direct comparisons between gravity-dependent and FW exercises are scarce, with just one recent intervention in footballers (Coratella et al., 2019), and a few studies in handball players (Madruga-Parera et al., 2020; Maroto-Izquierdo, García-López, & de Paz, 2017). Based on the available evidence, FW seems to offer added benefits to normal football practices, by improving sprinting, COD and jumping performances.

Moreover, COD performance seems to be improved to a greater extent when including FW interventions compared to a GD intervention.

Figure 5. Examples of inertial flywheel exercises using a cone-shaped device (author's elaboration).
A: acceleration step; B: deceleration step; C: cross-over step; D: hamstring back kick.

Hamstring emphasis

While the first flywheel study in professional footballers was almost two decades ago (Askling et al., 2003) which intervened for the first time in a group of professional footballers, very little evidence has emerged on this topic. In this study (Askling et al., 2003), footballers performed the hamstring leg curl exercise during pre-season (10 weeks, 1-2 sessions per week). Footballers showed enhanced sprinting performance and also a greater reduction in hamstring injuries compared to a control group. Even though it is a knee-based exercise, probably shows a different inter-muscular activation compared to the Nordic hamstring exercise (R. Fernandez-Gonzalo, Tesch, et al., 2016; Mendez-Villanueva et al., 2016).

A similar study performed with academy footballers from a professional Spanish team also showed improvements in sprint and CMJ performance, but no benefits in injury incidence with probably reduced injury severity in the intervention group (de Hoyo, Pozzo, et al., 2015). One difference with the former study was the inclusion of the squat exercise which could explain the improvements in CMJ performance. Also, the same group of authors showed greater peak braking forces and impulse during a crossover 60º

COD after the same FW intervention. This could in part explain the benefits of adding eccentrically biased interventions for improving COD performance.

In 2016, Tous-Fajardo and colleagues proposed a multi-component intervention, including a variety of FW exercises with vibration and the NHE, which could be of great interest for practitioners. Interestingly, the hamstring back kick (hip-based exercise) using a cone-shaped FW device (Figure 5) was included as part of the intervention, which offers a more sprint-specific (late-swing phase) position (Guex & Millet, 2013). That FW intervention was compared to a GD intervention that implemented three complexes (see Table 6). The FW intervention seems to offer superior benefits for COD performance with no sprint performance benefits (ES = -0.03 – 0.1). What was surprising was the large impairments in sprint performance (ES = -0.87 – -1.22) after the gravity-dependent intervention. Those results provided the between-group superiority in favour of the FW intervention even though the FW group did not improve sprint performance. The inclusion of a hip based exercise may provide greater involvement of the BFlh and semimembranosus instead of the semitendinosus muscle (Bourne, Timmins, et al., 2017), although much less activation compared to the FW leg curl or the NHE (R. Fernandez-Gonzalo, Tesch, et al., 2016). In 2006 Tous-Fajardo and colleagues (Tous-Fajardo et al., 2006) showed using root-mean-square electromyography that the FW leg curl exercise provided high eccentric hamstring activation at long muscle lengths (near knee extension) and also greater biceps femoris than semitendinosus involvement during braking moments. Later, Fernandez-Gonzalo and colleagues compared the hamstring muscle involvement during the NHE with the FW leg curl, showing greater BFlh T2 shifts during MRI, which could explain the potential benefits of this exercise for hamstring injury prevention (R. Fernandez-Gonzalo, Tesch, et al., 2016). Recently, a hamstring intervention (6 weeks) in amateur athletes comparing the variant of "2-1" loading paradigm (2 legs up, 1 leg down), with a standard concentric-eccentric loading using the leg curl FW device (Presland et al., 2020). Only the "2-1" variant provided positive adaptations for the BFlh fascicle lengths (ES = 1.98) with no benefits on strength (RFD, eccentric or isometric) after any of the two interventions.

Gravity-dependent interventions

The implementation of gravity-dependent training interventions in football is widely studied (Silva et al., 2015). During gravity-dependent exercises, a person's ability to perform a maximal concentric-isometric-eccentric cycle is limited by the force-velocity relationship (Hill, 1938), being the concentric phase the limiting factor (under-loading the eccentric phase) (Dudley et al., 1991). Hence, practitioners need to modify the exercises to overload the eccentric actions with supramaximal loads (greater than 1RM), which is a potent stimulus for neural and muscular adaptations (Douglas et al., 2016) and considered crucial for optimising the effects of resistance training (Aagaard, 2010; Folland & Williams, 2007; Roig et al., 2009; Walker et al., 2016). Such practices normally need third-party assistance which may be a constraint in some environments.

When prescribing training exercises, the specificity of the exercises (in regards to force and power production) performed is important, with sprinting, jumping and COD being the most specific exercises. The frontal plane of movement (squatting, jumping) is normally over-emphasised when using gravity-dependent exercises. However, due to sport-specificity, exercises trying to develop force and power through the sagittal (sprinting) or transversal (shuffling, changing direction) planes are gaining attention nowadays. However, while specific training needs to be implemented for performance adaptations, it is not the only solution (Rumpf et al., 2016). For instance, Mujika and colleagues in 2009 showed the strength-power stimulus (complex group) provided sprinting benefits while no benefits were present for the sprinting group (Iñigo Mujika et al., 2009). Examples of strength and power training interventions for performance enhancement in footballers are available (See Figure 6 and Table 7), with most of the studies focusing on the squat exercise (full squat, half squat), plyometrics (vertical, horizontal and lateral jumps), complex training (high-force low-velocity combined with low-force high-velocity exercises) and resisted sprints or sled towing (Arcos et al., 2014; Faude et al., 2013; Loturco et al., 2017; Inigo Mujika et al., 2009; Rønnestad et al., 2008; Spineti et al., 2019; Styles et al., 2016).

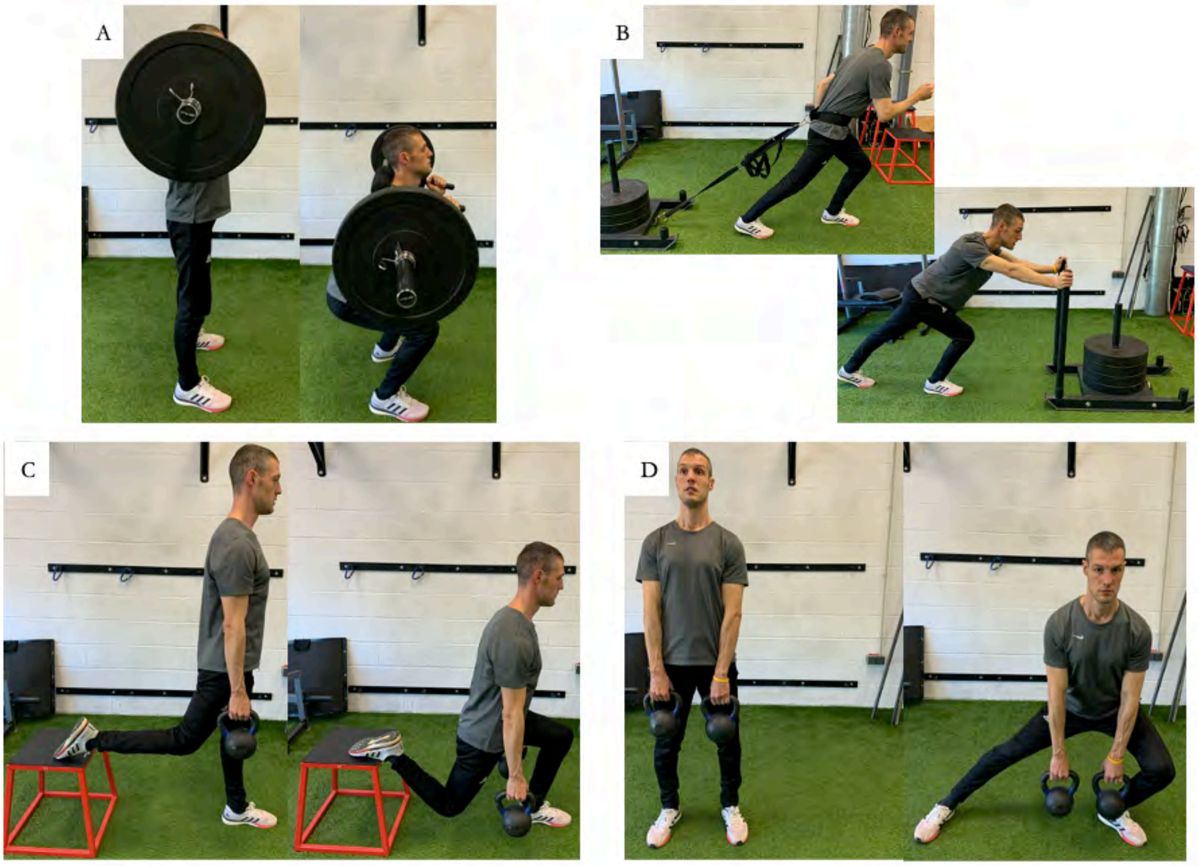


Figure 6. Examples of gravity-dependent exercises for performance improvements (author's elaboration).
A: Squat; B: Sled-pull and sled-push; C: rear-foot-elevated split squat ; D: lateral lunge.

Moreover, the combination of bilateral and unilateral exercises in training interventions are present in real-world practice. While using unilateral exercises may provide unique neuromuscular activation, it may also be interesting for improving between-leg asymmetries and subsequent performances (C. Bishop et al., 2018). A recent study showed the superiority of unilateral interventions in trained individuals (Appleby et al., 2020), however, both methods seem to offer improvements in sprinting, COD and jumping performance in football (Stern et al., 2020) and also other team sports such basketball (Gonzalo-Skok, Tous-Fajardo, Suarez-Arrones, et al., 2017) or rugby (Speirs et al., 2016), probably considering the combination of both as the most effective strategy for performance (Ramírez-Campillo et al., 2015). Surprisingly, little emphasis on the hamstring muscle complex has been placed for performance purposes, considering the major role of the hip extension muscles on sprinting performance.

Hamstring emphasis

While an eccentric focused exercise may be more suited for an "injury prevention" goal (Arnason et al., 2007; Owen et al., 2013), practitioners are also interested in the performance improvements from such exercises. Sometimes, research is trying to validate a single exercise for injury prevention, but those need to be tested in combination with other exercises, considering the ecological validity of the performance environment. In practice, fitness and strength and conditioning coaches should propose a multi-faceted training intervention (Mendiguchia et al., 2015a), with the inclusion of performance and injury prevention exercises, sometimes being difficult to distinguish between them. Also, a single exercise is not sufficient to drive performance adaptations. Even though sprint and COD performance enhancement is complex (Morin et al., 2015), there is evidence suggesting associations between eccentric hamstring strength with both sprint (Askling et al., 2003; Ishøi, Aagaard, et al., 2018; Ishøi, Hölmich, et al., 2018; Krommes et al., 2017; Markovic et al., 2020; Mendiguchia et al., 2015a; Suarez-Arrones et al., 2019) and COD (Chaabene et al., 2018; Emmonds et al., 2017; Jones et al., 2009; Spiteri et al., 2014) performance, making interventions aiming at improving eccentric strength interesting for practitioners.

Figure 7. Examples of gravity-dependent exercises for the hamstring muscle group (author's elaboration).
A: Nordic hamstring; B: Romanian deadlift; C: single-leg leg curl; single-leg Romanian deadlift.

The use of eccentrically biased exercise, such as the NHE, provides specific muscle adaptations, with increases in biceps femoris long head fascicle length, an improved (rightward shift) in the angle of peak knee flexor torque (greater strength at longer muscle lengths), and improvements in eccentric knee flexor strength as possible mechanisms for hamstring injury prevention (Bourne, Timmins, et al., 2017; Brughelli & Cronin, 2007). The Nordic hamstring exercise is one of the most studied exercises for the development of eccentric hamstring strength, due to its strong evidence at reducing the risk of future hamstring injuries in both professional and amateur footballers (Arnason et al., 2007; Petersen et al., 2011; van der Horst et al., 2015). While some will argue the NHE is not specific (neutral hip and knee flexed) to the injury mechanism (late swing phase, with flexed hip and knee extension) (Chumanov et al., 2012), it has been proven effective at reducing hamstring injuries. Owen and colleagues (2013) showed that a multi-component injury prevention intervention, including mobility, lower limb (knee based and hip based hamstring exercises) and lumbopelvic exercises, reduced almost by half (43%) the muscle injuries compared to the control season (Owen et al., 2013). One of the exercises implemented in the last intervention was the NHE, which ended doing 3 sets of 8 repetitions, which is a high volume close to the one proposed in the NHE protocol (3x12-10-8) (Mjolsnes et al., 2004). Yet, the NHE protocol seems not to be implemented in professional football (Bahr et al., 2015), and also difficult to accomplish adhesion in amateur football (van der Horst et al., 2018). Instead, an integration of sprinting, high-intensity running and a variety of hamstring eccentric exercises seems to be implemented in professional football (McCall et al., 2020). Knee-dominant

Table 7. Intervention studies in football players using gravity-dependent methods.

Study	Population N; age ± SD	Group 1 - exercises	Group 2 - exercises	Outcomes	Results
Rønnestad et al., 2008	Professional footballers RCT Intervention 1 = 6 males 23 ± 2 years Intervention 2 = 8 males 22 ± 2.5 years Control = 7 males 24 ± 1.5 years	Heavy resistance Pre-season, 14 sessions (7 weeks) 3-5 x 4-6reps (4-6RM) of half squat and hip flexion	Heavy resistance + plyometrics Pre-season, 14 sessions (7 weeks) Heavy strength (same as intervention 1) Plyometrics: 2-3 x 8-10 alternate leg bound 2 x 5 hurdle jump 2 x 5 forward hops	1RM half squat (kg) Horizontal 4 bounce test (m) SJ and CMJ (cm) SJ with 20-35-50kg PPO (w) 40 m sprint (s)	Pooled effects for the intervention groups showed within-group improvements in most of the performance measures: 25% 1RM, 8% SJ, 4% bounce test, PPO (8-10%) and sprint (1-2%). No differences between interventions.
Control group: normal football training					
Mujika, Santisteban & Castagna, 2009	Professional academy footballers RCT Intervention 1 = 10 males 18.1 ± 0.5 years Intervention 2 = 10 males 18.5 ± 0.7 years	Complex (heavy resistance + speed-power) In-season, 6 sessions (7 weeks) Hills, sled pulls, quadriceps complex, calf complex and psoas complex, jumps, stair climbing	Sprint In-season, 6 sessions (7 weeks) 2-4 x 4x30 m sprints	CMJ, ACMJ and CMJ-15s (cm) 15 m sprint ($m\cdot s^{-1}$) Agility-15 m ($m\cdot s^{-1}$)	Improvements only for the contrast group in 15 m sprint (2%). No differences between interventions.
Faude et al., 2013	Semi-professional footballers RCT Intervention = 8 males Control = 8 males 22.5 ± 2.5 years	In-season, 13 sessions (7 weeks) Day 1: 4x4 SL half squats @90% 1RM + 5 SL hurdle jumps Day 2: strength exercise @50-60% 1RM 3x 5 half-squats + 5 DJ + 5 m sprint 3x 5 calf raises + 5 high jumps + 1 header 2x 8 half-squats + 8 lateral jump + 10 COD 2x 8 step-ups + 4 bounding jumps + 3 headers	In-season, Control Technical – tactical football training	1RM half squat (kg) MVIC leg press (N) RFD leg press ($N\cdot ms^{-1}$) 10-30 m sprint (s) CMJ$_{bil}$ and CMJ$_{right\text{-}left}$ (cm) DJ (cm) and DJ-RI ($cm\cdot s^{-1}$) COD with ball (s) Intermittent endurance (m)	Intervention group improved 1RM (ES = 0.76), CMJ$_{bil}$ (ES = 0.58), CMJ$_{left}$ (ES = 0.51), DJ-RI (ES = 0.49), with no improvements in sprint, COD performance or intermittent endurance.

Arcos et al., 2014	Professional footballers RCT Intervention 1 = 7 males 20.3 ± 1.9 years Intervention 2 = 8 males 19.6 ± 1.6 years	Both interventions Pre- and in-season, 11 sessions (8 weeks) Same exercises: Half squat (bilateral and unilateral) + Calf exercise 2 x 5 at 30-70% PPO		Half squat PPO (kg) CMJ$_{bil}$, CMJ$_{d-nd}$ (cm) 5-15 m sprint (s) Individual anaerobic threshold (km·h^{-1})	Both groups improved PPO (ES = 0.87 and 0.80), and CMJ$_{bil}$ improvements (ES = 0.34) only for horizontal group. Greater CMJ$_{bil}$ in favour of horizontal group (6.4%), no other differences between groups.
		Vertically oriented exercises CMJ, VJ and DJ 1-3 x 3-5 reps	Horizontally oriented exercises Sled towing, hip extension wall drill, loaded horizontal jump, horizontal DJ		
Styles, Matthews & Comfort, 2016	Professional academy footballers Intervention = 17 males 18.3 ± 1.2 years	In-season, 12 sessions (6 weeks) 3-4 x 3-5reps @85-90% Back squat, RDL and Nordic hamstring	N/A	Squat 1RM (kg, kg·kg^{-1}) 5-10-20 m sprint (s)	Improvements in 5 m (ES = 0.55), 10 m (ES = 0.45) and 20 m (ES = 0.31) sprint times, and absolute (ES = 0.62) and relative (ES = 0.45) squat 1RM.
Loturco et al., 2017	Professional footballers RCT Intervention 1 = 7 males 21.7 ± 2.4 years Intervention 2 = 11 males 22.2 ± 2.4 years	Optimum Power Load + resisted sprint Pre-season, 12 sessions (5 weeks) 4-6 x 4-6 Squat Jump @optimum power 6-8 x 20-30 m sprint @5-20%BM	Optimum Power Load + plyometrics Pre-season, 12 sessions (5 weeks) 4-6 x 4-6 Squat Jump @optimum power 6-8 x 6 Horizontal jump or CMJ	Unloaded and resisted 5-10-20-30 m sprint (s) COD (s) SJ 40%BM (m·s^{-1}, W·kg^{-1}) SJ, CMJ, HJ (cm)	Both groups improved resisted sprints (almost certainly) and COD (ES = 0.86-0.87, likely and almost certainly). No difference between interventions.
Spineti et al., 2019	Professional academy footballers RCT Intervention 1 = 10 males Intervention 2 = 12 males 18.4 ± 0.4 years	Traditional strength In-season, 24 sessions (12 weeks) Day 1: 2 x 12-15RM Day 2: 3 x 8-10RM Day 3: 4 x 4-6RM Half squat, deadlifts, knee extension and flexion and hip adduction	Complex-contrast In-season, 24 sessions (12 weeks) Day 1: 2x6 CMJ @60%PPO + 10 hurdle hops, 10 SL bounds, 10 diagonal jumps Day 2: 2 x 5 high pull @5RM + 10 m sprint + hops + diagonal jumps Day 3: 2 x 4 CMJ @100% PPO + 10 lateral box jumps, 10 box-to-box, 10 depth jumps	SJ (cm) 5-10-20-30 m sprint (s) COD test (s)	Improvements only in complex-contrast group in SJ (ES = 0.8), 5 m (ES = 0.5) and COD (ES = 2.7). No between-groups analyses performed.

ACMJ: abalakov counter-movement jump; BM: body mass; CMJ: counter-movement jump; COD: change of direction; CON: concentric; DJ: drop jump; ECC: eccentric; ES: effect size; HJ: horizontal jump; PPO: peak power output; RFD: rate of force development; RM: repetition maximum; RI: reactive index; RSA: repeated-sprint ability; SJ: squat jump; W: power and hip dominant hamstring exercises with a variety of methods (free weights, bodyweight, flywheel inertial devices) are used (McCall et al., 2020). It is important to highlight this, since a combination of hip and knee -based exercises (see Figure 7), and also a variety of methods (providing specific loads at different muscle lengths) (Guex & Millet, 2013) will target different portions of the hamstring muscle group (Bourne, Williams, et al., 2017), in combination with other strategies seems important for a holistic "hamstring health" (Oakley et al., 2017). Other options for a knee-based hamstring exercise would be a leg curl with a weight-stack machine, a leg curl with a fitball or slider, which can also be biased towards an eccentric only phase or even an accentuated eccentric loading exercise (Suchomel et al., 2019), however, interventions using those exercises are not available nowadays. Those knee-based exercises tend to be more demanding for the medial hamstrings (Bourne, Timmins, et al., 2017). Instead, a hip-based exercise such as the hip extension exercise or the Romanian deadlift tends to be more demanding for the lateral hamstrings (Bourne, Timmins, et al., 2017). Those exercises can also be biased towards an eccentric-only phase which seems that high-intensity eccentric actions are crucial towards positive architectural muscle adaptations for injury prevention (Bourne, Timmins, et al., 2017). Also, the razor hamstring curl (NHE in hip flexion) has been proposed as an alternative exercise, by combining the knee extension to hip extension and producing greater medial hamstring activation (Oliver & Dougherty, 2009), but did not provide the same adaptation in BFlh fascicle length or eccentric hamstring strength than the NHE (Pollard et al., 2019). Other exercises such as forward lunges or jumping lunges have been regarded as interesting options for improving hamstring strength and sprint performance (Jönhagen et al., 2009; Mendiguchia et al., 2015b). Recently, a bounding program (3x30m jumps during in-season, with 12 weeks of build-up phase), aiming for a reduction in hamstring injury incidence and severity in amateur footballers has been proposed (van de Hoef et al., 2019). This bounding program was implemented in a big cluster-RCT including 400 players but failed to accomplish the reduction in hamstring injury incidence and severity (OR = 0.89, 95% CI 0.46-1.75) (van de Hoef et al., 2019). Those results may be related to the little eccentric and mainly isometric or concentric muscle actions involved in the jumping forward lunge (Jönhagen et al., 2009) Also, sprinting per se is regarded as an injury prevention exercise (Edouard et al., 2019; Mendiguchia et al., 2020), considering the high demands for the hamstring muscle complex during sprinting, and the difficulties of targeting them during strength exercises (Tillaar et al., 2017). It should be noted, that as speed increases, the work at the hamstring muscle complex is not proportional, being the work around 70% at 85% of maximum speed, 90% at 95% of maximum speed and 100% effort at maximum speed (Schache et al., 2012), so sprints >95% of maximum speed should be needed for stimulating the hamstrings for both a performance and injury prevention strategy. Mendiguchia and colleagues recently presented positive architectural adaptations on the BFlh following 6 weeks of a sprinting protocol, compared to an eccentric only intervention (NHE) (Mendiguchia et al., 2020). It seems that the sprinting protocol provided both performance and injury prevention adaptations (increase in BFlh fascicle length), which could be regarded as a win-win strategy for practitioners.

Considering all the available evidence, it is not possible to state which strategy (gravity-dependent or inertial flywheel intervention) is more effective at improving performance and eccentric hamstring strength in football players from all levels (professional to amateurs). Additionally, the effectiveness of an inertial flywheel intervention at preventing injuries in general, and more specifically hamstring injuries, has not been developed and compared to a gravity-dependent training intervention.

CHAPTER 2

Aims and hypothesis

The overall aim of this PhD project was to first compare the use of inertial flywheel with gravity-dependent resistance training for improving physical performance and thigh muscle strength and secondly, to test how previous injury, age and the off-season period affects physical performance and eccentric hamstring strength in semi-professional and amateur footballers.

The specific objectives and hypothesis were:

- to determine whether the use of inertial flywheel resistance training was superior to the use of gravity-dependent resistance training on strength and power outcomes (Publication I).
    - It was hypothesized that inertial flywheel resistance training would provide greater strength and power adaptations compared to gravity-dependent devices.

- to evaluate and critically appraise a publication that presented a similar objective as Publication I but presented methodological shortcomings and divergent results (Publication II).

- to assess the eccentric hamstring strength of semi-professional and amateur football players at the beginning of pre-season and its association with age and previous hamstring injury (Publication III).
    - It was hypothesized that semi-professional and amateur football players with a previous hamstring injury and older in age would show reduced eccentric hamstring strength at pre-season.

- to investigate the changes in selected performance measures and eccentric hamstring strength following the off-season period in semi-professional and amateur football players, and its association with age and previous hamstring injury (Publication IV).
    - It was hypothesized that semi-professional and amateur football players would show reduced performance (sprint and COD and eccentric hamstring strength) after the off-season period. It was also hypothesized that players with a previous hamstring injury and older in age would show larger reductions in performance during the off-season period.

- to investigate and compare the adaptations in physical performance measures and hamstring strength after an inertial flywheel or gravity-dependent resistance training intervention in semi-professional footballers during the off-season and pre-season periods (Publication V).
    - It is hypothesised that both training interventions will provide positive and similar adaptations, but the inertial flywheel providing greater COD performance and RSA than the gravity-dependent intervention.

CHAPTER 3

Material and methods

Five publications are included in the main body of this thesis. Three studies were carried out, with a letter to the Editor and the design of a randomised controlled trial completed. In the following sections, all the manuscripts are presented, including a copy of the actual publications. The publications are presented in the chronological order in which they were written.

The first publication is the systematic review with meta-analyses of randomised and non-randomised controlled trials, followed by the letter to the Editor. The following two publications are observational studies (a cross-sectional and a longitudinal study), assessing selected physical performance measures in semi-professional and amateur football players during the pre-season and off-season periods respectively. The last publication is the design of a randomised controlled trial in which includes the intervention protocol, comparing the use of inertial flywheel or gravity-dependent exercises in semi-professional footballers during the off-season and pre-season periods.

Readers are referred to the specific methods section of each publication for further information.

CHAPTER 4

Publications

PUBLICATION I

Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses

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Jordi Vicens-Bordas
Ernest Esteve
Azahara Fort-Vanmeerhaeghe
Thomas Bandholm
Kristian Thorborg

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Review

Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses

J. Vicens-Bordas[a,b,*], E. Esteve[a,b], A. Fort-Vanmeerhaeghe[c,b], T. Bandholm[d], K. Thorborg[d,e]

[a] Sportclínic, Physiotherapy and Sports Training Centre, Spain
[b] School of Health and Sport Sciences (EUSES), Universitat de Girona, Spain
[c] Blanquerna Faculty of Psychology, Education Sciences and Sport (FPCEE), Universitat Ramon Llull, Spain
[d] Physical Medicine & Rehabilitation Research – Copenhagen (PMR-C), Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Clinical Research Center, Amager-Hvidovre Hospital, Copenhagen University, Denmark
[e] Sports Orthopedic Research Center - Copenhagen (SORC-C), Department of Orthopedic Surgery, Amager-Hvidovre Hospital, University of Copenhagen, Denmark

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ABSTRACT

Objective: The primary aim of this systematic review was to determine if inertial flywheel resistance training is superior to gravity-dependent resistance training in improving muscle strength. The secondary aim was to determine whether inertial flywheel resistance training is superior to gravity-dependent resistance training in improving other muscular adaptations.
Design: A systematic review with meta-analyses of randomised and non-randomised controlled trials.
Methods: We searched MEDLINE, Scopus, SPORTDiscus, Web of Science and Cochrane Central Register of Controlled Trials with no publication date restrictions until November 2016. We performed meta-analyses on randomised and non-randomised controlled trials to determine the standardized mean difference between the effects of inertial flywheel and gravity-dependent resistance training on muscle strength. A total of 76 and 71 participants were included in the primary and secondary analyses, respectively.
Results: After systematic review, we included three randomised and four non-randomised controlled trials. In the primary analysis for the primary outcome muscle strength, the pooled results from randomised controlled trials showed no difference (SMD = −0.05; 95%CI −0.51 to 0.40; p = 0.82; $I^2 = 0\%$). In the secondary analyses of the primary outcome, the pooled results from non-randomised controlled trials showed no difference (SMD = 0.02; 95%CI −0.45 to 0.49; p = 0.93; $I^2 = 0\%$; and SMD = 0.03; 95%CI −0.43 to 0.50; p = 0.88; $I^2 = 0\%$). Meta-analysis on secondary outcomes could not be performed.
Conclusion: Based on the available data, inertial flywheel resistance training was not superior to gravity-dependent resistance training in enhancing muscle strength. Data for other strength variables and other muscular adaptations was insufficient to draw firm conclusions from.

1. Introduction

Resistance training, also known as strength or weight training, is becoming more popular and widely used nowadays by a large number of people with a diversity of aims and goals.[1,2] Many modes and methods of resistance training exist and a multitude of variables can be adjusted in order to improve performance and physiological adaptations.[3,4] Most research on resistance training has used free weights and weight stack machines,[1,5] considered in this systematic review as gravity-dependent (GD) resistance training.

GD resistance exercises involve sequences of concentric, isometric and eccentric actions. During GD resistance exercises, a person's ability to perform a maximal concentric-isometric-eccentric cycle is limited by the force-velocity relationship.[6] When the concentric-isometric-eccentric cycle is performed during GD training bouts, muscles are capable of achieving greater absolute forces during

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* Corresponding author.
E-mail address: jordi.vicensb@cadscrits.udg.edu (J. Vicens-Bordas).

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eccentric than concentric actions,[7] therefore the eccentric phase is considerably under-loaded as it is limited by the load lifted during the concentric phase.[8] Eccentric actions using supramaximal loads, that is, loads greater than 1 repetition maximum (RM), is a potent stimulus for enhancements in neural and muscular adaptations[9] and could be considered crucial for optimising the effects of resistance training.[10–13] Accentuated eccentric training can be produced using GD devices, but a third-party assistance is required which may be a limitation in many circumstances. Unquestionably, neural and muscular adaptations and the rate of their development depend on the mode and method of training, initial training status, and the muscle group investigated.[1,14]

Berg and Tesch[15] introduced the first inertial flywheel resistance (FW) device for space travellers exposed to non-gravity environments.[16,17] Since then, FW resistance training has been used in detrained populations,[18] disabled populations,[19] healthy adults[20–23] and also amateur and semi-professional athletes.[24–28] When using FW resistance devices, the rotation of the devices' flywheel is initiated by a concentric muscle action – unwinding the flywheel's strap – followed by an eccentric muscle action – rewinding the flywheel's strap –, immediately producing subsequent concentric-eccentric cycles. The force applied in the eccentric action to bring the flywheel to a stop will rely on the kinetic energy generated during the concentric action and also the strategy to apply force to the last third of the eccentric action.[15] Hence, FW resistance devices allow for maximal concentric force throughout the range of motion and short periods of greater eccentric than concentric force, provided maximal effort and the appropriate technique are employed.[20,29] Moreover, the inertia used during the FW resistance exercise will alter the force, power and work relationship, affecting also the use of the stretch-shortening cycle during the coupled concentric-eccentric actions.[30] Finally, compared to isotonic loading (e.g. gravity-dependent), inertial loading ensures accommodated resistance, which permits maximal forces to be produced from the very first repetition and force decline throughout the set.[31] In comparison, the maximal muscle activation during gravity-dependent exercises seems to be present at contraction failure or "sticking point"[32] where a third-party assistance may be needed.

It has been shown that FW resistance training is effective in producing early gains and combating the deleterious effects in muscle mass and strength during simulated microgravity and bed rest conditions[17,33,34] and in chronic stroke patients.[19] Likewise, marked maximum voluntary isometric contractions improvements,[21] and early gains in muscle hypertrophy have been promoted in adults with only 5 weeks of training.[20,35,36] Some studies have found FW resistance training to be effective in injury prevention[27,37] and rehabilitation.[38,39] In addition, performance improvements[40] and a potentiation effect[28] have also been promoted following training with FW resistance training devices in trained individuals. Moreover, it has been shown that a combination of different FW exercises[25] or a combination of FW exercises with superimposed vibration enhances cutting performance in soccer players.[26] Considering that most daily activities and human motions (e.g. walking, running, climbing and lifting) include coupled concentric and eccentric muscle actions, involving the stretch-shortening cycle,[41,42] FW resistance training enables athletes to emphasize the eccentric phase of the action using a specific movement pattern with no need of a third party-assistance, compared to other training modes, which may optimally contribute to enhanced performance adaptations.[25,26,30] Although a recent systematic review[43] has been published comparing FW resistance training and GD resistance training for improving muscle strength, this current study is the first study to provide Level 1 evidence, solely based upon randomised controlled trials, on the topic. Hence, at this point it is not known whether FW resistance training is superior in improving performance and physiological adaptations when compared to GD resistance training.

The primary aim of this systematic review was to determine if inertial flywheel resistance training is superior to gravity-dependent resistance training in improving muscle strength. The secondary aim of this review was to estimate whether inertial flywheel resistance training is superior to gravity-dependent resistance training in improving other muscular adaptations, such as muscle structure, muscle activation and/or muscle histology.

2. Methods

The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA)[44] was used as a guideline for reporting of this study. Prior to the search, a review protocol based on PRISMA-P[45] was completed and registered at PROSPERO (ID = CRD42015020337). The review protocol was updated during the review process and is publically available at http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42015020337.

MEDLINE, Scopus, SPORTDiscus, Web of Science and Cochrane Central Register of Controlled Trials (CENTRAL) were electronically searched with no publication date restrictions. The search included articles prior to 3 November 2016. Two blocks of keywords related to (1) inertial flywheel resistance device and (2) training intervention composed the search strategy. The complete search strategy can be seen in the supplementary material. The searches were customized to accommodate the layout and characteristics of each search engine and the application of additional free text words were based on the coverage of subject terms. A hand-search of the reference lists of relevant articles was also conducted for other potential relevant References.

Titles and abstracts identified in the search were downloaded into Mendeley Desktop (Glyph & Cog) cross references and duplicates were deleted. All publications potentially relevant for inclusion were independently assessed for inclusion by two reviewers (JVB and EE) and full texts were obtained if necessary. Any discrepancies were resolved during a consensus meeting, and a third reviewer was available if needed. Data from randomised (RCTs) and non-randomised (non-RCTs) controlled trials were included. We included studies with humans that participated into a resistance training intervention using an FW resistance device, as the sole intervention for the studied muscle group, and a comparator of GD resistance device. Studies had to report a measure of muscle strength as outcome. Whenever several publications reported data from the same trial, the "primary publication" was used. Only full text publications in English were considered.

For primary outcome, changes in muscle strength, such as maximal voluntary isometric and/or dynamic force (N), torque (Nm, Nm/kg, Nm/cm^2), power (W, W/kg, W/cm^2) and/or rate of force development (N/s) were considered. For secondary outcomes, changes in: muscle structure, such as muscle size measured as cross-sectional area (cm^2), muscle volume (cm^3 or mL), signal intensity (mean grey value), fascicle length (mm) and/or pennation angle (degrees); muscle activation, such as voluntary activation measured as electromyographic activity (μV, mV, %EMG$_{max}$); muscle histology, such as muscle proteins involved in hypertrophic signalling or substrate breakdown (mmol/kg dry wt, mmol kg^{-1} min^{-1}), water content proportion (%), and/or muscle fiber distribution (proportion fiber types (%), fiber CSA (μm); and possible adverse events as a result of the intervention, such as pain, discomfort or muscle soreness were considered.

Two reviewers (JVB and EE) independently extracted data using a specifically designed standardized form (see supplementary material). General study information, participants and intervention

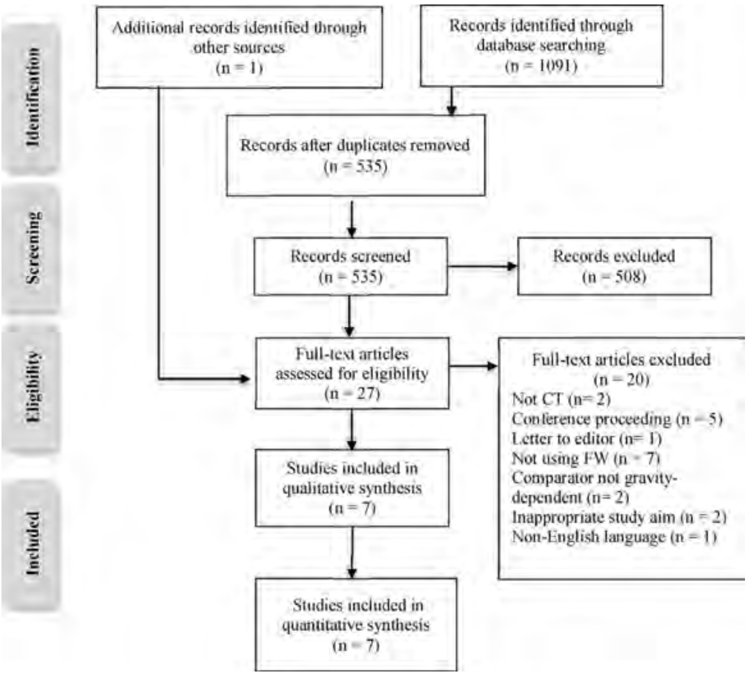


Fig. 1. Flow chart of included studies.

characteristics, and outcome measures were extracted. If data were not available from tables or the result section, the first author of the systematic review requested the missing data from the author(s). If the authors did not have access to their data, data on outcome measures were extracted from figures and graphs using AutoCAD 2015 (Autodesk, Inc., USA) by one author (JV). Another author (EE) verified the validity of the data extraction.

The studies included were assessed for the risk of bias by two independent raters (JVB and EE), with any disagreements resolved by consultation with a third party (KT). An assessment of the methodological quality was not implemented, as no evidence for such appraisals and judgments exists and therefore can be confusing when interpreting the results.[46] Using quality scales and summary scores is considered problematic, due to substantial variations between items and dimensions in scales covered, with little support relating to the internal validity of these evaluations.[47]

When assessing the RCTs mandatory bias items, the 'Cochrane Collaboration's tool for assessing risk of bias in randomised trials'[48] was used. Each bias domain was judged as high, low or unclear and provides a quote from the study report together with a justification for the judgment in the 'Risk of bias' table. When assessing the non-RCTs mandatory bias items, the 'Risk Of Bias in Non-Randomised Studies – of Interventions (ROBINS-I)'[49] was used. The ROBINS-I includes signalling questions alongside free-text boxes within each domain of bias to facilitate the judgements about the risk of bias. Each domain was judged as (1—low risk of bias; 2—moderate risk of bias; 3—serious risk of bias; 4—critical risk of bias; and, 5—no information). The risks of bias judgments were summarized across all studies included for each of the domains listed. Where information on risk of bias relates to unpublished data or correspondence with a trial list, it was noted in the 'Risk of bias' table.

With three or more RCTs included, we performed meta-analysis (primary analysis) using Review Manager Version 5.3 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). For the primary outcome, changes in muscle strength, intervention effects were calculated using standardised mean differences (SMD) with 95% confidence intervals (CI), since all data were continuous. The mean change scores and standard deviations of the change scores from the intervention and control groups were used to calculate the SMD. If the standard deviations of the change scores were not reported, these were calculated using the formula,[46] where correlation coefficients were conservatively set at 0.5.[50] A positive SMD represents an effect in favour of FW resistance training interventions and a negative SMD an effect in favour of GD resistance training interventions. Effect sizes were categorised as small (0.2), medium (0.5) or large (0.8 or greater).[51] Statistical heterogeneity was explored using chi-squared statistic and visual inspection of the forest plot; and inconsistency was calculated using I^2 statistic. The chi-squared and I^2 statistics describe heterogeneity or homogeneity of the comparisons with $p < 0.05$ indicating heterogeneity.[52] A random-effects model was selected for the analysis.

With three or more non-RCTs included we performed meta-analyses (secondary analyses) on the primary outcome – changes in muscle strength –. Whenever three or more RCTs and non-RCTs reported data on secondary outcomes – changes in other muscular adaptations –, meta-analyses were performed.

The within-groups effect sizes and 95%CI on measures of strength and other muscular adaptations were calculated (post-hoc analyses) in order to analyse the magnitude of the differences within groups. Effect sizes were calculated for each study using the Hedges and Olkin's g and using the correction factor for small samples.[53] A positive effect size translates to positive adaptations to training.

3. Results

The initial search identified 1091 unique references (Fig. 1). One additional record was identified through examination of reference lists and citations of relevant articles. After identification of duplicates, 535 titles and abstracts were screened. Twenty-seven studies remained for further full text analysis. Subsequently, 20 studies

Table 1a
Characteristics of the included randomised controlled trials.

Study	Population N (m/f); age	Group: exercise (equipment)	Primary outcomes	Secondary outcomes	Results
Greenwood et al.[39]	History of knee injury FW 15 (9/6) GD 14 (7/7) 37 ± 13 years	FW: knee extension (Yoyo Technology Inc, Sweden) GD: knee extension (Health and Leisure, UK)	MVIC at 80° (N) CON and ECC peak force at 60° s^{-1} and CON at 180° s^{-1} (N) Peak power (W)	CSA (cm^2) Central neural activation (twitch superimposition)	MVIC: no differences between groups CON and ECC peak force (60° s^{-1}): No differences between groups CON and ECC peak force (180° s^{-1}): No differences between groups Peak power: no differences between groups CSA: no differences between groups Central neural activation: no differences between groups[$]
Onambélé et al.[54]	Healthy older subjects FW 12 (6/6) GD 12 (6/6) 69.9 ± SD 1.3 years	FW: knee extension (Yoyo Technology Inc, Sweden) GD: knee extension (Technogym, Italy)	MVIC at 90° (Nm) Peak isokinetic power (W) at 180° s^{-1}	EMG-RMS (mV)	MVIC: no differences between groups Peak power: Significant differences in favour to FW[*] EMG-RMS: no differences between groups
de Hoyo et al.[22]	Healthy and physically active subjects FW 11 male GD 12 male 22 ± SD 2 years	FW: front step on inertial device (Sport Teach & Tools, Spain) GD: half-squat on smith machine (FITLAND, Spain)	MVIC at 90° (N)		MVIC: no differences between groups

CON: concentric; CSA: cross-sectional area; ECC: eccentric; EMG-RMS: electromyographic activity root-mean square; FW: flywheel; GD: gravity-dependent; MVIC: maximum voluntary contraction; (m/f): (male/female).

[*] Significance at $p < 0.05$.

[$] Significant differences at baseline ($p < 0.05$).

Table 1b
Characteristics of the included non-randomised controlled trials.

Study	Population N (m/f); age	Exercise (equipment)	Primary outcomes	Secondary outcomes	Results
Caruso et al.[23]	Healthy untrained subjects FW 11 male; 58.6 ± SEM 2.2 GD 12 male; 56.2 ± SEM 2.8	FW: seated leg press (Yoyo Technology Inc, Sweden) GD: standard leg press	CON and ECC peak torque at 93° s^{-1} and 278° s^{-1} (Nm)	Leg muscle mass (kg)	CON and ECC peak torque (93° s^{-1}): no differences between groups CON and ECC peak torque (278° s^{-1}): no differences between groups Leg muscle mass: no differences between groups
Caruso et al.[24]	Healthy college-age subjects FW 9 (7/2) GD 10 (7/3) Control 9 (6/3)	FW: seated leg press (Yoyo Technology Inc, Sweden) GD: standard leg press	Average peak torque 3 first reps at 180° s^{-1} (Nm)	Estimated CSA (cm^2)	Average peak torque: no differences between groups CSA: no differences between groups
Norrbrand et al.[20]	Healthy subjects FW 7 male; 39.1 ± SD 9.1 GD 8 male; 39.4 ± SD 8.1	FW: unilateral Knee extension (Yoyo Technology Inc, Sweden) GD: knee extension (World Class, Sweden)	MVIC at 90° and 120° (N) Knee extension Power (W)	Muscle volume (ml)	MVIC 90°: differences in favour to FW[*] MVIC 120°: no differences between groups
Norrbrand et al.[21]	Healthy subjects FW 9 male; 38.8 ± SD 5 GD 8 male; 39.4 ± SD 8.1	FW: unilateral Knee extension (Yoyo Technology Inc, Sweden) GD: unilateral Knee extension (World Class, Sweden)	MVIC at 120° (N) RFD	EMG-RMS (mV)	MVIC: non-significant differences EMG-RMS: differences on eccentric EMG in favour to FW[*]

CON: concentric; CSA: cross-sectional area; ECC: eccentric; EMG-RMS: electromyographic activity root-mean square; FW: flywheel; GD: gravity-dependent; MVIC: maximum voluntary contraction; RFD: rate of force development; (m/f): (male/female).

[*] Significance at $p < 0.05$.

were excluded. The most common reason for exclusion (7 studies) was that an FW resistance device was not used. Five references were conference proceedings and were also excluded. In the end, 7 studies were included in the final review process.

The most relevant characteristics of the included studies are summarized in Table 1a for RCTs and Table 1b for non-RCTs. For an overview of the training parameters used in each study, see Supplementary Table 1a for RCTs and Supplementary Table 1b for non-RCTs.

Three individually RCTs[22,39,54] involving 76 participants are included in the review. Two RCTs[39,54] assessed both male and females while the other RCT[22] assessed only males. Participants in the RCTs were identified as either untrained[54] or physically active with limited experience in resistance training (less than 3 months).[22] The ages differed between studies, from young[22] to old[54] and a mixture of ages.[39] One study[39] included participants with a history of knee injury and did not report the training age or experience of the participants. Exercise selection for both the FW and GD groups was the same (knee extension).[39,54] Instead, the exercise differed between interventions in the other study (front step (FW) and half squat (GD)).[22] The duration of resistance training programs diverged from 6 to 12 weeks. The load used during GD interventions were 10 RM,[39] 80% of 1 RM[54] and also one study used the load that elicited the maximum power output.[22] During FW interventions, one study did not mention the inertia used during training,[39] while the others used the inertia that elicited the maximum power output.[22,54]

Four non-RCTs trials[20,21,23,24] comprising 83 participants are included in the review. Three of them[20,21,23] assessed only male while the other[24] assessed both males and females. One study did not report participant's age[24] while the others were performed in middle-aged and old subjects. Participants in the non-RCT studies were identified as either healthy untrained[23] or healthy.[20,21,24] Exercise selection for both the FW and GD groups was the same, leg press[23,24] or knee extension.[20,21] The duration of resistance training programs diverged from 5 to 10 weeks. The load used during GD interventions ranged from 7 RM to 10 RM. During FW interventions, two studies did not mention the inertia used during training,[23,24] while the other two used a 4.2 kg flywheel with a moment inertia of 0.11 kg m.[2,20,21]

The authors of the three RCTs[22,39,54] were contacted to provide extra information on the study's data. Only data from one author could be obtained,[39] one was extracted from the graphs[22] and for the other, standard deviations from change scores were calculated.[54]

Results of the risk of bias assessment are presented in Supplementary Table 2a for RCTs and Supplementary Table 2b for non-RCTs. For RCTs, the main source of bias was blinding of participants and outcome assessors. For the non-RCTs, moderate bias was found relating to confounding factors inherent to lack of randomisation, and also the blinding of outcome assessors and participants.

The three RCTs were included in the primary analysis.[22,39,54] In the primary analysis for the primary outcome, changes in muscle strength (MVIC), the pooled results showed no difference (SMD = −0.05; 95%CI −0.51 to 0.40; p = 0.82; Fig. 2a). No heterogeneity was present $I^2 = 0\%$ in this analysis.

The four non-RCTs[20,21,23,24] were included in the secondary analyses for the primary outcome (changes in muscle strength). Two analyses were performed which only differed in the inclusion of either the concentric or the eccentric peak torque from Caruso et al.[23] The pooled results showed no difference in any of the secondary analyses (SMD = 0.02; 95%CI −0.45 to 0.49; p = 0.93; $I^2 = 0\%$; Fig. 2b; and SMD = 0.03; 95%CI −0.43 to 0.50; p = 0.88; $I^2 = 0\%$; Fig. 2c). Finally, analyses on secondary outcomes could not be performed for any RCT or non-RCT due to heterogeneity of outcomes between studies.

Within-groups effect sizes were calculated (post-hoc analyses) for each study in order to present the magnitude of the effects of each training intervention on primary and secondary outcomes for RCTs and non-RCTs. On primary outcome for RCTs (Supplementary Table 3a), small to large effects were present on MVIC and concentric and eccentric peak force for both FW and GD interventions. In addition, small effects were present on peak power for both FW and GD interventions. On secondary outcomes, medium effects were present for both FW and GD interventions. For the FW group, a large effect on central neural activation but a small negative effect on EMG-RMS was present, whereas small effects were present for GD in both central neural activation and EMG-RMS. For non-RCTs (Supplementary Table 3b), on primary outcome, small and medium effect sizes were present on MVIC, whereas no effect or small effects were present for concentric and eccentric peak torque. On muscle volume and CSA, no effects were present for GD and small effects for FW.

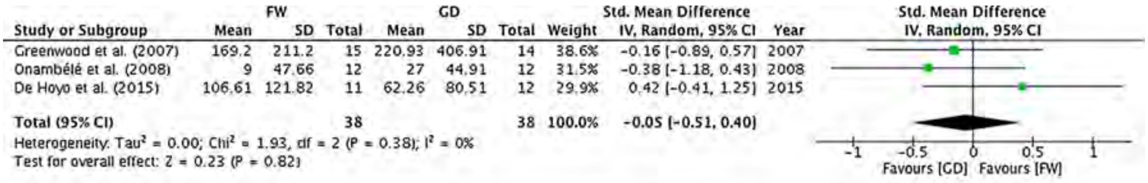
4. Discussion

In this systematic review and meta-analyses where the primary aim was to determine whether FW resistance training was superior to GD resistance training in improving muscle strength, superiority of FW compared to GD resistance training could not be documented.

A recent systematic review including a meta-analysis by Maroto-Izquierdo et al.[43] was published in 2017. The study investigated muscle size and functional adaptations to FW resistance training compared to GD resistance exercise in athletes and healthy subjects. While this study claimed to compare FW resistance training against GD resistance training on RCTs, most of the studies included in the review did not use GD resistance training group as a comparator.[55] To the best of our knowledge, the present study is therefore the first systematic review and meta-analysis to exclusively provide Level 1 evidence of the efficacy of FW resistance training compared to GD resistance training on muscle strength and other muscular adaptations.

Our study reveals that for maximal voluntary isometric contraction (MVIC), no differences are present in RCTs between FW and GD resistance training (SMD = −0.05; 95%CI −0.51 to 0.40). Unfortunately, concentric and eccentric muscle strength measures could not be included in the meta-analyses of RCTs, as only one study[39] covered this outcome. However, two non-RCTs[23,24] were included in the secondary analyses using measures of concentric and eccentric muscle strength. The pooled results for non-RCTs showed no differences on muscle strength in any of the secondary analyses (SMD = 0.02; 95%CI −0.45 to 0.49 and SMD = 0.03; 95%CI −0.43 to 0.50). Although CIs for these estimates overlapped both groups, suggesting uncertainty in the point estimate, we interpret these findings as being unclear and that more data are required to improve confidence in the interpretation of these outcomes.

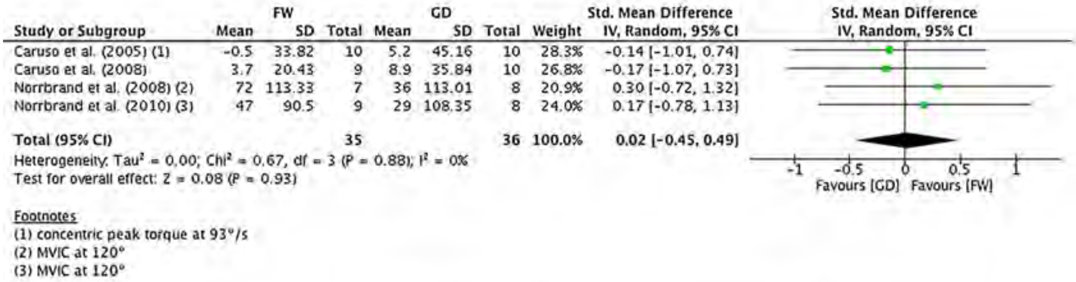
Based on post-hoc analyses, small to large within-group effect sizes were found in RCTs for both FW and GD resistance training interventions on muscle strength measures. Those results indicate similar improvements in strength can be achieved using both resistance training modes. In non-RCTs greater within-group effect sizes were found for FW resistance training on MVIC strength measures but greater within-group effect sizes were found for GD on concentric and eccentric measures of strength. The diversity on the improvements could either be due to a lack of randomization, the heterogeneity between participants or even differences in exercise selection and loading used in each study. Nonetheless, those results only represent within-group effect sizes and comparisons between FW and GD cannot be drawn from these post-hoc analyses. Other studies in the literature not using an active control group, showed improvements on MVIC of 39%[36] and 10–12%[56] following 5 weeks of FW resistance training. Askling et al.[37] found improvements in both concentric and eccentric isokinetic strength at $60^\circ\,\mathrm{s}^{-1}$, after a FW resistance training intervention on the hamstring muscle group. Fernandez-Gonzalo et al.[18] found a 25% and 20% improvement on 1 RM for men and women respectively, after 6 weeks of training on a FW supine squat device without a control group. A previous systematic review with meta-analyses[10] found no differences in MVIC improvements between participants exercising either eccentrically or concentrically suggesting both training stimulus produce similar MVIC adaptations. Roig and colleagues[10] showed that eccentric training is more effective at increasing eccentric strength and muscle mass than concentric training. The large effect size found in Greenwood et al.[39]



Study or Subgroup	FW Mean	FW SD	FW Total	GD Mean	GD SD	GD Total	Weight	Std. Mean Difference IV, Random, 95% CI	Year
Greenwood et al. (2007)	169.2	211.2	15	220.93	406.91	14	38.6%	-0.16 [-0.89, 0.57]	2007
Onambélé et al. (2008)	9	47.66	12	27	44.91	12	31.5%	-0.38 [-1.18, 0.43]	2008
De Hoyo et al. (2015)	106.61	121.82	11	62.26	80.51	12	29.9%	0.42 [-0.41, 1.25]	2015
Total (95% CI)			38			38	100.0%	-0.05 [-0.51, 0.40]	

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 1.93$, df = 2 (P = 0.38); $I^2 = 0\%$
Test for overall effect: Z = 0.23 (P = 0.82)

a: Strength changes (MVIC) of RCTs forest plot

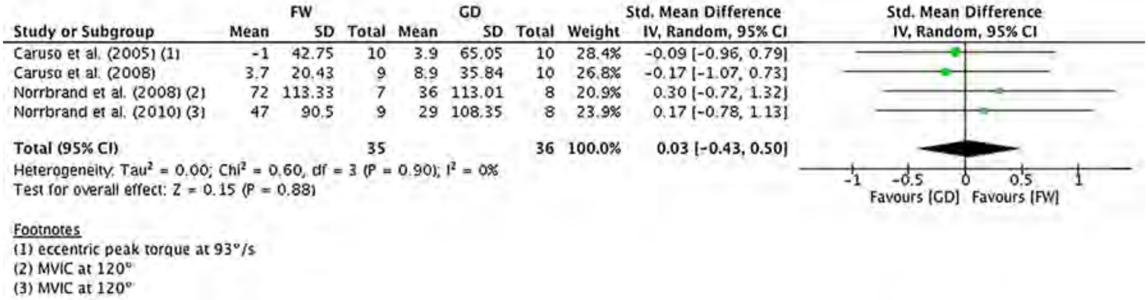


Study or Subgroup	FW Mean	FW SD	FW Total	GD Mean	GD SD	GD Total	Weight	Std. Mean Difference IV, Random, 95% CI
Caruso et al. (2005) (1)	-0.5	33.82	10	5.2	45.16	10	28.3%	-0.14 [-1.01, 0.74]
Caruso et al. (2008)	3.7	20.43	9	8.9	35.84	10	26.8%	-0.17 [-1.07, 0.73]
Norrbrand et al. (2008) (2)	72	113.33	7	36	113.01	8	20.9%	0.30 [-0.72, 1.32]
Norrbrand et al. (2010) (3)	47	90.5	9	29	108.35	8	24.0%	0.17 [-0.78, 1.13]
Total (95% CI)			35			36	100.0%	0.02 [-0.45, 0.49]

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.67$, df = 3 (P = 0.88); $I^2 = 0\%$
Test for overall effect: Z = 0.08 (P = 0.93)

Footnotes
(1) concentric peak torque at 93°/s
(2) MVIC at 120°
(3) MVIC at 120°

b: Strength changes of non-RCTs forest plot (concentric peak torque at $93^{\circ}s^{-1}$)



Study or Subgroup	FW Mean	FW SD	FW Total	GD Mean	GD SD	GD Total	Weight	Std. Mean Difference IV, Random, 95% CI
Caruso et al. (2005) (1)	-1	42.75	10	3.9	65.05	10	28.4%	-0.09 [-0.96, 0.79]
Caruso et al. (2008)	3.7	20.43	9	8.9	35.84	10	26.8%	-0.17 [-1.07, 0.73]
Norrbrand et al. (2008) (2)	72	113.33	7	36	113.01	8	20.9%	0.30 [-0.72, 1.32]
Norrbrand et al. (2010) (3)	47	90.5	9	29	108.35	8	23.9%	0.17 [-0.78, 1.13]
Total (95% CI)			35			36	100.0%	0.03 [-0.43, 0.50]

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.60$, df = 3 (P = 0.90); $I^2 = 0\%$
Test for overall effect: Z = 0.15 (P = 0.88)

Footnotes
(1) eccentric peak torque at 93°/s
(2) MVIC at 120°
(3) MVIC at 120°

c: Strength changes of non-RCTs forest plot (eccentric peak torque at $93^{\circ}s^{-1}$)

Fig. 2. (a) Strength changes (MVIC) of RCTs forest plot. (b) Strength changes of non-RCTs forest plot (concentric peak torque at 93° s^{-1}). (c) Strength changes of non-RCTs forest plot (eccentric peak torque at 93° s^{-1}).

on eccentric peak torque at 60° s^{-1} after FW resistance training might indicate a great stimulus for eccentric adaptations. However, this point remains unclear at this moment since meta-analyses of eccentric measures could not be performed due to lack of studies covering this outcome and eccentric adaptations therefore need further attention in future investigations.

Meta-analysis of other muscular adaptations could not be implemented due to the heterogeneity of type of outcomes from the included studies. Based on post-hoc analyses, both GD and FW resistance training showed medium within-group effect sizes in the increment of the vastus lateralis CSA.[39] For non-RCTs, no within-group effects were found for GD resistance training but small effects were found for FW resistance training in CSA and muscle volume. Similar increases were found in healthy men and women after FW resistance training, such as a 5% in leg muscle mass,[18] a 6% in muscle volume[35] and a 7% in CSA.[36] Other muscular adaptations such fascicle length and pennation angles have been found to be a 10% and 8% increase respectively after 5 weeks of FW resistance training.[36] As it has been demonstrated,[57–60] concentric loading leads to greater muscle pennation angles by adding sarcomeres in parallel, and eccentric loading leads to longer fascicles lengths and decreased pennation angles by adding sarcomeres in series, with disparities between muscle groups. Pennation angles and fascicle lengths adaptations after FW resistance training remain unclear at present. In addition, on behalf of muscle volume and muscle mass, FW resistance training shows some potential but no comparison against GD resistance training can be made at this point. Importantly, considerations regarding (1) the equipment, such as magnetic resonance imaging, computed tomography or ultrasound, used to measure other muscular adaptations, (2) the methodology and (3) reliability of the measures from practitioners are needed in order to obtain valid results and be able to compare muscle adaptations after training interventions.[61]

Based on post-hoc analyses, one of the RCTs[54] analysed the adaptations on muscle activation using EMG-RMS, while another RCT[39] analysed adaptations on the central neural activation using the twitch superimposition technique. While Greenwood et al.[39] found greater central neural activation, Onambélé et al.[54] found reduced muscle activation after FW resistance training. The only non-RCT analysing muscle activation[21] found that FW resistance training increased the vastus lateralis activation (EMG-RMS) while GD resistance training did not. The same study also showed that muscle activity was angle-specific depending on exercise mode. During FW resistance training, the greater muscle activity was present at the eccentric phase (almost isometric at 90°), instead during GD resistance training, the greater muscle activity was present at the concentric phase near full extension at 150°. This greater eccentric muscle activation is indicative of greater mechanical tension during the eccentric phase when using FW compared to GD resistance training, resulting in more robust stimulus promoting enhanced protein synthesis and eventually leading to greater muscle hypertrophy.[21] However, other factors such as nutrition, recovery and the training methods used also need to be considered when assessing muscle hypertrophy.[4,62,63] Other studies confirm the greater muscle activation during FW resistance training[29,36,64] while others do not.[35] Although muscle activity will not explain muscle hypertrophy[65,66] it will explain the intensity of a muscle's contraction. Hence, a combination of muscle activity and muscle hypertrophy outcomes will be needed to monitor both training adaptations.

Although meta-analyses of performance adaptations such as jumping or sprinting were not the aim of this study, two RCTs[22,39] and one non-RCT[24] reported outcomes on performance adaptations. Greenwood et al.[39] showed no difference between groups on vertical jumping performance. de Hoyo et al.[22] showed greater effects after GD than FW resistance training in the counter-movement jump and similar effects in change of direction sprints. Finally, Caruso et al.[24] showed similar adaptations on jumping performances, but the FW group tended to be better on depth jumps involving the longer stretch-shortening cycle, while the GD group tended to be better on a four-jump test, where faster stretch-shortening cycle is needed. It has to be mentioned that this study combined the leg press exercise with a calf press exercise, which may have contributed to the greater performance in a four-jump test. Therefore, further studies giving information regarding the loading protocol (inertia) and the strategy used to stop the FW may be needed in order to better understand adaptations to jumping performance. Other studies in the literature have shown the efficacy of FW resistance training on performance adaptations.[25,27,37] Although more evidence is needed, the potential application of FW resistance training to performance adaptations is promising because of the high level of specificity that can be applied during some tasks. Accordingly, in some sports where decelerations and changes of directions are crucial, FW devices allow to include both bilateral and unilateral exercises with an eccentric emphasis. Furthermore, FW devices such as conic pulleys allow for performance of exercises on a multi-planar accentuation – specifically in the sagittal and transverse planes –, in order to produce performance enhancements.[25]

While FW resistance training produces higher eccentric forces compared to GD resistance training,[21] when an appropriate strategy is used, adverse effects such as injuries or delayed onset of muscle soreness after FW resistance training have not been documented. However, as with any training mode, adverse effects such as delayed onset of muscle soreness can be present but prevented by appropriately progressing the loading scheme.[67] Even though a loading scheme for FW resistance training remains to be established, the subjects can modulate their effort during FW resistance training.[16] As FW resistance training is an accommodated resistance, it also permits to modulate the intensity during the exercise.[16] Therefore FW resistance training is considered to be a safe training mode provided that is supervised by qualified professionals and consistent with the needs, goals and abilities of the subjects.

The main limitations of this study is that a very few RCTs on this subject are published and that a wide range of the participants age exists in the included studies. FW resistance training is a unique training mode that is increasing its popularity among the research community. However, more studies, preferably RCTs, are needed in order to diminish the risk of bias as this will allow researchers to draw more robust conclusions. In addition, more homogeneous research on studies' outcomes, exercise interventions (exercise selection and loading) and subjects' training experience is needed to understand the efficacy of FW resistance training compared to GD resistance training. Certainly, experienced athletes in FW resistance training maximize the benefits of this training by having greater coordination and using an appropriate technique.[29] None of the interventions of the included studies lasted longer than 12 weeks. The short-term nature of those interventions may impede to draw conclusions regarding the long-term effectiveness of FW resistance training. For RCTs, the main source of bias was lack of blinding of participants and outcome assessors. For the non-RCTs, moderate biases were found relating to confounding factors inherent to lack of randomisation, and also the lack of blinding of participants and outcome assessors. Although the inclusion of non-RCTs in the review broadens the spectrum of evidence, the results from the RCTs should be considered the greatest source of evidence.[46] Another limitation of this review with meta-analyses may be the inclusion of power and rate of force development as measures of strength. However, this limitation did not affect any conclusions in relation to the primary outcome (strength), as no data on power was included in the analysis regarding the primary outcome. In the future it may be important not to include measures of strength and power in combination in future updates, and look at these physical qualities separately.

5. Conclusions

This systematic review and meta-analyses showed that inertial flywheel resistance training is not superior to gravity-dependent resistance training on enhancing muscle strength. The conclusion is based upon the current available literature where only three RCTs qualified for meta-analysis. Data for other strength variables and other muscular adaptations were insufficient to draw firm conclusions. We encourage practitioners to try to perform RCTs in order to control for confounding variables and produce a convincing body of evidence. Future research should aim to investigate eccentric strength adaptations and performance and structural adaptations in order to understand the role of inertial flywheel resistance training.

Practical implications

- Inertial flywheel resistance training is not superior to gravity-dependent resistance training for muscle strength improvements.
- Outcomes on eccentric muscle strength, muscle structural and performance adaptations comparing inertial flywheel to gravity-dependent resistance training could not be documented.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2017.10.006.

References

1. Ratamess NA, Brent A, Evetoch T et al. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc* 2009; 41(3):687–708. http://dx.doi.org/10.1249/MSS.0b013e3181915670.
2. Lloyd RS, Faigenbaum AD, Stone MH et al. Position statement on youth resistance training: the 2014 international consensus. *Br J Sports Med* 2014; 48(7):498–505. http://dx.doi.org/10.1136/bjsports-2013-092952.
3. Lesinski M, Prieske O, Granacher U. Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *Br J Sports Med* 2016; 50(13):781–795. http://dx.doi.org/10.1136/bjsports-2015-095497.
4. Wernbom M, Augustsson J, Thome R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sport Med* 2007; 37(3):225–264. http://dx.doi.org/10.2165/00007256-200737030-00004.
5. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Med Sci Sports Exerc* 2004; 36(4):674–688. http://dx.doi.org/10.1249/01.MSS.0000121945.36635.61.
6. Hill A. The heat of shortening and the dynamic constants of muscle. *Proc R Soc B Biol Sci* 1938; 126(843):136–195. http://dx.doi.org/10.1098/rspb.1938.0050.
7. Hortobágyi T, Hill JP, Houmard JA et al. Adaptive responses to muscle lengthening and shortening in humans. *J Appl Physiol* 1996; 80(3):765–772.
8. 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.
9. Douglas J, Pearson S, Ross A et al. Chronic adaptations to eccentric training: a systematic review. *Sport Med* 2016:1–25. http://dx.doi.org/10.1007/s40279-016-0628-4.
10. 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. http://dx.doi.org/10.1136/bjsm.2008.051417.
11. Aagaard P. The use of eccentric strength training to enhance maximal muscle strength, explosive force (RDF) and muscular power – consequences for athletic performance. *Open Sports Sci J* 2010; 3(1):52–55. http://dx.doi.org/10.2174/1875399X01003010052.
12. Folland JP, Williams AG. The adaptations to strength training. *Sport Med* 2007; 37(2):145–168. http://dx.doi.org/10.2165/00007256-200737020-00004.
13. Walker S, Blazevich AJ, Haff GG et al. Greater strength gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. *Front Physiol* 2016; 7:149. http://dx.doi.org/10.3389/fphys.2016.00149.
14. Campos GER, Luecke TJ, Wendeln HK et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur J Appl Physiol* 2002; 88(1–2):50–60. http://dx.doi.org/10.1007/s00421-002-0681-6.
15. Berg HE, Tesch PA. A gravity-independent ergometer to be used for resistance training in space. *Aviat Space Environ Med* 1994; 65(8):752–756.
16. Tesch PA, Fernandez-gonzalo R, Lundberg TR. Clinical applications of iso-inertial. *Resist Exerc* 2017; 8. http://dx.doi.org/10.3389/fphys.2017.00241.
17. Berg HE, Tesch PA. Force and power characteristics of a resistive exercise device for use in space. *Acta Astronaut* 1998; 42(1–8):219–230. http://dx.doi.org/10.1016/S0094-5765(98)00119-2.
18. 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. http://dx.doi.org/10.1007/s00421-014-2836-7.
19. 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(1):37. http://dx.doi.org/10.1186/s12984-016-0144-7.
20. 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. http://dx.doi.org/10.1007/s00421-007-0583-8.
21. 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. http://dx.doi.org/10.1007/s00421-010-1575-7.
22. de Hoyo M, Sañudo B, Carrasco L et al. Effects of traditional versus horizontal inertial flywheel power training on common sport-related tasks. *J Hum Kinet* 2015; 47(1):155–167. http://dx.doi.org/10.1515/hukin-2015-0071.
23. Caruso JF, Hamill JL, Hernandez DA et al. A comparison of isoload and isoinertial leg press training on bone and muscle outcomes. *J Strength Cond Res* 2005; 19(3):592–598.
24. Caruso JF, Coday MA, Ramsey CA et al. Leg and calf press training modes and their impact on jump performance adaptations. *J Strength Cond Res* 2008; 22(3):766–772. http://dx.doi.org/10.1519/JSC.0b013e31816a849a.
25. Gonzalo-Skok O, Tous-Fajardo J, Valero-Campo C et al. Eccentric overload training in team-sports functional performance: constant bilateral vertical vs. variable unilateral multidirectional movements. *Int J Sports Physiol Perform* 2016; 12(7):951–958 https://doi.org/10.1123/ijspp.2016-0251.
26. Tous-Fajardo J, Gonzalo-Skok O, Arjol-Serrano JL et al. 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. http://dx.doi.org/10.1123/ijspp.2015-0010.
27. de Hoyo M, Pozzo M, Sañudo 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. http://dx.doi.org/10.1123/ijspp.2013-0547.
28. de Hoyo M, de la Torre A, Pradas F et al. Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med* 2014; 36(4):308–314. http://dx.doi.org/10.1055/s-0034-1395521.
29. 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.
30. 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* 2016:1. http://dx.doi.org/10.1519/JSC.0000000000001635.
31. Norrbrand L. *Acute and early chronic responses to resistance exercise using flywheel or weights*, Mid Sweden University, 2010.
32. Kompf J, Arandjelović O. Understanding and overcoming the sticking point in resistance exercise. *Sport Med* 2016; 46(6):751–762. http://dx.doi.org/10.1007/s40279-015-0460-2.
33. 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(1-2):44–49. http://dx.doi.org/10.1007/s00421-003-0850-2.
34. Alkner BA, 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(3):345–357. http://dx.doi.org/10.1111/j.1365-201X.2004.01293.x.
35. 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. http://dx.doi.org/10.1046/j.0001-6772.2003.01225.x.
36. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol* 2006; 102(1):368–373. http://dx.doi.org/10.1152/japplphysiol.00789.2006.
37. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sport* 2003; 13(4):244–250. http://dx.doi.org/10.1034/j.1600-0838.2003.00312.x.
38. 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. http://dx.doi.org/10.1016/j.ptsp.2010.10.003.
39. Greenwood J, Morrissey MC, Rutherford OM et al. Comparison of conventional resistance training and the fly-wheel ergometer for training the quadriceps muscle group in patients with unilateral knee injury. *Eur J Appl Physiol* 2007; 101(6):697–703. http://dx.doi.org/10.1007/s00421-007-0548-y.
40. Gual G, Fort-Vanmeerhaeghe A, Romero-Rodríguez D et al. Effects of in-season inertial resistance training with eccentric overload in a sports population at risk for patellar tendinopathy. *J Strength Cond Res* 2016; 30(7):1834–1842. http://dx.doi.org/10.1519/JSC.0000000000001286.
41. Nicol C, Avela J, Komi PV. The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sports Med* 2006; 36(11):977–999.
42. Cormie P, McGuigan MR, Newton RU. Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Med Sci Sports Exerc* 2010; 42(9):1731–1744. http://dx.doi.org/10.1249/MSS.0b013e3181d392e8.
43. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R et al. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport* 2017; 20(10):943–951 https://doi.org/10.1016/j.jsams.2017.03.004.
44. Liberati A, Altman DG, Tetzlaff J et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Ann Intern Med* 2009; 151(4). http://dx.doi.org/10.1371/journal.pmed.1000100.
45. 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(3):g7647. http://dx.doi.org/10.1136/bmj.g7647.
46. Higgins JPT, Green S, editors. *Cochrane handbook for systematic reviews of interventions version 5.1.0.*; 2011. www.handbook.cochrane.org.
47. Jüni P, Altman DG, Egger M. Systematic reviews in health care: assessing the quality of controlled clinical trials. *BMJ* 2001; 323(7303):42–46.
48. Higgins JPT, Altman DG, Gotzsche PC et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ* 2011; 343:d592. http://dx.doi.org/10.1136/bmj.d5928.
49. Sterne JA, Hernán MA, Reeves BC et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ* 2016:i4919. http://dx.doi.org/10.1136/bmj.i4919.

50. Follmann D, Elliott P, Suh I et al. Variance imputation for overviews of clinical trials with continuous response. *J Clin Epidemiol* 1992; 45(7):769–773. http://dx.doi.org/10.1016/0895-4356(92)90054-Q.
51. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. USA, Lawrence Erlbaum Associates, 1988.
52. Higgins JPT, Thompson SG, Deeks JJ et al. Measuring inconsistency in meta-analyses. *BMJ Br Med J* 2003; 327(7414):557–560. http://dx.doi.org/10.1136/bmj.327.7414.557.
53. Hedges LV, Olkin I. Statistical methods for meta-analysis. *J Educ Stat* 1988; 13(1):75. http://dx.doi.org/10.2307/1164953.
54. Onambélé 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. http://dx.doi.org/10.1016/j.jbiomech.2008.09.004.
55. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A et al. Letter to the Editor: skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport* 2017. http://dx.doi.org/10.1016/j.jsams.2017.09.001 [ahead of print].
56. Tesch PA, Trieschmann JT, Ekberg A. Hypertrophy of chronically unloaded muscle subjected to resistance exercise. *J Appl Physiol* 2004; 96(4):1451–1458. http://dx.doi.org/10.1152/japplphysiol.01051.2003.
57. Reeves ND, Maganaris CN, Longo S et al. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol* 2009; 94(7):825–833. http://dx.doi.org/10.1113/expphysiol.2009.046599.
58. 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. http://dx.doi.org/10.1111/apha.12225.
59. Timmins RG, Ruddy JD, Presland J et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. *Med Sci Sports Exerc* 2016; 48(3):499–508 https://doi.org/10.1249/MSS.0000000000000795.
60. Blazevich AJ, Cannavan D, Coleman DR et al. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol* 2007; 103(5):1565–1575. http://dx.doi.org/10.1152/japplphysiol.00578.2007.
61. Kwah LK, Pinto RZ, Diong J et al. Reliability and validity of ultrasound measurements of muscle fascicle length and pennation in humans: a systematic review. *J Appl Physiol* 2013; 114(2013):761–769. http://dx.doi.org/10.1152/japplphysiol.01430.2011.
62. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 2010; 24(10):2857–2872. http://dx.doi.org/10.1519/JSC.0b013e3181e840f3.
63. Schoenfeld BJ. Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sport Med* 2013; 43(3):179–194. http://dx.doi.org/10.1007/s40279-013-0017-1.
64. 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. http://dx.doi.org/10.3357/ASEM.2867.2011.
65. Earp JE, Stucchi DT, DeMartini JK et al. Regional surface electromyography of the vastus lateralis during strength and power exercises. *J Strength Cond Res* 2016; 30(6):1585–1591. http://dx.doi.org/10.1519/JSC.0000000000001405.
66. Narici MV, Hoppeler H, Kayser B et al. Human quadriceps cross-sectional area, torque and neural activation during 6 months strength training. *Acta Physiol Scand* 1996; 157(2):175–186. http://dx.doi.org/10.1046/j.1365-201X.1996.483230000.x.
67. Cheung K, Hume PA, Maxwell L. Delayed onset muscle soreness. *Sport Med* 2003; 33(2):145–164. http://dx.doi.org/10.2165/00007256-200333020-00005.

PUBLICATION II

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

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Jordi Vicens-Bordas
Ernest Esteve
Azahara Fort-Vanmeerhaeghe
Thomas Bandholm
Kristian Thorborg

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Letter to the Editor

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

It is with specific interest that we have read the recent paper "Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis" published in *Journal of Science and Medicine in Sport*.[1] The reason being that we registered a very similar protocol for a systematic review and meta-analysis at PROSPERO on 8 May 2015 (http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42015020337), which is now under review. Such overlap is unfortunate and could have been avoided if the authors had registered their protocol following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analyses Protocols (PRISMA-P)[2] and the PRISMA statement.[3] The lack of a protocol registration preceding a systematic review and meta-analysis is problematic, as it increases the possibility for research duplication, and thus research waste, as individual groups may unknowingly end up performing almost identical systematic reviews.[4] Such issue have been raised by members of our group in the sports medicine literature before.[5]

Interestingly though, the two apparently identical reviews yield very different results.[1,6] More specifically our data do not support the findings that inertial flywheel resistance training is superior promoting muscle strength, muscle power and muscle hypertrophy compared to traditional resistance training as shown in the review by Maroto-Izquierdo et al.,[1] which may be partly explained by the included studies. The primary aim of Maroto-Izquierdo et al. was to compare flywheel training-induced adaptations with those triggered by traditional resistance exercise interventions. The main concern is that 6 out of 9 of the studies included in the systematic review cannot answer this question, as no traditional resistance training group was used as a comparator.[7–12] Furthermore, the meta-analysis is supposed to be performed on randomised controlled trials, but when looking at the individual studies, one of them is not a randomised controlled trial.[11] In this regard we would like to highlight that combining the results in a meta-analysis from randomised and non-randomised controlled trials is not recommended by the Cochrane Handbook of Systematic Reviews of Interventions,[13] as greater heterogeneity and higher risk of bias are present in non-randomised trials. Additionally, Maroto-Izquierdo specified in their systematic review that an article was only eligible if it was published in a peer-reviewed journal. Despite this, a randomised controlled trial from Maroto-Izquierdo[14] was included although it was not published and could not be found in any database at the moment of search.

While we commend the increased attention to inertial flywheel technology, we believe the methodological shortcomings in the article by Maroto-Izquierdo et al.[1] does not provide us with any confidence in the conclusion — that inertial flywheel resistance training is superior to traditional weight stack exercise, to promote skeletal muscle adaptations in terms of strength, power and size in healthy subjects and athletes. To further support this claim we have therefore decided to submit our systematic review[6] to the same journal with the hope that this letter will eventually be brought alongside both articles on the subject for others to evaluate and critically appraise — so that valid conclusions on the use of specific strength training equipment can be drawn upon Level 1 data using relevant comparators.

Acknowledgments

All authors have contributed substantially to the conception, design and drafting of this letter, and/or revising it critically for important intellectual content, as well as approval of the final version.

References

1. Maroto-Izquierdo S, García-López D, Fernandez-Gonzalo R et al. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *J Sci Med Sport* 2017; 20(10). http://dx.doi.org/10.1016/j.jsams.2017.03.004.
2. 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(3):g7647. http://dx.doi.org/10.1136/bmj.g7647.
3. Moher D, Liberati A, Tetzlaff J et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA Statement. *Open Med* 2009; 3(3):e123–e130.
4. Lund H, Brunnhuber K, Juhl C et al. Towards evidence based research. *BMJ* 2016; 355:1–5. http://dx.doi.org/10.1136/bmj.i5440.
5. Thorborg K, Krommes K, Esteve E et al. High risk of bias and low transparency in "How effective are F-MARC injury prevention programs for soccer players? A systematic review and meta-analysis. *Sport Med* 2016; 46(2):293–294. http://dx.doi.org/10.1007/s40279-015-0458-9.
6. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A et al. Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. *J Sci Med Sport* 2017 (in preparation).
7. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sport* 2003; 13(4):244–250. http://dx.doi.org/10.1034/j.1600-0838.2003.00312.x.
8. 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. http://dx.doi.org/10.1046/j.0001-6772.2003.01225.x.
9. 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* 2013:1. http://dx.doi.org/10.1519/JSC.0b013e3182a993c2.
10. Naczk M, Brzenczek-Owczarzak W, Arlet J et al. Training effectiveness of the inertial training and measurement system. *J Hum Kinet* 2014; 44(1):19–28. http://dx.doi.org/10.2478/hukin-2014-0107.
11. de Hoyo M, Pozzo M, Sañudo 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. http://dx.doi.org/10.1123/ijspp.2013-0547.

http://dx.doi.org/10.1016/j.jsams.2017.09.001

12. 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.
13. Higgins JPT, Green S (Editors). *Cochrane Handbook for Systematic Reviews of Interventions Version 5.1.0*; 2011. www.handbook.cochrane.org.
14. Maroto-Izquierdo S, Garcia-Lopez D, De Paz JA. Functional and muscle-size effects of flywheel resistance training with eccentric overload in professional handball players. *J Hum Kinet* ahead of print 2017; http://dx.doi.org/10.1515/hukin-2017-0096.

J. Vicens-Bordas [a,b,*]
[a] *School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Spain*
[b] *Sportclínic, Physiotherapy and Sports Training Centre, Girona, Spain*

E. Esteve [a,b]
[a] *School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Spain*
[b] *Sportclínic, Physiotherapy and Sports Training Centre, Girona, Spain*

A. Fort-Vanmeerhaeghe [a,b]
[a] *School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Spain*
[b] *Blanquerna Faculty of Psychology, Education Sciences and Sport (FPCEE), Universitat Ramon Llull, Barcelona, Spain*

T. Bandholm
Physical Medicine & Rehabilitation Research — Copenhagen (PMR-C), Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Clinical Research Center, Amager-Hvidovre Hospital, Copenhagen University, Hvidovre, Denmark

K. Thorborg [a,b]
[a] *Physical Medicine & Rehabilitation Research — Copenhagen (PMR-C), Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Clinical Research Center, Amager-Hvidovre Hospital, Copenhagen University, Hvidovre, Denmark*
[b] *Sports Orthopedic Research Center, Arthroscopic Centre Amager, Amager-Hvidovre Hospital, University of Copenhagen, Hvidovre, Denmark*

[*] Corresponding author.
E-mail address: jvicensbordas@gmail.com
(J. Vicens-Bordas)

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PUBLICATION III

Eccentric hamstring strength is associated with age and duration of previous season hamstring injury in male soccer players

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Jordi Vicens-Bordas
Ernest Esteve
Azahara Fort-Vanmeerhaeghe
Thomas Bandholm
Mikkel Bek Clausen
Anthony Shield
David Opar
Kristian Thorborg

IJSPT

ORIGINAL RESEARCH

ECCENTRIC HAMSTRING STRENGTH IS ASSOCIATED WITH AGE AND DURATION OF PREVIOUS SEASON HAMSTRING INJURY IN MALE SOCCER PLAYERS

Jordi Vicens-Bordas, MSc[1-3]
Ernest Esteve, PT, MSc[1,2]
Azahara Fort-Vanmeerhaeghe, PhD[4]
Mikkel Bek Clausen, PT, PhD[5,6]
Thomas Bandholm, PT, PhD[7]
David Opar, PhD[8]
Anthony Shield, PhD[9]
Kristian Thorborg, PT, PhD[5,7]

ABSTRACT

Background: Eccentric hamstring strength seems important in reducing the odds of future hamstring injuries. While age and previous injury are well-known risk factors for future hamstring injuries, the association of age and previous hamstring injury with eccentric hamstring strength in the following season is unknown.

Purpose: To investigate the association of age and previous hamstring injury with preseason eccentric hamstring strength in soccer players, and to investigate the association between previous hamstring injury duration and preseason eccentric hamstring strength.

Study design: Descriptive, cross-sectional study

Methods: A convenience sample of 284 male amateur soccer players (age 18-38 years) was included in the analyses. Self-reported information about previous season hamstring injury and its duration (three weeks or less; more than three weeks) was collected. Preseason eccentric hamstring strength was obtained during the Nordic hamstring exercise using a field-based device.

Results: Age had a negative association with preseason eccentric hamstring strength with 0.9% reduction per year. Players with a previous hamstring injury duration of more than three weeks (n = 27) had 13% lower preseason eccentric hamstring strength compared to players without previous hamstring injury.

Conclusion: Older players have lower preseason eccentric hamstring strength than younger players. Players with a previous hamstring injury duration of more than three weeks have lower preseason eccentric hamstring strength than the rest of the players. These results highlight the need to monitor and address the identified weaknesses in eccentric hamstring strength in amateur soccer players, with specific emphasis on older players with a previous hamstring injury of longer duration.

Level of evidence: 2b

Keywords: knee-flexor, muscle injuries, hamstrings, performance, football

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[1] Sportclinic. Physiotherapy and Sports Training Centre. Girona, Catalonia, Spain
[2] School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Catalonia, Spain.
[3] Research Group of Clinical Anatomy, Embriology and Neuroscience (NEOMA), Department of Medical Sciences, Universitat de Girona (UdG), Girona, Catalonia, Spain.
[4] Faculty of Psychology, Education Sciences and Sport (FPCEE) and School of Health Sciences (FCS) Blanquerna, Universitat Ramon Llull, Barcelona, Catalonia, Spain
[5] Sports Orthopedic Research Center - Copenhagen (SORC-C), Department of Orthopedic Surgery, Amager-Hvidovre Hospital, University of Copenhagen, Denmark
[6] Bachelor's Degree Programme in Physiotherapy, Department of Physiotherapy and Occupational Therapy, Faculty of Health and Technology, Metropolitan University College, Denmark
[7] Physical Medicine and Rehabilitation Research – Copenhagen (PMR-C), Clinical Research Center, Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Amager-Hvidovre Hospital, Copenhagen University Hospital, Denmark
[8] School of Exercise Sciences, Australian Catholic University, Melbourne, Australia
[9] Faculty of Health, School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia; and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

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CORRESPONDING AUTHOR

Jordi Vicens-Bordas
School of Health and Sport Sciences (EUSES),
Universitat de Girona.
Carrer de Francesc Macià, 65, 17190 Salt
(Girona), Catalonia, Spain.
E-Mail: jvicensbordas@gmail.com

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INTRODUCTION

Eccentric hamstring weakness has been identified as a risk factor for future hamstring strain injury (HSI) in sports with high intensity running demands, such as soccer[1] and Australian rules football (AFL).[2] Recently, a device has been developed to measure eccentric hamstring strength during the Nordic hamstring exercise (NHE).[3] In a large prospective study including 152 professional soccer players assessed using the NHE device, those with eccentric hamstring strength below 4.35 $N \cdot kg^{-1}$ were 4.4 times more likely (RR; 95% CI 1.1 to 17.5) to sustain an HSI in the following season compared to stronger players.[1] In contrast, no association between eccentric hamstring weaknessess and hamstring injury risk was found in a cohort of 413 professional Qatari soccer players who were assessed using the NHE device.[4] Univariate analysis of eccentric hamstring strength may not predict future HSI,[4] but it seems that multivariate analyses including age, previous hamstring injury, and reduced levels of eccentric hamstring strength may identify players at a greater risk of future HSI.[1] Measuring preseason eccentric hamstring strength in amateur soccer players and identifying those with poorer results may have some merit.

Age[4–6] and previous hamstring injury[7] have often been linked to future HSI. Professional soccer players older than 23 years have been reported to be at an elevated risk of sustaining an HSI[6] and each year of age has been reported to increase the risk of sustaining an HSI up to 1.8-fold (OR; 95% CI 1.2 to 2.7) in English Premier League soccer players.[5] This apparent effect of age on injury risk could, at least in part, be due to age related changes in hamstring strength. However, the impact of age on eccentric hamstring strength has not previously been investigated in soccer players at any level.

While the effects of a previous HSI on eccentric hamstring strength have been addressed in the literature,[8] most of the studies have been performed in mixed groups of athletes, with small sample sizes and have used isokinetic dynamometry to examine strength. Furthermore, previous studies have not accounted for injury severity.[8] Players with previous HSI may present persistent biceps femoris long head muscle atrophy,[9,10] and neuromuscular inhibition.[7,11] This may limit the effectiveness of the rehabilitation process and thereby increase the risk of re-injuries,[7] due to persistent inadequate muscle structure and/or function. Accordingly, the observed activation and strength deficits during eccentric actions remain present despite apparently successful rehabilitation and return to pre-injury levels of training and match play.[12] As a consequence, it is plausible that a hamstring injury sustained in the previous season could negatively influence eccentric hamstring strength at the beginning of the next season. Presently, however, the association of a previous hamstring injury with eccentric hamstring strength in the following season is unknown.

The purpose of the present study was to investigate the association of age and previous hamstring injury with preseason eccentric hamstring strength in soccer players. The secondary purpose was to investigate the association between previous hamstring injury duration and preseason eccentric hamstring strength.

MATERIALS AND METHODS

Design and participants

This study employed a cross-sectional exploratory and descriptive design and includes data from a large cohort study investigating hamstring and groin injuries, self-reported outcome and muscle strength in amateur male soccer players.[13]

The reporting of the present study follows the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) statement, using the checklist for cross-sectional studies.[14] Male players (n = 363) from a convenience sample of 17 sub-elite soccer teams from the northeast of Spain, competing in the 3rd national and the 1st and 2nd regional divisions (4th to 6th tier), were screened for eligibility. Players from those teams performed the baseline testing during the preseason (July-August 2015). Players were included if they were over 18 years of age, were free from current hamstring injury, were able to participate in a training session on the day of testing, could understand Catalan or Spanish, provided written informed consent and completed all testing procedures. This study was approved by a regional ethics committee (Consell Català de l'Esport, approval number = 08/2015CEICEGC).

Testing procedure

Three members of the research team who were trained in the measurement procedures, one physiotherapist (insert initials) and two sport scientists (insert initials), performed all the baseline measurements at the respective team facilities. Team physiotherapists, physical trainers and members of the technical staff of the respective teams collaborated in the assessments, providing questionnaires and forms and helping to conduct the standardized warm-up, which consisted of low intensity shuttle runs and active lower limb mobility exercises. Players were asked to arrive 90 minutes before the start of a regular preseason training session to perform the test battery.

Using a standardized form, players provided personal information (date of birth) and data on current hamstring injury (Yes; No), previous season hamstring injury (Yes; No), previous season hamstring injury duration in week ranges (three weeks or less; more than three weeks; as a possible surrogate measure of injury severity), side of injury (right; left). Additionally, weight and height were measured and registered for each player.

The NHE device, previously assessed for reliability (0.83-0.90 ICC and 5.8-8.5% CV),[3] was used for the assessment of eccentric hamstring strength. Participants knelt on a padded board, with the ankles secured superior to the lateral malleolus by individual ankle braces attached to custom-made uniaxial load cells (Delphi Force Measurement, Gold Coast, Australia). Immediately before testing, players were provided with a demonstration of the NHE by the investigators. After a three-repetition warm-up set and one minute of rest, participants were asked to perform one set of three maximal repetitions of the NHE. Participants were instructed to gradually lean forward at the slowest possible speed while maximally resisting this movement with both limbs while keeping the trunk and hips in a neutral position throughout, and the hands held across the chest.[3] Standardized verbal encouragement was given throughout the range of motion to ensure maximal effort. The investigators closely monitored all trials to ensure proper technique, which, if considered invalid, additional trials were allowed. The results were only visible to the outcome assessor during the testing and were shown to the player after the completion of all testing. All eccentric strength testing was performed in a rested state before the team training session.

Data analysis

Force data for both limbs during the NHE were logged to a personal computer at 100Hz through base station receiver (Mantracourt, Devon, UK). Peak force for each of the three repetitions was averaged for all statistical comparisons. Average of both legs was analyzed and reported normalized to body weight ($N \cdot kg^{-1}$). Inter-limb asymmetry was analyzed using the formula: (strongest limb-weakest limb)/ Total (sum of both limbs); noting that this has been suggested as an appropriate method for computing inter-limb differences from bilateral tests.[15]

Statistical analysis

For descriptive statistics, means and standard deviations (SD) were used for continuous variables, while numbers (percentages) were used for dichotomous variables. Simple linear regression models were performed to investigate the differences in preseason eccentric hamstring strength on soccer players including 1) age, 2) previous season hamstring injury, and 3) hamstring injury duration of three weeks or less and more than three weeks. Preseason eccentric hamstring strength was included as the dependent variable, while age, previous season hamstring injury and hamstring injury duration, respectively, were included as the independent variables of interest. Moreover, two standard multiple regressions were performed for previous season hamstring injury and hamstring injury duration, including age as covariate. Confidence intervals were set at 95% for all analyses. All the assumptions for all regression models were met. Estimates of the differences in eccentric hamstring strength were presented as absolute mean differences and percentages –by dividing the absolute mean difference by the estimated mean of the reference group. All statistical analyses were performed using SPSS v22.0.0.1 (IBM Corporation, Chicago, IL). Players with incomplete data, due to time constraints during testing or not completing three valid repetitions for other reason were not included in the analyses. Hence, data were analyzed as complete cases (no imputation of missing data). Information regarding missing data are provided in Figure 1.

RESULTS

In total, 284 amateur male players were included in the analyses (age = 23 ± 4years; weight = 74.0 ± 7.8kg; height = 178.3 ± 6.4cm; see Table 1 and Figure 1). Twenty-two players did not complete testing and were not included in the analyses. From the 284 players, 56 (19.7%) had sustained a hamstring injury in the previous season. From those injured players, 29 (51.8%) reported having a hamstring injury duration of three weeks or less, whereas 27 players (48.2%) reported having a hamstring injury of more than three weeks. Between limb asymmetry was present in both injured and uninjured groups (Table 1).

Age had a significant negative association with pre-season eccentric hamstring strength with a mean reduction of 0.9% per year increase in player's

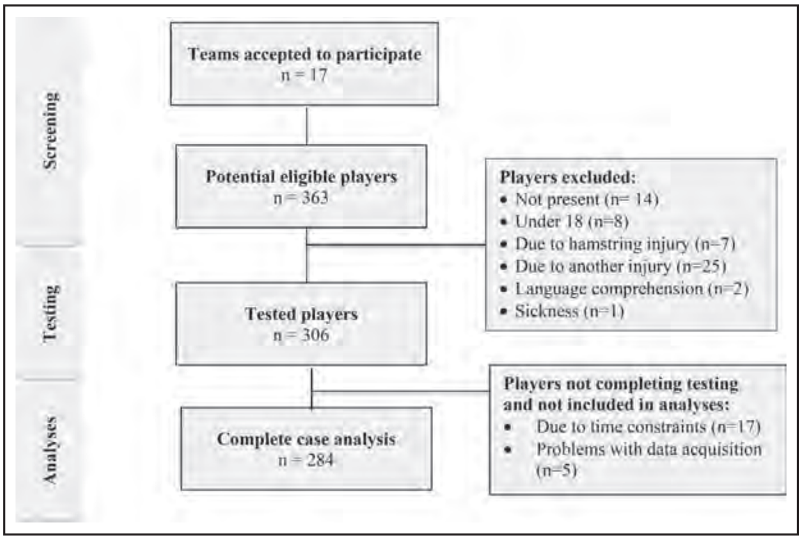

Figure 1. *Flowchart of participants.*

Table 1. *Descriptives (Mean ± SD) for age, weight, height and eccentric hamstring strength.*

	No hamstring injury	Previous hamstring injury	Duration ≤ 3 weeks	Duration > 3 weeks
N (%)*	228 (80.3)	56 (19.7)	29 (10.2)	27 (9.5)
Age (years)	23 ± 4	24 ± 4	23 ± 4	25 ± 5
Weight (kg)	74.2 ± 7.8	73.5 ± 7.8	73.9 ± 7.0	73.0 ± 8.6
Height (cm)	178.1 ± 6.1	178.7 ± 7.5	178.4 ± 7.5	179.0 ± 7.5
Eccentric hamstring strength ($N \cdot kg^{-1}$)				
Average	4.40 ± 1.01	4.09 ± 0.97	4.34 ± 1.02	3.83 ± 0.85
Injured limb	-	4.05 ± 1.14	4.43 ± 1.10	3.82 ± 1.12
Non-injured limb	-	3.92 ± 1.12	4.15 ± 1.07	3.71 ± 1.05
Right	4.47 ± 1.00	4.12 ± 1.03	4.41 ± 1.14	3.87 ± 1.01
Left	4.33 ± 1.10	4.01 ± 0.97	4.26 ± 1.00	3.79 ± 1.02
Asymmetries between limbs	5% ± 5%	6% ± 5%	2% ± 6%	1% ± 5%

* Percentage of total participants (n=284)

Table 2. *Estimates from simple linear regressions of age, previous hamstring injury and hamstring injury duration.*

		B	(95% CI)	*p-value*
1a	Constant	5.51	(4.81 to 6.21)	<.001
	Age	-0.05	(-0.08 to -0.02)	.001**
1b	Constant	4.40	(4.27 to 4.53)	<.001
	Previous hamstring injury	-0.31	(-0.60 to -0.01)	.041*
1c	Constant	4.40	(4.27 to 4.53)	<.001
	Duration of 3 weeks or less	-0.06	(-0.45 to 0.33)	.749
	Duration of more than 3 weeks	-0.57	(-0.97 to -0.017)	.005**

N=284
* p<0.05; **p<0.01

age (Table 2, 1a; Figure 2). Players with previous hamstring injury had 7% lower preseason eccentric hamstring strength compared to players with no previous hamstring injury (Table 2, 1b). When adjusting for age (Table 3, Model A), players with a previous hamstring injury had a non-significant difference (5%) in preseason eccentric hamstring strength compared to players with no previous hamstring injury.

Players with hamstring injury duration of more than three weeks had 13% lower preseason eccentric hamstring strength compared to players with no previous hamstring injury (Table 2, 1c). When adjusting for age (Table 3, Model B), players with a hamstring injury duration of more than three weeks had 9% lower preseason eccentric hamstring strength compared to players with no previous hamstring injury. Players with a hamstring injury duration of three weeks or less had no difference in preseason eccentric hamstring strength compared to players with no previous hamstring injury in any of the analyses (Table 2, 1c; and Table 3, Model B).

DISCUSSION

This study is the first to investigate how age and previous season hamstring injury are associated with preseason eccentric hamstring strength in a large cohort of male amateur soccer players using an on-field and time-efficient testing device (the NHE device). The most important findings of this study are the negative association of age and previous hamstring injury duration (more than three weeks) with preseason eccentric hamstring strength.

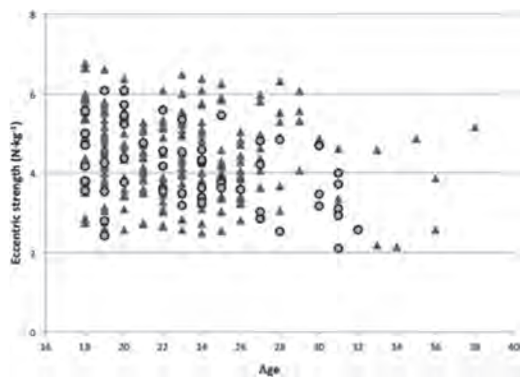

Figure 2. *Scatter plot of age (years) and eccentric hamstring strength (N·kg-1). Triangles represent individual players without previous hamstring injury; circles represent individual players with previous hamstring injury.*

Estimates revealed that a 0.9% decrease in strength could be expected for a year increase in player age. This is a small but important association, considering that in 10 years of age difference, a reduction of 9% on preseason eccentric hamstring strength may be present (0.5N·kg^{-1} or 37N for a 74kg soccer player). Moreover, players with a hamstring injury duration of more than three weeks had 9% lower preseason eccentric hamstring strength compared to players with no previous hamstring injury. Taking these results together, older and previously injured soccer players had even lower preseason eccentric hamstring strength compared to younger and non-injured counterparts. These results are relevant since prospective studies have shown that higher

Table 3. *Estimates from multiple regressions of previous hamstring injury and duration including age as a covariate.*

		B	(95% CI)	*P-value*
Model A	Constant	5.51	(4.81 to 6.20)	<.001
	Age	-0.05	(-0.08 to -0.02)	.002**
	Previous hamstring injury	-0.27	(-0.56 to 0.02)	.072
Model B	Constant	5.45	(4.79 to 6.17)	<.001
	Age	-0.05	(-0.08 to -0.02)	.003**
	Duration of 3 weeks or less	-0.06	(-0.44 to 0.32)	.755
	Duration of more than 3 weeks	-0.49	(-0.89 to -0.10)	.015**

N=284
*p<0.05; **p<0.01

levels of eccentric hamstring strength were important in older and previously injured soccer[1] and AFL[2] players to reduce the odds of sustaining future HSI injuries.

Hamstring strength deficits after a hamstring injury have been addressed in the literature before,[8] however, those studies were performed in a mixed group of athletes, with smaller sample sizes, and using other testing devices such isokinetic dynamometry. Furthermore, previous studies have not accounted for any possible impact of prior injury severity. The current data showing the negative association of age with preseason eccentric hamstring strength in amateur soccer players is a novel finding. Although increasing age has been identified as a potential risk factor for HSI in soccer players[5,6] no convincing explanation has been given as to why older players are at significantly greater risk than younger players.[7] The results of the present study, showing a decrease in strength related to increasing age, may partly explain the increased risk of future HSI in older soccer players.[5,6] Also, this relationship between reduced eccentric hamstring strength and age could be also explained by a longer exposure to soccer or history of several HSIs (preceding the previous season), which has not been recorded in this study. Furthermore, the impact of age on eccentric hamstring strength may be greater in amateur than professional soccer players given that the former are less likely to engage in frequent and supervised strength training. Future investigations should consider prioritising serial monitoring of hamstring eccentric strength during the season to establish trends and the relationship between strength other variables such as training load.

Previous hamstring injury duration of more than three weeks was associated with low preseason eccentric hamstring strength, regardless of player age in the present study. Conversely, previous hamstring injuries of shorter duration did not affect eccentric hamstring strength. This finding is supported by previous studies linking injury duration, which is likely a surrogate measure for injury severity, to a higher degree of neuromuscular maladaptation (neuromuscular inhibition, selective hamstring atrophy, and shifts in the torque-joint angle relationships) and consequently an increased deficit in eccentric hamstring strength.[7,9–11] Hence, looking at hamstring injury duration instead of previous hamstring injury may be a more relevant approach to classify amateur soccer players with suspected lower levels of eccentric hamstring strength and greater propensity to sustain future HSI in the new season.

The existing evidence regarding the deficits in eccentric hamstring strength after an HSI is mixed,[8] perhaps partly because a diversity of methods are used and heterogeneous populations are compared. One previous study has used the NHE device to measure eccentric hamstring strength in professional AFL players.[16] Players with previous HSI displayed higher eccentric hamstring strength compared to players without HSI at preseason testing.[16] The differences between these findings may be related to training practices, as professional AFL players may have more strictly supervised rehabilitation programs than amateur soccer players. We would assume that a vast majority of professional AFL players might be performing intense eccentric hamstring strength exercises during rehabilitation[17] while most amateur soccer players may not.

Eccentric hamstring strength can be improved through strength exercises[18] and intervention studies suggest that eccentric hamstring exercises are effective at improving strength,[19,20] hamstring muscle volume and cross-sectional area[20] and fascicle length in the long head of the biceps femoris.[20] Performing eccentric hamstring exercises such as the NHE reduces the risk of future HSI in both amateur[21,22] and professional soccer players,[21] possibly as a consequence of increased eccentric hamstring strength and also neuromuscular and architectural adaptations. Those studies revealed that HSI incidence, but not severity, can be reduced to approximately one-third of those in control teams by an NHE intervention.[21,22] Moreover, previously injured players who employed the NHE were approximately six times less likely to suffer a recurrence than previously injured players from control teams.[21] These results may give an insight into previous findings, since a decrease in eccentric hamstring strength following a hamstring injury duration of more than three weeks is likely to be carried into the following season unless it is countered by the implementation of adequate reconditioning.

Considering that training loads may also be a crucial component for injury risk management,[23] it seems that stronger and fitter players better tolerate high increases in training load[24] which highlights the importance of assessing players strength levels at the beginning of the season. Interestingly, the present study found that amateur soccer players with a previous history of hamstring injury of more than three weeks had reduced eccentric hamstring strength at the beginning of a soccer season, while eccentric hamstring strength was also lower in older amateur soccer players. Importantly, those two factors are not exclusive, meaning that older soccer players with a history of hamstring injury will present with even more accentuated decrements in eccentric hamstring strength. Altogether, those findings highlight the importance of monitoring eccentric strength and implementing adequate conditioning emphasising older players and players with a more severe hamstring injury history.

It should be acknowledged that some limitations are present in the current study. First, the retrospective recollection of injury history limits the accuracy of the data on injury duration. Recall bias associated with the use of a self-reported injury history questionnaire from the previous season may be present. However, in order to minimize recall bias, the injury form comprised a small number of simple questions including a clear definition of injury and also details in relation to anatomical regions, which has shown to result in better recall.[25] Furthermore, we also limited the time-frame of injury reporting to 12 months, since this has been shown to reduce the impact of recall bias.[26]

CONCLUSIONS

Amateur soccer players with a hamstring injury of more than three weeks in the previous season present with lower eccentric hamstring strength at the beginning of the soccer preseason. Moreover, increasing age is associated with a decrease in eccentric hamstring strength in amateur soccer players. These results highlight the need to monitor and consequently address identified weaknesses in eccentric hamstring strength in amateur football players, with specific emphasis on older players with a previous hamstring injury of longer duration.

REFERENCES

1. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2015;bjsports-2015-095362.
2. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med Sci Sports Exerc*. 2015;47(4):857-865.
3. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther*. 2013;43(9):636-640.
4. van Dyk N, Bahr R, Burnett AF, et al. A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: a prospective cohort study of 413 professional football players. *Br J Sports Med*. 2017;51(23):1695-1702.

5. Henderson G, Barnes CA, Portas MD. Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *J Sci Med Sport*. 2010;13(4):397-402.
6. Woods C, Hawkins RD, Maltby S, et al. The Football Association Medical Research Programme: an audit of injuries in professional football -analysis of hamstring injuries. *Br J Sports Med*. 2004;38(1):36-41.
7. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. *Sport Med*. 2012;42(3):209-226.
8. Maniar N, Shield AJ, Williams MD, Timmins RG, Opar DA. Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. *Br J Sports Med*. 2016;50(15):909-920.
9. Croisier J-L. Factors associated with recurrent hamstring injuries. *Sport Med*. 2004;34(10):681-695.
10. Silder A, Heiderscheit BC, Thelen DG, Enright T, Tuite MJ. MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiol*. 2008;37(12):1101-1109.
11. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*. 2013;23(3):523-530.
12. Bourne MN, Opar DA, Williams MD, Al Najjar A, Shield AJ. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scand J Med Sci Sport*. 2016;26(6):666-674.
13. Esteve E, Rathleff MS, Vicens-Bordas J, et al. Preseason adductor squeeze strength in 303 Spanish male soccer athletes: a cross-sectional study. *Orthop J Sport Med*. 2018;6(1):232596711774727.
14. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol*. 2008;61(4):344-349.
15. Bishop C, Read P, Lake J, Chavda S, Turner A. Effects of inter-limb asymmetries on physical and sports performance: A systematic review. *Strength Cond J*. 2018;36:1135-1144.
16. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. The effect of previous hamstring strain injuries on the change in eccentric hamstring strength during preseason training in elite Australian footballers. *Am J Sports Med*. 2015;43(2):377-384.
17. Pizzari T, Wilde V, Coburn P. Management of hamstring muscle strain injuries in the Australian Football League (AFL): A survey of current practice. *J Sci Med Sport*. 2010;13:e76.
18. Bourne MN, Timmins RG, Opar DA, et al. An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sport Med*. 2017.
19. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand J Med Sci Sport*. 2003;13(4):244-250.
20. Bourne MN, Duhig SJ, Timmins RG, et al. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *Br J Sports Med*. 2016:bjsports-2016-096130.
21. Petersen J, Thorborg K, Nielsen MB, Budtz-Jørgensen E, Hölmich P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *Am J Sports Med*. 2011;39(11):2296-2303.
22. van der Horst N, Smits D-WW, Petersen J, Goedhart EA, Backx FJG. The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *Am J Sports Med*. 2015;43(6):1-8.
23. Gabbett TJ. The training-injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*. 2016:1-9.
24. Malone S, Hughes B, Doran DA, Collins K, Gabbett TJ. Can the workload–injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *J Sci Med Sport*. 2018;22(1):29-34.
25. Askling C, Lund H, Saartok T, Thorstensson A. Self-reported hamstring injuries in student-dancers. *Scand J Med Sci Sports*. 2002;12(4):230-235.
26. Gabbe BJ. How valid is a self reported 12 month sports injury history? *Br J Sports Med*. 2003;37(6):545-547.

PUBLICATION IV

Performance changes during the off-season period in football players – effects of age and previous hamstring injury

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Jordi Vicens-Bordas
Ernest Esteve
Azahara Fort-Vanmeerhaeghe
Martí Casals
Thomas Bandholm
Lasse Ishøi
Anthony Shield
David Opar
Kristian Thorborg

Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, Casals M, Bandholm T, Ishoi L, Opar D, Shield A, Thorborg K. "Performance changes during the off-season period in football players – effects of age and previous hamstring injury". *J Sports Sci*. (July 2020) : 1-11. doi: 10.1080/02640414.2020.1792160

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Abstract

The aims of this study were to investigate changes in selected performance measures during an off-season period, their association, and the potential role of age and previous hamstring injury in semi-professional and amateur football players. Seventy-four male players (age: 25 ± 4 years, stature: 178.0 ± 6.6 cm, body mass: 74.9 ± 8.1 kg) were assessed at the beginning and end of the off-season summer-period for sprint, change-of-direction performance and eccentric hamstring strength. Small to medium increases in sprint times were observed at 5 ($d = 0.26$, $p = 0.057$), 10 ($d = 0.42$, $p < 0.001$) and 30 m ($d = 0.64$, $p < 0.001$). Small ($d = -0.23$, $p = 0.033$) improvements were observed for COD performance, and no changes in eccentric hamstring strength ($d = 0.10$, $p = 0.317$). The changes in the outcomes were not affected by age ($p = 0.449$ to 0.928) or previous hamstring injury ($p = 0.109$ to 0.995). The impaired sprint performance was not related to changes in eccentric hamstring strength ($r = -0.21$ to 0.03, $p = 0.213$ to 0.856), instead, changes in COD performance were associated with changes in eccentric hamstring strength ($r = -0.42$, $p = 0.008$).

Keywords:

Soccer; injury prevention; detraining; transition period; pre-season

PUBLICATION V

Performance improvements after a short-term off-season training program in semi-professional footballers: the design of a randomised-controlled trial. A comparison of inertial flywheel and gravity-dependent resistance training methods

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Jordi Vicens-Bordas
Azahara Fort-Vanmeerhaeghe

Open Science Framework *doi: 10.17605/OSF.IO/G8YBQ*

Intervention protocol

Title

Performance improvements after a short-term off-season training program in semi-professional footballers: the design of a randomised-controlled trial. A comparison of inertial flywheel and gravity-dependent resistance training methods

Authors

Jordi Vicens-Bordas[1-3]; Azahara Fort-Vanmeerhaeghe[4]

Affiliations

[1]Sport and Physical Activity Studies Centre (CEEAF), University of Vic – Central University of Catalonia (UVic-UCC), Spain

[2]Research Group of Clinical Anatomy, Embryology and Neuroscience (NEOMA), Department of Medical Sciences, Universitat de Girona, Girona, Spain

[3]School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Spain.

[4]Department of Sports Sciences, Ramon Llull University, FPCEE and FCS Blanquerna, Barcelona, Spain

Corresponding author:
Jordi Vicens-Bordas
University of Vic – Central University of Catalonia (UVic-UCC)
Carrer de la Sagrada Família, 7, 08500 Vic, Barcelona, Spain.
E-Mail: jordi.vicens@uvic.cat

Figures: 1
Tables: 3

Background

Professional football has experienced an increase in technical and physical demands over the past 13 years (Bradley et al., 2016), with players experiencing an increase in high-intensity actions during matches such as sprinting and changes of direction (COD) (Ade, Fitzpatrick, & Bradley, 2016; Barnes, Archer, Hogg, Bush, & Bradley, 2014). While most of the football research is looking at performance changes during the in-season period in football, very few studies are focusing on the changes during the off-season period. Most of the football players will consider the off-season as a break, mainly recovering from the high physical and psychological demands of the competitive period (9-10 months) (Silva, Brito, Akenhead, & Nassis, 2016). However, a complete cessation or near absence of training stimuli may not be the most appropriate action for players (Silva et al., 2016) since the lack of sport-specific training during this period will impair football players' performance (Silva et al., 2016). Studies showed decrements in sprinting (-1 to -3%) (Caldwell & Peters, 2009; Koundourakis et al., 2014; Nakamura, Suzuki, Yasumatsu, & Akimoto, 2012; Vicens-Bordas et al., 2020) and COD (-2%) (Caldwell & Peters, 2009) performances following the off-season period. Instead, no decrements in COD performance (d = 0.26), and no decrements in eccentric hamstring strength were shown in amateur and semi-professional football players following non-supervised off-season practices (Vicens-Bordas et al., 2020). Instead, no decrements in sprinting or jumping performances were shown, after the inclusion of aerobic and strength and power sessions in elite football players (Requena et al., 2017), which highlights the importance of implementing training interventions during this period.

Strength training interventions should pursue a twofold objective, to increase strength, power and athletic performance (Suchomel, Nimphius, & Stone, 2016) and also to reduce the risk of injuries (Bourne et al., 2017; Lauersen, Andersen, & Andersen, 2018; Lauersen, Bertelsen, & Andersen, 2014). Several resistance training methods, including a variety of gravity-dependent exercises (traditional, ballistic, plyometrics and Olympic-lifting), have been proved effective at improving physical performance in professional football players (Brito, Vasconcellos, Oliveira, Krustrup, & Rebelo, 2014; Faude, Roth, Giovine, Zahner, & Donath, 2013; Loturco et al., 2017; Loturco, Ugrinowitsch, Tricoli, Pivetti, & Roschel, 2013; Silva, Nassis, & Rebelo, 2015), and also reduce in-season hamstring injury incidence in professional and amateur football players (Harøy et al., 2019; Petersen, Thorborg, Nielsen, Budtz-Jørgensen, & Hölmich, 2011; van der Horst, Smits, Petersen, Goedhart, & Backx, 2015) which is of great interest for practitioners.

In the last decade, a considerable amount of research has focused on the use of inertial flywheel resistance training, which offers an alternative method for improving strength, power and athletic performance (Askling, Karlsson, & Thorstensson, 2003; De Hoyo et al., 2014; Francisco Javier Núñez et al., 2018; Suarez-Arrones et al., 2018; Tous-Fajardo, Gonzalo-Skok, Arjol-Serrano, & Tesch, 2016). While the benefits of strength and power training are unquestionable, studies comparing flywheel inertial with gravity-dependent resistance training methods are limited, with no differences in strength adaptations between conditions (Vicens-Bordas, Esteve, Fort-Vanmeerhaeghe, Bandholm, & Thorborg, 2018). One of the advantages of using inertial flywheel devices, compared to gravity-dependent exercises, is to provide a higher overload and activation in the eccentric phase (Norrbrand, Pozzo, & Tesch, 2010; Tous-Fajardo, Maldonado, Quintana, Pozzo, & Tesch, 2006). Moreover, the use of inertial flywheel devices, such as the conical pulley, allows practitioners to include sport-specific actions in multiple planes of direction (Gonzalo-Skok et al., 2017), with promising results showing greater improvements in

COD performance, when compared to gravity-dependent interventions, in football (Tous-Fajardo et al., 2016) or handball (Madruga-Parera, Bishop, Gonzalo-skok, & Romero-rodríguez, 2020) players.

Age and previous hamstring injury are regarded as non-modifiable risk factors for future hamstring strain injuries (HSI). However, eccentric hamstring weakness has been identified as a modifiable risk factor for future hamstring strain injury (HSI) in sports with high intensity running demands, such as football (Timmins, Shield, Williams, Lorenzen, & Opar, 2015). Players returning to sport after a HSI show reduced eccentric but not concentric hamstring voluntary activation and strength (Buhmann, Trajano, Kerr, & Shield, 2020), with also hampered sprint (J. Mendiguchia et al., 2014) and repeated sprint ability (RSA) (Røksund et al., 2017) performances. Recent investigations have also indicated that decreased eccentric hamstring strength not only could lead to increased injury risk profiles but also compromised sprint acceleration performance (Askling et al., 2003; Mendiguchia et al., 2015; Morin et al., 2015). Altogether, these findings highlight the need to measure preseason eccentric hamstring strength in football players in order to address which players present lower levels of eccentric hamstring muscle performance and subsequently hampered sprint performance. Hence, practitioners are considering the off-season period as a window of opportunity to intervene on the players' physical abilities (Requena et al., 2017; Silva et al., 2016), in order to build more robust athletes and minimise the performance and strength deficits related to this period.

The main aim of the present study is to investigate and compare the changes in physical performance measures after an inertial flywheel or gravity-dependent resistance training intervention in semi-professional footballers during the off-season (3 weeks) and pre-season (4 weeks) periods. The secondary aim is to investigate and compare the changes in hamstring strength, which is a known modifiable hamstring injury risk factor.

METHODS: Participants, interventions and outcomes

Study design and setting

The design of this study is a randomized pre-mid-post parallel-group trial, with an allocation ratio of 1:1, with a framework of superiority, comparing the effectiveness of two training interventions (inertial flywheel vs gravity-dependent) on the outcomes assessed. It is hypothesised that both training interventions will provide positive and similar adaptations, but the inertial flywheel providing greater COD performance and RSA than the gravity-dependent intervention. Sprint (30 m with 5 m splits), repeated sprint ability (6 x 20+20 m), COD (modified-505), jumping (CMJ bilateral and unilateral) performances and hamstring strength (eccentric and isometric) will be assessed pre- (1 week before), mid- (3 weeks into) and post- (1 week after) intervention, at the same facility. Participants will enrol in the study two weeks before the start of the intervention and will be screened for inclusion. All included participants will receive an unsupervised 2-weeks' training plan (including strength and aerobic type conditioning (Requena et al., 2017), to ensure a minimum training dose before starting the supervised intervention. Baseline measures and their reliability will be taken between the first two weeks. The supervised training period will last for 7 weeks, with the first 2 sessions being used to familiarize the players with the exercises and devices. Players will perform 3 supervised sessions a week during the off-season period (3 weeks) while performing only 1 supervised session a week during the pre-season period (4 weeks). Mid-testing will be performed after the 3 weeks of off-season training, while post-testing will be performed after the 4 weeks of pre-season training. The study schedule is presented in Figure 1. The study protocol is reported in accordance with the SPIRIT guideline (Chan et al., 2013).

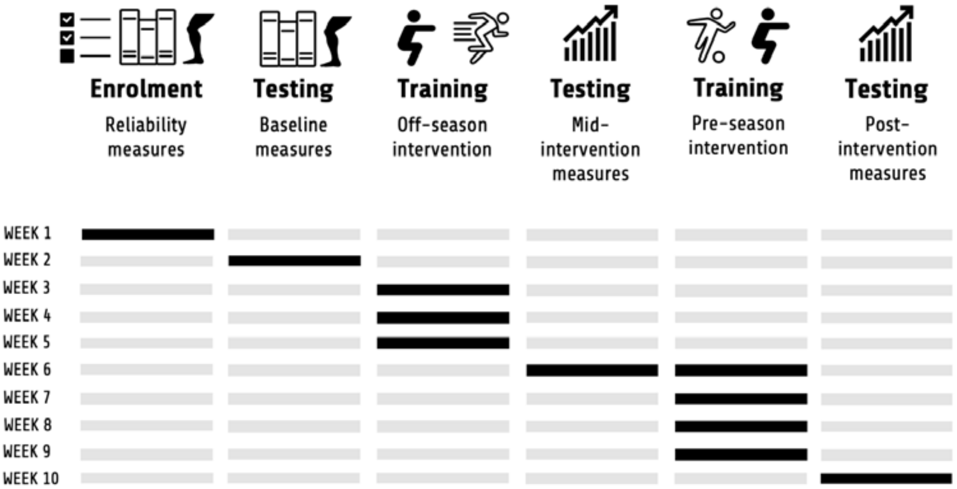


Figure 1. Study schedule. Weeks 1-2: enrolment, reliability measures, baseline testing, and unsupervised conditioning. Weeks 3-5: start of training intervention (3x week). Week 6: mid-testing. Weeks 6-9: pre-season intervention (1x week). Week 10: post-testing.

Eligibility criteria

Semi-professional players from 3^{rd} to 5^{th} tier (2^{nd} B division, 3^{rd} division and Catalan 1^{st} division) football clubs will be contacted to participate in the study, as per convenience sample. All players included will be above 18 years of age and goalkeepers will be excluded. All players will have a minimum participation of 4 training sessions per week, plus a football game during the pre-season period. Players will also have football experience of at least five consecutive years in youth, semi-professional or professional football and a minimum of one-year experience in strength and power training. Participants are required to be free of lower-limb injuries at the time of testing. Surgery of the lower limbs within 12 months of the study will be considered as exclusion criteria. In addition, subjects will be required not to consume nutritional supplements specifically for muscle growth (e.g. creatine) and will not be allowed to take nonsteroidal anti-inflammatory drugs during the study. Participants will be instructed before the study to keep their diet as consistent as possible and to avoid substantial dietary changes during the study.

Interventions

Both training interventions, the inertial flywheel resistance (FW) and the gravity-dependent resistance (GD) will have the same volume, frequency and duration, including gym-based strength and power sessions (2/week), on-field sprinting, COD and plyometrics sessions (1/week), and unsupervised metabolic conditioning sessions (2-3/week) during the off-season intervention period (see Tables 1-2). Instead, the pre-season intervention period will include only one strength and power session a week (see Table 3) since players will also be involved with their regular football team practice. Players will be asked to avoid any extra conditioning activity throughout the 3-weeks off-season intervention period, not to perform any strenuous exercise the day before each test, to avoid caffeine ingestion 8 hours before testing, and to consume their last meal at least 3 hours before the scheduled test time.

During training sessions, both groups will perform the same standardized and supervised warm-up (8-9 min) including active stretching (long-length isometrics 2 x 4-6 s and 6 reps of ballistic movements for the quadriceps, hamstrings, adductors, and calves muscle groups for each leg, and 6 sumo squats, 6 lunges, 6 RDLs, and 4 inversed Nordics, during 4-5 minutes), running-drills (20 m run, 10 m high knees, 10 m butt kicks, 10 m lateral skips, 10 m carioca, 20 m lateral shuffle, 20 m bounding, 6 lateral leaps each leg, during 4 minutes). Two experienced S&C coaches will control every training session, providing verbal encouragement to each participant.

In the strength and power sessions, main exercises and complementary exercises are proposed. The main exercises will be the comparator/dependent variable of the interventions (FW vs GD) and will comprehend exercises for the development of strength and power of the lower limbs. The intervention will include main exercises involving squatting patterns and its variants; knee- and hip-based exercises for the posterior chain; and exercises to work the hip adduction and the plantar-flexion. The complementary exercises will be the same in both groups and will focus on the work of the hip abduction, hip extension, and anti-lumbar extension and anti-lateral trunk flexion. The main and complementary exercises will be implemented using a circuit-training, by using two blocks of three exercises, working on different muscle groups to avoid neuromuscular fatigue and allow maximum power output in all sets and repetitions (Martorelli et al., 2015; Sabido, Hernández-Davó, Capdepon, & Tous-Fajardo, 2020). Thirty seconds of passive recovery will be provided between sets-legs, one minute between exercises and two minutes between blocks.

Inertial flywheel

The FW intervention will include bilateral and unilateral exercises, working on the vertical, horizontal and lateral planes of movement (Madruga-Parera et al., 2020; F. Javier Núñez, Galiano, Muñoz-López, & Floria, 2020; Tous-Fajardo et al., 2016), hip (back kick) and knee dominant (leg curl) exercises for the hamstring muscle complex (Fernandez-Gonzalo et al., 2016; Tous-Fajardo et al., 2006). Adductors and calves' exercises have not been studied before in the literature but will be adapted for the use of FW devices as per personal experience. Also, FW exercises will involve high force (cylinder-shaped device) and lower force (cone-shaped device) to provide a wide range of training stimuli (F. Javier Núñez et al., 2020). During FW exercises, players were encouraged to perform the concentric phase as fast as possible, while delaying the braking action to the last third of the eccentric phase. An inertial portable conical pulley (Versa-Pulley, Costa Mesa, CA; Inertia 0.27 kg·m^2, speed:force ratio 1 and 2), a Yoyo squat (YoYo Technology AB, Stockholm, Sweden; Inertia 0.11 kg/m2) and a Yoyo leg curl (YoYo Technology AB, Stockholm, Sweden; Inertia 0.11 kg/m2) will be used for the training intervention. A full description of the training intervention with specific sets and repetitions and the load progression are provided in Table 1.

Gravity-dependent

The GD intervention will include bilateral and unilateral exercises, working on the vertical, horizontal and lateral planes of movement, such as the squat, Bulgarian split squat, forward and lateral lunges and the acceleration step (De Hoyo et al., 2016; Hicks, Schuster, Samozino, & Morin, 2019; Speirs, Bennett, Finn, & Turner, 2016), hip and knee dominant exercises for the hamstring muscle complex such as the Nordic hamstring and the single-leg or 2/1 Romanian deadlift (SL RDL) (Bourne et al., 2017; Howe, Waldron, & Read, 2017), the Copenhagen adductor exercise (Harøy et al., 2019) and calves' exercises (Maio Alves, Rebelo, Abrantes, & Sampaio, 2010). For the squat, forward and lateral lunges, Bulgarian split squat, acceleration step, SL RDL, and calves, players were encouraged to perform the concentric phase as fast as possible. For the Nordic hamstring and Copenhagen ADD, players were encouraged to perform the eccentric phase as controlled as possible. Smith Machine and free weights will be used for the training intervention. A full description of the training intervention with specific sets and repetitions and the load progression are provided in Table 1.

On-field training

The on-field training will contain three main blocks to develop general physical characteristics, including plyometrics, sprinting and COD exercises, in combination with some technical skills (passing, dribbling and shooting). The plyometric block will include jumps on the three planes of motion. Thirty seconds of passive recovery will be provided between sets-legs, one minute between exercises and two minutes between blocks.

Conditioning

HIIT sessions will be programmed (Table 2), performed without supervision, but controlled for compliance. The other conditioning session will be free of choice, but the players will be encouraged to perform an activity between 40' and 60' such as running, cycling, hiking or playing other sports.

Training monitoring: RPE, DOMS and compliance

Upon completion (30 min) of each training session, rating of perceived exertion (RPE) scores will be taken on a scale of 0-10, with a written description (McGuigan & Foster, 2004). In addition, muscle soreness will be assessed using a visual analogue scale (VAS) (Lau, Muthalib, & Nosaka, 2013), which will be administered before every training day during the first 3 weeks. Subjects will perform 3 air squats to parallel, 3 RDLs, 3 lateral lunges and 3 heel raises and record their perceived soreness of the main muscle groups involved in the training intervention (quadriceps, hamstrings, adductors, calves) on a 100 mm line with left and right ends of the line corresponding to "no soreness" and "extreme soreness", respectively. Compliance will be monitored daily throughout the training period and expressed as a percentage of training completion. Prospectively, training and match exposure (minutes) and load (sRPE) will be recorded.

Outcomes

Two/three members of the research team who are trained in the measurement procedures will perform the baseline measurements. Players will be asked to perform the test battery 2 weeks and 1 week (reliability analysis) before the start of the training intervention, 3 weeks into the training intervention (mid-testing, before the start of pre-season) and 4 weeks into pre-season. Testing sessions will take place at the same time of the day to minimize circadian rhythms' effect and players will be asked to wear the same footwear during all testing sessions.

Before testing, all participants will perform a 12 min standardized and supervised warm-up including active stretching (long-length isometrics 2 x 4-6 s and 6 reps of ballistic movements for the quadriceps, hamstrings, adductors, and calves muscle groups for each leg, and 6 sumo squats, 6 lunges, 6 RDLs, during 4 minutes), running-drills (20 m run, 10 m high knees, 10 m butt kicks, 10 m lateral skips, 10 m carioca, 20 m lateral shuffle, 20 m bounding, 6 lateral leaps each leg, during 4 minutes), and progressive sprinting and COD (1x10 m, 1x20 m, 2x 30 m, and 2 reps of the COD test) during 4 minutes). Players will rest 3 minutes after the warm-up before the start of the testing battery. Players were verbally encouraged to give maximal effort during all tests. Tests will be performed on an indoor facility.

The outcomes are the changes in physical performance: sprinting (30 m with 5 m splits), repeated sprint ability (6 x 20+20 m), COD (modified-505), bilateral (CMJ) and unilateral (SL CMJ) vertical jump and hamstring muscle strength (eccentric and isometric).

Sample Size

To calculate the sample size, statistical software (GPower, Dusseldorf, Germany) will be used. Given the study design (2 groups, 3 repeated measures), an effect size of 0.25 (medium), α-error < 0.05, a desired power (1-β err prob) of 0.8, a correlation between the repeated measures of 0.5 and a non-sphericity correction ε of 1, the total sample size resulted in 28 participants. To prevent the effect of any possible drop-out (20%) on the statistical power, 34 participants will be included.

METHODS: Assignment of interventions

Allocation

Individual randomization is going to be performed according to a computer-generated sequence, using blocked randomisation (ABBA distribution), stratified by team and sprint performance. Allocation concealment will be ensured, as the participants will not know the intervention until all baseline measurements have been completed. The randomisation will be conducted by an external investigator not participating in the project, in order to keep the authors blinded. Participants will be randomized into an inertial flywheel resistance (FW, 17 participants) or a gravity-dependent resistance (GD, 17 participants) training intervention. Participants are able to withdraw from the study at any time; however, all efforts will be made to avoid missing data.

METHODS: Data collection, management and analysis

Data collection

The primary outcomes are the changes in physical performance: sprinting (30 m with 5 m splits), repeated sprint ability (6 x 20+20 m), COD (modified-505), bilateral (CMJ) and unilateral (SL CMJ) and hamstring muscle strength (eccentric and isometric). The tests will be performed in two different days, the first day will include the isometric hamstring strength, the sprinting and the repeated sprint ability tests. The second day will include the jumping, the COD and the eccentric hamstring strength tests. 24-48h of rest between testing sessions will be provided.

Sprinting performance

Sprint performance will be evaluated by 30 m sprint times using a two-point stance, with the front foot placed 0.5

m before the initial mark. The start and end of the sprint will be monitored using single-beam timing gates (1.5 m apart and 0.9 m height) (Chronojump Bosco System v1.6.2, Barcelona, Spain). The test will be performed twice with 3 minutes of recovery. The best 30 m performance will be used for the statistical analysis. The investigators will closely monitor all trials to ensure proper starting position, and if considered invalid (not standing still start), additional trials will be allowed. The 5 m and 10 m split times were extracted by the main author (blinded to injury and eccentric hamstring strength) using a valid and reliable (1.00 ICC and 0.03% CV) video-based analysis (Romero-Franco et al., 2017), by placing poles (1.6 m height) at the set distances (correcting for parallax error) and the phone mounted on a tripod, positioned at 15 m and 10 m away from the linear course, as described in the App manual (MySprint App, iPhone 7).

Repeated sprint ability

The RSA test will consist of six 40 m (20 + 20 m with a 180º turn) shuttle sprints separated by 20 s of passive recovery (Rampinini et al., 2007). The participants will start using a two-point stance, with the front foot placed 0.5 m before the initial mark and will be asked to pass the lines of the COD, indicated on the turf surface, with the entire foot at the turn. After 20 s of passive recovery, the participants will continue performing sprints until 6 repetitions are completed. The test will be monitored using a single-beam timing gate (1.5 m apart and 0.9 m height), (Chronojump Bosco System v1.6.2, Barcelona, Spain). Five seconds before the start of each sprint, participants will get ready and will wait for the acoustic start signal (with 5 s of countdown). Best time in a single trial (RSAbest), mean time (RSAmean) and decrement (RSAdecrement) will be determined (Rampinini et al., 2007).

Change of direction performance

Players will perform two left and right 10 m COD (5+5 m) tests with 180º turns, by stepping between each pair of cones separated by 0.7 m. The start and end of the COD test will be monitored using a single-beam timing gate (1.5 m apart and 0.9 m height), for the 180º COD test (Chronojump Bosco System v1.6.2, Barcelona, Spain). The participants will start using a two-point stance, with the front foot placed 0.5 m before the initial mark and will be asked to pass the lines of the COD, indicated on the turf surface, with the entire foot at the turn. The investigators will closely monitor all trials to ensure proper technique (starting position and reaching changing of direction marks if considered invalid (slipping or not reaching the COD mark), additional trials will be allowed. The COD test will be executed twice, with 2 minutes of recovery. The best performance will be chosen for analysis. Excellent reliability scores (>0.92 ICC and <1.4% CV) have been shown for the test (Suarez-Arrones et al., 2020).

Jumping tests

The CMJ (Bosco, Luhtanen, & Komi, 1983) and single-leg CMJ tests will be performed on a contact mat with flight time being recorded using Chronojump software (Chronojump Boscosystem, Barcelona, Spain) to calculate vertical jump height. When ready, participants will perform a countermovement jump to a self-selected depth, following the instruction to "jump as high as you can". Each trial will be validated by a visual inspection to ensure that each landing is without any leg flexion and players will be instructed to maintain their hands on their hips throughout the duration of the jump. Each trial will be separated by a rest period of 60-s.

For single-leg CMJ, participants will be instructed to stand on one leg, descend into a countermovement of self-selected depth, and then rapidly extend the stance leg to jump as high as possible in the vertical direction (Meylan et al., 2009). The swing of the opposite leg prior to the jump is not allowed. A trial will be considered successful if the hands remained on the hips throughout the movement. For the three trials of each jump, participants will start with their preferred leg and the order of the right and left legs will be alternated thereafter. Each trial will be separated by a 60 s recovery period. The highest vertical jump height will be used for further analysis.

Isometric and eccentric strength

Isometric hamstring strength will be evaluated by a trained and expert physiotherapist using a hand-held dynamometer (MicroFet2; Hoggan Health Industries). The knee flexion (lying supine, 0º hip flexion and 30º knee flexion assessed by a digital goniometer) reliable test will be used for the assessment of isometric hamstring strength (Goossens, Witvrouw, Vanden Bossche, & De Clercq, 2015). A belt will be placed around the hip to avoid raising of the hip during the isometric hamstring test. The results will be reported as absolute strength (N) and torque (N·m), and also normalized to body weight for strength ($N \cdot kg^{-1}$) and torque ($N \cdot m \cdot kg^{-1}$).

The Nordic hamstring exercise (NHE) device previously assessed for reliability (0.83-0.90 ICC and 5.8-8.5% CV) (Opar, Piatkowski, Williams, & Shield, 2013) will be used for the assessment of eccentric hamstring strength. Participants will be kneeling on a padded board, with the ankles secured superior to the lateral malleolus by individual ankle braces attached to custom-made uniaxial load cells (Delphi Force Measurement, Gold Coast, Australia). Immediately before testing, players will be provided with a demonstration of the NHE from the main investigator. After a three-repetition warm-up set and one minute of rest, participants will be asked to perform one set of three maximal repetitions of the NHE. Participants will be instructed to gradually lean forward at the slowest possible speed while maximally resisting this movement with both limbs keeping the trunk and hips in a neutral position throughout, and the hands held across the chest (Opar et al., 2013). Standardized verbal encouragement will be given throughout the range of motion to ensure maximal effort. The investigators will closely monitor all trials to ensure proper technique, if considered invalid, additional trials will be allowed. The results will only be visible to the outcome assessor during the testing and will be shown to the player after the completion of all testing. Peak force for each of the three repetitions will be averaged for all statistical comparisons. The average of both legs will be reported as absolute strength (N) and torque (N·m), and also normalized to body weight for strength ($N \cdot kg^{-1}$) and torque ($N \cdot m \cdot kg^{-1}$).

Statistical methods

Normality of the data will be assessed using Shapiro-Wilk's test of normality and Q-Q plots. Homogeneity of variance will be assessed using Levene's test. Data will be reported as mean ± standard deviation (SD), and 95% confidence intervals (CI) unless otherwise stated.

Between-session reliability will be used to account for normal fluctuations in athletes' performance. The two-way random intraclass correlation coefficient (ICC) and the coefficient of variation (CV %), from which standard error of measurement (SEM) will be calculated using the formula: SD Pooled + (√1 – ICC). To assess the "real" change, the minimum detectable change (MDC) will be calculated using the formula: $\text{MDC} = \text{SEM} * 1.96 * \sqrt{2}$ (Weir, 2005). For interpretation, ICC values are >0.9 excellent, 0.9-0.75 good, 0.75-0.5 moderate and <0.5 poor (Koo & Li, 2016) and CV values will be considered acceptable if <10% (Cormack, Newton, McGuigan, & Doyle, 2008).

A repeated-measures analysis of variance with baseline as a covariate will be used to assess the effectiveness of the two interventions. A two-way ANCOVA will be performed, including the intervention group ("FW", "GD") as a between-subject factor; testing ("Mid", "Post") as the within-subject factor, and group x time to account for the interaction effects. Whenever a significant interaction effect is observed, the Bonferroni-adjusted post-hoc test will be used. Within-group effects sizes (ES) will be calculated using Cohen's d (mean differences / pooled SD) and interpreted as trivial (<0.2), small (≥ 0.2), moderate (≥ 0.6), large (≥ 1.2) effects (Hopkins, Marshall, Batterham, & Hanin, 2009). Assessments of statistical procedures will be performed using JASP (JASP Team 2020, JASP v0.13.1), with statistical significance set at $p < 0.05$.

Ethics and dissemination

The study will be sent to the University's Human Research Ethics Committee and await ethical approval before starting any data collection procedure. The study follows the Declaration of Helsinki (1975). The participants will be carefully informed about any potential risks due to the investigation's procedures, and also that they are able to withdraw from the study at any time. Then, the informed consent will be obtained from them.

References

Ade, J., Fitzpatrick, J., & Bradley, P. S. (2016). High-intensity efforts in elite soccer matches and associated movement patterns, technical skills and tactical actions. Information for position-specific training drills. *Journal of Sports Sciences*, *34*(24), 2205–2214. https://doi.org/10.1080/02640414.2016.1217343

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports*, *13*(4), 244–250. https://doi.org/10.1034/j.1600-0838.2003.00312.x

Barnes, C., Archer, D. T., Hogg, B., Bush, M., & Bradley, P. S. (2014). The evolution of physical and technical performance parameters in the English Premier League. *International Journal of Sports Medicine*, *35*(13), 1095–1100. https://doi.org/10.1055/s-0034-1375695

Bosco, C., Luhtanen, P., & Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology*, *50*(2), 273–282.

Bourne, M. N., Timmins, R. G., Opar, D. A., Pizzari, T., Ruddy, J. D., Sims, C., … Shield, A. . J. (2017). An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Medicine*. https://doi.org/10.1007/s40279-017-0796-x

Bradley, P. S., Archer, D. T., Hogg, B., Schuth, G., Bush, M., Carling, C., & Barnes, C. (2016). Tier-specific evolution of match performance characteristics in the English Premier League: it's getting tougher at the top. *Journal of Sports Sciences*, *34*(10), 980–987. https://doi.org/10.1080/02640414.2015.1082614

Brito, J., Vasconcellos, F., Oliveira, J., Krustrup, P., & Rebelo, A. (2014). Short-term performance effects of three different low-volume strength-training Programmes in college male soccer players. *Journal of Human Kinetics*, *40*(1), 121–128. https://doi.org/10.2478/hukin-2014-0014

Buhmann, R., Trajano, G., Kerr, G., & Shield, A. (2020). Voluntary activation and reflex responses following hamstring strain injury. *Medicine & Science in Sports & Exercise*, 1. https://doi.org/10.1249/MSS.0000000000002327

Caldwell, B. P., & Peters, D. M. (2009). Seasonal variation in physiological fitness of a semiprofessional soccer team. *Journal of Strength and*

Conditioning Research, *23*(5), 1370–1377. https://doi.org/10.1519/JSC.0b013e3181a4e82f

Chan, A. W., Tetzlaff, J. M., Gøtzsche, P. C., Altman, D. G., Mann, H., Berlin, J. A., … Moher, D. (2013). SPIRIT 2013 explanation and elaboration: guidance for protocols of clinical trials. *BMJ (Clinical Research Ed.)*, *346*, 1–42. https://doi.org/10.1136/bmj.e7586

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, *3*(2), 131–144. https://doi.org/10.1123/ijspp.3.2.131

De Hoyo, M., de la Torre, A., Pradas, F., Sañudo, B., Carrasco, L., Mateo-Cortes, J., … Fernandes, O. (2014). Effects of eccentric overload bout on change of direction and performance in soccer players. *International Journal of Sports Medicine*, *36*(04), 308–314. https://doi.org/10.1055/s-0034-1395521

De Hoyo, M., Gonzalo-Skok, O., Sañudo, B., Carrascal, C., Plaza-Armas, J. R., Camacho-Candil, F., & Otero-Esquina, C. (2016). Comparative effects of in-season full-back squat, resisted sprint training, and plyometric training on explosive performance in u-19 elite soccer players. *Journal of Strength and Conditioning Research*, *30*(2), 368–377. https://doi.org/10.1519/JSC.0000000000001094

Faude, O., Roth, R., Giovine, D. Di, Zahner, L., & Donath, L. (2013). Combined strength and power training in high-level amateur football during the competitive season: A randomised-controlled trial. *Journal of Sports Sciences*, *31*(13), 1460–1467. https://doi.org/10.1080/02640414.2013.796065

Fernandez-Gonzalo, R., Tesch, P. A., Linnehan, R. M., Kreider, R. B., Di Salvo, V., Suarez-Arrones, L., … Rodas, G. (2016). Individual muscle use in hamstring exercises by soccer players assessed using functional MRI. *International Journal of Sports Medicine*, *37*(7), 559–564. https://doi.org/10.1055/s-0042-100290

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-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *International Journal of Sports Physiology and Performance*, *12*(7), 951–958. https://doi.org/10.1123/ijspp.2016-0251

Goossens, L., Witvrouw, E., Vanden Bossche, L., & De Clercq, D. (2015). Lower eccentric hamstring strength and single leg hop for distance predict hamstring injury in PETE students. *European Journal of Sport Science*, *15*(5), 436–442. https://doi.org/10.1080/17461391.2014.955127

Harøy, J., Clarsen, B., Wiger, E. G., Øyen, M. G., Serner, A., Thorborg, K., … Bahr, R. (2019). The Adductor Strengthening Programme prevents groin problems among male football players: A cluster-randomised controlled trial. *British Journal of Sports Medicine*, *53*(3), 145–152. https://doi.org/10.1136/bjsports-2017-098937

Hicks, D. S., Schuster, J. G., Samozino, P., & Morin, J.-B. (2019). Improving Mechanical Effectiveness During Sprint Acceleration. *Strength and Conditioning Journal*, 1. https://doi.org/10.1519/ssc.0000000000000519

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–12. https://doi.org/10.1249/MSS.0b013e31818cb278

Howe, L. P., Waldron, M., & Read, P. (2017). A systems-based approach to injury prevention for the strength and conditioning coach. *Strength and Conditioning Journal*, *39*(6), 60–69. https://doi.org/10.1519/SSC.0000000000000346

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Koundourakis, N. E., Androulakis, N. E., Malliaraki, N., Tsatsanis, C., Venihaki, M., & Margioris, A. N. (2014). Discrepancy between exercise performance, body composition, and sex steroid response after a six-week detraining period in professional soccer players. *PLoS ONE*, *9*(2). https://doi.org/10.1371/journal.pone.0087803

Lau, W. Y., Muthalib, M., & Nosaka, K. (2013). Visual analog scale and pressure pain threshold for delayed onset muscle soreness assessment. *Journal of Musculoskeletal Pain*, *21*(4), 320–326. https://doi.org/10.3109/10582452.2013.848967

Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: A systematic review, qualitative analysis and meta-analysis. *British Journal of Sports Medicine*, *52*(24), 1557–1563. https://doi.org/10.1136/bjsports-2018-099078

Lauersen, J. B., Bertelsen, D. M., & Andersen, L. B. (2014). The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *British Journal of Sports Medicine*, *48*(11), 871–877. https://doi.org/10.1136/bjsports-2013-092538

Loturco, I., Kobal, R., Kitamura, K., Cal Abad, C. C., Faust, B., Almeida, L., & Pereira, L. A. (2017). Mixed training methods: Effects of combining resisted sprints or plyometrics with optimum power loads on sprint and agility performance in professional soccer players. *Frontiers in Physiology*, *8*(DEC), 1–9. https://doi.org/10.3389/fphys.2017.01034

Loturco, I., Ugrinowitsch, C., Tricoli, V., Pivetti, B., & Roschel, H. (2013). Different loading schemes in power training during the preseason promote similar performance improvements in Brazilian elite soccer players. *Journal of Strength and Conditioning Research*, *27*(7), 1791–1797. https://doi.org/10.1519/JSC.0b013e3182772da6

Madruga-Parera, M., Bishop, C., Gonzalo-skok, O., & Romero-rodríguez, D. (2020). Effects of 8-weeks of iso-inertial vs . cable-resistance training on motor skills performance and inter-limb asymmetries. *Journal of Strength & Conditioning Research.*

Maio Alves, J. M. V., Rebelo, A. N., Abrantes, C., & Sampaio, J. (2010). Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. *Journal of Strength and Conditioning Research*, *24*(4), 936–941. https://doi.org/10.1519/JSC.0b013e3181c7c5fd

Martorelli, A., Bottaro, M., Vieira, A., Rocha-Júnior, V. A., Cadore, E. L., Prestes, J., … Martorelli, S. (2015). Neuromuscular and blood lactate responses to squat power training with different rest intervals between sets. *Journal of Sports Science and Medicine*, *14*(2), 269–275.

McGuigan, M. R., & Foster, C. (2004). A New Approach to Monitoring Resistance Training. *Strength & Conditioning Journal*, *26*(6), 42–47.

Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., … Mendez-Villanueva, A. (2015). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine and Science in Sports*, *25*(6), e621–e629. https://doi.org/10.1111/sms.12388

Meylan, C., McMaster, T., Cronin, J., Mohammad, N. I., Rogers, C., & Deklerk, M. (2009). Single-leg lateral, horizontal, and vertical jump assessment: reliability, interrelationships, and ability to predict sprint and change-of-direction performance. *Journal of Strength and Conditioning Research*, *23*(4), 1140–1147.

Morin, J. B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., … Mendiguchia, J. (2015). Sprint acceleration mechanics: the major role of hamstrings in horizontal force production. *Frontiers in Physiology*, *6*(December), 1–14. https://doi.org/10.3389/fphys.2015.00404

Nakamura, D., Suzuki, T., Yasumatsu, M., & Akimoto, T. (2012). Moderate running and plyometric training during off-season did not show a significant difference on soccer-related high-intensity performances compared with no-training controls. *Journal of Strength and Conditioning Research*, *26*(12), 3392–3397. https://doi.org/10.1519/JSC.0b013e3182474356

Norrbrand, L., Pozzo, M., & Tesch, P. A. (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. *European Journal of Applied Physiology*, *110*(5), 997–1005. https://doi.org/10.1007/s00421-010-1575-7

Núñez, F. Javier, Galiano, C., Muñoz-López, A., & Floria, P. (2020). Is possible an eccentric overload in a rotary inertia device? Comparison of force profile in a cylinder-shaped and a cone-shaped axis devices. *Journal of Sports Sciences*, *00*(00), 1–5. https://doi.org/10.1080/02640414.2020.1754111

Núñez, Francisco Javier, 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), 1–13. https://doi.org/10.1371/journal.pone.0193841

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *The Journal of Orthopaedic and Sports Physical Therapy*, *43*(9), 636–640. https://doi.org/10.2519/jospt.2013.4837

Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in Men's soccer: A cluster-randomized controlled trial. *American Journal of Sports Medicine*, *39*(11), 2296–2303. https://doi.org/10.1177/0363546511419277

Rampinini, E., Bishop, D., Marcora, S. M., Ferrari Bravo, D., Sassi, R., & Impellizzeri, F. M. (2007). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *International Journal of Sports Medicine*, *28*(3), 228–235. https://doi.org/10.1055/s-2006-924340

Requena, B., García, I., Suárez-Arrones, L., Sáez de Villarreal, E., Naranjo Orellana, J., & Santalla, A. (2017). Off-season effects on functional performance, body composition, and blood parameters in top-level professional soccer players. *Journal of Strength and Conditioning Research*, *31*(4), 939–946. https://doi.org/10.1519/JSC.0000000000001568

Røksund, O. D., Kristoffersen, M., Bogen, B. E., Wisnes, A., Engeseth, M. S., Nilsen, A. K., … Gundersen, H. (2017). Higher drop in speed during a repeated sprint test in soccer players reporting former hamstring strain injury. *Frontiers in Physiology*, *8*(JAN), 1–8. https://doi.org/10.3389/fphys.2017.00025

Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., … Balsalobre-Fernández, C. (2017). Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *European Journal of Sport Science*, *17*(4), 386–392. https://doi.org/10.1080/17461391.2016.1249031

Sabido, R., Hernández-Davó, J. L., Capdepon, L., & Tous-Fajardo, J. (2020). How Are Mechanical, Physiological, and Perceptual Variables Affected by the Rest Interval Between Sets During a Flywheel Resistance Session? *Frontiers in Physiology*, *11*(June), 1–8. https://doi.org/10.3389/fphys.2020.00663

Silva, J. R., Brito, J., Akenhead, R., & Nassis, G. P. (2016). The transition period in soccer: a window of opportunity. *Sports Medicine*, *46*(3), 305–313. https://doi.org/10.1007/s40279-015-0419-3

Silva, J. R., Nassis, G. P., & Rebelo, A. (2015). Strength training in soccer with a specific focus on highly trained players. *Sports Medicine - Open*, *1*(1). https://doi.org/10.1186/s40798-015-0006-z

Speirs, D. E., Bennett, M. A., Finn, C. V., & Turner, A. P. (2016). Unilateral vs. bilateral squat training for strength, sprints, and agility in academy rugby players. *Journal of Strength and Conditioning Research*, *30*(2), 386–392. https://doi.org/10.1519/JSC.0000000000001096

Suarez-Arrones, L., de Villarreal, E. S., Núñez, F. J., Di Salvo, V., Petri, C., Buccolini, A., … Mendez-Villanueva, A. (2018). In-season eccentric-overload training in elite soccer players: Effects on body composition, strength and sprint performance. *PLoS ONE*, *13*(10), 1–16. https://doi.org/10.1371/journal.pone.0205332

Suarez-Arrones, L., Gonzalo-Skok, O., Carrasquilla, I., Asián-Clemente, J., Santalla, A., Lara-Lopez, P., & Núñez, F. J. (2020). Relationships between change of direction, sprint, jump, and squat power performance. *Sports*, *8*(3), 38. https://doi.org/10.3390/sports8030038

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine*, *46*(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2015). Biceps femoris long head architecture: A reliability and retrospective injury study. *Medicine and Science in Sports and Exercise*, *47*(5), 905–913. https://doi.org/10.1249/MSS.0000000000000507

Tous-Fajardo, J., Gonzalo-Skok, O., Arjol-Serrano, J. L. J. L., & Tesch, P. (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *International Journal of Sports Physiology and Performance*, *11*(1), 66–73. https://doi.org/10.1123/ijspp.2015-0010

Tous-Fajardo, J., Maldonado, R. A., Quintana, J. M., Pozzo, M., & Tesch, P. A. (2006). The flywheel leg-curl machine: offering eccentric overload for hamstring development. *International Journal of Sports Physiology and Performance*, *1*(3), 293–298. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19116442

van der Horst, N., Smits, D.-W. W., Petersen, J., Goedhart, E. A., & Backx, F. J. G. (2015). The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *The American Journal of Sports Medicine*, *43*(6), 1–8. https://doi.org/10.1177/0363546515574057

Vicens-Bordas, J., Esteve, E., Fort-Vanmeerhaeghe, A., Bandholm, T., Ishøi, L., Opar, D., & Shield, A. (2020). Performance changes during the off-season period in football players – Effects of age and previous hamstring injury. *Journal of Sports Sciences*, *00*(00), 1–11. https://doi.org/10.1080/02640414.2020.1792160

Vicens-Bordas, J., Esteve, E., Fort-Vanmeerhaeghe, A., Bandholm, T., & Thorborg, K. (2018). Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. *Journal of Science and Medicine in Sport*, *21*(1), 75–83. https://doi.org/10.1016/j.jsams.2017.10.006

Weir, J. P. (2005). Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. *The Journal of Strength and Conditioning Research*, *19*(1), 231. https://doi.org/10.1519/15184.1

Table 1. Off-season training, strength and power sessions

				Week 1			**Week 2**			**Week 3**		
Sessions	**Block**	**FW Exercise**	**GD Exercise**	**sets x reps**	**FW Intensity**	**GD Intensity**	**sets x reps**	**FW Intensity**	**GD Intensity**	**sets x reps**	**FW Intensity**	**GD Intensity**
1, 3, 5	A1	Half squat	Half squat	3 x 8	0.11kg·m^2	10 RM	3 x 6	0.11kg·m^2	8 RM	4 x 6	0.11kg·m^2	8 RM
	A2	Acceleration step	Acceleration step	3 x 8	S:F 1 – 0.27kg·m^2	Band	3 x 6	S:F 1 – 0.27kg·m^2	Band	4 x 6	S:F 2 – 0.27kg·m^2	Band
	A3	Front plank		3 x 4 x 8”	BW		3 x 6 x 8”	BW		4 x 8 x 8”	BW	
	B1	Leg curl	Nordic Hamstring	3 x 8	0.11kg·m^2	BW	3 x 6	0.11kg·m^2	BW	4 x 6	0.11kg·m^2	BW
	B2	Bilateral heel raises	Bilateral heel raises	3 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10 RM	3 x 6	S:F 1 – 0.27kg·m^2	8 RM	4 x 6	S:F 2 – 0.27kg·m^2	8 RM
	B3	Side bridge		3 x 6 x 3” (e/l)	BW		3 x 8 x 3” (e/l)	BW		3 x 10 x 3” (e/l)	BW	
2, 4, 6	A1	Deceleration step	Bulgarian Split Squat	3 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10 RM	3 x 6 (e/l)	S:F 1 – 0.27kg·m^2	8 RM	4 x 6 (e/l)	S:F 2 – 0.27kg·m^2	8 RM
	A2	Adductor	Copenhagen Adductor	3 x 8 (e/l)	S:F 1 – 0.27kg·m^2	BW	3 x 6 (e/l)	S:F 1 – 0.27kg·m^2	BW	4 x 6 (e/l)	S:F 2 – 0.27kg·m^2	BW
	A3	Hip thrust		3 x 10	12 RM		3 x 8	10 RM		3 x 6	8 RM	
	B1	Cross-over step	Forward / lateral lunge	3 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10 RM	3 x 6 (e/l)	S:F 1 – 0.27kg·m^2	8 RM	4 x 6 (e/l)	S:F 2 – 0.27kg·m^2	8 RM
	B2	Back kick	SL RDL 2/1	3 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10 RM	3 x 6 (e/l)	S:F 1 – 0.27kg·m^2	8 RM	4 x 6 (e/l)	S:F 2 – 0.27kg·m^2	8 RM
	B3	Side plank		3 x 2 x 8” (e/l)	BW		3 x 3 x 8” (e/l)	BW		3 x 4 x 8” (e/l)	BW	

Table 2. Off-season training, on-field sessions and metabolic conditioning

Sessions	Block	Exercise	Week 1	Week 2	Week 3
			Plyometric, sprint and COD		
1-3	A1	Repeated vertical jump (bilateral)	3 x 3 reps	3 x 4 reps	3 x 5 reps
	A2	Lateral jump (unilateral)	3 x 3 reps (e/l)	3 x 4 reps (e/l)	3 x 5 reps (e/l)
	A3	Repeated forward jump (unilateral)	3 x 3 reps (e/l)	3 x 4 reps (e/l)	3 x 5 reps (e/l)
	B	Sprint	5 x 15 m	2 x 15 m 3 x 20 m	2 x 15 m 3 x 30 m
	C1	2*90º COD drill	4 reps (15 m)	4 reps (22.5 m)	4 reps (30 m)
	C2	1*180º COD drill	4 reps (e/l) (20 m)	4 reps (e/l) (25 m)	4 reps (e/l) (30 m)
	Total jumps - distance		45 jumps - 295 m	60 jumps - 380 m	75 jumps - 480 m

Sessions	Block	Exercise	Week 1	Week 2	Week 3
			Metabolic conditioning		
1, 3, 5	A	HIIT	2 x 8' (15":15") @90% IFT	2 x 10' (15":15") @90% IFT	2 x 6' (20":10") @90% IFT
2, 4, 6	A	Free	60-90'	60-90'	60-90'

Table 3. Pre-season training, strength and power sessions

				Weeks 4-5			**Weeks 6-7**		
					FW			**FW**	**GD**
Sessions	**Block**	**FW exercise**	**GD exercise**	**sets x reps**	**Intensity**	**GD Intensity**	**sets x reps**	**Intensity**	**Intensity**
7-10	A1	Half squat	Half squat	2 x 8	S:F 1 – 0.11kg·m^2	10 RM	2 x 6	S:F 1 – 0.11kg·m^2	8 RM
	A2	Acceleration step or Bilateral heel raises	Acceleration step or Bilateral heel raises	2 x 8	S:F 1 – 0.27kg·m^2	Band or 10 RM	2 x 6	S:F 1 – 0.27kg·m^2	Band or 8 RM
	A3	Front plank		2 x 4 x 8”	BW		2 x 6 x 8”	BW	
	B1	Leg curl	Nordic Hamstring	2 x 6	S:F 1 – 0.11kg·m^2	BW	2 x 8	S:F 1 – 0.11kg·m^2	BW
	B2	Adductor	Copenhagen Adductor	2 x 6 (e/l)	S:F 1 – 0.27kg·m^2	BW	2 x 8	S:F 1 – 0.27kg·m^2	BW
	B3	Side bridge or side plank		2 x 6 x 3” (e/l)	BW		2 x 8 x 3” (e/l)	BW	
	C1	Deceleration step or Cross-over step	Split Squat or Forward / lateral lunge	2 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10 RM	2 x 6 (e/l)	S:F 1 – 0.27kg·m^2	8 RM
	C2	Back kick	SL RDL 2/1	2 x 8 (e/l)	S:F 1 – 0.27kg·m^2	10RM	2 x 6 (e/l)	S:F 1 – 0.27kg·m^2	8 RM
	C3	Hip thrust		2 x 8	10 RM		2 x 6	8 RM	

CHAPTER 5

Discussion

This thesis aimed to firstly compare the use of inertial flywheel with gravity-dependent resistance training for improving physical performance and thigh muscle strength and performance, and secondly, to test how previous injury, age and the off-season period affects physical performance and eccentric hamstring strength in semi-professional and amateur footballers. Initially, the superiority of inertial flywheel resistance training compared to gravity-dependent resistance training on strength and power was analysed with the available literature (publications I and II). Secondly, the analysis of selected performance measures and eccentric hamstring strength was examined during the off-season and pre-season periods, with an emphasis on the effects of age and previous hamstring injury (publications III and IV). Finally, a comprehensive training intervention during the off-season and pre-season periods has been developed to compare the effects of inertial flywheel against gravity-dependent exercises on physical performance and hamstring strength measures (publication V). In the following sub-sections, the findings of each publication will be discussed and contrasted with the existing literature, with the inclusion of suggestions for practitioners, the main conclusions and limitations of the thesis and some directions for future research.

Is inertial flywheel resistance training an alternative method for improving strength and performance?

The results from the systematic review with meta-analyses (Publication I) showed that inertial flywheel resistance training provided similar improvements in strength to gravity-dependent resistance training. Those results were contrary to the initial hypothesis where inertial flywheel resistance training would provide greater performance and strength effects. The literature comparing inertial flywheel against gravity-dependent interventions was scarce at the moment of performing the systematic review with meta-analyses (Publication I), with none of the included studies intervening on football players. While the population of interest of this thesis are football players, most of the studies from the systematic review and meta-analyses (Publication I) included active and healthy participants, showing both interventions (FW and GD) an increase in strength (MVIC), with no superiority to any of them. Comparisons between training modalities looking at the eccentric strength, or even the stretch-shortening cycle improvements need to be further studied since the available evidence could not answer this question. Moreover, the meta-analyses on performance variables (sprint, COD and jump) were not performed due to a lack of data from the included studies. Unexpectedly, a very similar paper was published at that time, providing very dissimilar results to the ones presented. The work from Maroto-Izquierdo and colleagues (2017) showed the superiority of inertial flywheel interventions compared to gravity-dependent interventions (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017). While all the concerns regarding the study design and interpretation of results have been discussed in the Letter to the Editor (Publication II), one of the main problems detected were the inclusion of studies comparing inertial flywheel interventions against control groups (not performing any strength intervention) and concluding inertial flywheel as a superior intervention, when such a comparison was not made. Instead, in Publication I, the comparator group included was a gravity-dependent intervention which showed to be equally effective to an inertial flywheel intervention. Moreover, it needs to be highlighted, that one of the main limitations when comparing FW and GD interventions is the intention to match the training load between conditions, due to the nature of the stimulus and the mode of execution. Very little research has put great emphasis on this, such as the work from Lena Norrbrand (Norrbrand, 2010), which should be taken into consideration when developing intervention studies, by controlling the load using either force platforms, strain gauges or other devices to control for the loading parameters between exercises. For instance, some of the studies included in Publication I, with the intent to compare between conditions, may have not performed the FW exercise as effective as it could be. Greenwood and colleagues used a metronome to control the FW rhythm will negatively influence the desired adaptations (Greenwood et al., 2007). Also, the work from Caruso and colleagues (2005) it is not clear how the intensity was progressed during the exercise, on top of the decreased eccentric work at the end of the training intervention which is not usual after 10 weeks of training (Caruso et al., 2005). Hence, more detailed information on the loading parameters (devices and inertias used) are needed to critically assess the interventions and whether or not some bias may be present.

While some evidence suggests that inertial flywheel could improve in a higher extent jumps with greater eccentric demands and longer SSC such as depth jumps, gravity-dependent interventions provided greater adaptations on the CMJ and a 4-jump test (shorter SSC) (Caruso et al., 2008). One study that was available at the moment of the search was the one from Tous-Fajardo and colleagues (2016), however, it could not be included since the FW intervention contained some GD exercises and an exercise with a vibration platform that all could affect the results (Tous-Fajardo et al., 2016). While this type of intervention is ecologically valid and close to a real-world scenario, practitioners cannot ascertain that FW is greater than GD, but it shows a very interesting alternative mainly when looking for multi-planar exercises aiming at COD performance. Since the publication of the first study of this thesis (Publication I), compelling research comparing FW and GD interventions has emerged (Coratella et al., 2019; Madruga-Parera et al., 2020; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017; Sagelv et al., 2020; Stojanović et al., 2021). All those studies were conducted on team-sport athletes, three of them were performed in handball (Madruga-Parera et al., 2020; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017), two in football (Coratella et al., 2019; Sagelv et al., 2020) and one in basketball (Stojanović et al., 2021) players.

The work from Sabido and colleagues (2017) found improvements in the half squat 1RM, 20 m sprint and CMJ performances to a similar extent for both interventions, but greater benefits in the triple hop for distance for the FW group (Sabido et al., 2017). Instead, the work from Maroto-Izquierdo and colleagues (2017) found greater improvements after FW intervention in most of the power-related actions such as jumping, sprinting and COD performances, but again similar improvements in strength outcomes such as the leg extension 1RM (Maroto-Izquierdo, García-López, & de Paz, 2017). Similar results were shown in a recent study in well-trained basketball players a very showed greater performance adaptations (sprint, COD and jump) after an 8-week FW intervention (0.075 kg/m2) compared to a gravity-dependent intervention (80%RM), including the Romanian deadlift and squat exercises, and again no differences between groups were present for strength outcomes. Instead, this study on recreational footballers found greater squat 1RM for the GD group and similar improvements in sprinting and jumping performance between groups (Sagelv et al., 2020). Instead, a recent study on semi-professional footballers looked at the adaptations of including just one exercise (squat), comparing FW vs GD, on performance and strength adaptations. This intervention showed superiority for FW in COD performance and the knee functional ratio (Hecc:Qcon) and COD performance but no difference in squat 1RM, jumping or sprinting performance(Coratella et al., 2019). While this type of interventions, looking at similar movement kinematics (squat) but just differing on the device (FW vs GD), are needed to help interpret specific differences between FW and GD, the use of a single exercise may not be implemented in real-world practice. Following the line of multi-exercise research (Tous-Fajardo et al., 2016), Madruga-Parera and colleagues (2020) presented a multi-faceted FW intervention (including multi-directional exercises and progressions with the cone-shaped device) in adolescent handball players, showing greater improvements in repeated COD performance compared to a similar GD intervention (Madruga-Parera et al., 2020). For instance, the intervention by Madruga-Parera and colleagues (2020) provided the same construct (similar exercise technique or kinematics comparing devices), but implementing more sport-specific and multidirectional movements. While being a very complete training program, one of the limitations of that work could be that the gravity-dependent intervention did not use more traditional or conventional exercises. Moreover, it included weight-stack exercises (with similar kinematics) which have not been studied in the literature before, omitting the importance of exercise kinetics for training adaptations. All this recent evidence is very interesting since all studies are performed in team-sport athletes, and not only look at strength improvements but performance outcomes. While an update of the meta-analysis could provide greater insights on which intervention is superior to the other on strength and performance outcomes (FW vs GD), it could be hypothesised that similar strength but greater performance (mainly COD and jumping) adaptations following FW interventions may be present.

One of the advantages which offers the use of inertial flywheel devices with a horizontal orientation of the strap, such as the cone-shaped pulley, is the ability to perform more sport-specific movements such as multidirectional COD, with a focus on the eccentric phase due to the loading paradigm of inertial flywheel devices compared to gravity-dependent alternatives (Tous-Fajardo et al., 2016). Even though the available evidence does not show the superiority of inertial flywheel devices at the moment, considering the abundant evidence on the importance of strength training interventions (Brito et al., 2014; Faude et al., 2013; Loturco et al., 2013, 2017; Silva et al., 2015), with growing interest around inertial flywheel devices lately (de Hoyo et al., 2014; Fernández-Valdés et al., 2020; Moras et al., 2018; Moras & Vázquez-Guerrero, 2015; Núñez et al., 2018; Suarez-Arrones et al., 2018; Tous-Fajardo et al., 2016), it arises as an interesting alternative for strength and performance adaptations in football players. Accordingly, in team sports where decelerations and changes of directions are crucial, FW devices allow to include both bilateral and unilateral exercises with an eccentric emphasis. Furthermore, FW devices such as conic pulleys allow executing exercises on a multi-planar accentuation -specifically in the sagittal and transverse planes, to produce performance enhancements. For this reason, the intervention protocol (Publication V) has been developed, looking at performance and strength adaptations, to compare both modalities using a randomised controlled trial in semi-professional footballers.

The intervention protocol (Publication V), comprises a multi-component training intervention, including strength exercises, plyometrics, COD and sprinting, with both training interventions (inertial flywheel or gravity-dependent) providing positive performance adaptations as shown in Chapter 1. However, it has been hypothesized that the inertial flywheel stimulus will enhance to a greater extent COD performance and RSA compared to the gravity-dependent stimulus since the FW intervention seems to offer superior benefits for COD performance (ES = -0.03 – 0.1) (Tous-Fajardo et al., 2016). There is no evidence in the literature showing greater RSA improvements after inertial flywheel resistance training. While RSA improvements are very complex with neuromuscular and metabolic factors playing their role, the loading paradigm offered by inertial flywheel devices, with high intensities at the last part of the eccentric phase (emphasizing high-intensity stretch-shortening cycles) could lead to greater RSA improvements, and even more considering the RSA test includes a 180-degree change of direction.

Finally, when looking at the ability to improve one of the modifiable risk factors for hamstring injuries, such as hamstring strength, the evidence on the use of inertial flywheel devices is scarce. The ability to reduce hamstring injuries after an eccentric-biased (gravity-dependent) exercise such as the NHE has been shown effective in amateur footballers (Arnason et al., 2007; Petersen et al., 2011; van der Horst et al., 2015), but a lack of effectiveness in the professional football settings has also been regarded (Bahr et al., 2015). It has also been suggested that not only knee-based exercises but hip-based exercises should be performed to target all the hamstring muscle groups (Bourne, Timmins, et al., 2017), which seems to be adopted by practitioners in professional football with the inclusion of inertial flywheel devices (McCall et al., 2020). A recent hamstring intervention (6 weeks) on amateur athletes using either a "2-1" (2 legs up, 1 leg down) or unilateral leg curls using the FW device did not show any strength improvements in isometric, eccentric or RFD (Presland et al., 2020). These latest results are surprising and counterintuitive, considering the amount of hamstring specific stimulus performed by the athletes (48-96 repetitions per week), and also the evidence on positive strength adaptations after FW interventions such as the work by Askling and colleagues (2003) in professional football players, and also as shown by the small to large within-group effect sizes from the systematic review and meta-analyses (see Table 3a in Appendices). Several aspects need to be taken into accounts, such as the inertia used and the technique involved during the exercise, which could be monitored using a rotational encoder or strain gauge to measure exercise kinetics. In addition to that, the possibility of including a hip-based exercise (back-kick) using an inertial flywheel device allows practitioners to train the hamstring muscles with a breaking emphasis at greater muscle lengths (mimicking injury mechanism, the late swing phase) which may provide a potent stimulus from an injury prevention perspective (Guex & Millet, 2013). While Askling and colleagues (2003) showed lower hamstring injury rates in the intervention group (n = 15, 1 team) compared to the control group (n = 15, 1 team), the sample was relatively small, and also the injuries from the control group were too high (10 injuries) when compared to the football literature (5-6 hamstring injuries per team per season) (Ekstrand et al., 2016) which may give a greater effect in favour of the inertial flywheel intervention. However, the reduced number of hamstring injuries could be related to the increased hamstring strength following the intervention, which is an interesting finding. Still, the comparison between an inertial flywheel and a gravity-dependent intervention (such as the NHE) on the strength benefits remains to be established. Hence, there is still room for research to be performed looking at hamstring strength and physical performance adaptations following an inertial flywheel intervention.

Is there an association between age, previous hamstring injury and eccentric hamstring strength in amateur and semi-professional footballers?

As introduced in section "Risk factors for hamstring injuries", age (Henderson et al., 2010; Woods et al., 2004) and previous hamstring injury (Green et al., 2020) are considered non-modifiable risk factors for future hamstring injuries. Instead, eccentric hamstring strength could be considered as one of the modifiable risk factors for future hamstring injuries (Burkett et al. 1970, cited in Opar et al., 2012). Before getting into more details, it should be noted that the eccentric hamstring measure assessed in Publications III and IV it is only measuring knee-flexor eccentric strength (using the NHE). Hence, all conclusions are based on this measure of hamstring strength. For other testing procedures for assessing hamstring strength, see Table 5 in Chapter 1 "Testing physical performance".

Increasing age has been identified as a potential risk factor for HSI in footballers, despite no convincing explanation has been given as to why older players are at significantly greater risk than younger players (Opar et al., 2012). Results from Publication III showed that a 0.9% decrease in eccentric hamstring strength could be expected for a year increase in player age, which confirmed the initial hypothesis. This is a very small effect, but considering that in 10 years of age-difference, a reduction of 9% on preseason eccentric hamstring strength may be present (0.5N·kg-1 or 37N for a 74kg football player) it could be considered important. However, considering the typical error of measurement (6.5 to 8.4%) and the minimal detectable change of 60-70N (Opar et al., 2013), or a 12% difference (Buchheit et al., 2016) should be considered meaningful or important. These results may partly explain the increased risk of future HSI in older football players (Henderson et al., 2010; Woods et al., 2004). In Publication IV, it was hypothesised that age would affect the changes in eccentric hamstring strength during the off-season, being older players more prone to reduced eccentric hamstring strength. However, age was not related to the change in strength during the off-season period. With the current findings, we can suggest that age is not affecting the change in strength or performance during the off-season, which is a very short period, but longer periods may negatively affect strength. For instance, longer exposure to football, or history of several HSIs (preceding the previous season) could also be related to decreased eccentric hamstring strength, possibly reflecting the importance of players age. Additionally, strength training exposure is another variable of interest, with footballers not being exposed to regular hamstring strengthening (eccentrically biased preferably), which may predispose them to a reduction of this capacity with its subsequent consequences.

Previous hamstring injury (per se) was not negatively associated with eccentric hamstring strength in Publication III, instead, hamstring injury duration (more than 3 weeks) was. Players with a hamstring injury duration of more than three weeks had 9% ($p<0.005$) lower preseason eccentric hamstring strength (3.83 ± 0.83 $N \cdot kg^{-1}$) compared to players with no previous hamstring injury (4.40 ± 1.01 $N \cdot kg^{-1}$) or players with a hamstring injury of less than three weeks (4.34 ± 1.02 $N \cdot kg^{-1}$). Recently, a very similar study, performed with professional Brazilian footballers, showed reduced eccentric hamstring strength ($d = 0.56$, $p>0.01$) in the injured compared to the uninjured limb (350.9 ± 60.8 N vs 385.8 ± 63.5 N) (Ribeiro-Alvares et al., 2020). In Publication III, no differences between injured and uninjured limb were present. One explanation could be that Ribeiro-Alvares and colleagues (2020) included hamstring injuries diagnosed by club medical doctors via imaging and examination. This was impossible in our cohort since in the amateur setting it is very difficult to have access to imaging diagnostics in the clubs and the retrospective study design could not overcome such limitation. However, Ribeiro-Alvares and colleagues (2020) did not look at injury severity (days lost), which could also have affected the results, probably overlooking consequent minor hamstring injuries.

Contemplating previously injured players may face fewer improvement in eccentric hamstring strength after an eccentric-biased intervention period during pre-season, as shown in previously injured elite Australian footballers (Opar et al., 2015a), and also reduced ability to generate force during the first meters of the acceleration phase (Mendiguchia et al., 2016), the prospective study (Publication IV) was developed. The results from Publication IV showed that previous hamstring injury did not affect eccentric hamstring strength during the off-season period. However, with the prospective cohort of 74 players, the relationship between injury duration (3 weeks or less vs. >3 weeks) and changes in eccentric hamstring strength could not be analysed, since only 3 players suffered a more severe hamstring injury (>3 weeks) during the season. Hence, it could not be addressed whether players with a hamstring injury resulting in greater time loss already start the off-season period with lower eccentric hamstring strength, or instead may face greater decrements during this period. While eccentric hamstring strength did not seem to be altered by players' off-season practices, players ending the season with low levels of eccentric hamstring strength will likely return with low levels of strength after the off-season.

When considering age and previous injury altogether, in Publication III, older and previously injured football players had even lower preseason eccentric hamstring strength compared to younger and non-injured counterparts. These results are relevant since prospective studies have shown that higher levels of eccentric hamstring strength were important in older and previously injured football (Timmins et al., 2016) and AFL (Opar et al., 2015b) players to reduce the odds of sustaining future HSI injuries. Moreover, the injury duration or absence of days could be related to injury severity, hence a higher degree of neuromuscular maladaptation (neuromuscular inhibition, selective hamstring atrophy, and shifts in the torque-joint angle relationships) and consequently an increased deficit in eccentric hamstring strength (Croisier, 2004; Fyfe et al., 2013; Opar et al., 2012; Silder et al., 2008). Hence, looking at hamstring injury duration instead of previous hamstring injury may be a more relevant approach to classify football players with suspected lower levels of eccentric hamstring strength and greater propensity to sustain future HSI in the new season.

Is sprint and COD performance affected during the off-season period in semi-professional and amateur footballers?

There is strong evidence supporting reduced sprint performance following the off-season period (Caldwell & Peters, 2009; Koundourakis et al., 2014; Nakamura et al., 2012; Requena et al., 2017), from professional to amateurs, considering no specific training is performed. In Publication IV, even though semi-professional and amateur footballers performed some amount of activity during the off-season period, their normal practices were not sufficient to avoid decrements in sprint performance (around -2% in 10 and 30 m sprint times). Those results confirmed the initial hypothesis. This suggests that players lost the ability to produce power during all the phases of the sprint, even though it may not be clearly present at 5 m, but already apparent at 10 m. While professional footballers (Spanish 1st division) following specific conditioning did not show decrements in 15-30 m sprint performance (Requena et al., 2017), recent evidence from another Spanish 1st division team showed similar 10 m sprint performance decrements (from 2.13 s to 2.16 s) as in Publication IV (from 2.24 s to 2.28 s) after the off-season period (Jiménez-Reyes et al., 2020), which were related to the loss in theoretical maximal force (F0), maximal power (Pmax) and the maximal ratio of force

(RFpeak). Probably, the main differences between the studies could be the lack of intervention in Jiménez-Reyes and colleagues (Jiménez-Reyes et al., 2020) during the off-season period, instead, Requena and colleagues provided an intervention (11 strength and endurance sessions) to reduce the negative off-season adaptations (Requena et al., 2017). Considering 1st division teams from the top of the table may need to perform and compete early in pre-season (qualifiers or finals), this off-season intervention could be a good strategy. Instead, teams that do not need to compete early in pre-season, may adopt a more conservative and progressive intervention during the off-season or first 2 weeks of pre-season.

Less convincing evidence is present in the literature when looking at COD performance changes during the off-season (Caldwell & Peters, 2009). When comparing COD performance results between studies, several aspects need to be contemplated, since the test utilised (single or multiple COD, COD angles, linear sprinting and total distance covered) will directly affect the results and could lead to wrong interpretations. In Publication IV, contrary to the initial hypothesis, players showed improved COD performance (0.7%, d=0.24, small) during the V-cut test at follow-up. It needs to be highlighted that the change (0.7%) was lower than the coefficient of variation (1.1-1.3%) during the V-cut test in this cohort. This may suggest that the changes in the values are just normal variability and not real change, hence, it should be considered with caution. Instead, Caldwell and colleagues (Caldwell & Peters, 2009) showed decreased COD performance during the Illinois agility test. For example, the Illinois agility test is very long (>14 s; compared to the <7 s in the V-cut), since it includes 4x10 m linear sprints and 2x10 m with COD, in which sprinting acceleration will directly affect the test outcome. Considering this COD test being biased to linear sprint, it is not surprising the results since the footballers also showed decreased 15 m sprinting performance (-3.3%) (Nimphius et al., 2018). To better evaluate COD ability and performance, the use of the COD deficit (Nimphius et al., 2016) could be an alternative that can improve the interpretation of results and applicability for practitioners and researchers. The moderate negative associations observed between the changes in eccentric hamstring strength and the changes in COD times (Publication IV, r = -0.42 to -0.44, see Figure 3 in Supplementary material) could be of interest to practitioners. However, no association was present between the changes in 5 m split time and the changes in COD performance in our cohort of football players, which seems surprising, considering short acceleration performance (0 to 5 m) was related to COD performance in professional football players (Loturco, A. Pereira, et al., 2019). From those results, eccentric hamstring strength only explained around 20% of the variance, hence 80% of the variance could be explained by other lower-limb strength and power properties, and biomechanical factors (e.g. COD technique, foot contact times, peak flexion angles, body mass, GRFs and momentum) contribute to performance (Chaabene et al., 2018; Chaouachi et al., 2012; Sheppard & Young, 2006) which were not assessed. Also, the use of inertial flywheel devices (Madruga-Parera et al., 2019) has been proposed to evaluate strength and power very close to a COD action. Contemplating the nature of multidirectional and multiple COD, acceleration and deceleration actions in football, the inertial flywheel assessment could complement a testing battery, looking at the physical weaknesses (eccentric strength or SSC), since stronger athletes can break or decelerate later in the approaching COD, compared to their weaker counterparts. Moreover, when including a more specific COD test, such as the V-cut test, a closer look at the technical attributes (body lean posture, foot placement and stride adjustment) could help understand the complexity of COD performance and future training targets (physical or technical). Unfortunately, this could not be evaluated in the current study but should be taken into account in future investigations.

How the off-season period should be approached?

As introduced earlier, most professional football players will consider the off-season break as a need to recover from the high physical and psychological demands of the competitive period (Silva et al., 2016). A complete cessation or near absence of training stimuli may not be the most appropriate action for football players (Silva et al., 2016), and could be approached as an opportunity to build fitness and correct muscle deficiencies (Nassis et al., 2019). In Publication IV, semi-professional and amateur football players showed reasonable activity levels during this period (between 216 to 316 min·week-1 on average), however with very heterogeneous levels of activity between players as shown by high standard deviations. Additionally, very little attention was placed to lower body strength training, with players performing less than 60 minutes a week on average. Since eccentric hamstring strength improvements are most likely to be gained by performing eccentrically biased training interventions, this information (exercise type, order and volume) was not available in Publication IV and as such cannot be analysed.

Even though pre-season is a period of low HSI occurrences compared to in-season (Hägglund, Waldén, & Ekstrand, 2013), the importance of managing training loads and the development of structured strength and conditioning sessions during the off-season, pre-season and in-season may be a crucial component for the injury risk management (Gabbett, 2016; Owen et al., 2013). Essentially, the main objective from practitioners is that players need to be prepared for congested periods of football games and sudden spikes in high-intensity running and sprinting loads, factors which likely contribute to HSIs incidence (Hägglund, Waldén, & Ekstrand, 2013). It seems that stronger and fitter players better tolerate increases in training load (Malone et al., 2019) and stronger players better recover after games (Owen et al., 2015), which highlights the importance of assessing players performance and strength levels at various intervals across a season, ideally. However, this best scenario may not be feasible for the vast majority, especially semi-professionals and amateurs. Then, one suggestion would be to implement a training intervention to develop eccentric hamstring strength, especially for players with a history of hamstring injury (greater than 3 weeks) and older in age, considering the most susceptible athletes are those older, with a history of an HSI and also a hamstring strength deficit, but not those athletes presenting a hamstring deficit by itself (Green et al., 2020). This suggestion is supported by the results from Publications III and IV, as players with low eccentric hamstring strength at the end of the season are consequently likely to start the following season with low levels of eccentric hamstring strength (ineffective off-season normal practices), and as such, appropriate remediation strategies still need to be considered. It should be highlighted that following an eccentric hamstring intervention other neuromuscular adaptations may also contribute to the hamstring injury risk reduction, such as intra- and intermuscular coordination, biceps femoris architecture (fascicle length and pennation angle), aponeurosis geometry or the muscle-tendinous junction (Bourne et al., 2020b).

Some could argue that strength exercises performed during pre-season, as the such NHE, is enough at reducing in-season hamstring injury incidence in professional and amateur football players (Petersen et al., 2011; van der Horst et al., 2015), but the number of hamstring injuries during pre-season could also be improved (Woods et al., 2004). Additionally, it seems that the NHE is not implemented by most of the highest level teams in Europe for several reasons (Bahr et al., 2015), and also it seems challenging to place eccentric strength exercises during the micro-cycle that may cause delayed onset of muscle soreness (DOMS) to the players (Goode et al., 2015; Lovell et al., 2018). One suggestion for practitioners could be that if players perform some eccentric strength work during the off-season, players are more likely to mitigate the symptoms of DOMS due to the repeated bout effect (Cheung et al., 2003) and might be better prepared to tolerate pre-season and in-season loads, including the eccentric hamstring exercises to a well-rounded strength training. Moreover, for professional football players with the need to compete early in pre-season or seeking to maintain sprinting performance early in pre-season, a training intervention during the last few weeks of the off-season period is required, with demonstrated interventions (including strength, plyometric and sprinting exercises) in elite football players (Requena et al., 2017). In practice, the player's motivation, ambitions and goals will possibly affect the activity performed during the off-season period. Nonetheless, as practitioners we should give advice and help the development of footballers, contemplating this period as an opportunity to focus on players' weaknesses, with one possibility being the training intervention presented in the study protocol (Publication V).

While this study protocol is including two intervention groups, both groups are intended to improve performance and hamstring strength measures, which in the end can help to reduce the risk of future hamstring injuries as shown by existing literature. Therefore, assuming both interventions show positive benefits for performance and hamstring strength, it could be a very interesting training program for semi-professional footballers during the off-season period. Such an approach would permit players to disconnect and relax at the beginning of the off-season (including low intensity and less frequent activities), and then train the aforementioned contents (more regularly and at greater intensities) three weeks before starting the pre-season with their respective teams. Moreover, if inertial flywheel can provide greater improvements in COD and RSA performances, it should be reasonable to include them in the training practices. Finally, bigger RCTs and multi-centre studies testing the efficacy and effectiveness of those hamstring interventions would also be crucial for researchers and practitioners.

Conclusions

The main conclusions of this thesis are presented below:

- Inertial flywheel resistance training is not superior to gravity-dependent resistance training on enhancing muscle strength (MVIC). The conclusion is based upon the currently available literature where only three RCTs and four non-RCTs qualified for meta-analysis. There was not enough evidence to analyse other strength variables (eccentric or RFD), muscular adaptations or performance outcomes (sprint, jump or COD) at the moment of the search.

- Recent evidence in team-sport athletes shows interesting results regarding strength and performance adaptations. While an update of the meta-analysis could provide a clearer picture, it could be hypothesised that similar strength but greater performance adaptations (mainly COD and jumping) in favour of inertial flywheel interventions.

- The systematic review with meta-analysis appraised in the Letter to the Editor presented methodological shortcomings since some of the included articles did not perform such comparisons. Hence, the superiority of inertial flywheel resistance interventions against gravity-dependent interventions which were concluded is not supported by the available literature.

- Amateur footballers with a previous hamstring injury of more than three weeks present lower eccentric hamstring strength at the beginning of preseason. Moreover, increasing age is associated with lower eccentric hamstring strength at the beginning of preseason in amateur footballers.

- Semi-professional and amateur footballers show impaired sprint performance after the off-season period, independent of age, previous hamstring injury and length of the off-season. Such decrements in sprint performance are not related to the changes in eccentric hamstring strength, which is not altered after the off-season period.

- The intervention protocol is intended to improve physical performance and hamstring strength in both groups. Even though both training interventions appear to produce similar improvements in performance, greater change of direction and repeated sprint ability performances for the inertial flywheel group is expected.

Limitations and directions for future research

In the present work, some limitations need to be highlighted. In Publication I, very few RCTs and non-RCTs comparing inertial flywheel against gravity-dependent interventions were available, with only one study involving football players. For this reason, an intervention protocol (Publication V) has been developed aiming to contribute to the research on this topic. Heterogeneity in study outcomes, type of interventions (exercise selection and loading paradigms) and participants characteristics and training experience were present, which should be taken into account when interpreting results. Moreover, as most of the training studies available in the literature, interventions lasted no longer than 12 weeks, where long-term effectiveness of inertial flywheel interventions may be needed.

Numerous areas could be investigated on the topic of training adaptations (performance and muscle adaptations) after inertial flywheel training, and also its relationship with injury rates. Moreover, the need to perform an RCT to control for confounding variables and produce a convincing body of evidence is warranted, as it is planned in the intervention protocol (Publication V). Regarding studies' outcomes, the inclusion of performance outcomes such as sprint, jump or COD performances, but also muscle power outcomes (such as RFD), should be included when studying physical performance in football players.

In Publication III and IV, history and duration of hamstring injury were collected using the retrospective and self-reported recall from football players. While recall bias may be present, the injury form comprised a small number of simple questions, including a clear definition of injury and details concerning the anatomical region, which was shown to reduce recall bias. Moreover, the time frame of injury reporting was limited to the previous season (10-12 months), which also may provide less recall bias compared to greater time frames but ignores hamstring injuries that occurred before this period.

In publication IV, due to the observational and prospective nature of the study, it was not possible to standardize the off-season training programmes or activities performed by the footballers. While off-season activity was collected every week, very heterogeneous profiles were present. Some players may be involved in sports activities and voluntary non-periodized training programs, while others may have followed specific off-season training programs from professionals, which could be linked to different stimulus and result in different adaptations. Such analysis was not part of the study aim but could be an interesting study to look at whether supervised training or non-supervised training could lead to similar or different off-season adaptations. Lastly, while publication IV was sufficiently powered to detect pre to post changes in performance and strength outcomes, it was underpowered to analyse the possible effect of HSI on sprint, COD performance and eccentric hamstring strength, given the relatively small sample of previously injured athletes.

The possibility of assessing the reliability and validity of the hamstring musculature using inertial flywheel devices, such as the back-kick exercise is an area of interest. The dynamic nature of the action during a hamstring hip-based exercise, including concentric and eccentric power and force outputs and the use of the stretch-shortening cycle, plus maintaining the specificity of the exercise kinematics, could provide optimistic insights for sprinting performance and hamstring injury prevention.

While movement specificity seems to be important for sport-specific performance adaptations, not always similar exercise kinematics may provide the best performance result. Hence, the study of the exercise kinetics (vertical and horizontal GRFs) using force platforms, while maintaining exercise kinematics, comparing between inertial flywheel exercises against gravity-dependent (pulleys, weights, bands) is an area of interest to be exploited in the future.

Finally, even though inertial flywheel devices can be widely used nowadays, and growing evidence is supporting their use, the loading parameters for performance adaptations seems to be understudied. Considering exercise intensity as the driver of performance adaptations, it seems important to understand the relationship between the loading paradigm (inertias and moment of forces) used during inertial flywheel exercises and its performance adaptations.

References

Aagaard, P. (2010). The Use of Eccentric Strength Training to Enhance Maximal Muscle Strength, Explosive Force (RDF) and Muscular Power - Consequences for Athletic Performance. *The Open Sports Sciences Journal*, *3*(1), 52–55. https://doi.org/10.2174/1875399X01003010052

Ade, J., Fitzpatrick, J., & Bradley, P. S. (2016). High-intensity efforts in elite soccer matches and associated movement patterns, technical skills and tactical actions. Information for position-specific training drills. *Journal of Sports Sciences*, *34*(24), 2205–2214. https://doi.org/10.1080/02640414.2016.1217343

AEPFL. (2005). *European Leagues*. https://europeanleagues.com

Akenhead, R., Hayes, P. R., Thompson, K. G., & French, D. (2013). Diminutions of acceleration and deceleration output during professional football match play. *Journal of Science and Medicine in Sport*, *16*(6), 556–561. https://doi.org/10.1016/j.jsams.2012.12.005

Al Attar, W. S. A., Soomro, N., Sinclair, P. J., Pappas, E., & Sanders, R. H. (2017). Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: a systematic review and meta-analysis. *Sports Medicine*, *47*(5), 907–916. https://doi.org/10.1007/s40279-016-0638-2

Appleby, B. B., Cormack, S. J., & Newton, R. U. (2020). Unilateral and bilateral lower-body resistance training does not transfer equally to sprint and change of direction performance. *Journal of Strength and Conditioning Research*, *34*(1), 54–64. https://doi.org/10.1519/JSC.0000000000003035

Arcos, A. L., Yanci, J., Mendiguchia, J., Salinero, J. J., Brughelli, M., & Castagna, C. (2014). Short-term training effects of vertically and horizontally oriented exercises on neuromuscular performance in professional soccer players. *International Journal of Sports Physiology and Performance*, *9*(3), 480–488. https://doi.org/10.1123/IJSPP.2013-0063

Arnason, A., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2007). Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian Journal of Medicine & Science in Sports*, *18*(1), 40–48. https://doi.org/10.1111/j.1600-0838.2006.00634.x

Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports*, *13*(4), 244–250. https://doi.org/10.1034/j.1600-0838.2003.00312.x

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, *26*(4), 217–238. https://doi.org/10.2165/00007256-199826040-00002

Bahr, R., Thorborg, K., & Ekstrand, J. (2015). Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: The Nordic Hamstring survey. *British Journal of Sports Medicine*, *49*(22), 1466–1471. https://doi.org/10.1136/bjsports-2015-094826

Balsalobre-Fernández, C., Bishop, C., Beltrán-Garrido, J. V., Cecilia-Gallego, P., Cuenca-Amigó, A., Romero-Rodríguez, D., & Madruga-Parera, M. (2019). The validity and reliability of a novel app for the measurement of change of direction performance. *Journal of Sports Sciences*, *37*(21), 2420–2424. https://doi.org/10.1080/02640414.2019.1640029

Balsalobre-Fernández, C., Glaister, M., & Lockey, R. A. (2015). The validity and reliability of an iPhone app for measuring vertical jump performance. *Journal of Sports Sciences*, *33*(15), 1574–1579. https://doi.org/10.1080/02640414.2014.996184

Barnes, C., Archer, D. T., Hogg, B., Bush, M., & Bradley, P. S. (2014). The evolution of physical and technical performance parameters in the English Premier League. *International Journal of Sports Medicine*, *35*(13), 1095–1100. https://doi.org/10.1055/s-0034-1375695

Bengtsson, H., Ekstrand, J., & Hägglund, M. (2013). Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, *47*(12), 743–747. https://doi.org/10.1136/bjsports-2013-092383

Berg, H. E., & Tesch, P. A. (1994). A gravity-independent ergometer to be used for resistance training in space. *Aviation, Space, and Environmental Medicine*, *65*(8), 752–756.

Berg, H. E., & Tesch, P. A. (1998). Force and power characteristics of a resistive exercise device for use in space. *Acta Astronautica*, *42*(1–8), 219–230. https://doi.org/10.1016/S0094-5765(98)00119-2

Bishop, C., Turner, A., & Read, P. (2018). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences*, *36*(10), 1135–1144. https://doi.org/10.1080/02640414.2017.1361894

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-Sprint Ability – Part II. *Sports Medicine*, *41*(9), 741–756. https://doi.org/10.2165/11590560-000000000-00000

Bittencourt, N. F. N., Meeuwisse, W. H., Mendonça, L. D., Nettel-Aguirre, A., Ocarino, J. M., & Fonseca, S. T. (2016). Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition - Narrative review and new concept. *British Journal of Sports Medicine*, *50*(21), 1309–1314. https://doi.org/10.1136/bjsports-2015-095850

Bizzini, M., & Dvorak, J. (2015). FIFA 11+: An effective programme to prevent football injuries in various player groups worldwide - A narrative review. *British Journal of Sports Medicine*, *49*(9), 577–579. https://doi.org/10.1136/bjsports-2015-094765

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science & Medicine*, *6*(1), 63–70. https://doi.org/10.1371/journal.pone.0095773

Bourne, M. N., Opar, D. A., Williams, M. D., Al Najjar, A., & Shield, A. J. (2016). Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scandinavian Journal of Medicine and Science in Sports*, *26*(6), 666–674. https://doi.org/10.1111/sms.12494

Bourne, M. N., Schuermans, J., Witvrouw, E., Aagaard, P., & Shield, A. (2020a). Neuromuscular factors related to hamstring muscle function, performance and injury. In K. Thorborg, D. Opar, & A. Shield (Eds.), *Prevention and Rehabilitation of Hamstring Injuries* (pp. 117–143). Springer

International Publishing. https://doi.org/10.1007/978-3-030-31638-9_5

Bourne, M. N., Schuermans, J., Witvrouw, E., Aagaard, P., & Shield, A. (2020b). Neuromuscular factors related to hamstring muscle function, performance and injury. *Prevention and Rehabilitation of Hamstring Injuries*, 117–143. https://doi.org/10.1007/978-3-030-31638-9_5

Bourne, M. N., Timmins, R. G., Opar, D. A., Pizzari, T., Ruddy, J. D., Sims, C., Williams, M. D., & Shield, A. . J. (2017). An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Medicine*. https://doi.org/10.1007/s40279-017-0796-x

Bourne, M. N., Williams, M. D., Opar, D. A., Al Najjar, A., Kerr, G. K., & Shield, A. J. (2017). Impact of exercise selection on hamstring muscle activation. *British Journal of Sports Medicine*, *51*(13), 1021–1028. https://doi.org/10.1136/bjsports-2015-095739

Bradley, P. S., & Ade, J. D. (2018). Are current physical match performance metrics in elite soccer fit for purpose or is the adoption of an integrated approach needed? *International Journal of Sports Physiology and Performance*, *13*(5), 656–664. https://doi.org/10.1123/ijspp.2017-0433

Bradley, P. S., Archer, D. T., Hogg, B., Schuth, G., Bush, M., Carling, C., & Barnes, C. (2016). Tier-specific evolution of match performance characteristics in the English Premier League: it's getting tougher at the top. *Journal of Sports Sciences*, *34*(10), 980–987. https://doi.org/10.1080/02640414.2015.1082614

Bradley, P. S., Carling, C., Gomez Diaz, A., Hood, P., Barnes, C., Ade, J., Boddy, M., Krustrup, P., & Mohr, M. (2013). Match performance and physical capacity of players in the top three competitive standards of English professional soccer. *Human Movement Science*, *32*(4), 808–821. https://doi.org/10.1016/j.humov.2013.06.002

Bradley, P. S., & Noakes, T. D. (2013). Match running performance fluctuations in elite soccer: Indicative of fatigue, pacing or situational influences? *Journal of Sports Sciences*, *31*(15), 1627–1638. https://doi.org/10.1080/02640414.2013.796062

Brito, J., Vasconcellos, F., Oliveira, J., Krustrup, P., & Rebelo, A. (2014). Short-term performance effects of three different low-volume strength-training Programmes in college male soccer players. *Journal of Human Kinetics*, *40*(1), 121–128. https://doi.org/10.2478/hukin-2014-0014

Brughelli, M., & Cronin, J. (2007). Altering the length-tension relationship with eccentric exercise. *Sports Medicine*, *37*(9), 807–826. https://doi.org/10.2165/00007256-200737090-00004

Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport: a review of resistance training studies. *Sports Medicine (Auckland, N.Z.)*, *38*(12), 1045–1063.

Buchheit, M., Cholley, Y., Nagel, M., & Poulos, N. (2016). The Effect of Body Mass on Eccentric Knee-Flexor Strength Assessed With an Instrumented Nordic Hamstring Device (Nordbord) in Football Players. *International Journal of Sports Physiology and Performance*, *11*(6), 721–726. https://doi.org/10.1123/ijspp.2015-0513

Buchheit, M., Eirale, C., Simpson, B. M., & Lacome, M. (2018). Injury rate and prevention in elite football: let us first search within our own hearts. *British Journal of Sports Medicine*, bjsports-2018-099267. https://doi.org/10.1136/bjsports-2018-099267

Buchheit, M., Haydar, B., & Ahmaidi, S. (2012). Repeated sprints with directional changes: do angles matter? *Journal of Sports Sciences*, *30*(6), 555–562. https://doi.org/10.1080/02640414.2012.658079

Buchheit, M., Simpson, B. M., Hader, K., & Lacome, M. (2020). Occurrences of near-to-maximal speed running bouts in elite soccer: insights for training prescription and injury mitigation Submission. *Science and Medicine in Football*. https://doi.org/10.11428/jhej1987.42.189

Buckthorpe, M., Wright, S., Bruce-Low, S., Nanni, G., Sturdy, T., Gross, A. S., Bowen, L., Styles, B., Della Villa, S., Davison, M., & Gimpel, M. (2019). Recommendations for hamstring injury prevention in elite football: Translating research into practice. *British Journal of Sports Medicine*, *53*(7), 449–456. https://doi.org/10.1136/bjsports-2018-099616

Buhmann, R., Trajano, G., Kerr, G., & Shield, A. (2020). Voluntary activation and reflex responses following hamstring strain injury. *Medicine & Science in Sports & Exercise*, 1. https://doi.org/10.1249/MSS.0000000000002327

Bush, M., Barnes, C., Archer, D. T., Hogg, B., & Bradley, P. S. (2015). Evolution of match performance parameters for various playing positions in the English Premier League. *Human Movement Science*, *39*, 1–11. https://doi.org/10.1016/j.humov.2014.10.003

Caldwell, B. P., & Peters, D. M. (2009). Seasonal variation in physiological fitness of a semiprofessional soccer team. *Journal of Strength and Conditioning Research*, *23*(5), 1370–1377. https://doi.org/10.1519/JSC.0b013e3181a4e82f

Carling, C., & Orhant, E. (2010). Variation in body composition in professional soccer players: interseasonal and intraseasonal changes and the effects of exposure time and player position. *Journal of Strength and Conditioning Research*, *24*(5), 1332–1339. https://doi.org/10.1519/JSC.0b013e3181cc6154

Caruso, J. F., Coday, M. A., Ramsey, C. A., Griswold, S. H., Polanski, D. W., Drummond, J. L., & Walker, R. H. (2008). Leg and calf press training modes and their impact on jump performance adaptations. *Journal of Strength and Conditioning Research*, *22*(3), 766–772. https://doi.org/10.1519/JSC.0b013e31816a849a

Caruso, J. F., Hamill, J. L., Hernandez, D. A., & Yamauchi, M. (2005). A comparison of isoload and isoinertial leg press training on bone and muscle outcomes. *Journal of Strength & Conditioning Research*, *19*(3), 592. https://doi.org/10.1519/R-15724.1

Casamichana, D., Castellano, J., & Castagna, C. (2012). Comparing the physical demands of friendly matches and small-sided games in semiprofessional soccer players. *Journal of Strength and Conditioning Research*, *26*(3), 837–843. https://doi.org/10.1519/JSC.0b013e31822a61cf

Casamichana, D., Castellano, J., Diaz, A. G., Gabbett, T. J., & Martin-Garcia, A. (2019). The most demanding passages of play in football competition: A comparison between halves. *Biology of Sport*, *36*(3), 233–240. https://doi.org/10.5114/biolsport.2019.86005

Castellano, J., Blanco-Villaseñor, A., & Álvarez, D. (2011). Contextual variables and time-motion analysis in soccer. *International Journal of Sports Medicine*, *32*(6), 415–421. https://doi.org/10.1055/s-0031-1271771

Castellano, J., & Casamichana, D. (2013). Differences in the number of accelerations between small-sided games and friendly matches in soccer. *Journal of Sports Science and Medicine*, *12*(1), 209–210.

Castillo-Rodríguez, A., Cano-Cáceres, F. J., Figueiredo, A., & Fernández-García, J. C. (2020). Train like you compete? Physical and physiological responses on semi-professional soccer players. *International Journal of Environmental Research and Public Health*, *17*(3). https://doi.org/10.3390/ijerph17030756

Chaabene, H., Prieske, O., Negra, Y., & Granacher, U. (2018). Change of direction speed: toward a strength training approach with accentuated eccentric muscle actions. *Sports Medicine*, *48*(8), 1773–1779. https://doi.org/10.1007/s40279-018-0907-3

Chaouachi, A., Manzi, V., Chaalali, A., Wong, D. P., Chamari, K., & Castagna, C. (2012). Determinants analysis of change-of-direction ability in elite soccer players. *Journal of Strength and Conditioning Research*, *26*(10), 2667–2676. https://doi.org/10.1519/JSC.0b013e318242f97a

Cheung, K., Hume, P. A., & Maxwell, L. (2003). Delayed onset muscle soreness. *Sports Medicine*, *33*(2), 145–164. https://doi.org/10.2165/00007256-200333020-00005

Chumanov, E. S., Schache, A. G., Heiderscheit, B. C., & Thelen, D. G. (2012). Hamstrings are most susceptible to injury during the late swing phase of sprinting. *British Journal of Sports Medicine*, *46*(2), 90–90. https://doi.org/10.1136/bjsports-2011-090176

Cometti, G., Maffiuletti, N. A., Pousson, M., Chatard, J. C., & Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International Journal of Sports Medicine*, *22*(1), 45–51. https://doi.org/10.1055/s-2001-11331

Comfort, P., Stewart, A., Bloom, L., & Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *Journal of Strength and Conditioning Research*, *28*(1), 173–177. https://doi.org/10.1519/JSC.0b013e318291b8c7

Coratella, G., Beato, M., Cè, E., Scurati, R., Milanese, C., Schena, F., & Esposito, F. (2019). Effects of in-season enhanced negative work-based vs traditional weight training on change of direction and hamstrings-to-quadriceps ratio in soccer players. *Biology of Sport*, *36*(3), 241–248. https://doi.org/10.5114/biolsport.2019.87045

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. *Journal of Strength and Conditioning Research*, *23*(1), 177–186. https://doi.org/10.1519/JSC.0b013e3181889324

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 1 - Biological basis of maximal power production. *Sports Medicine*, *41*(1), 17–38. https://doi.org/10.2165/11537690-000000000-00000

Croisier, J. L. (2004). Factors associated with recurrent hamstring injuries. *Sports Medicine*, *34*(10), 681–695. https://doi.org/10.2165/00007256-200434100-00005

Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J.-M. M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *The American Journal of Sports Medicine*, *36*(8), 1469–1475. https://doi.org/10.1177/0363546508316764

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *The Journal of Strength and Conditioning Research*, *19*(2), 349. https://doi.org/10.1519/14323.1

Dauty, M., Menu, P., & Fouasson-Chailloux, A. (2018). Cutoffs of isokinetic strength ratio and hamstring strain prediction in professional soccer players. *Scandinavian Journal of Medicine & Science in Sports*, *28*(1), 276–281. https://doi.org/10.1111/sms.12890

de Hoyo, M., de la Torre, A., Pradas, F., Sañudo, B., Carrasco, L., Mateo-Cortes, J., Domínguez-Cobo, S., Fernandes, O., & Gonzalo-Skok, O. (2014). Effects of Eccentric Overload Bout on Change of Direction and Performance in Soccer Players. *International Journal of Sports Medicine*, *36*(04), 308–314. https://doi.org/10.1055/s-0034-1395521

de Hoyo, M., Pozzo, M., Sañudo, B., Carrasco, L., Gonzalo-Skok, O., Domínguez-Cobo, S., & Morán-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. https://doi.org/10.1123/ijspp.2013-0547

de Hoyo, M., Sañudo, B., Carrasco, L., Domínguez-Cobo, S., Mateo-Cortes, J., Cadenas-Sánchez, M. M., & Nimphius, S. (2015). Effects of Traditional Versus Horizontal Inertial Flywheel Power Training on Common Sport-Related Tasks. *Journal of Human Kinetics*, *47*(1), 155–167. https://doi.org/10.1515/hukin-2015-0071

de Hoyo, M., Sañudo, B., Suárez-Arrones, L., Carrasco, L., Joel, T., Domínguez-Cobo, S., & Núñez, F. J. (2018). Analysis of the acceleration profile according to initial speed and positional role in elite professional male soccer players. *The Journal of Sports Medicine and Physical Fitness*, *58*(12), 1774–1780. https://doi.org/10.23736/S0022-4707.17.08003-3

De Paula Simola, R. Á., Harms, N., Raeder, C., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2015). Assessment of neuromuscular function after different strength training protocols using tensiomyography. *Journal of Strength and Conditioning Research*, *29*(5), 1339–1348. https://doi.org/10.1519/JSC.0000000000000768

de Visser, H., Reijman, M., Heijboer, M., & Bos, P. (2012). Risk factors of recurrent hamstring injuries: a systematic review. *British Journal of Sports Medicine*, *46*(2), 124–130. https://doi.org/10.1136/bjsports-2011-090317

Dellal, A., Hill-Haas, S., Lago-Penas, C., & Chamari, K. (2011). Small-sided games in soccer: amateur vs. professional players' physiological responses, physical, and technical activities. *Journal of Strength and Conditioning Research*, *25*(9), 2371–2381. https://doi.org/10.1519/JSC.0b013e3181fb4296

Dellal, A., Lago-Peñas, C., Rey, E., Chamari, K., & Orhant, E. (2015). The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *British Journal of Sports Medicine*, *49*(6), 390–394. https://doi.org/10.1136/bjsports-2012-091290

Di Salvo, V., Baron, R., Tschan, H., Calderon Montero, F. J., Bachl, N., & Pigozzi, F. (2007). Performance characteristics according to playing position in elite soccer. *International Journal of Sports Medicine*, *28*(3), 222–227. https://doi.org/10.1055/s-2006-924294

Di Salvo, V., Pigozzi, F., González-Haro, C., Laughlin, M., & De Witt, J. (2012). Match performance comparison in top English soccer leagues. *International Journal of Sports Medicine*, *34*(06), 526–532. https://doi.org/10.1055/s-0032-1327660

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The effect of angle and velocity on change of direction biomechanics: an angle-velocity trade-off. *Sports Medicine*, *48*(10), 2235–2253. https://doi.org/10.1007/s40279-018-0968-3

Dos'Santos, T., Thomas, C., Jones, P. A., & Comfort, P. (2017). Mechanical determinants of faster change of direction speed performance in male athletes. *Journal of Strength and Conditioning Research*, *31*(3), 696–705. https://doi.org/10.1519/JSC.0000000000001535

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2016). Chronic adaptations to eccentric training: a systematic review. *Sports Medicine*, 1–25. https://doi.org/10.1007/s40279-016-0628-4

Dudley, G. A., Tesch, P. A., Miller, B. J., & Buchanan, P. (1991). Importance of eccentric actions in performance adaptations to resistance training. *Aviation, Space, and Environmental Medicine*, *62*(6), 543–550.

Duhig, S., Shield, A. J., Opar, D. A., Gabbett, T. J., Ferguson, C., & Williams, M. (2016). Effect of high-speed running on hamstring strain injury risk. *British Journal of Sports Medicine*, *50*(24), 1536–1540. https://doi.org/10.1136/bjsports-2015-095679

Dupont, G., Nedelec, M., McCall, A., McCormack, D., Berthoin, S., & Wisløff, U. (2010). Effect of 2 soccer matches in a week on physical performance and injury rate. *American Journal of Sports Medicine*, *38*(9), 1752–1758. https://doi.org/10.1177/0363546510361236

Dvorak, J., Graf-Baumann, T., Peterson, L., & Junge, A. (2000). Football, or soccer, as it is called in North America, is the most popular sport worldwide. *The American Journal of Sports Medicine*, *28*(5 Suppl), S1-2. http://www.ncbi.nlm.nih.gov/pubmed/11032100

Edouard, P., Mendiguchia, J., Guex, K., Lahti, J., Samozino, P., & Morin, J. B. (2019). Sprinting: a potential vaccine for hamstring injury? *Sport Performance and Science Reports*, *48*(1). https://doi.org/10.16603/ijspt20170718

Ekstrand, J. (2013). Keeping your top players on the pitch: The key to football medicine at a professional level. *British Journal of Sports Medicine*, *47*(12), 723–724. https://doi.org/10.1136/bjsports-2013-092771

Ekstrand, J., Hägglund, M., & Waldén, M. (2011a). Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine*, *45*(7), 553–558. https://doi.org/10.1136/bjsm.2009.060582

Ekstrand, J., Hägglund, M., & Waldén, M. (2011b). Epidemiology of muscle injuries in professional football (soccer). *The American Journal of Sports Medicine*, *39*(December 2016), 1226–1232. https://doi.org/10.1177/0363546510395879

Ekstrand, J., Waldén, M., & Hägglund, M. (2016). Hamstring injuries have increased by 4% annually in men's professional football, since 2001: A 13-year longitudinal analysis of the UEFA Elite Club injury study. *British Journal of Sports Medicine*, *50*(12), 731–737. https://doi.org/10.1136/bjsports-2015-095359

Emmonds, S., Nicholson, G., Beggs, C., Jones, B., & Bissas, A. (2017). Importance of physical qualities for speed and change of direction ability in elite female soccer players. *Journal of Strength and Conditioning Research*, 1. https://doi.org/10.1519/jsc.0000000000002114

Engebretsen, A. H., Myklebust, G., Holme, I., Engebretsen, L., & Bahr, R. (2010). Intrinsic risk factors for hamstring injuries among male soccer players: A prospective cohort study. *American Journal of Sports Medicine*, *38*(6), 1147–1153. https://doi.org/10.1177/0363546509358381

Esmaeili, A., Hopkins, W. G., Stewart, A. M., Elias, G. P., Lazarus, B. H., & Aughey, R. J. (2018). The individual and combined effects of multiple factors on the risk of soft tissue non-contact injuries in elite team sport athletes. *Frontiers in Physiology*, *9*(SEP), 1–16. https://doi.org/10.3389/fphys.2018.01280

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences*, *30*(7), 625–631. https://doi.org/10.1080/02640414.2012.665940

Faude, O., Roth, R., Giovine, D. Di, Zahner, L., & Donath, L. (2013). Combined strength and power training in high-level amateur football during the competitive season: A randomised-controlled trial. *Journal of Sports Sciences*, *31*(13), 1460–1467. https://doi.org/10.1080/02640414.2013.796065

Fernandez-Gonzalo, R., Tesch, P. A., Linnehan, R. M., Kreider, R. B., Di Salvo, V., Suarez-Arrones, L., Alomar, X., Mendez-Villanueva, A., & Rodas, G. (2016). Individual Muscle use in Hamstring Exercises by Soccer Players Assessed using Functional MRI. *International Journal of Sports Medicine*, *37*(7), 559–564. https://doi.org/10.1055/s-0042-100290

Fernandez-Gonzalo, Rodrigo, Fernandez-Gonzalo, S., Turon, M., Prieto, C., Tesch, P. A., & García-Carreira, M. del 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*(1), 37. https://doi.org/10.1186/s12984-016-0144-7

Fernandez-Gonzalo, Rodrigo, 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. https://doi.org/10.1007/s00421-014-2836-7

Fernández-Valdés, B., Sampaio, J., Exel, J., González, J., Tous-Fajardo, J., Jones, B., & Moras, G. (2020). The Influence of Functional Flywheel Resistance Training on Movement Variability and Movement Velocity in Elite Rugby Players. *Frontiers in Psychology*, *11*(June). https://doi.org/10.3389/fpsyg.2020.01205

Fitzharris, N., Jones, G., Jones, A., & Francis, P. (2017). The first prospective injury audit of League of Ireland footballers. *BMJ Open Sport and Exercise Medicine*, *3*(1), 1–7. https://doi.org/10.1136/bmjsem-2017-000220

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training. *Sports Medicine*, *37*(2), 145–168. https://doi.org/10.2165/00007256-200737020-00004

Fousekis, K., Tsepis, E., Poulmedis, P., Athanasopoulos, S., & Vagenas, G. (2011). Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *British Journal of Sports Medicine*, *45*(9), 709–714. https://doi.org/10.1136/bjsm.2010.077560

Freckleton, G., & Pizzari, T. (2013). Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*, *47*(6), 351–358. https://doi.org/10.1136/bjsports-2011-090664

Fyfe, J. J., Opar, D. A., Williams, M. D., & Shield, A. J. (2013). The role of neuromuscular inhibition in hamstring strain injury recurrence. *Journal of Electromyography and Kinesiology*, *23*(3), 523–530. https://doi.org/10.1016/j.jelekin.2012.12.006

Gabbett, T. J. (2016). The training-injury prevention paradox: should athletes be training smarter and harder? *British Journal of Sports Medicine*, 1–9. https://doi.org/10.1136/bjsports-2015-095788

Girard, O., Mendez-Villanueva, A., & Bishop, D. (2011). Repeated-Sprint Ability – Part I. *Sports Medicine*, *41*(8), 673–694. https://doi.org/10.2165/11590550-000000000-00000

Gissis, I., Papadopoulos, C., Kalapotharakos, V., Sotiropoulos, A., Komsis, G., & Manolopoulos, E. (2006). Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Research in Sports Medicine*, *14*(3), 205–214. https://doi.org/10.1080/15438620600854769

Gonzalo-Skok, O., Tous-Fajardo, J., Arjol-Serrano, J. L., Suarez-Arrones, L., Casajús, J. A., & Mendez-Villanueva, A. (2016). Improvement of repeated-sprint ability and horizontal-jumping performance in elite young basketball players with low-volume repeated-maximal-power training. *International Journal of Sports Physiology and Performance*, *11*(4), 464–473. https://doi.org/10.1123/ijspp.2014-0612

Gonzalo-Skok, O., Tous-Fajardo, J., Suarez-Arrones, L., Arjol-Serrano, J. L., Casajús, J. A., & Mendez-Villanueva, A. (2017). Single-Leg Power Output and Between-Limbs Imbalances in Team-Sport Players: Unilateral Versus Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance*, *12*(1), 106–114. https://doi.org/10.1123/ijspp.2015-0743

Gonzalo-Skok, O., Tous-Fajardo, J., Valero-Campo, C., Berzosa, C., Bataller, A. V., Arjol-Serrano, J. L., Moras, G., & Mendez-Villanueva, A. (2017). Eccentric-Overload Training in Team-Sport Functional Performance: Constant Bilateral Vertical Versus Variable Unilateral Multidirectional Movements. *International Journal of Sports Physiology and Performance*, *12*(7), 951–958. https://doi.org/10.1123/ijspp.2016-0251

Goode, A. P., Reiman, M. P., Harris, L., DeLisa, L., Kauffman, A., Beltramo, D., Poole, C., Ledbetter, L., & Taylor, A. B. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*(6), 349–356. https://doi.org/10.1136/bjsports-2014-093466

Green, B., Bourne, M. N., & Pizzari, T. (2018). Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *52*(5), 329–336. https://doi.org/10.1136/bjsports-2017-098101

Green, B., Bourne, M. N., van Dyk, N., & Pizzari, T. (2020). Recalibrating the risk of hamstring strain injury (HSI) - A 2020 systematic review and meta-analysis of risk factors for index and recurrent HSI in sport. *British Journal of Sports Medicine*, bjsports-2019-100983. https://doi.org/10.1136/bjsports-2019-100983

Greenwood, J., Morrissey, M. C., Rutherford, O. M., & Narici, M. V. (2007). Comparison of conventional resistance training and the fly-wheel ergometer for training the quadriceps muscle group in patients with unilateral knee injury. *European Journal of Applied Physiology*, *101*(6), 697–703. https://doi.org/10.1007/s00421-007-0548-y

Greig, M., & Siegler, J. C. (2009). Soccer-specific fatigue and eccentric hamstrings muscle strength. *Journal of Athletic Training*, *44*(2), 180–184. https://doi.org/10.4085/1062-6050-44.2.180

Guex, K., & Millet, G. P. (2013). Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Medicine*, *43*(12), 1207–1215. https://doi.org/10.1007/s40279-013-0097-y

Hägglund, M., Waldén, M., & Ekstrand, J. (2013). Risk Factors for Lower Extremity Muscle Injury in Professional Soccer. *The American Journal of Sports Medicine*, *41*(2), 327–335. https://doi.org/10.1177/0363546512470634

Hägglund, M., Waldén, M., & Ekstrand, J. (2016). Injury recurrence is lower at the highest professional football level than at national and amateur levels: does sports medicine and sports physiotherapy deliver? *British Journal of Sports Medicine*, *50*, bjsports-2015-095951. https://doi.org/10.1136/bjsports-2015-095951

Hägglund, M., Waldén, M., Magnusson, H., Kristenson, K., Bengtsson, H., & Ekstrand, J. (2013). Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *British Journal of Sports Medicine*, *47*(12), 738–742. https://doi.org/10.1136/bjsports-2013-092215

Harper, D. J., Carling, C., & Kiely, J. (2019). High-intensity acceleration and deceleration demands in elite team sports competitive match play: a systematic review and meta-analysis of observational studies. *Sports Medicine*, *49*(12), 1923–1947. https://doi.org/10.1007/s40279-019-01170-1

Haugen, T., & Buchheit, M. (2016). Sprint running performance monitoring: methodological and practical considerations. *Sports Medicine*, *46*(5), 641–656. https://doi.org/10.1007/s40279-015-0446-0

Henderson, G., Barnes, C. A., & Portas, M. D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of Science and Medicine in Sport*, *13*(4), 397–402. https://doi.org/10.1016/j.jsams.2009.08.003

Hickey, J. T., Hickey, P. F., Maniar, N., Timmins, G., Williams, M. D., & Pitcher, C. A. (2017). *A novel apparatus measuring knee flexor strength during various hamstring exercises:* www.jospt.org

Hickey, J. T., Shield, A. J., Williams, M. D., & Opar, D. A. (2014). The financial cost of hamstring strain injuries in the Australian Football League. *British Journal of Sports Medicine*, *48*(8), 729–730. https://doi.org/10.1136/bjsports-2013-092884

Higashihara, A., Ono, T., Kubota, J., Okuwaki, T., & Fukubayashi, T. (2010). Functional differences in the activity of the hamstring muscles with increasing running speed. *Journal of Sports Sciences*, *28*(10), 1085–1092. https://doi.org/10.1080/02640414.2010.494308

Higashihara, A., Ono, T., Tokutake, G., Kuramochi, R., Kunita, Y., Nagano, Y., & Hirose, N. (2019). Hamstring muscles' function deficit during overground sprinting in track and field athletes with a history of strain injury. *Journal of Sports Sciences*, *37*(23), 2744–2750. https://doi.org/10.1080/02640414.2019.1664030

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B - Biological Sciences*, *126*(843), 136–195. https://doi.org/10.1098/rspb.1938.0050

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*(1), 1–15. https://doi.org/10.2165/00007256-200030010-00001

Hulme, A., & Finch, C. F. (2015). From monocausality to systems thinking: a complementary and alternative conceptual approach for better understanding the development and prevention of sports injury. *Injury Epidemiology*, *2*(1), 1–12. https://doi.org/10.1186/s40621-015-0064-1

Ingebrigtsen, J., Bendiksen, M., Randers, M. B., Castagna, C., Krustrup, P., & Holtermann, A. (2012). Yo-Yo IR2 testing of elite and sub-elite soccer players: Performance, heart rate response and correlations to other interval tests. *Journal of Sports Sciences*, *30*(13), 1337–1345. https://doi.org/10.1080/02640414.2012.711484

Ishøi, L., Aagaard, P., Nielsen, M. F., Thornton, K. B., Krommes, K., Hölmich, P., & Thorborg, K. (2018). The influence of hamstring muscle peak torque and rate of torque development for sprinting performance in football players: a cross-sectional study. *International Journal of Sports Physiology and Performance*, *14*(5), 1–27. https://doi.org/10.1123/ijspp.2018-0464

Ishøi, L., Hölmich, P., Aagaard, P., Thorborg, K., Bandholm, T., & Serner, A. (2018). Effects of the Nordic Hamstring exercise on sprint capacity in male football players: a randomized controlled trial. *Journal of Sports Sciences*, *36*(14), 1663–1672. https://doi.org/10.1080/02640414.2017.1409609

Jansen, P., Lehmann, J., Fellner, B., Huppertz, G., Loose, O., Achenbach, L., & Krutsch, W. (2019). Relation of injuries and psychological symptoms in amateur soccer players. *BMJ Open Sport and Exercise Medicine*, *5*(1). https://doi.org/10.1136/bmjsem-2019-000522

Jiménez-Reyes, P., Garcia-Ramos, A., Párraga-Montilla, J. A., Morcillo-Losa, J. A., Cuadrado-Peñafiel, V., Castaño-Zambudio, A., Samozino, P., & Morin, J.-B. (2020). Seasonal changes in the sprint acceleration force-velocity profile of elite male soccer players. *Journal of Strength and Conditioning Research*, *24*, 1. https://doi.org/10.1519/jsc.0000000000003513

Jiménez-Reyes, P., Samozino, P., García-Ramos, A., Cuadrado-Peñafiel, V., Brughelli, M., & Morin, J. B. (2018). Relationship between vertical and horizontal force-velocity-power profiles in various sports and levels of practice. *PeerJ*, *2018*(11), 1–18. https://doi.org/10.7717/peerj.5937

Jones, P., Bampouras, T. M., & Marrin, K. (2009). An investigation into the physical determinants of change of direction speed. *The Journal of Sports Medicine and Physical Fitness*, *49*(1), 97–104.

Jönhagen, S., Halvorsen, K., & Benoit, D. L. (2009). Muscle activation and length changes during two lunge exercises: Implications for rehabilitation. *Scandinavian Journal of Medicine and Science in Sports*, *19*(4), 561–568. https://doi.org/10.1111/j.1600-0838.2007.00692.x

Junge, A., & Dvorak, J. (2004). Soccer injuries: A review on incidence and prevention. *Sports Medicine*, *34*(13), 929–938. https://doi.org/10.2165/00007256-200434130-00004

Kelln, B. M., McKeon, P. O., Gontkof, L. M., & Hertel, J. (2008). Hand-held dynamometry: Reliability of lower extremity muscle testing in healthy, physically active, young adults. *Journal of Sport Rehabilitation*, *17*(2), 160–170. https://doi.org/10.1123/jsr.17.2.160

Koundourakis, N. E., Androulakis, N. E., Malliaraki, N., Tsatsanis, C., Venihaki, M., & Margioris, A. N. (2014). Discrepancy between exercise performance, body composition, and sex steroid response after a six-week detraining period in professional soccer players. *PLoS ONE*, *9*(2). https://doi.org/10.1371/journal.pone.0087803

Krommes, K., Petersen, J., Nielsen, M. B., Aagaard, P., Hölmich, P., & Thorborg, K. (2017). Sprint and jump performance in elite male soccer players following a 10-week Nordic Hamstring exercise Protocol: A randomised pilot study. *BMC Research Notes*, *10*(1), 1–6. https://doi.org/10.1186/s13104-017-2986-x

Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: A systematic review, qualitative analysis and meta-analysis. *British Journal of Sports Medicine*, *52*(24), 1557–1563. https://doi.org/10.1136/bjsports-2018-099078

Lauersen, J. B., Bertelsen, D. M., & Andersen, L. B. (2014). The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *British Journal of Sports Medicine*, *48*(11), 871–877. https://doi.org/10.1136/bjsports-2013-092538

Lee, J. W. Y., Mok, K. M., Chan, H. C. K., Yung, P. S. H., & Chan, K. M. (2018). Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players. *Journal of Science and Medicine in Sport*, *21*(8), 789–793. https://doi.org/10.1016/j.jsams.2017.11.017

Lehance, C., Binet, J., Bury, T., & Croisier, J. L. (2009). Muscular strength, functional performances and injury risk in professional and junior elite soccer players. *Scandinavian Journal of Medicine and Science in Sports*, *19*(2), 243–251. https://doi.org/10.1111/j.1600-0838.2008.00780.x

Lieber, R. L., & Friden, J. (1993). Muscle damage is not a function of muscle force but active muscle strain. *Journal of Applied Physiology*, *74*(2), 520–526. https://doi.org/10.1152/jappl.1993.74.2.520

Linke, D., Link, D., Weber, H., & Lames, M. (2018). Decline in match running performance in football is affected by an increase in game interruptions. *Journal of Sports Science & Medicine*, *17*(4), 662–667.

Lloyd, R. S., Faigenbaum, A. D., Stone, M. H., Oliver, J. L., Jeffreys, I., Moody, J. a, Brewer, C., Pierce, K. C., McCambridge, T. M., Howard, R., Herrington, L., Hainline, B., Micheli, L. J., Jaques, R., Kraemer, W. J., McBride, M. G., Best, T. M., Chu, D. a, Alvar, B. a, & Myer, G. D. (2014). Position statement on youth resistance training: the 2014 International Consensus. *British Journal of Sports Medicine*, *48*(7), 498–505. https://doi.org/10.1136/bjsports-2013-092952

Loose, O., Fellner, B., Lehmann, J., Achenbach, L., Krutsch, V., Gerling, S., Jansen, P., Angele, P., Nerlich, M., & Krutsch, W. (2019). Injury incidence in semi-professional football claims for increased need of injury prevention in elite junior football. *Knee Surgery, Sports Traumatology, Arthroscopy*, *27*(3), 978–984. https://doi.org/10.1007/s00167-018-5119-8

Lord, C., Blazevich, A. J., Drinkwater, E. J., & Ma'ayah, F. (2019). Greater loss of horizontal force after a repeated-sprint test in footballers with a previous hamstring injury. *Journal of Science and Medicine in Sport*, *22*(1), 16–21. https://doi.org/10.1016/j.jsams.2018.06.008

Lord, C., Ma'ayah, F., & Blazevich, A. J. (2018). Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scandinavian Journal of Medicine & Science in Sports*, *28*(3), 1235–1243. https://doi.org/10.1111/sms.13007

Loturco, I., A. Pereira, L., T. Freitas, T., E. Alcaraz, P., Zanetti, V., Bishop, C., & Jeffreys, I. (2019). Maximum acceleration performance of professional soccer players in linear sprints: Is there a direct connection with change-of-direction ability? *PLOS ONE*, *14*(5), e0216806. https://doi.org/10.1371/journal.pone.0216806

Loturco, I., Kobal, R., Kitamura, K., Cal Abad, C. C., Faust, B., Almeida, L., & Pereira, L. A. (2017). Mixed training methods: Effects of combining resisted sprints or plyometrics with optimum power loads on sprint and agility performance in professional soccer players. *Frontiers in Physiology*, *8*(DEC), 1–9. https://doi.org/10.3389/fphys.2017.01034

Loturco, I., Suchomel, T., Bishop, C., Kobal, R., Pereira, L. A., & McGuigan, M. (2019). One-repetition-maximum measures or maximum bar-power output: Which is more related to sport performance? *International Journal of Sports Physiology and Performance*, *14*(1), 33–37.

https://doi.org/10.1123/ijspp.2018-0255

Loturco, I., Ugrinowitsch, C., Tricoli, V., Pivetti, B., & Roschel, H. (2013). Different loading schemes in power training during the preseason promote similar performance improvements in Brazilian elite soccer players. *Journal of Strength and Conditioning Research*, *27*(7), 1791–1797. https://doi.org/10.1519/JSC.0b013e3182772da6

Lovell, R., Whalan, M., Marshall, P. W. M., Sampson, J. A., Siegler, J. C., & Buchheit, M. (2018). Scheduling of eccentric lower limb injury prevention exercises during the soccer micro-cycle: Which day of the week? *Scandinavian Journal of Medicine and Science in Sports*, *28*(10), 2216–2225. https://doi.org/10.1111/sms.13226

Madruga-Parera, M., Bishop, C., Fort-Vanmeerhaeghe, A., Beltran-Valls, M. R., Skok, O. G., & Romero-Rodríguez, D. (2019). Interlimb asymmetries in youth tennis players. *Journal of Strength and Conditioning Research*, *1*, 1. https://doi.org/10.1519/jsc.0000000000003152

Madruga-Parera, M., Bishop, C., Gonzalo-skok, O., & Romero-rodríguez, D. (2020). Effects of 8-weeks of iso-inertial vs . cable-resistance training on motor skills performance and inter-limb asymmetries. *Journal of Strength & Conditioning Research.*

Malone, S., Hughes, B., Doran, D. A., Collins, K., & Gabbett, T. J. (2019). Can the workload–injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *Journal of Science and Medicine in Sport*, *22*(1), 29–34. https://doi.org/10.1016/j.jsams.2018.01.010

Malone, S., Owen, A., Newton, M., Mendes, B., Collins, K. D., & Gabbett, T. J. (2017). The acute:chonic workload ratio in relation to injury risk in professional soccer. *Journal of Science and Medicine in Sport*, *20*(6), 561–565. https://doi.org/10.1016/j.jsams.2016.10.014

Malone, S., Roe, M., Doran, D. A., Gabbett, T. J., & Collins, K. D. (2017). Protection against spikes in workload with aerobic fitness and playing experience: The role of the acute: Chronic workload ratio on injury risk in elite gaelic football. *International Journal of Sports Physiology and Performance*, *12*(3), 393–401. https://doi.org/10.1123/ijspp.2016-0090

Maniar, N., Shield, A. J., Williams, M. D., Timmins, R. G., & Opar, D. A. (2016). Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. *British Journal of Sports Medicine*, *50*(15), 909–920. https://doi.org/10.1136/bjsports-2015-095311

Markovic, G., Sarabon, N., Boban, F., Zoric, I., Jelcic, M., Sos, K., & Scappaticci, M. (2020). Nordic hamstring strength of highly trained youth football players and its relation to sprint performance. *Journal of Strength and Conditioning Research*, *34*(3), 800–807. https://doi.org/10.1519/JSC.0000000000002800

Maroto-Izquierdo, S., García-López, 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*(1), 133–143. https://doi.org/10.1515/hukin-2017-0096

Maroto-Izquierdo, S., García-López, D., Fernandez-Gonzalo, R., Moreira, O. C., González-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. https://doi.org/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. https://doi.org/10.1519/JSC.0000000000001635

Matinlauri, A., Alcaraz, P. E., Freitas, T. T., Abedin-Maghanagi, A., Martínez-Ruiz, E., Castillo, A., Mendiguchia, J., & Cohen, D. D. (2017). A comparison of the isometric force fatigue-recovery profile in two posterior chain lower limb tests following simulated football. *British Journal of Sports Medicine*, *51*(4), 285.2-285. https://doi.org/10.1136/bjsports-2016-097372.5

McCall, A., Nedelec, M., Carling, C., Le Gall, F., Berthoin, S., & Dupont, G. (2015). Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players. *Journal of Sports Sciences*, *33*(12), 1298–1304. https://doi.org/10.1080/02640414.2015.1022579

McCall, A., Pruna, R., Van der Horst, N., Dupont, G., Buchheit, M., Coutts, A. J., Impellizzeri, F. M., & Fanchini, M. (2020). Exercise-based strategies to prevent muscle injury in male elite footballers: an expert-led Delphi survey of 21 practitioners belonging to 18 teams from the big-5 European Leagues. *Sports Medicine*, *0123456789*. https://doi.org/10.1007/s40279-020-01315-7

Mendez-Villanueva, A., Suarez-Arrones, L., Rodas, G., Fernandez-Gonzalo, R., Tesch, P., Linnehan, R., Kreider, R., & Di Salvo, V. (2016). MRI-based regional muscle use during hamstring strengthening exercises in elite soccer players. *PLOS ONE*, *11*(9), e0161356. https://doi.org/10.1371/journal.pone.0161356

Mendiguchia, J., Alentorn-Geli, E., & Brughelli, M. (2012). Hamstring strain injuries: are we heading in the right direction? *British Journal of Sports Medicine*, *46*(2), 81–85. https://doi.org/10.1136/bjsm.2010.081695

Mendiguchia, J., Conceição, F., Edouard, P., Fonseca, M., Pereira, R., Lopes, H., Morin, J. B., & Jiménez-Reyes, P. (2020). Sprint versus isolated eccentric training: Comparative effects on hamstring architecture and performance in soccer players. *PLoS ONE*, *15*(2), 1–19. https://doi.org/10.1371/journal.pone.0228283

Mendiguchia, J., Edouard, P., Samozino, P., Brughelli, M., Cross, M., Ross, A., Gill, N., & Morin, J. B. (2016). Field monitoring of sprinting power–force–velocity profile before, during and after hamstring injury: two case reports. *Journal of Sports Sciences*, *34*(6), 535–541. https://doi.org/10.1080/02640414.2015.1122207

Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., Esparza-Ros, F., & Mendez-Villanueva, A. (2015a). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine and Science in Sports*, *25*(6), e621–e629. https://doi.org/10.1111/sms.12388

Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., Esparza-Ros, F., & Mendez-Villanueva, A. (2015b). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine and Science in Sports*, *25*(6), e621–e629. https://doi.org/10.1111/sms.12388

Mendiguchia, J., Samozino, P., Martinez-Ruiz, E., Brughelli, M., Schmikli, S., Morin, J. B., & Mendez-Villanueva, A. (2014). Progression of mechanical properties during on-field sprint running after returning to sports from a hamstring muscle injury in soccer players. *International Journal of Sports Medicine*, *35*(8), 690–695. https://doi.org/10.1055/s-0033-1363192

Mjolsnes, R., Arnason, A., Osthagen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine and Science in Sports*, *14*(5), 311–317. https://doi.org/10.1046/j.1600-0838.2003.367.x

Mohr, M., Krustrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences*, *21*(7), 519–528. https://doi.org/10.1080/0264041031000071182

Moras, G. (2017). El entrenamiento tridimensional y cuadrimensional de la fuerza en los deportes de equipo. In F. Seirul·lo (Ed.), *El entrenamiento en los deportes de equipo* (pp. 82–115). Mastercede.

Moras, G., Fernández-Valdés, B., Vázquez-Guerrero, J., Tous-Fajardo, J., Exel, J., & Sampaio, J. (2018). Entropy measures detect increased movement variability in resistance training when elite rugby players use the ball. *Journal of Science and Medicine in Sport*, *21*(12), 1286–1292. https://doi.org/10.1016/j.jsams.2018.05.007

Moras, G., & Vázquez-Guerrero, J. (2015). Force production during squats performed with a rotational resistance device under stable versus unstable conditions. *Journal of Physical Therapy Science*, *27*(11), 3401–3406. https://doi.org/10.1589/jpts.27.3401

Morin, J. B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Mendiguchia, J. (2015). Sprint acceleration mechanics: the major role of hamstrings in horizontal force production. *Frontiers in Physiology*, *6*(December), 1–14. https://doi.org/10.3389/fphys.2015.00404

Mujika, Inigo, & Padilla, S. (2000). Detraining: loss of training-induced physiological and performance adaptations. Part II: Long term insufficient training stimulus. *Sports Medicine (Auckland, N.Z.)*, *30*(3), 145–154. https://doi.org/10.2165/00007256-200030030-00001

Mujika, Iñigo, Santisteban, J., & Castagna, C. (2009). In-season effect of short-term sprint and power training programs on elite junior soccer players. *Journal of Strength and Conditioning Research*, *23*(9), 2581–2587. https://doi.org/10.1519/JSC.0b013e3181bc1aac

Mujika, Inigo, Santisteban, J., Impellizzeri, F. M., & Castagna, C. (2009). Fitness determinants of success in men's and women's football. *Journal of Sports Sciences*, *27*(2), 107–114. https://doi.org/10.1080/02640410802428071

Nakamura, D., Suzuki, T., Yasumatsu, M., & Akimoto, T. (2012). Moderate running and plyometric training during off-season did not show a significant difference on soccer-related high-intensity performances compared with no-training controls. *Journal of Strength and Conditioning Research*, *26*(12), 3392–3397. https://doi.org/10.1519/JSC.0b013e3182474356

Nassis, G. P., Brito, J., Figueiredo, P., & Gabbett, T. J. (2019). Injury prevention training in football: Let's bring it to the real world. *British Journal of Sports Medicine*, *53*(21), 1328–1329. https://doi.org/10.1136/bjsports-2018-100262

Newton, R. U., Gerber, A., Nimphius, S., Shim, J. K., Doan, B. K., Robertson, M., Pearson, D. R., Craig, B. W., Häkkinen, K., & Kraemer, W. J. (2006). Determination of functional strength imbalance of the lower extremities. *Journal of Strength and Conditioning Research*, *20*(4), 971–977. https://doi.org/10.1519/R-5050501x.1

Newton, R. U., Laursen, P. B., & Young, W. (2008). Clinical exercise testing and assessment of athletes. In *Olympic Textbook of Medicine in Sport* (pp. 160–199). Wiley-Blackwell. https://doi.org/10.1002/9781444300635.ch4

Nimphius, S., Callaghan, S. J., Bezodis, N. E., & Lockie, R. G. (2018). Change of direction and agility tests: challenging our current measures of performance. *Strength and Conditioning Journal*, *40*(1), 26–38. https://doi.org/10.1519/SSC.0000000000000309

Nimphius, S., Callaghan, S. J., Spiteri, T., & Lockie, R. G. (2016). Change of direction deficit. *Journal of Strength and Conditioning Research*, *30*(11), 3024–3032. https://doi.org/10.1519/JSC.0000000000001421

Norrbrand, L. (2010). Acute and early chronic responses to resistance exercise using flywheel or weights. In *Mid Sweden University*.

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. https://doi.org/10.1007/s00421-007-0583-8

Norrbrand, L., Pozzo, M., & Tesch, P. A. (2010). Flywheel resistance training calls for greater eccentric muscle activation than weight training. *European Journal of Applied Physiology*, *110*(5), 997–1005. https://doi.org/10.1007/s00421-010-1575-7

Noya Salces, J., Gomez-Carmona, P. M., Moliner-Urdiales, D., Gracia-Marco, L., & Sillero-Quintana, M. (2014). An examination of injuries in Spanish Professional Soccer League. *The Journal of Sports Medicine and Physical Fitness*, *54*(6), 765–771.

Núñez, F. J., Galiano, C., Muñoz-López, A., & Floria, P. (2020). Is possible an eccentric overload in a rotary inertia device? Comparison of force profile in a cylinder-shaped and a cone-shaped axis devices. *Journal of Sports Sciences*, *00*(00), 1–5. https://doi.org/10.1080/02640414.2020.1754111

Núñez, 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), 1–13. https://doi.org/10.1371/journal.pone.0193841

O'Brien, J., Finch, C. F., Pruna, R., & McCall, A. (2019). A new model for injury prevention in team sports: the Team-sport Injury Prevention (TIP) cycle. *Science and Medicine in Football*, *3*(1), 77–80. https://doi.org/10.1080/24733938.2018.1512752

Oakley, A. J., Jennings, J., & Bishop, C. (2017). Holistic hamstring health: not just the Nordic hamstring exercise. *British Journal of Sports Medicine*, *0*(0), bjsports-2016-097137. https://doi.org/10.1136/bjsports-2016-097137

Oliver, G. D., & Dougherty, C. P. (2009). The Razor Curl: A Functional Approach to Hamstring Training. *Journal of Strength and Conditioning Research*, *23*(2), 401–405. https://doi.org/10.1519/JSC.0b013e31818f08d0

Opar, D. A., Piatkowski, T., Williams, M. D., & Shield, A. J. (2013). A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *The Journal of Orthopaedic and Sports Physical Therapy*, *43*(9), 636–640. https://doi.org/10.2519/jospt.2013.4837

Opar, D. A., Williams, M. D., & Shield, A. J. (2012). Hamstring strain injuries: factors that lead to injury and re-injury. *Sports Medicine*, *42*(3), 209–226. https://doi.org/10.2165/11594800-000000000-00000

Opar, D. A., Williams, M. D., Timmins, R. G., Hickey, J., Duhig, S. J., & Shield, A. J. (2015a). The effect of previous hamstring strain injuries on the change in eccentric hamstring strength during preseason training in elite Australian footballers. *The American Journal of Sports Medicine*, *43*(2), 377–384. https://doi.org/10.1177/0363546514556638

Opar, D. A., Williams, M. D., Timmins, R. G., Hickey, J., Duhig, S. J., & Shield, A. J. (2015b). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, *47*(4), 857–865. https://doi.org/10.1249/MSS.0000000000000465

Otero-Esquina, C., de Hoyo, M., Gonzalo-Skok, Ó., Domínguez-Cobo, S., & Sánchez, H. (2017). Is strength-training frequency a key factor to develop performance adaptations in young elite soccer players? *European Journal of Sport Science*, *17*(10), 1241–1251. https://doi.org/10.1080/17461391.2017.1378372

Owen, A., Dunlop, G., Rouissi, M., Chtara, M., Paul, D., Zouhal, H., & Wong, D. P. (2015). The relationship between lower-limb strength and match-related muscle damage in elite level professional European soccer players. *Journal of Sports Sciences*, *33*(20), 2100–2105. https://doi.org/10.1080/02640414.2015.1064155

Owen, A., Wong, D. P., Dellal, A., Paul, D. J., Orhant, E., & Collie, S. (2013). Effect of an injury prevention program on muscle injuries in elite professional soccer. *Journal of Strength and Conditioning Research*, *27*(12), 3275–3285. https://doi.org/10.1519/JSC.0b013e318290cb3a

Paul, D. J., Bradley, P. S., & Nassis, G. P. (2015). Factors Affecting Match Running Performance of Elite Soccer Players: Shedding Some Light on the Complexity. *International Journal of Sports Physiology and Performance*, *10*(4), 516–519. https://doi.org/10.1123/ijspp.2015-0029

Paul, D. J., Gabbett, T. J., & Nassis, G. P. (2016). Agility in team sports: testing, training and factors affecting performance. *Sports Medicine*, *46*(3), 421–442. https://doi.org/10.1007/s40279-015-0428-2

Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in Men's soccer: A cluster-randomized controlled trial. *American Journal of Sports Medicine*, *39*(11), 2296–2303. https://doi.org/10.1177/0363546511419277

Pizzari, T., Green, B., & van Dyk, N. (2020). Extrinsic and intrinsic risk factors associated with hamstring injury. In *Prevention and Rehabilitation of Hamstring Injuries*. https://doi.org/10.1007/978-3-030-31638-9_4

Pollard, C. W., Opar, D. A., Williams, M. D., Bourne, M. N., & Timmins, R. G. (2019). Razor hamstring curl and Nordic hamstring exercise architectural adaptations: Impact of exercise selection and intensity. *Scandinavian Journal of Medicine and Science in Sports*, *29*(5), 706–715. https://doi.org/10.1111/sms.13381

Presland, J. D., Opar, D. A., Williams, M. D., Hickey, J. T., Maniar, N., Lee Dow, C., Bourne, M. N., & Timmins, R. G. (2020). Hamstring strength and architectural adaptations following inertial flywheel resistance training. *Journal of Science and Medicine in Sport*, *23*(11), 1093–1099. https://doi.org/10.1016/j.jsams.2020.04.007

Presland, J. D., Timmins, R. G., Bourne, M. N., Williams, M. D., & Opar, D. A. (2018). The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scandinavian Journal of Medicine & Science in Sports*, *28*(7), 1775–1783. https://doi.org/10.1111/sms.13085

Ramírez-Campillo, R., Burgos, C. H., Henríquez-Olguín, C., Andrade, D. C., Martínez, C., Álvarez, C., Castro-Sepúlveda, M., Marques, M. C., & Izquierdo, M. (2015). Effect of Unilateral, Bilateral, and Combined Plyometric Training on Explosive and Endurance Performance of Young Soccer Players. *Journal of Strength and Conditioning Research*, *29*(5), 1317–1328. https://doi.org/10.1519/JSC.0000000000000762

Rampinini, E., Impellizzeri, F. M., Castagna, C., Coutts, A. J., & Wisløff, U. (2009). Technical performance during soccer matches of the Italian Serie A league: Effect of fatigue and competitive level. *Journal of Science and Medicine in Sport*, *12*(1), 227–233. https://doi.org/10.1016/j.jsams.2007.10.002

Rampinini, E., Sassi, A., Morelli, A., Mazzoni, S., Fanchini, M., & Coutts, A. J. (2009). Repeated-sprint ability in professional and amateur soccer players. *Applied Physiology, Nutrition and Metabolism*, *34*(6), 1048–1054. https://doi.org/10.1139/H09-111

Randell, A. D., Cronin, J. B., Keogh, J. W. L., Gill, N. D., & Pedersen, M. C. (2011). Effect of Instantaneous Performance Feedback During 6 Weeks of Velocity-Based Resistance Training on Sport-Specific Performance Tests. *Journal of Strength and Conditioning Research*, *25*(1), 87–93. https://doi.org/10.1519/JSC.0b013e3181fee634

Ratamess, N. A., Brent, A., Evetoch, T., Housh, T., Kibler, B., Kraemer, W. J., & Triplett-McBride, T. (2009). Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise*, *41*(3), 687–708. https://doi.org/10.1249/MSS.0b013e3181915670

Raya-González, J., Castillo, D., Domínguez-Díez, M., & Hernández-Davó, J. L. (2020). Eccentric-overload production during the flywheel squat exercise in young soccer players: Implications for injury prevention. *International Journal of Environmental Research and Public Health*, *17*(10). https://doi.org/10.3390/ijerph17103671

Requena, B., Garcia, I., Requena, F., Bressel, E., Saez-Saez de Villarreal, E., & Cronin, J. (2014). Association between traditional standing vertical jumps and a soccer-specific vertical jump. *European Journal of Sport Science*, *14*(SUPPL.1), 37–41. https://doi.org/10.1080/17461391.2012.708790

Requena, B., García, I., Suárez-Arrones, L., Sáez de Villarreal, E., Naranjo Orellana, J., & Santalla, A. (2017). Off-season effects on functional performance, body composition, and blood parameters in top-level professional soccer players. *Journal of Strength and Conditioning Research*, *31*(4), 939–946. https://doi.org/10.1519/JSC.0000000000001568

Requena, B., González-Badillo, J. J., Villareal, E. S. S. de, Ereline, J., García, I., Gapeyeva, H., & Pääsuke, M. (2009). Functional performance, maximal strength, and power characteristics in isometric and dynamic actions of lower extremities in soccer players. *Journal of Strength and Conditioning Research*, *23*(5), 1391–1401. https://doi.org/10.1519/JSC.0b013e3181a4e88e

Reurink, G., Goudswaard, G. J., Moen, M. H., Tol, J. L., Verhaar, J. A. N., & Weir, A. (2016). Strength Measurements in Acute Hamstring Injuries: Intertester Reliability and Prognostic Value of Handheld Dynamometry. *Journal of Orthopaedic & Sports Physical Therapy*, *46*(8), 689–696. https://doi.org/10.2519/jospt.2016.6363

Ribeiro-Alvares, J. B., Oliveira, G. S., de Lima-e-Silva, F. X., & Baroni, B. M. (2020). Eccentric knee flexor strength of professional football players with and without hamstring injury in the prior season. *European Journal of Sport Science*, *0*(0), 1–26.

https://doi.org/10.1080/17461391.2020.1743766

Roe, M., Malone, S., Delahunt, E., Collins, K., Gissane, C., Persson, U. M. C., Murphy, J. C., & Blake, C. (2018). Eccentric knee flexor strength profiles of 341 elite male academy and senior Gaelic football players: Do body mass and previous hamstring injury impact performance? *Physical Therapy in Sport*, *31*, 68–74. https://doi.org/10.1016/j.ptsp.2018.01.006

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. https://doi.org/10.1136/bjsm.2008.051417

Røksund, O. D., Kristoffersen, M., Bogen, B. E., Wisnes, A., Engeseth, M. S., Nilsen, A. K., Iversen, V. V., Mæland, S., & Gundersen, H. (2017). Higher drop in speed during a repeated sprint test in soccer players reporting former hamstring strain injury. *Frontiers in Physiology*, *8*(JAN), 1–8. https://doi.org/10.3389/fphys.2017.00025

Romero-Franco, N., Jiménez-Reyes, P., Castaño-Zambudio, A., Capelo-Ramírez, F., Rodríguez-Juan, J. J., González-Hernández, J., Toscano-Bendala, F. J., Cuadrado-Peñafiel, V., & Balsalobre-Fernández, C. (2017). Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *European Journal of Sport Science*, *17*(4), 386–392. https://doi.org/10.1080/17461391.2016.1249031

Romero-Rodriguez, D., Gual, G., & Tesch, P. A. (2011). Efficacy of an inertial resistance training paradigm in the treatment of patellar tendinopathy in athletes: A case-series study. *Physical Therapy in Sport*, *12*(1), 43–48. https://doi.org/10.1016/j.ptsp.2010.10.003

Rønnestad, B. R., Kvamme, N. H., Sunde, A., & Raastad, T. (2008). Short-Term Effects of Strength and Plyometric Training on Sprint and Jump Performance in Professional Soccer Players. *Journal of Strength and Conditioning Research*, *22*(3), 773–780. https://doi.org/10.1519/JSC.0b013e31816a5e86

Ruddy, J. D., Cormack, S. J., Whiteley, R., Williams, M. D., Timmins, R. G., & Opar, D. A. (2019). Modeling the risk of team sport injuries: a narrative review of different statistical approaches. *Frontiers in Physiology*, *10*(July), 1–16. https://doi.org/10.3389/fphys.2019.00829

Ruddy, J. D., Pollard, C. W., Timmins, R. G., Williams, M. D., Shield, A. J., & Opar, D. A. (2016). Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. *British Journal of Sports Medicine*, *March 2014*, bjsports-2016-096777. https://doi.org/10.1136/bjsports-2016-096777

Rumpf, M. C., Lockie, R. G., Cronin, J. B., & Jalilvand, F. (2016). Effect of different sprint training methods on sprint performance over various distances. *Journal of Strength and Conditioning Research*, *30*(6), 1767–1785. https://doi.org/10.1519/JSC.0000000000001245

Sabido, R., Hernández-Davó, 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. https://doi.org/10.1080/17461391.2017.1282046

Sagelv, E. H., Pedersen, S., Nilsen, L. P. R., Casolo, A., Welde, B., Randers, M. B., & Pettersen, S. A. (2020). Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial. *BMC Sports Science, Medicine and Rehabilitation*, *12*(1), 1–13. https://doi.org/10.1186/s13102-020-00210-y

Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise*, *44*(4), 647–658. https://doi.org/10.1249/MSS.0b013e318236a3d2

Schuermans, J., Danneels, L., Van Tiggelen, D., Palmans, T., & Witvrouw, E. (2017). Proximal neuromuscular control protects against hamstring injuries in male soccer players: a prospective study with electromyography time-series analysis during maximal sprinting. *American Journal of Sports Medicine*, *45*(6), 1315–1325. https://doi.org/10.1177/0363546516687750

Schuermans, J., Van Tiggelen, D., Danneels, L., & Witvrouw, E. (2016). Susceptibility to hamstring injuries in soccer: a prospective study using muscle functional magnetic resonance imaging. *The American Journal of Sports Medicine*, *44*(5), 1276–1285. https://doi.org/10.1177/0363546515626538

Schuermans, J., Van Tiggelen, D., Palmans, T., Danneels, L., & Witvrouw, E. (2017). Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? *Gait and Posture*, *57*(June), 270–277. https://doi.org/10.1016/j.gaitpost.2017.06.268

Seitz, L. B., Reyes, A., Tran, T. T., de Villarreal, E. S., & Haff, G. G. (2014). Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Medicine*, 1693–1702. https://doi.org/10.1007/s40279-014-0227-1

Sheppard, J., & Young, W. (2006). Agility literature review: Classifications, training and testing. *Journal of Sports Sciences*, *24*(9), 919–932. https://doi.org/10.1080/02640410500457109

Siff, M. C. (2008). Biomechanical foundations of strength and power training. *Biomechanics in Sport*, 103–139. https://doi.org/10.1002/9780470693797.ch6

Silder, A., Heiderscheit, B. C., Thelen, D. G., Enright, T., & Tuite, M. J. (2008). MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology*, *37*(12), 1101–1109. https://doi.org/10.1007/s00256-008-0546-0

Silva, J. R., Brito, J., Akenhead, R., & Nassis, G. P. (2016). The transition period in soccer: a window of opportunity. *Sports Medicine*, *46*(3), 305–313. https://doi.org/10.1007/s40279-015-0419-3

Silva, J. R., Nassis, G. P., & Rebelo, A. (2015). Strength training in soccer with a specific focus on highly trained players. *Sports Medicine - Open*, *1*(1). https://doi.org/10.1186/s40798-015-0006-z

Silvers-Granelli, H. J., Bizzini, M., Arundale, A., Mandelbaum, B. R., & Snyder-Mackler, L. (2018). Higher compliance to a neuromuscular injury prevention program improves overall injury rate in male football players. *Knee Surgery, Sports Traumatology, Arthroscopy*, *26*(7), 1975–1983. https://doi.org/10.1007/s00167-018-4895-5

Slettaløkken, G., & Rønnestad, B. R. (2014). High-intensity interval training every second week maintains VO2max in soccer players during off-season. *Journal of Strength and Conditioning Research*, *28*(7), 1946–1951. https://doi.org/10.1519/JSC.0000000000000356

Sonderegger, K., Tschopp, M., & Taube, W. (2016). The challenge of evaluating the intensity of short actions in soccer: A new methodological approach using percentage acceleration. *PLoS ONE*, *11*(11), 1–10. https://doi.org/10.1371/journal.pone.0166534

Sousa, P., Rebelo, A., & Brito, J. (2013). Injuries in amateur soccer players on artificial turf: A one-season prospective study. *Physical Therapy in Sport*, *14*(3), 146–151. https://doi.org/10.1016/j.ptsp.2012.05.003

Spanish Football Federation. (2017). *Licencias*. Memoria de Actividades 2016/2017. https://www.rfef.es/competiciones/licencias

Speirs, D. E., Bennett, M. A., Finn, C. V., & Turner, A. P. (2016). Unilateral vs. bilateral squat training for strength, sprints, and agility in academy rugby players. *Journal of Strength and Conditioning Research*, *30*(2), 386–392. https://doi.org/10.1519/JSC.0000000000001096

Spineti, J., Figueiredo, T., Willardson, J., Bastos de Oliveira, V., Assis, M., Fernandes de Oliveira, L., Miranda, H., Machado de Ribeiro Reis, V. M., & Simão, R. (2019). Comparison between traditional strength training and complex contrast training on soccer players. *Journal of Sports Medicine and Physical Fitness*, *January*, 42–49. https://doi.org/10.23736/S0022-4707.18.07934-3

Spiteri, T., Newton, R. U., Binetti, M., Hart, N. H., Sheppard, J. M., & Nimphius, S. (2015). Mechanical determinants of faster change of direction and agility performance in female basketball athletes. *Journal of Strength and Conditioning Research*, *29*(8), 2205–2214. https://doi.org/10.1519/JSC.0000000000000876

Spiteri, T., Newton, R. U., & Nimphius, S. (2015). Neuromuscular strategies contributing to faster multidirectional agility performance. *Journal of Electromyography and Kinesiology*, *25*(4), 629–636. https://doi.org/10.1016/j.jelekin.2015.04.009

Spiteri, T., Nimphius, S., Hart, N. H., Specos, C., Sheppard, J. M., & Newton, R. U. (2014). Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. *Journal of Strength and Conditioning Research*, *28*(9), 2415–2423. https://doi.org/10.1519/JSC.0000000000000547

Stern, D., Gonzalo-Skok, O., Loturco, I., Turner, A., & Bishop, C. (2020). A comparison of bilateral vs. unilateral-biased strength and power training interventions on measures of physical performance in elite youth soccer players. *Journal of Strength and Conditioning Research*, *34*(8), 2105–2111. https://doi.org/10.1519/jsc.0000000000003659

Stojanović, M. D. M., Mikić, M., Drid, P., Calleja-González, J., Maksimović, N., Belegišanin, B., & Sekulović, V. (2021). Greater power but not strength gains using flywheel versus equivolumed traditional strength training in junior basketball players. *International Journal of Environmental Research and Public Health*, *18*(3), 1–12. https://doi.org/10.3390/ijerph18031181

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength and Conditioning Research*, *17*(1), 140–147. https://doi.org/10.1519/1533-4287(2003)017<0140:PAMSRD>2.0.CO;2

Stubbe, J. H., Van Beijsterveldt, A. M. C., Van Der Knaap, S., Stege, J., Verhagen, E. A., Van Mechelen, W., & Backx, F. J. G. (2015). Injuries in professional male soccer players in the Netherlands: A prospective cohort study. *Journal of Athletic Training*, *50*(2), 211–216. https://doi.org/10.4085/1062-6050-49.3.64

Styles, W. J., Matthews, M. J., & Comfort, P. (2016). Effects of Strength Training on Squat and Sprint Performance in Soccer Players. *Journal of Strength and Conditioning Research*, *30*(6), 1534–1539. https://doi.org/10.1519/JSC.0000000000001243

Suarez-Arrones, L., de Villarreal, E. S., Núñez, F. J., Di Salvo, V., Petri, C., Buccolini, A., Maldonado, R. A., Torreno, N., & Mendez-Villanueva, A. (2018). In-season eccentric-overload training in elite soccer players: Effects on body composition, strength and sprint performance. *PLoS ONE*, *13*(10), 1–16. https://doi.org/10.1371/journal.pone.0205332

Suarez-Arrones, L., Lara-Lopez, P., Rodriguez-Sanchez, P., Lazaro-Ramirez, J. L., Di Salvo, V., Guitart, M., Fuentes-Nieto, C., Rodas, G., & Mendez-Villanueva, A. (2019). Dissociation between changes in sprinting performance and Nordic hamstring strength in professional male football players. *Plos One*, *14*(3), e0213375. https://doi.org/10.1371/journal.pone.0213375

Suarez-Arrones, L., Núñez, F. J., Lara-Lopez, P., Di Salvo, V., & Méndez-Villanueva, A. (2020). Inertial flywheel knee- And hip-dominant hamstring strength exercises in professional soccer players: Muscle use and velocity-based (mechanical) eccentric overload. *PLoS ONE*, *15*(10 October). https://doi.org/10.1371/journal.pone.0239977

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine*, *46*(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., & Stone, M. H. (2019). Implementing eccentric resistance training—Part 1: a brief review of existing methods. *Journal of Functional Morphology and Kinesiology*, *4*(2), 38. https://doi.org/10.3390/jfmk4020038

Tesch, P. A., Fernandez-Gonzalo, R., & Lundberg, T. R. (2017). Clinical applications of iso-Inertial, eccentric-overload (YoYo™) resistance exercise. *Frontiers in Physiology*, *8*(April). https://doi.org/10.3389/fphys.2017.00241

Tierney, P. J., Young, A., Clarke, N. D., & Duncan, M. J. (2016). Match play demands of 11 versus 11 professional football using Global Positioning System tracking: Variations across common playing formations. *Human Movement Science*, *49*, 1–8. https://doi.org/10.1016/j.humov.2016.05.007

Tillaar, R. Van Den, Asmund, J., & Solheim, B. (2017). Comparison of hamstring muscle activation during high-speed running and various hamstring strengthening exercises. *International Journal of Sports Physical Therapy*, *12*(5), 718–727. https://doi.org/10.16603/ijspt20170718

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *British Journal of Sports Medicine*, *50*(24), 1524–1535. https://doi.org/10.1136/bjsports-2015-095362

Tous-Fajardo, J. (2017). Todo es fuerza. In F. Seirul·lo (Ed.), *El entrenamiento en los deportes de equipo* (pp. 44–79). Mastercede.

Tous-Fajardo, J., Gonzalo-Skok, O., Arjol-Serrano, J. L. J. L., & Tesch, P. (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *International Journal of Sports Physiology and Performance*, *11*(1), 66–73. https://doi.org/10.1123/ijspp.2015-0010

Tous-Fajardo, J., Maldonado, R. A., Quintana, J. M., Pozzo, M., & Tesch, P. A. (2006). The flywheel leg-curl machine: offering eccentric overload for hamstring development. *International Journal of Sports Physiology and Performance*, *1*(3), 293–298. http://www.ncbi.nlm.nih.gov/pubmed/19116442

van Beijsterveldt, A. M. C., Steffen, K., Stubbe, J. H., Frederiks, J. E., van de Port, I. G. L., & Backx, F. J. G. (2014). Soccer injuries and recovery in Dutch male amateur soccer players. *Clinical Journal of Sport Medicine*, *24*(4), 337–342. https://doi.org/10.1097/JSM.0000000000000028

van Beijsterveldt, A. M. C., Stubbe, J. H., Schmikli, S. L., van de Port, I. G. L., & Backx, F. J. G. (2015). Differences in injury risk and characteristics between Dutch amateur and professional soccer players. *Journal of Science and Medicine in Sport*, *18*(2), 145–149. https://doi.org/10.1016/j.jsams.2014.02.004

van Beijsterveldt, A. M. C., van de Port, I. G. L. L., Vereijken, A. J., & Backx, F. J. G. G. (2013). Risk factors for hamstring injuries in male soccer players: a systematic review of prospective studies. *Scandinavian Journal of Medicine and Science in Sports*, *23*(3), 253–262. https://doi.org/10.1111/j.1600-0838.2012.01487.x

van de Hoef, P. A., Brink, M. S., Huisstede, B. M. A., van Smeden, M., de Vries, N., Goedhart, E. A., Gouttebarge, V., & Backx, F. J. G. (2019). Does a bounding exercise program prevent hamstring injuries in adult male soccer players? – A cluster-RCT. *Scandinavian Journal of Medicine and Science in Sports*, *29*(4), 515–523. https://doi.org/10.1111/sms.13353

van der Horst, N., Backx, F. J. G., Goedhart, E. A., & Huisstede, B. M. A. M. (2017). Return to play after hamstring injuries in football (soccer): A worldwide Delphi procedure regarding definition, medical criteria and decision-making. *British Journal of Sports Medicine*, *51*(22), 1583–1591. https://doi.org/10.1136/bjsports-2016-097206

van der Horst, N., Hoef, S. van de, Otterloo, P. van, Klein, M., Brink, M., & Backx, F. (2018). Effective but not adhered to: how can we improve adherence to evidence-based hamstring injury prevention in amateur football? *Clinical Journal of Sport Medicine*, *00*(00), 1. https://doi.org/10.1097/JSM.0000000000000710

van der Horst, N., Smits, D.-W. W., Petersen, J., Goedhart, E. A., & Backx, F. J. G. (2015). The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *The American Journal of Sports Medicine*, *43*(6), 1–8. https://doi.org/10.1177/0363546515574057

Van Dyk, N., Bahr, R., Burnett, A. F., Whiteley, R., Bakken, A., Mosler, A., Farooq, A., & Witvrouw, E. (2017). A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: A prospective cohort study of 413 professional football players. *British Journal of Sports Medicine*, *51*(23), 1695–1702. https://doi.org/10.1136/bjsports-2017-097754

Van Dyk, N., Behan, F. P., & Whiteley, R. (2019). Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: A systematic review and meta-analysis of 8459 athletes. *British Journal of Sports Medicine*, *53*(21), 1362–1370. https://doi.org/10.1136/bjsports-2018-100045

van Mechelen, W., Hlobil, H., & Kemper, H. C. G. (1992). Incidence, severity, aetiology and prevention of sports injuries. *Sports Medicine*, *14*(2), 82–99.

Verhagen, E., Van Dyk, N., Clark, N., & Shrier, I. (2018). Do not throw the baby out with the bathwater; Screening can identify meaningful risk factors for sports injuries. *British Journal of Sports Medicine*, *52*(19), 1223–1224. https://doi.org/10.1136/bjsports-2017-098547

Waldén, M., Ekstrand, J., Hägglund, M., Waldén, M., & Ekstrand, J. (2009). Injuries among male and female elite football players. *Scandinavian Journal of Medicine and Science in Sports*, *19*(6), 819–827. https://doi.org/10.1111/j.1600-0838.2008.00861.x

Waldén, M., Hägglund, M., Orchard, J. W., Kristenson, K., & Ekstrand, J. (2013). Regional differences in injury incidence in European professional football. *Scandinavian Journal of Medicine and Science in Sports*, *23*(4), 424–430. https://doi.org/10.1111/j.1600-0838.2011.01409.x

Walker, S., Blazevich, A. J., Haff, G. G., Tufano, J. J., Newton, R. U., & Hakkinen, K. (2016). Greater strength gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. *Frontiers in Physiology*, *7*, 149. https://doi.org/10.3389/fphys.2016.00149

Weakley, J., Till, K., Sampson, J., Banyard, H., Leduc, C., Wilson, K., Roe, G., & Jones, B. (2019). The Effects of Augmented Feedback on Sprint, Jump, and Strength Adaptations in Rugby Union Players After a 4-Week Training Program. *International Journal of Sports Physiology and Performance*, *14*(9), 1205–1211. https://doi.org/10.1123/ijspp.2018-0523

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology*, *89*(5), 1991–1999. https://doi.org/10.1152/jappl.2000.89.5.1991

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, *38*(3), 285–288. https://doi.org/10.1136/bjsm.2002.002071

Wollin, M., Purdam, C., & Drew, M. K. (2016). Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players. *Journal of Science and Medicine in Sport*, *19*(1), 93–96. https://doi.org/10.1016/j.jsams.2015.01.012

Wollin, M., Thorborg, K., & Pizzari, T. (2017). The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players. *Scandinavian Journal of Medicine and Science in Sports*, *27*(3), 282–288. https://doi.org/10.1111/sms.12655

Woods, C., Hawkins, R. D., Maltby, S., Hulse, M., Thomas, A., & Hodson, A. (2004). The Football Association Medical Research Programme: An audit of injuries in professional football - Analysis of hamstring injuries. *British Journal of Sports Medicine*, *38*(1), 36–41. https://doi.org/10.1136/bjsm.2002.002352

Woods, C., Hawkins, R., Hulse, M., & Hodson, A. (2002). The Football Association Medical Research Programme - analysis of preseaon injuries. *Thr British Journal of Sports Medicine*, *36*(6), 436–441.

Young, W. B., Dawson, B., & Henry, G. J. (2015). Agility and change-of-direction speed are independent skills: implications for training for agility in invasion sports. *International Journal of Sports Science & Coaching*, *10*(1), 159–169. https://doi.org/10.1260/1747-9541.10.1.159

APPENDICES

Appendix I - Supplementary tables from Publication I

Supplementary Table 1a Overview of training parameters within each study (RCTs)

Study	Duration (sessions/week)	Loading	Sets, Reps, Rest between set
Greenwood et al. (2007)	12 weeks (3/week)	FW: not mentioned GD: 10 RM	FW and GD: 4 sets, 10 reps, >1min rest
Onambélé et al. (2008)	12 weeks (3/week)	FW: maximum power output, increased 20% every 2 weeks GD: 80% of 1RM, reassessed every 2 weeks	FW and GD: Week 1: 1 sets, 8 reps, 5min rest Week 12: 4 sets, 12 reps, 5min rest
De Hoyo et al. (2015)	6 weeks (3/week)	FW: maximum power output GD: maximum power output	FW and GD: Weeks 1-2: 5 sets, 8 reps, 3min rest Weeks 3-4: 6 sets, 8 reps, 3min rest Weeks 5-6: 7 sets, 8 reps, 3min rest

RCT: Randomised Controlled Trial; Non-RCT: non Randomized Controlled Trial; FW: flywheel; GD: gravity-dependent; RM: Repetition Maximum.

Supplementary Table 2a Risk of Bias (RCTs)

Study	Domain					
	Random sequence generation	Allocation concealment	Blinding of participants and researchers	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Greenwood et al. (2007)	Unclear	Unclear	High	High	Unclear	Unclear	-
Onambélé et al. (2008)	Unclear	Unclear	High	High	Unclear	Low	-
De Hoyo et al. (2015)	Unclear	Unclear	High	High	Low	Unclear	-

Supplementary Table 3a Within-group effect sizes (95% CI) on muscle strength and other muscular adaptations (RCTs).

Study	Group	Primary outcome				Secondary outcomes	
		MVIC	CON	ECC	Power	Muscle structure	Voluntary activation
Greenwood et al. (2007)	*FW*	0.84 (-0.09, 1.58) at 90º	0.50 (-0.23, 1.22) at 60ºs^{-1} 0.41 (-0.31, 1.13) at 180ºs^{-1}	0.91 (-0.16, 1.66) at 60ºs^{-1}	0.49 (-0.24, 1.21)	0.53 (-0.20, 1.26) CSA	2.09 (-1.17, 3.01) central neural activation
	GD	0.60 (-0.16, 1.36) at 90º	0.55 (-0.21, 1.30) at 60ºs^{-1} 0.13 (-0.61, 0.88) at 180ºs^{-1}	0.60 (-0.16, 1.36) at 60ºs^{-1}	0.46 (-0.29, 1.21)	0.69 (-0.07, 1.45) CSA	0.27 (-0.47, 1.01) central neural activation
Onambélé et al. (2008)	*FW*	0.18 (-0.62, 0.98) at 90º	N/A	N/A	0.45 (-0.36, 1.26)	N/A	-0.30 (-1.10, 0.51) EMG-RMS
	GD	0.59 (-0.23, 1.41) at 90º	N/A	N/A	0.21 (-0.59, 1.01)	N/A	0.37 (-0.44, 1.18) EMG-RMS
De Hoyo et al. (2015)	*FW*	0.46[$] (-0.38, 1.31) at 90º	N/A	N/A	N/A	N/A	N/A
	GD	0.42[$] (-0.39, 1.23) at 90º	N/A	N/A	N/A	N/A	N/A

CMJ: Counter-Movement Jump; CON: Concentric; COD: Change Of Direction; CSA: Cross-Sectional Area; ECC: Eccentric; EMG-RMS: Root-Mean Square Electromyographic Activity; FW: flywheel; GD: gravity-dependent; MVIC: Maximum Voluntary Contraction; N/A: not available (not assessed or not reported sufficiently in the study); Non-RCT: non Randomized Controlled Trial; RCT: Randomised Controlled Trial.

[$] Data was calculated and not in accordance with the data presented in the original publication.

Supplementary Table 1b Overview of training parameters within each study (non-RCTs)

Study	Duration (sessions/week)	Loading	Sets, Reps, Rest between set
Caruso et al. (2005)	10 weeks (3/week)	FW: not mentioned GD: 8 RM resistance increased through the period	FW and GD: 4 sets, 8 reps, 90sec rest
Caruso et al. (2008)	6 weeks (2/week)	FW: not mentioned GD: 10 RM resistance increased through the period	FW and GD: 3 sets, 10 reps, 2min rest
Norrbrand et al. (2008)	5 weeks (2/week on weeks 1, 3 and 5) (3/week on weeks 2 and 4)	FW: 4.2 kg flywheel with a moment inertia of 0.11 kg·m^2 GD: 7 RM resistance increased through the period	FW and GD: 4 sets, 7 reps, 2min rest
Norrbrand et al. (2010)	5 weeks (2/week on weeks 1, 3 and 5) (3/week on weeks 2 and 4)	FW: 4.2 kg flywheel with a moment inertia of 0.11 kg·m^2 GD: 7 RM resistance increased through the period	FW and GD: 4 sets, 7 reps, 2min rest

RCT: Randomised Controlled Trial; Non-RCT: non Randomized Controlled Trial; FW: flywheel; GD: gravity-dependent; RM: Repetition Maximum.

Supplementary Table 2b Risk of Bias (non-RCTs)

Study	Domain							Overall judgment
	Bias due to confounding	Bias in selection of participants	Bias in classification of interventions	Bias due to departures from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of reported results	
Caruso et al. (2005)	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Caruso et al. (2008)	Moderate	Low	Low	Low	No information	Moderate	Low	Moderate
Norrbrand et al. (2008)	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
Norrbrand et al. (2010)	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate

Supplementary Table 3b Within-group effect sizes (95%CI) on muscle strength and other muscular adaptations (non-RCTs).

Study	Group	Primary outcome			Secondary outcomes
		MVIC	CON	ECC	Muscle structure
Caruso et al. (2005)	*FW*	N/A	-0.01 (-0.89, 0.86) at 93ºs^{-1} 0.20 (-0.68, 1.08) at 278ºs^{-1}	-0.02 (-0.90, 0.85) at 93ºs^{-1} 0.11(-0.77, 0.99) at 278ºs^{-1}	0.12 (-0.76, 1.00) muscle mass
	GD	N/A	0.11 (-0.77, 0.99) at 93ºs^{-1} 0.28 (-0.60, 1.16) at 278ºs^{-1}	0.06 (-0.82, 0.94) at 93ºs^{-1} 0.20 (-0.68, 1.07) at 278ºs^{-1}	0.09 (-0.79, 0.97) muscle mass
Caruso et al. (2008)	*FW*	N/A	0.17 (-0.75, 1.10) at 180º·s^{-1}	N/A	0.33 (-0.60, 1.26) CSA
	GD	N/A	0.24 (-0.64, 1.12) at 180º·s^{-1}	N/A	0.14 (-0.74, 1.02) CSA
Norrbrand et al. (2008)	*FW*	0.40 (-0.66, 1.46) at 90º 0.62 (-0.45, 1.70) at 120º	N/A	N/A	0.34 (-0.72, 1.39) muscle volume
	GD	-0.25 (-1.23, 0.73) at 90º 0.30 (-0.68, 1.29) at 120º	N/A	N/A	0.11 (-0.87, 1.09) muscle volume
Norrbrand et al. (2010)	*FW*	0.49 (-0.44, 1.43) at 120º	N/A	N/A	N/A
	GD	0.25 (-0.73, 1.24) at 120º	N/A	N/A	N/A

CMJ: Counter-Movement Jump; CON: Concentric; COD: Change Of Direction; CSA: Cross-Sectional Area; DJ: drop-jump; ECC: Eccentric; EMG-RMS: Root-Mean Square Electromyographic Activity; FW: flywheel; GD: gravity-dependent; MVIC: Maximum Voluntary Contraction; N/A: not available (not assessed or not reported sufficiently in the study); Non-RCT: non Randomized Controlled Trial; RCT: Randomised Controlled Trial.

Appendix II - Supplementary material from Publication IV

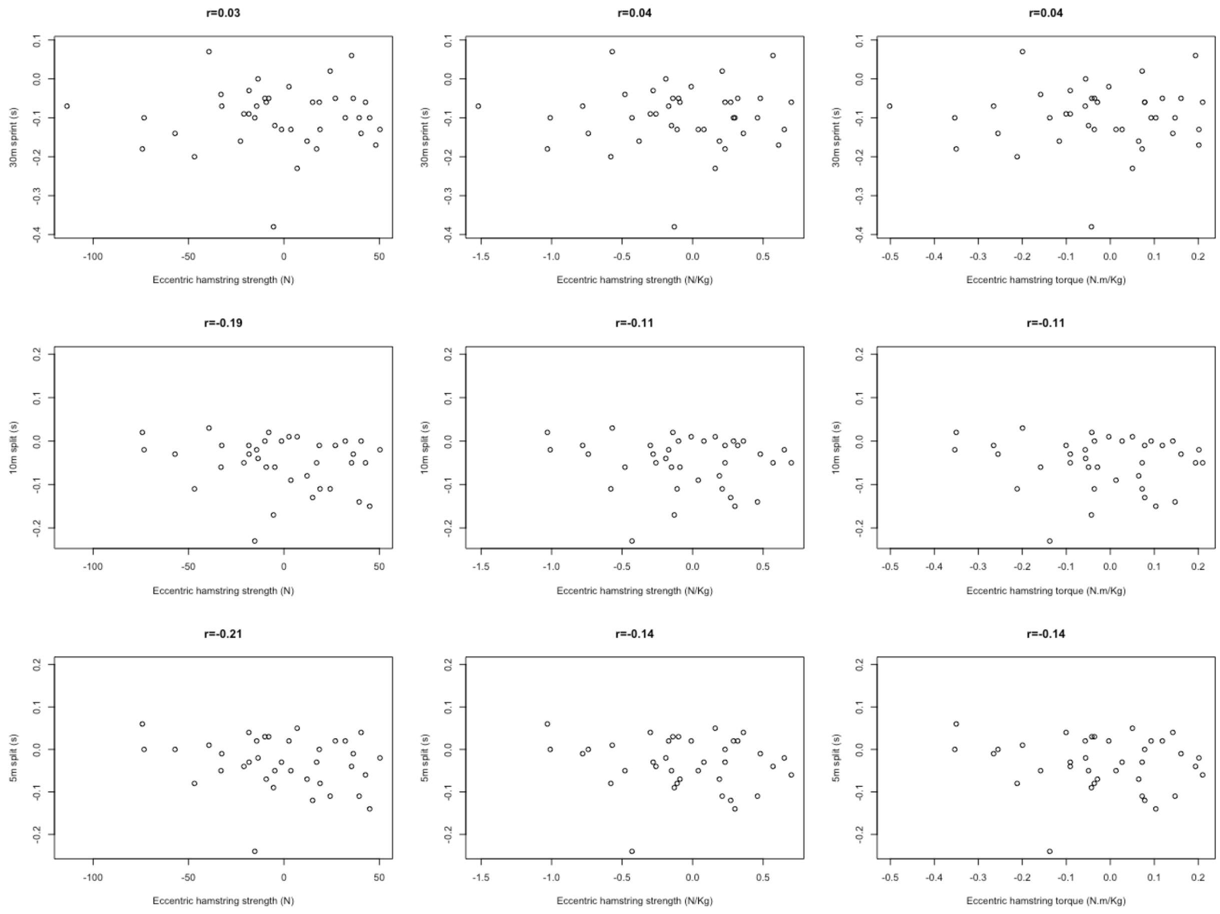


Figure 1: Changes in sprint and strength correlations

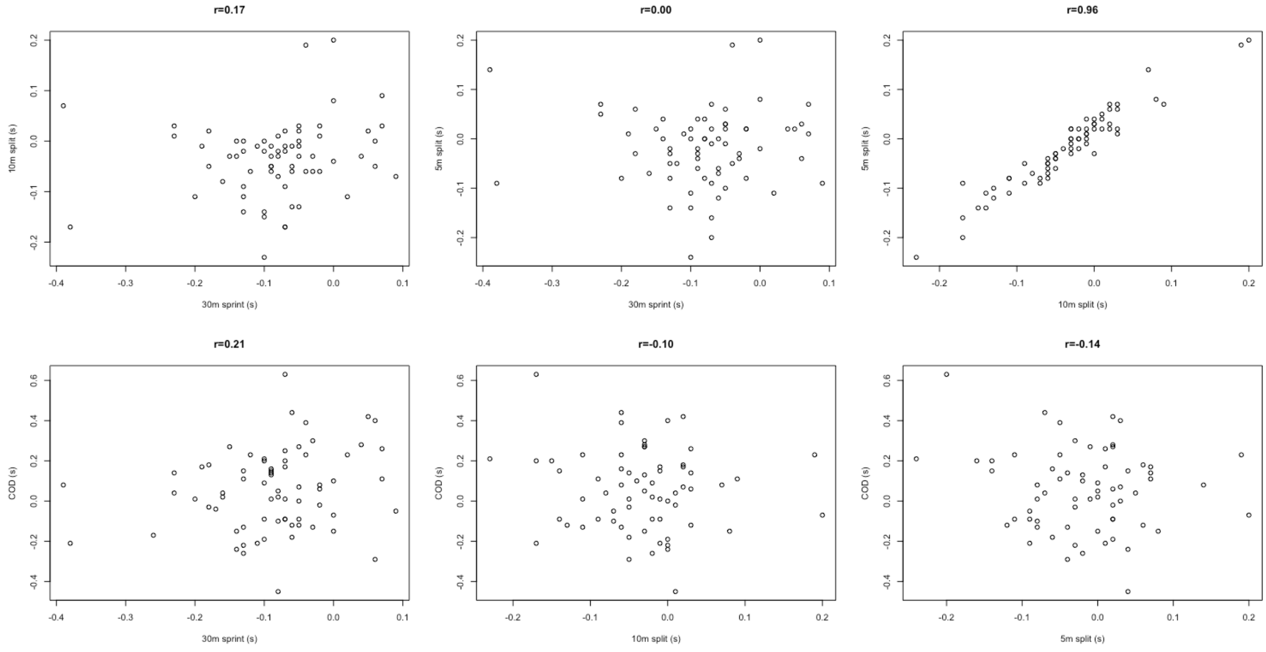


Figure 2: Changes in sprint and COD correlations

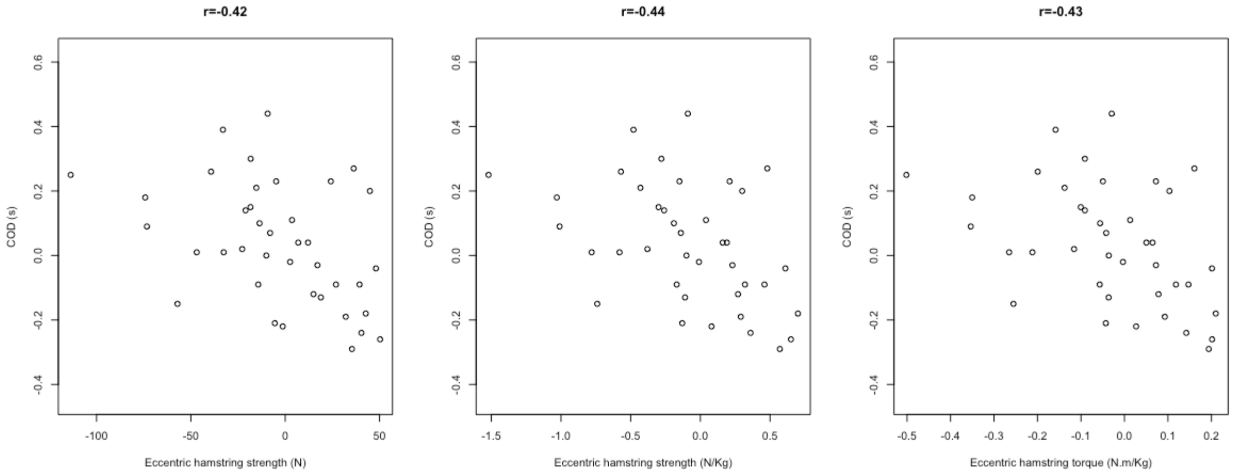


Figure 3: Changes in strength and COD correlations

R scripts from LMM

```
#30m sprint
library (nlme)
library(lmerTest)
mod1<-
summary(lme(post.sprint.best~pre.sprintbest+age+season.ham.injury+days.between.tests,na.action=na.omit,data=dades_nor,random=~1|id))
mod1
print (plot(mod1))
print (qqnorm(mod1, abline=c(0,1))
residuals <- resid(mod1)
summary(residuals)
hist(residuals)

#5m split
library (nlme)
library(lmerTest)
mod2<-
summary(lme(post.mysprint.5m~pre.mysprint.5m+age+season.ham.injury+days.between.tests,na.action=na.omit,data=dades_nor,random=~1|id))
mod2
print (plot(mod2))
print (qqnorm(mod2, abline=c(0,1))
residuals <- resid(mod2)
summary(residuals)
hist(residuals)

#10m split
library (nlme)
library(lmerTest)
mod3<-
summary(lme(post.mysprint.10m~pre.mysprint.10m+age+season.ham.injury+days.between.tests,na.action=na.omit,data=dades_nor,random=~1|id))
mod3
print (plot(mod3))
print (qqnorm(mod3, abline=c(0,1))
residuals <- resid(mod3)
summary(residuals)
hist(residuals)

#Vcut
library (nlme)
library(lmerTest)
mod4<-
summary(lme(post.vcut.best~pre.vcut.best+age+season.ham.injury+days.between.tests,na.action=na.omit,data=dades_nor,random=~1|id))
mod4
print (plot(mod4))
print (qqnorm(mod4, abline=c(0,1))
residuals <- resid(mod4)
summary(residuals)
hist(residuals)

#Eccentric hamstring strength N
library (nlme)
library(lmerTest)
mod5<-summary(lme(post.eccham.avg3.both~pre. eccham.avg3.both
+age+season.ham.injury+days.between.tests,na.action=na.omit,data=dades_nor,random=~1|id))
mod5
```

Appendix III - Poster presentation IOC World Conference on Prevention of Injury and Illness in Sport - Monaco 2020 (postponed)

ECCENTRIC HAMSTRING STRENGTH AND SPRINTING PERFORMANCE CHANGES DURING THE OFF-SEASON IN SPANISH FOOTBALLERS

J. Vicens-Bordas[1-4]; E. Esteve[1,2]; A. Fort-Vanmeerhaeghe[5]; M. Casals[4,6,7];
T. Bandholm[8]; L. Ishøi[9]; D. Opar[10]; A. Shield[11,12]; K. Thorborg[8,9]

IOC WORLD CONFERENCE
ON PREVENTION OF INJURY & ILLNESS IN SPORT

[1]Sportclínic. Physiotherapy and Sports Training Centre, Spain; [2]School of Health and Sport Sciences (EUSES), Universitat de Girona, Spain; [3]Research Group of Clinical Anatomy, Embryology and Neuroscience (NEOMA), Universitat de Girona, Spain; [4]Sport and Physical Activity Studies Centre (CEEAF), University of Vic – Central University of Catalonia (UVic-UCC), Spain; [5]Faculty of Psychology, Education Sciences and Sport, Ramon Llull University, Spain; [6]Sport Performance Analysis Research Group, UVic-UCC, Spain; [7]Medical Department, FCBarcelona, Barça Innovation Hub, Spain; [8]Physical Medicine & Rehabilitation Research – Copenhagen (PMR-C), Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Clinical Research Center, Amager-Hvidovre Hospital, Copenhagen University, Hvidovre, Denmark.[9]Sports Orthopedic Research Center – Copenhagen (SORC-C), Department of Orthopedic Surgery, Copenhagen University Hospital, Amager-Hvidovre, Denmark;[10]School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, Australia;[11]Faculty of Health, School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia;[12]Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

BACKGROUND:

Low eccentric hamstring strength and sprinting performance are associated with hamstring injury (HI) in football; however, the off-season effects on both qualities are unknown.

PURPOSE:

The aim of the study was to investigate eccentric hamstring strength and sprinting performance changes during the off-season period in football players.

METHODS:

Design and setting:
Prospective study with semi-professional (3rd-4th tier) and amateur (5th-8th tier) Spanish footballers.

Participants:
Male footballers (n=107) were contacted to participate. Seventy-four footballers (25±4 years, 178.0±6.6 cm, 74.9±8.1 kg) were included in the final analyses.

Assessments:
Eccentric hamstring strength (Figure C; N and N·kg^{-1}) and sprint performance (Figures A and B; s) were assessed at the beginning (May-June 2017) and at the end of the off-season (July-August 2017). Previous HI, age and off-season length were considered as the independent variables.

Main Outcome Measurements:
All outcomes were proposed before any data collection. Data was analyzed using paired t-tests and Linear Mixed Models (LMM).

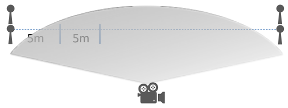


Figure A - 30m sprint with 5-10m splits

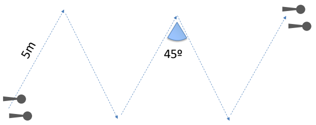


Figure B – Vcut test

Figure C – Eccentric hamstring strength test

RESULTS:

Table 1. Sprint, COD and eccentric hamstring strength changes during the off-season.

Outcomes	N	Baseline	Follow-up	Mean Difference (95% CI)	P–value	Cohen's d
30m sprint (s)	71	4.04 ± 0.12	4.13 ± 0.14	0.09 (0.06 – 0.11)	<0.001	**0.96 (large)**
10m split (s)	67	2.24 ± 0.08	2.28 ± 0.08	0.03 (0.02 – 0.05)	<0.001	**0.46 (small)**
5m split (s)	67	1.52 ± 0.08	1.54 ± 0.08	0.02 (0.00 – 0.04)	0.057	0.24 (small)
Eccentric hamstring strength (N)	41	364.7 ± 63.3	367.4 ± 56.0	2.7 (-8.9 – 14.2)	0.641	0.07 (trivial)
Eccentric hamstring strength (N·kg^{-1})	41	4.87 ± 0.80	4.95 ± 0.72	0.08 (-0.08 – 0.23)	0.317	0.16 (trivial)
COD test (s)	69	6.77 ± 0.25	6.71 ± 0.21	-0.05 (-0.10 – 0.00)	0.033	**-0.26 (small)**

Table 2. Linear Mixed Model of the 30m sprint.

30m sprint	Value	Standard Error	DF	t-value	p-value
Intercept	0.564	0.358	66	1.576	0.120
Age	0.001	0.003	66	0.179	0.859
Baseline 30m sprint (s)	0.882	0.090	66	9.779	**<0.001**
Previous injury	-0.022	0.027	66	-0.831	0.409
Off-season length	-0.000	0.001	66	-0.133	0.894

CONCLUSIONS:

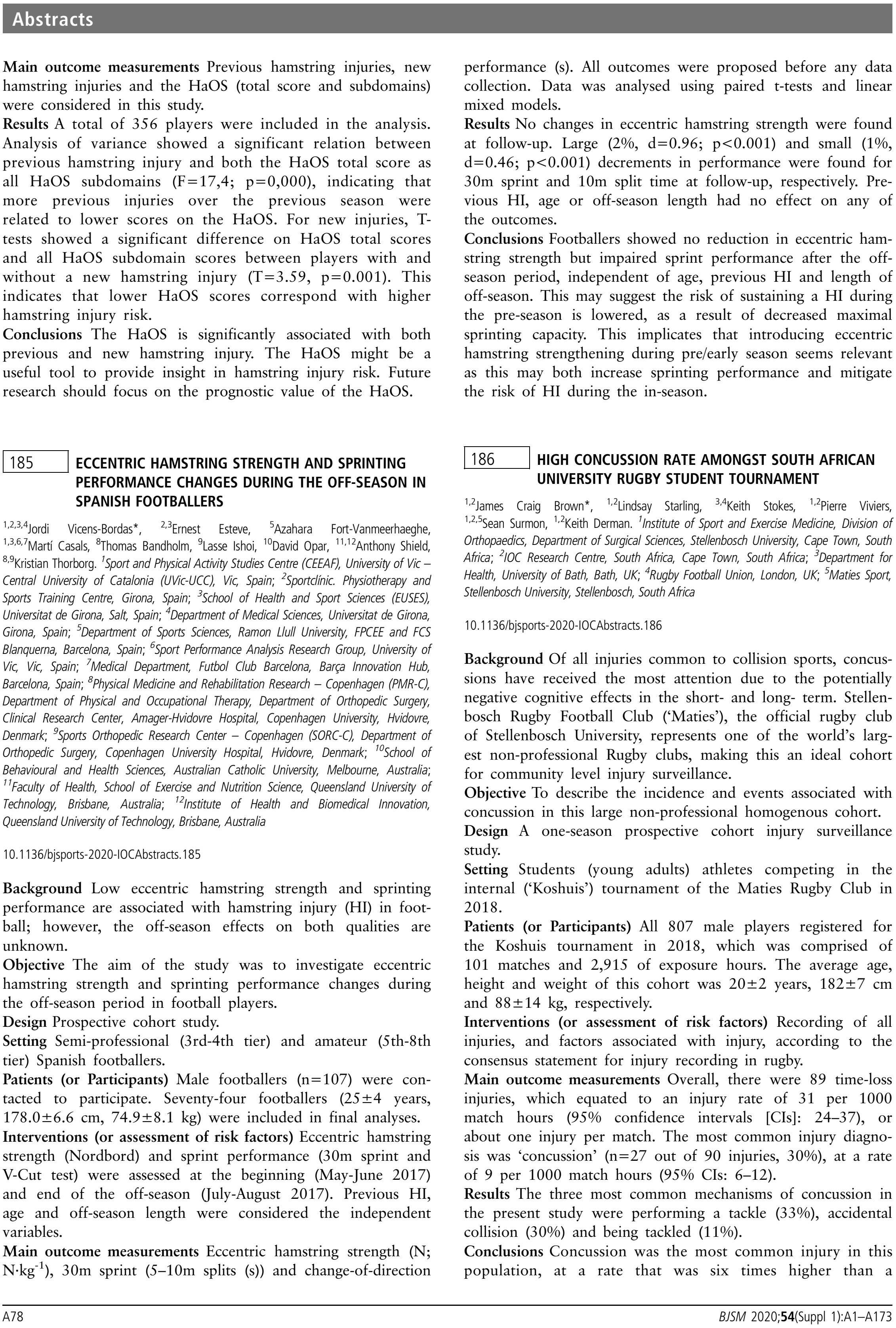
- ✓ Footballers showed no reduction in eccentric hamstring strength but impaired sprint performance after the off-season period, independent of age, previous HI and length of off-season.
- ✓ This may suggest the risk of sustaining a HI during the pre-season is lowered, as a result of decreased maximal sprinting capacity.
- ✓ Introducing eccentric hamstring strengthening during pre/early season seems relevant as this may both increase sprinting performance and mitigate the risk of HI during the in-season.

REFERENCES:

1. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. Br J Sports Med. 2015;(May 2016):bjsports-2015-095362. doi:10.1136/bjsports-2015-095362
2. Silva JR, Brito J, Akenhead R, Nassis GP. The Transition Period in Soccer: A Window of Opportunity. Sport Med. 2016;46(3):305-313. doi:10.1007/s40279-015-0419-3
3. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A, et al. Eccentric hamstring strength is associated with age and duration of previous season hamstring injury in male football players. Int J Sports Phys Ther. 2019

@jordivicensb
Jordi Vicens-Bordas
jordi.vicens@uvic.cat

Appendix IV - Eccentric hamstring strength and sprinting performance changes during the off-season in Spanish footballers. *British Journal of Sports Medicine,* Vol. 54, Suppl 1, (Mar 2020): A78. doi:10.1136/bjsports-2020-IOCAbstracts.185



Main outcome measurements Previous hamstring injuries, new hamstring injuries and the HaOS (total score and subdomains) were considered in this study.

Results A total of 356 players were included in the analysis. Analysis of variance showed a significant relation between previous hamstring injury and both the HaOS total score as all HaOS subdomains (F=17,4; p=0,000), indicating that more previous injuries over the previous season were related to lower scores on the HaOS. For new injuries, T-tests showed a significant difference on HaOS total scores and all HaOS subdomain scores between players with and without a new hamstring injury (T=3.59, p=0.001). This indicates that lower HaOS scores correspond with higher hamstring injury risk.

Conclusions The HaOS is significantly associated with both previous and new hamstring injury. The HaOS might be a useful tool to provide insight in hamstring injury risk. Future research should focus on the prognostic value of the HaOS.

185 ECCENTRIC HAMSTRING STRENGTH AND SPRINTING PERFORMANCE CHANGES DURING THE OFF-SEASON IN SPANISH FOOTBALLERS

[1,2,3,4]Jordi Vicens-Bordas*, [2,3]Ernest Esteve, [5]Azahara Fort-Vanmeerhaeghe, [1,3,6,7]Martí Casals, [8]Thomas Bandholm, [9]Lasse Ishoi, [10]David Opar, [11,12]Anthony Shield, [8,9]Kristian Thorborg. *[1]Sport and Physical Activity Studies Centre (CEEAF), University of Vic – Central University of Catalonia (UVic-UCC), Vic, Spain; [2]Sportclínic. Physiotherapy and Sports Training Centre, Girona, Spain; [3]School of Health and Sport Sciences (EUSES), Universitat de Girona, Salt, Spain; [4]Department of Medical Sciences, Universitat de Girona, Girona, Spain; [5]Department of Sports Sciences, Ramon Llull University, FPCEE and FCS Blanquerna, Barcelona, Spain; [6]Sport Performance Analysis Research Group, University of Vic, Vic, Spain; [7]Medical Department, Futbol Club Barcelona, Barça Innovation Hub, Barcelona, Spain; [8]Physical Medicine and Rehabilitation Research – Copenhagen (PMR-C), Department of Physical and Occupational Therapy, Department of Orthopedic Surgery, Clinical Research Center, Amager-Hvidovre Hospital, Copenhagen University, Hvidovre, Denmark; [9]Sports Orthopedic Research Center – Copenhagen (SORC-C), Department of Orthopedic Surgery, Copenhagen University Hospital, Hvidovre, Denmark; [10]School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, Australia; [11]Faculty of Health, School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia; [12]Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia*

10.1136/bjsports-2020-IOCAbstracts.185

Background Low eccentric hamstring strength and sprinting performance are associated with hamstring injury (HI) in football; however, the off-season effects on both qualities are unknown.

Objective The aim of the study was to investigate eccentric hamstring strength and sprinting performance changes during the off-season period in football players.

Design Prospective cohort study.

Setting Semi-professional (3rd-4th tier) and amateur (5th-8th tier) Spanish footballers.

Patients (or Participants) Male footballers (n=107) were contacted to participate. Seventy-four footballers (25±4 years, 178.0±6.6 cm, 74.9±8.1 kg) were included in final analyses.

Interventions (or assessment of risk factors) Eccentric hamstring strength (Nordbord) and sprint performance (30m sprint and V-Cut test) were assessed at the beginning (May-June 2017) and end of the off-season (July-August 2017). Previous HI, age and off-season length were considered the independent variables.

Main outcome measurements Eccentric hamstring strength (N; N·kg^{-1}), 30m sprint (5–10m splits (s)) and change-of-direction performance (s). All outcomes were proposed before any data collection. Data was analysed using paired t-tests and linear mixed models.

Results No changes in eccentric hamstring strength were found at follow-up. Large (2%, d=0.96; $p<0.001$) and small (1%, d=0.46; $p<0.001$) decrements in performance were found for 30m sprint and 10m split time at follow-up, respectively. Previous HI, age or off-season length had no effect on any of the outcomes.

Conclusions Footballers showed no reduction in eccentric hamstring strength but impaired sprint performance after the off-season period, independent of age, previous HI and length of off-season. This may suggest the risk of sustaining a HI during the pre-season is lowered, as a result of decreased maximal sprinting capacity. This implicates that introducing eccentric hamstring strengthening during pre/early season seems relevant as this may both increase sprinting performance and mitigate the risk of HI during the in-season.

186 HIGH CONCUSSION RATE AMONGST SOUTH AFRICAN UNIVERSITY RUGBY STUDENT TOURNAMENT

[1,2]James Craig Brown*, [1,2]Lindsay Starling, [3,4]Keith Stokes, [1,2]Pierre Viviers, [1,2,5]Sean Surmon, [1,2]Keith Derman. *[1]Institute of Sport and Exercise Medicine, Division of Orthopaedics, Department of Surgical Sciences, Stellenbosch University, Cape Town, South Africa; [2]IOC Research Centre, South Africa, Cape Town, South Africa; [3]Department for Health, University of Bath, Bath, UK; [4]Rugby Football Union, London, UK; [5]Maties Sport, Stellenbosch University, Stellenbosch, South Africa*

10.1136/bjsports-2020-IOCAbstracts.186

Background Of all injuries common to collision sports, concussions have received the most attention due to the potentially negative cognitive effects in the short- and long- term. Stellenbosch Rugby Football Club ('Maties'), the official rugby club of Stellenbosch University, represents one of the world's largest non-professional Rugby clubs, making this an ideal cohort for community level injury surveillance.

Objective To describe the incidence and events associated with concussion in this large non-professional homogenous cohort.

Design A one-season prospective cohort injury surveillance study.

Setting Students (young adults) athletes competing in the internal ('Koshuis') tournament of the Maties Rugby Club in 2018.

Patients (or Participants) All 807 male players registered for the Koshuis tournament in 2018, which was comprised of 101 matches and 2,915 of exposure hours. The average age, height and weight of this cohort was 20±2 years, 182±7 cm and 88±14 kg, respectively.

Interventions (or assessment of risk factors) Recording of all injuries, and factors associated with injury, according to the consensus statement for injury recording in rugby.

Main outcome measurements Overall, there were 89 time-loss injuries, which equated to an injury rate of 31 per 1000 match hours (95% confidence intervals [CIs]: 24–37), or about one injury per match. The most common injury diagnosis was 'concussion' (n=27 out of 90 injuries, 30%), at a rate of 9 per 1000 match hours (95% CIs: 6–12).

Results The three most common mechanisms of concussion in the present study were performing a tackle (33%), accidental collision (30%) and being tackled (11%).

Conclusions Concussion was the most common injury in this population, at a rate that was six times higher than a

Appendix V – List of other publications

Altarriba-Bartes, A., Peña, J., **Vicens-Bordas, J**., Milà-Villaroel, R., Calleja-González J. (2020). Post-competition recovery strategies in elite male soccer players. Effects on performance: A systematic review and meta-analysis. PLoS ONE, 15(10), 0-0. doi: 10.1371/journal.pone.0240135.

Altarriba-Bartes, A., Peña, J., **Vicens-Bordas, J.**, Casals, M., Peirau, X., Calleja-González J. (2020). The use of recovery strategies by Spanish first division soccer teams: a cross-sectional survey. Physician and Sportsmedicine, Sep 15; 1-11. doi: 10.1080/00913847.2020.1819150

Esteve, E., Clausen, M., Rathleff, M. S., **Vicens-Bordas, J.**, Casals, M., Palahí-Alcàcer, A., Hölmich, P., Thorborg, K. (2020). Prevalence and severity of groin problems in Spanish football: A prospective study beyond the time-loss approach. Scandinavian Journal of Medicine & Science in Sports 30 (5) doi: 10.1111/sms.13615

Esteve, E., Rathleff, M.S., Hölmich, P., Casals, M., Clausen, M. B., **Vicens-Bordas, J.**, Thorborg K. (2020). Groin problems from pre- to in-season: A prospective study on 386 male spanish footballers . Research in Sports Medicine, 0-0 doi: 10.1080/15438627.2020.1860044.

Fort-Vanmeerhaeghe, A., Bishop, C., Buscà, B., Aguilera-Castells, J., **Vicens-Bordas, J**., Gonzalo-Skok, O. (2020). Inter-limb asymmetries are associated with decrements in physical performance in youth elite team sports athletes. Plos One 15 (3) doi:10.1371/journal.pone.0229440

Peña, J., Altarriba-Bartes, A., **Vicens-Bordas, J**., Gil-Puga, B., Piniés-Penadés, G., Alba-Jiménez C., Merino-Tantiñà J., Baena-Riera, A., Loscos-Fàbregas, E., Casals, M. Sports in time of COVID-19: Impact of the lockdown on team activity, Apunts Sports Medicine, Volume 56, Issue 209, 2021, doi:10.1016/j.apunsm.2020.100340.

The saddest aspect of life right now is that science gathers knowledge faster than society gathers wisdom

Isaac Asimov