Universidad Miguel Hernández de Elche

DEPARTAMENTO PSICOLOGÍA DE LA SALUD

Programa de Doctorado en Psicología de la Salud

LABORATORY AND FIELD TESTS TO ASSESS CORE STABILITY

Doctoral Thesis

A dissertation presented by
Diego López Plaza

Graduate in Physical Activity and Sports Science

Elche, 2017

El Dr. D. Juan Carlos Marzo Campos, director del Departamento de Psicología de la Salud de la Universidad Miguel Hernández de Elche.

AUTORIZA:

Que el trabajo de investigación titulado: “LABORATORY AND FIELD TESTS TO ASSESS CORE STABILITY” realizado por D. Diego López Plaza bajo la dirección de Dr. D. Francisco José Vera García y Dr. D. Francisco David Barbado Murillo, sea depositado en el departamento y posteriormente defendido como Tesis Doctoral en esta Universidad ante el tribunal correspondiente.

Lo que firmo para los efectos oportunos en

Elche a 1 de septiembre de 2017

Fdo.: Juan Carlos Marzo Campos

Director del Departamento de Psicología de la Salud

Universidad Miguel Hernández de Elche

UNIVERSIDAD MIGUEL HERNÁNDEZ DE ELCHE

Departamento: Psicología de la Salud

Programa de Doctorado: Psicología de la Salud

Título de la Tesis

LABORATORY AND FIELD TESTS TO ASSESS CORE STABILITY

Tesis Doctoral presentada por:

D. Diego López Plaza

Dirigida por el Dr. D. Francisco José Vera García y el Dr. D. Francisco David Barbado Murillo

Los Directores **El Doctorando**

Elche, 1 de septiembre de 2017

DEPARTAMENTO DE PSICOLOGÍA DE LA SALUD

Programa de Doctorado en Psicología de la Salud

LABORATORY AND FIELD TESTS TO ASSESS CORE STABILITY

A dissertation presented by
Diego López Plaza

Directores:
Dr. D. Francisco José Vera García
Dr. D. Francisco David Barbado Murillo

“*La vida es larga y tenemos que sin pausa, pero sin prisa, aprender a saborearla*”.

María Trinidad Plaza García

“El caos es un orden aún por descifrar”.

José Saramago

“No has de ganar cada discusión; solo debes estar de acuerdo con no estar de acuerdo”.

Regina Brett

AGRADECIMIENTOS

La propia naturaleza del ser humano, definido como un ser condicionado por la sociedad y la cultura en las que se desenvuelve, le lleva a construir, a crear integrándose en grupos; trabajando en equipo. Tanto es así, que el total desarrollo de una persona en cada una de sus dimensiones, se encuentra determinado por la influencia de aquellas que le rodean. Sí, podríamos afirmar que el concepto de *persona* es, "también" complejo y dependiente del contexto[1]. Por ello y sin ser mi caso personal una excepción, voy a tener en consideración la idea mencionada anteriormente para afirmar que, todo el proceso que precede y acompaña en el tiempo a la elaboración y presentación de este documento, ha contado con la colaboración, ya sea de forma directa o indirecta, de distintas personas. Y es que el hecho de tener en mi pensamiento el apartado de *Agradecimientos* prácticamente desde el comienzo de esta etapa de formación investigadora hasta su culminación, es posiblemente una buena señal; quizás tenga mucho que agradecer.

En primer lugar, a mi familia, definida como ese pilar central, fundamental[2], constituido por un material cuasi-indestructible que actúa desde que nacemos como soporte y apoyo en cada paso que damos a lo largo de nuestra vida. A mis padres, por haberme dado todo lo que llevo en mi mochila, mis fortalezas y mis miedos, siempre con la mejor de vuestras intenciones. A mi hermano, por haberme curtido en mil y una "batallas" y por el cariño con el que contigo comparto todos mis malos y buenos recuerdos. A mis tíos y primos, especialmente a mi

---

[1] Símil con el objeto de estudio de esta Tesis Doctoral.
[2] En este caso, mi pilar fundamental.

Tito Pepe, el guardián y protector de la familia, por su implicación más profunda en todos los problemas familiares. A mi prima María José, por su incondicional apoyo, siempre a caballo entre un estrecho vínculo familiar y la más profunda amistad. A mi abuela Trina, por haber sido mi segunda madre y a mis abuelos, Carmen y Gabriel, aunque no puedan estar ya presentes. A mi abuelo Diego, por quien llevo mi nombre, porque sé que estarías orgulloso de presenciar este momento, de saborearlo junto a mí; porque aunque no estés desde hace más de 15 años, nunca te llegaste a ir.

En segundo lugar, a mis amigos, aquellos pilares que se ubican en distintas posiciones, con mayor o menor cercanía al pilar central. Ellos también están formados por un material muy rígido y resistente y, aunque algunos caigan antes de lo esperado o deseado, otros terminan haciéndose más fuertes y consistentes; importantes con el transcurso del tiempo. A los que llevan más de media vida a mi lado y a los que se fueron uniendo por el camino, amigos desde aquella inocente al tiempo que divertida etapa en el instituto, desde cuando hemos compartido momentos (ahora lo hacemos en forma de recuerdos) de todas las formas, texturas, tamaños y colores; personas que han permanecido a mi lado tanto en los mejores momentos, como en aquellos que fueron más difíciles: Fran, Álvaro, Pepe, Cristina González, Casi, Ana, Héctor, Rocío, gracias por haberme permitido disfrutar de tantas experiencias a vuestro lado. A Joaquín y a Fran, amigos del barrio de toda la vida. A Sergio Parra y a los hermanos Zamora, Antonio y Víctor, quienes demostraron, cuando más falta hizo, tener un gran corazón. Paco Quero, porque a pesar de la distancia nunca olvidaremos los buenos momentos. Yo tampoco olvidaré aquellos detalles que dan muestra de tu calidad humana. Ángela, porque has necesitado

muy poco tiempo para demostrarme mucho. Cristina, porque desde que coincidimos en el Celia Viñas, he sentido un vínculo muy fuerte hacia ti; aún cuando ahora no podemos vernos con tanta frecuencia, diré que nunca dejarás de ser mi alumna favorita. Tania, porque aunque te conocí en una etapa algo complicada, siempre sentí tu apoyo; porque a pesar de que ahora estás lejos, eres un "pilar" ya eterno en mi vida. Sergio, por tu amistad; por tu carácter divertido y animado, por todo el positivismo que has transmitido a cualquier persona que tuvo la suerte de cruzarse contigo en algún instante y por la filosofía con la que afrontas la vida. Ezequiel, porque desde el momento en el que te conocí, supe que nuestra amistad duraría toda la vida; porque llevas demasiados años fuera conquistando empresas, países y corazones, pero sólo con recordar el tiempo que hemos vivido juntos, siento que mereció la pena que se cruzasen nuestros caminos, así como el deseo de que vuelvas pronto. Almudena, por la alegría que te define; capaz de transmitir y contagiar tus emociones a cualquier persona, siendo yo siempre uno de los principales afectados. Gracias por tu amistad y tu cariño, por tantos besos y abrazos como me has regalado, por cada sonrisa de esas que me alegraban el día y que ahora extraño en la distancia. Paco, por la amistad y el fuerte vínculo que he sentido durante todos estos años hacia ti; porque a pesar de las diferencias que hemos encontrado por el camino, estoy seguro de que siempre has tenido la mejor intención. Gracias porque en mi recuerdo, siempre va a ganar con rotundidad esa carcajada contagiosa, imposible de evitar y que a nadie dejaba indiferente, y la buena sensación que siempre has transmitido al robarte uno de esos abrazos que tanto costaba conseguir. Lidia, "cómo hablar" y escribir aquí para ti un agradecimiento, cuando sueles conocer

mis intenciones en cada momento. Siempre he pensado que eres un ejemplo de superación en todos los sentidos. Gracias por estar siempre cerca, o al menos, por hacerme sentir que lo estás; porque lo hemos compartido todo y por regalarme tantos momentos de alegría y tanto apoyo en aquellos de tristeza; gracias por no soltarme hasta mi último paso errado. Gracias por tu incondicional amistad. Pablo, gracias por tu talante, tu inteligencia, por tu capacidad de calmar las aguas más agitadas; por compartir conmigo tantas emociones desde aquella etapa tan crítica llamada adolescencia y por haber grabado en mi recuerdo, pese a la vivencia de duros momentos, tanta felicidad. Gracias por ser receptor de mis secretos y en mi camino, compañero.

A dos figuras docentes que han dejado huella en mi persona y en mi mente. A Carmen López, quien durante mi primera etapa en el instituto, en el I.E.S. Cruz de Caravaca, se implicó hasta en nuestros problemas extracurriculares; gracias por ser mucho más que la profesora de biología. A Antonia Torres, profesora de Educación Física en mi etapa de bachillerato en el I.E.S. Celia Viñas, quien ahora compañera y amiga, ha sido en distintas formas y sentidos una persona clave en mi decisión de estar hoy donde estoy. Gracias. A Jesús Tello y a Carmen Lucena, por vuestro apoyo en aquellos momentos más difíciles y por todo el afecto que siempre me habéis ofrecido. Al Dr. Pedro Serrano y al centro hospitalario Aita Menni, por devolverme la que con algunos cambios, es hoy mi vida.

Durante los años que he estado estudiando en Elche, mi día a día fuera de casa ha sido mucho más fácil gracias a la presencia de distintas personas, amigos que de diferente manera, han “aliñado” mi experiencia ilicitana. Gracias Adrián, por esas charlas, por lo agradable que es arreglar el mundo cuando nos juntamos; gracias por tus lecciones de moral, por el sentido común y la dignidad con la que afrontas las dificultades. Nieves, Vero, Liset, Juan Carlos, Juanvi, Higinio, por vuestra amistad durante todos estos años y por los buenos momentos que he podido disfrutar junto a vosotros. Gracias Patricia, por el tiempo en el que compartimos nuestras vidas; gracias Paula y Antonio, por hacerme sentir como en casa. Sonia y Noelia, gracias por enseñarme a relativizarlo todo y por permitirme disfrutar de uno de los años más divertidos de mi etapa en Elche. Ana Cristina, o Dra. Sierra, por haber compartido conmigo dos años en prácticamente todos los ámbitos de nuestra rutina diaria. Gracias a aquellos compañeros, ahora amigos, con quienes compartí tantas horas en mis breves pero intensos meses de verano trabajando en JC Ferrero Equélite Sport Academy: Ana, Jorge, Víctor, Álvaro, David, Nacor, Guille, Martín, Esther, Elizabeth y César. A mi equipo de conserjería: Maite, Inma, Jesús, Rubén, María y Susy[3], gracias por todos los años que hemos sido compañeros y aún más por la amistad que nos une a raíz de ello. Ilse, quien en pocos meses dejó buen calado de ese punto de locura que tanta falta hace en la vida. Octavio, por ser un gran compañero y amigo en muchos sentidos, y por dejarme claro que nadie debe "contármelo"; por las locuras que sólo se viven una vez... o dos. Gracias Samora, por lucir esa fortaleza que posiblemente la vida te haya obligado a desarrollar; por ser un ejemplo de persona, por tu buen corazón. Gracias por haber llegado a nuestra familia. Bea, porque marcaste un antes y un después con tu llegada a Elche; porque con tu energía y tu alegría, conseguiste atrapar a este "norteño" en los 22. Gracias porque, aunque te echamos de menos desde que terminaste aquí tu trabajo, representas esa amistad que

---

[3] Capitana del equipo.

nunca debe perderse. Gracias por cruzarte en mi camino. A mis compañeros del C.E.I.P. Baix Vinalopó: Ada, Shere, Rafa, Elia, Marga, Alex, Noelia, Alberto y Adolfo. Gracias por ofrecerme la oportunidad de trabajar con vosotros y por haberme hecho sentir parte del equipo. Gracias Adolfo, ya no solo por contar conmigo, sino por la percepción que he tenido siempre de tu voluntad de querer ayudarme.

Es cierto que a lo largo de nuestra vida, con mayor o menor frecuencia, corremos el "riesgo" de cruzarnos con esa persona especial, a veces cuando menos nos lo esperamos. Yo he tenido la suerte de haberlo experimentado en estos últimos años y puedo decir que, cuando una historia se complica, o es directamente compleja desde el comienzo, ya sea por motivos de distancia o por diferencias culturales, existe una mayor razón para estar agradecido y para valorar a la persona con la que compartes tu vida. Gracias Mihaela, por acompañarme en mi camino. Gracias por toda la ayuda que estás siempre dispuesta a prestarme, sin importarte lo que pueda suponer. Gracias por todos los momentos de alegría y felicidad que me has regalado hasta ahora y por tu temple y actitud a la hora de solventar aquellos de conflicto. Gracias por hacerme desear que continúe esta loca y compleja aventura con cada una de tus sonrisas.

Por otro lado, quiero agradecer la colaboración de todas esas personas que, de forma más directa, han estado implicadas en este proceso. Y es que éste no habría sido posible sin la participación de los estudiantes que se prestaron voluntarios para la realización de los estudios que conforman esta Tesis; gracias a todos por ser partícipes de la ciencia y concretamente de este trabajo. Gracias a todos los miembros de la familia del CID: Dori, la auténtica “decana”, por hacerme sentir tu aprecio cada vez que te veo por el Centro[4]. Gracias Juan Pedro, por hacerte imprescindible para el funcionamiento de cualquier trabajo. Gracias por responder siempre con un “sí”, antes de explicarte para qué necesitamos tu ayuda. Gracias a todos los compañeros de comportamiento motor, liderados por Eduardo, por desarrollar esa enorme labor; gracias Vicente y David, por vuestra implicación en la ciencia y en su transmisión; gracias por captar con vuestras impecables actuaciones docentes mi interés en materias que no me habrían resultado tan llamativas de otro modo. Gracias a todos los compañeros de entrenamiento: Manolo, Fito, Raúl, Jaime, a quienes admiro desde que fui su alumno. Gracias a mis compañeros de “complementos” Adrián García y Félix, y a Miguel con quien compartí un intenso año de máster; gracias Diego por esas carcajadas que despiertan y alegran a todo el Centro y a Sarabia, por tu brillantez y tu buena disposición para ayudar cada vez que acudo a ti. Gracias Artur, por mostrarme desde que coincidimos en el máster, la calidad humana que portas. A mis "vecinas" de control motor, Carla, María y Marta, que aunque en pocas ocasiones, pude disfrutar de muy buenos momentos con vosotras. Gracias Álvaro y Xoxe, por esos contados pero valiosos y siempre divertidos momentos que he pasado con vosotros y a Tomás, por tu apoyo cuando es necesario y por los sabios consejos que sueles dejar. A Francis y a Raúl, por ser piezas fundamentales del CID, por el trabajo que desempeñáis en este Centro. Gracias Alba, porque aunque has llegado este último año, has dejado ya sello de tu amabilidad y alegría; siempre recordaré esas “mini-conversaciones” con las que nos animábamos mutuamente para llegar “a tiempo”. Gracias Rafa, por contar conmigo y por tu

---

[4] Sí, con mayúscula.

ayuda; gracias por tenderme tu mano. Gracias Manolo Peláez, porque aunque ahora te vea menos por el CID, nunca olvidaré como desde que llegamos a Elche como estudiantes de segundo ciclo, nos trataste con tu extraordinaria amabilidad.

Para terminar, no puede faltar la mención a mis compañeros más próximos, los del grupo BIOMEC: Alberto y Carlos, quienes recién llegados a la "manada", estáis demostrando esa capacidad de trabajo que tanto vais a necesitar y vuestra buena disposición para ayudar a los demás. Pedro, aunque no llevas demasiado tiempo con nosotros, es un placer coincidir y debatir contigo de cualquier tema. Gracias por estar ahí cuando se te necesita. Víctor Moreno, por permitirme aprender de tu conocimiento y por el trato que siempre me has dado. Gracias a Fran Ayala y a Sergio Hernández, por darme la oportunidad de participar en mi primer proyecto de investigación. Gracias por vuestro apoyo en cada conversación. Alejandro López, porque contigo empecé mi aventura en el laboratorio con nuestras maratonianas sesiones de registro, que conseguíamos amenizar entre risas. Gracias Ramón, porque aunque escasas, las veces en las que hemos coincidido me has demostrado ser un gran compañero; gracias por cambiar mi perspectiva en este tramo final del camino y por ayudarme a atribuir la importancia justa a las cosas. Casto, gracias por tu paciencia y por tu dedicación, ayuda que sobre todo en los últimos meses, ha sido imprescindible para poder llegar hasta aquí. Gracias Mari Pili, por tu gran sentido del compañerismo, por hacerme admirar tu capacidad de trabajo y por haber compartido conmigo, especialmente en los últimos años, esas horas de trabajo y estrés durante las que siempre quedaba tiempo para reír. Gracias Iñaki, Ñako o Ignacio, como te gusta que te citen, porque con tu exceso de ironía y tu peculiar y ácido

sentido del humor, te has ganado a todos y cada uno de los componentes del Centro; gracias por tus lecciones de moral. Gracias Belén, por todas las horas que hemos compartido en mediciones de todo tipo; gracias por tu apoyo, amiga dentro y fuera del laboratorio. Gracias por tus consejos; gracias por tu amistad. José Luis, por trabajar "en silencio" para el adecuado desarrollo de proyectos y estudios de nuestro grupo de investigación. Gracias por aportar con tu característica calma, esa humilde mente privilegiada. David, el componente del CID más solicitado, gracias por haber invertido parte de tu tiempo en solucionar mis torpes pasos hacia ningún sitio; gracias por tu impagable trabajo que tanto le ha dado a este grupo y a este Centro. Gracias también por ese feedback positivo que siempre proporcionas y que a mí personalmente me ha dado fuerzas y ganas de continuar con esto en momentos que no fueron del todo fáciles.

A la persona que posiblemente haya tenido una mayor importancia e influencia en este proceso, profesor que ha despertado la admiración de cualquier alumno/a que haya frecuentado sus clases; gran partícipe, con su rigor metodológico y con un trato excelente, tanto a los datos como a las personas, del "click" en mi mente que sin saber exactamente cuándo, inspiró este interés por la investigación. Gracias Fran, por tu tiempo y por la paciencia que has tenido durante este período, por tu cercanía y por tu talante; gracias por la honestidad y la claridad con la que siempre te has dirigido hacia mí. Especialmente gracias, porque durante los 7 años que he estado viviendo en Elche y conociendo el funcionamiento de esta facultad de CAFD, muchas han sido las ocasiones en las que me he ilusionado, soñando con introducirme en este "mundo de la ciencia"; gracias por haberme dado la oportunidad de llevarlo a cabo.

Porque nunca terminaremos de saber hacia dónde vamos, ni tan siquiera, de conocer dónde nos encontramos.

TABLE OF CONTENTS

LIST OF FIGURES

Figure 9. Pictures showing a participant performing the *Star Excursion Timing Test* along: (A) the left-posterior reach direction; and (B) the left-lateral reach direction.

Figure 10. Regression analysis between arm length (cm) and raw scores of each *Star Excursion Sitting Test* (SEST) direction (cm), SEST composite index (cm) and *Star Excursion Timing Test* (SETT) composite index (cm). The axis *x* in the graphs represents the limb-length; the axis *y* represents the reach distance.

LIST OF TABLES

ABSTRACT

Core stability is a current topic that has sparked interest in sport sciences in the last 20 years, so many different protocols have been used to assess it in laboratory and field settings. However, there are important limitations in the scientific literature that make the selection and application of tests to measure core stability difficult. Based on these limitations, the general objectives of this Doctoral Thesis were: 1) to analyse the reliability and relationship between some of the most representative tests used to assess core stability in biomechanics laboratories and field settings; 2) to develop new field tests to measure core stability and to analyse the main characteristics of these protocols in order to facilitate their adequate use. In order to achieve these objectives, two correlational and reliability test-retest studies were carried out, in which the participants (healthy and recreationally active males) performed the tests twice, spaced a month apart. In the first study, the following variables were measured: trunk angular displacement, stiffness and damping in the *Sudden Loading Test*, centre of pressures displacement in the *Stable and Unstable Sitting Test*, position-holding time in the *Biering-Sorensen Test*, visual scores of the participants' postural control in the *Three Plane Core Strength Test*, and lumbopelvic displacement during the *Double-leg Lowering Test*. Based on our results, *Sudden Loading Test, Stable and Unstable Sitting Test* and *Biering-Sorensen Test* were the only tests which provided reliable variables. The absence of correlations between these protocols, and even between the loading directions of the *Sudden Loading Test*, suggest that core stability measurements are not generalizable, as they probably assess different dimensions of core stability, or in the case of *Biering-Sorensen Test*, a different capacity (i.e. trunk extensor endurance). In the second study, three field tests were analysed: the *Star Excursion Balance Test* and two variations of this test developed to assess trunk postural control while sitting, i.e. the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*. The reliability analysis showed the consistency of the three field tests to measure postural control. Regarding the correlational analysis, although the three protocols have similar characteristics, the scores of the *Star Excursion Balance Test* did not correlate with the scores of the *Star Excursion Sitting Test* and the *Star Excursion Timing Test.* This may be because while the *Star Excursion Balance Test* assesses postural control in single-leg stance, the new protocols were performed in sitting position, which increased the role of the upper-body in postural control, obtaining measures more related to core stability. Overall, the results of this Doctoral Thesis show the complexity of core stability assessment and provide useful information about some popular tests and two new protocols to measure this ability. This information may help coaches, clinicians and researchers to choose the most appropriate tests for each situation and to interpret and apply their results.

Key words: *postural control; reliability; spine biomechanics; testing; trunk muscles.*

RESUMEN

La estabilidad del *core* o *core stability* es un tema actual que ha despertado mucho interés en ciencias del deporte en los últimos 20 años, de forma que diferentes protocolos han sido utilizados para valorar esta cualidad en trabajos de campo y laboratorio. Sin embargo, en la literatura científica encontramos importantes limitaciones que dificultan la selección y aplicación de estos test como medidas de estabilidad del core. Basándonos en estas limitaciones, los objetivos generales de esta Tesis Doctoral fueron: 1) analizar la fiabilidad de algunos de los test más representativos utilizados para valorar la estabilidad del core en estudios biomecánicos y trabajos de campo, así como la posible relación entre ellos; 2) desarrollar nuevos test de campo para medir la estabilidad del core y analizar las características principales de estos protocolos para facilitar su adecuado uso. Con el fin de alcanzar estos objetivos, se llevaron a cabo dos estudios correlacionales y de fiabilidad test-retest, en los cuales los participantes (varones sanos y físicamente activos) realizaron los test en dos ocasiones, separados por un espacio temporal de un mes. En el primer estudio, se midieron las siguientes variables: desplazamiento angular, rigidez y amortiguamiento del tronco en el *Sudden Loading Test*; desplazamiento del centro de presiones en el *Stable and Unstable Sitting Test*; duración del *Biering-Sorensen Test*; valoración visual del control postural de los participantes en el *Three Plane Core Strength Test*; y desplazamiento lumbopélvico durante el *Double-leg Lowering Test*. Tal y como se desprende de nuestros resultados, el *Sudden Loading Test*, el *Stable and Unstable Sitting Test* y el *Biering-Sorensen Test* fueron los únicos test que mostraron variables fiables. La ausencia de correlaciones entre estos protocolos, e incluso entre las direcciones del *Sudden Loading Test*, sugieren que estas medidas de estabilidad del core no son generalizables, ya que probablemente valoran diferentes dimensiones de esta capacidad, o en el caso del *Biering-Sorensen Test*, una capacidad diferente (resistencia de la musculatura extensora del tronco). En el segundo estudio, se analizaron tres test de campo: el *Star Excursion Balance Test* y dos variaciones de este test desarrolladas para valorar el control postural del tronco en sedestación, es decir, el *Star Excursion Sitting Test* y el *Star Excursion Timing Test*. El análisis de fiabilidad mostró la consistencia de los tres test de campo para medir el control postural. Respecto al análisis correlacional, aunque los tres protocolos tienen características similares, las puntuaciones del *Star Excursion Balance Test* no correlacionaron con las puntuaciones del *Star Excursion Sitting Test*, ni con las del *Star Excursion Timing Test.* Esto puede ser debido a que, mientras el *Star Excursion Balance Test* valora el control postural en apoyo monopodal, los nuevos protocolos se llevaron a cabo en sedestación, lo que incrementó el rol del tren superior en el control postural, obteniendo medidas más relacionadas con la estabilidad del core. En general, los resultados de esta Tesis Doctoral muestran la complejidad de la valoración de la estabilidad del core y proporcionan información valiosa sobre varios test para medir esta habilidad, algunos de ellos bastante populares y otros diseñados para la ejecución de este trabajo de investigación. Esta información puede ayudar a entrenadores, profesionales clínicos e investigadores a elegir los test más apropiados para cada situación, así como a interpretar y aplicar sus resultados.

Palabras clave: *biomecánica del raquis; control postural; fiabilidad; músculos del tronco; valoración.*

ABBREVIATIONS

AL: Anterior-lateral direction in the *Star Excursion Balance Test*.

AM: Anterior-medial direction in the *Star Excursion Balance Test*.

ANOVA: Analysis of variance with repeated measures.

CL: Confidence limits.

CM: Change in the mean.

CoP: Centre of pressure.

ICC: Intra-class correlation coefficient.

k: Kappa index.

LA: Left-anterior direction in the *Star Excursion Sitting Test*.

LL: Left-lateral direction in the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*.

LP: Left-posterior direction in the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*.

MDC: Minimum detectable change.

PL: Posterior-lateral direction in the *Star Excursion Balance Test*.

PM: Posterior-medial direction in the *Star Excursion Balance Test*.

RA: Right-anterior direction in the *Star Excursion Sitting Test*.

RL: Right-lateral direction in the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*.

RP: Right-posterior direction in the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*.

SAP: Stable sitting task while performing anterior-posterior displacements with feedback.

SCD: Stable sitting task while performing circular displacements with feedback.

SD: Standard deviation.

SEBT: *Star Excursion Balance Test*.

SEM: Standard error of measurement.

SEST: *Star Excursion Sitting Test*.

SETT: *Star Excursion Timing Test*.

SML: Stable sitting task while performing medial-lateral displacements with feedback.

SNF: Stable sitting task without feedback.

SWF: Stable sitting task with feedback.

TE: Typical error.

UAP: Unstable sitting task while performing anterior-posterior displacements with feedback.

UCD: Unstable sitting task while performing circular displacements with feedback.

UML: Unstable sitting task while performing medial-lateral displacements with feedback.

UNF: Unstable sitting task without feedback.

UWF: Unstable sitting task with feedback.

CHAPTER 1

GENERAL INTRODUCTION

CHAPTER 1

GENERAL INTRODUCTION

1.1. The concept of *core stability*

Core is a functional concept especially used in sport training and sport medicine to refer to the osteoarticular and neuromuscular structures of the central part of the body (especially the lumbodorsal spine, pelvis and hips), which take part together in actions that imply great kinetic chains, such as running, dribbling, throwing or kicking (Borghuis, Hof & Lemmink, 2008; Kibler, Press & Sciascia, 2006; Escamilla et al., 2010; Vera-Garcia, Barbado, Moreno-Pérez, Hernández-Sánchez, Juan-Recio & Elvira, 2015a). Taking this concept as a basis, the term *core stability* arises, which has raised great interest in the last 20 years in different fitness, sport, research and injury prevention and rehabilitation fields (Akuthota, Ferreiro, Moore & Fredericson, 2008; Kibler et al., 2006; Silfies, Ebaugh, Pontillo & Butowicz, 2015; Wirth, Hartmann, Mickel, Szilvas, Keiner & Sander, 2017).

There are numerous definitions of core stability in the scientific literature (Borghuis et al., 2008; Kibler et al., 2006; Vera-Garcia et al., 2015a) as well as similar concepts, which have traditionally been used in biomechanics, engineering and rehabilitation, such as *trunk stability*, *spine stability* or *lumbopelvic stability* (McGill, Grenier, Kavcic & Cholewicki, 2003; Reeves, Narendra & Cholewicki, 2007; Zazulak, Cholewicki & Reeves, 2008). Generally, all these concepts have been used as synonyms, but nevertheless, the term core stability is the one which has acquired the greatest popularity, as its use has generalized in both the scientific and mass media. What follows are different definitions of core stability depending on the professional and/or scientific field in which the term has been developed and/or used.

From a mechanical point of view, one of the most relevant definitions is the one provided by Bergmark (1989), who described spine stability as the ability to maintain the spine in static balance under perturbations, this is to say, the resistance of the spine to modify it state of balance. This author mathematically related the concepts of minimum potential energy, stiffness and stability of the lumbar spine, which allowed the development of mathematical models to quantify the spine stability using the elastic potential energy approach (Cholewicki & McGill, 1996). Following this definition by Bergmark, the higher the force or energy needed to change the static balance of the spine, the more stable the spine is (which shows the stiffness of its structures). According to Panjabi (1992), spine stability depends both on the stiffness of its osteoarticular and ligamentous elements, as well as on the muscular activation and its correct performance under the coordination of the nervous system.

In this sense, the stiffness of the lumbar spine increases quickly and asymptotically with trunk muscle activation, so low levels of muscle activity are able to develop stiff and stable spinal joints (McGill & Cholewicki, 2001; Vera-Garcia, Brown, Gray & McGill, 2006), especially when the trunk muscles are co-activated through highly coordinated muscle activation patterns (Brown, Vera-Garcia & McGill, 2006; McGill et al., 2003). Nevertheless, the concept of mechanical stability based on stiffness is not easily applied to dynamic situations (Granata & England, 2006; Reeves, Everding, Cholewicki & Morrisette, 2006), reason why authors such as Zazulak et al. (2008) have operationally defined trunk stability as "*the capacity of the body to maintain or resume a relative position (static) or trajectory (dynamic) of the trunk following perturbation*".

The term *clinical spinal instability* has been developed in the clinical field and considered as an important cause of low back pain (Panjabi, 2003). White & Panjabi

(1990) defined this concept as "*the loss of the spine's ability to maintain its patterns of displacement under physiologic loads so there is no initial or additional neurologic deficit, no major deformity, and no incapacitating pain*". While mechanical instability is mainly related to the inability of the spine to carry internal and external loads, clinical instability encloses the clinical penalties of neurological deficit and/or pain (Panjabi, 2003). Furthermore, in order to facilitate the application of this concept to the clinical assessment, lumbopelvic stability has been defined as "*the ability to control motion of the lumbar spine and pelvis relative to an arbitrarily defined neutral position*" (Mills, Taunton & Mills, 2005).

From a closer perspective to the sports medicine field, Kibler et al. (2006) defined core stability as "*the ability to control the position and motion of the trunk over the pelvis and leg to allow optimum production, transfer and control of force and motion to the terminal segment in integrated kinetic chain activities*". This concept stresses the importance of providing local or proximal strength and balance to maximize the function of the distal elements of the kinetic chains in all types of sport activities, maximizing force generation and control and minimizing joint penalty loads (Kibler et al., 2006). In this sense, Hodges & Richardson (1997) used fine-wire and surface electromyography to prove that trunk muscle activation happens prior to the activation of the muscles that move the limbs, this fact being interpreted as a way to create a stable base for lower-limb and/or upper-limb movements.

In sport science and medicine, the term core stability has frequently been used interchangeably with the term *core strength*, and understood as a wide concept which encompasses different abilities, especially sensory-motor control, strength/power and endurance (Abt, Smoliga, Brick, Jolly, Lephart & Fu, 2007; Akuthota et al., 2008;

Akuthota & Nadler, 2004; Arendt, 2007; Chevidikunnan, Al Saif, Gaowqzeh & Mamdouh, 2016; Clark et al., 2016; Hoppes et al., 2016; Kang, 2015; Ko, Chun, Kim, Yi, Kim & Hong, 2016; Sharma, Geovinson & Singh, 2012; Sharma & Kaur, 2017; Sharrock, Cropper, Mostad, Johnson & Malone, 2011; Tinto, Camapanella & Fasano, 2017). Following this perspective, it is difficult to establish training and assessment methods that cover all the abilities that this term encompasses, which makes its use and implementation difficult. That is why authors such as Reed, Ford, Myer & Hewett (2012) have differentiated between both terms, defining core strength as the ability of the core muscles to produce and maintain force, and core stability as the ability of passive and active core structures to maintain proper trunk and hip posture, balance and control during the application of core strength or in response to perturbations (Reed et al., 2012).

As can be seen from the different definitions mentioned in the previous paragraphs, the term core stability is used ambiguously in different scientific and professional settings, which make the analysis of the scientific literature and the contextualisation of this Doctoral Thesis difficult. Taking into account the convenience of the use of a single definition of stability by the scientific community (Reeves et al., 2007; Zazulak et al., 2008), Vera-Garcia et al. (2015a) suggested a concept of core stability that includes many of the contributions of the different authors and which we have used as a starting point for the development of this Doctoral Thesis: "*ability of the osteoarticular and muscle structures, coordinated by the motor control system, to maintain or resume a trunk position or trajectory when it is subject to internal or external forces*". This concept is very similar to the definition of trunk stability by Zazulak et al. (2008), but it also includes the different elements or subsystems which according to Panjabi (1992) interact within the spine stability system, i.e. passive elements, active elements and neural control elements. Furthermore, it is a concept that can be applied in static (positions) and dynamic (trajectories) situations, and therefore it could be useful in different contexts (sport training, fitness, rehabilitation, research, etc.).

1.2. The role of core stability in athletic performance and in injury prevention and treatment

Core stability has attracted much interest of coaches, physical trainers, clinicians and researchers, as it has been related to injury prevention and rehabilitation (Hides, Jull & Richardson, 2001; Leetun, Ireland, Willson, Ballantyne & Davis, 2004; Whyte, Richter, O’Connor & Moran, 2017; Zazulak, Hewett, Reeves, Goldberg & Cholewicki, 2007a, b), sport performance (Manchado, García-Ruiz, Cortell-Tormo & Tortosa-Martínez, 2017; Romero-Franco, Martínez-López, Lomas-Vega, Hita-Contreras & Martínez-Amat, 2012; Watson et al., 2017) and functional capacity for everyday tasks (Kang, 2015; Ketelhut, Kindred, Manago, Hebert & Rudroff, 2015). In this sense, core stabilisation exercises have become key elements of sport training and injury rehabilitation programs (Borghuis et al., 2008; Vera-Garcia et al., 2015a).

1.2.1. Core stability and injury prevention and rehabilitation

The importance of core stability for injury prevention is mainly based on the results of epidemiological and biomechanical studies, which related poor core stability (i.e. low scores in tests or parameters used to assess core stability) to occurrence of lumbar spinal (Cholewicki et al., 2005; Radebold, Cholewicki, Panjabi & Patel, 2000; Reeves, Cholewicki & Milner, 2005) and lower-limb (Leetun et al., 2004; Zazulak et al., 2007a, b) injuries. For example, cross-sectional and observational cohort studies have shown that individuals with low back pain have trunk postural control deficits (Radebold et al., 2000; Reeves et al., 2005; Radebold, Cholewicki, Polzhofer & Greene, 2001), longer trunk muscle response latencies to sudden external perturbations (Radebold et al., 2000; Reeves et al., 2005) and internal forces (Hodges & Richardson, 1996, 1998) and abnormal trunk muscle recruitment patterns in activities with high stability demands (van Dieën, Selen & Cholewicki, 2003). Interestingly, it seems that these deficits in trunk neuromuscular control may persist after injury, as an interesting study performed by Cholewicki, Greene, Polzhofer, Galloway, Shah & Radebold (2002) found that asymptomatic athletes who had a recent history of acute low back injury and had returned to regular competition showed altered muscle response pattern to sudden trunk loading (Cholewicki et al., 2002). Although the referred studies do not allow to establish a causal relation between low values of core stability and a higher risk of suffering low back pain/injury, a prospective study with 292 athletes (Cholewicki et al., 2005) showed that those individuals with longer trunk muscle response latencies to sudden loading had a higher probability of suffering a lumbar injury in a period between two and three years after taking part in the study.

Based on the results obtained in the previous studies, different authors have recently developed experimental studies with the aim of establishing cause-effect relations between the implementation of core stability intervention programs and the improvement of the symptoms associated to low back disorders (Esser, 2017; Javadian, Akbari, Talhebi, Taghipour-Darzi & Janmohammadi, 2015; Kliziene, Sipaviciene, Klizas & Imbrasiene, 2015). In a study that involved swimmers, Esser (2017) found a reduction in lumbar pain and other benefits related with the functional improvement in different activities after a training program for the trunk stabilizer muscles (8-week). Other authors (Javadian et al., 2015) analysed the effects of core stability exercises in patients with clinical diagnosis of non-specific and chronic low back pain, reaching the conclusion that this type of training combined with general exercises was more effective than training based solely on general exercises to reduce lumbar segmental instability in these patients. Likewise, Kliziene et al. (2015) found that a core stabilisation exercise program significantly increased multifidus muscle cross-sectional area in both healthy females and females with chronic low-back pain, which could help improve the function of this spine stabilizer muscle. In the same way, Wang et al. (2012) carried out a meta-analysis to compare between the efficiency of core stability exercise programs and general exercise programs in patients with chronic low back pain, finding that in the short-term core stability exercises are more effective than general exercises to decrease pain, and may improve physical function in this population.

Despite the results presented in the previous paragraphs, other works have not found any improvements in the health or physical condition of patients with low back pain (Shamsi, Rezaei, Zamanlou, Sadeghi & Pourahmadi, 2016; Shamsi, Sarrafzadeh, Jamshidi, Zarabi & Pourahmadi, 2016; Smith, Littlewood & May, 2014). Furthermore, there are not many experimental studies that deal with the efficiency of this type of interventions and, in general, these works present important limitations (Stilwell & Harman, 2017; Stuber, Bruno, Sajko & Hayden, 2014). In this sense, some of the interventions measured the effect of stabilization training on the pathology, but not on core stability (Esser, 2017; Javadian et al., 2015; Kliziene et al., 2015; Shamsi et al., 2016; Shamsi, Sarrafzadeh et al., 2016), and the works that measured stability used very diverse methodologies, some of which showed reliability and/or validity problems (Araujo, Cohen & Hayes, 2015; Sharma & Kaur, 2017; Watson et al., 2017). Furthermore, most studies compared the effect of different type of exercises, but the criteria used to control and increase the training load was not clear (Manchado et al., 2017; Sharma & Kaur, 2017; Watson et al., 2017).

Regarding the relation of core stability and lower-limb injury, prospective evidence supports the hypothesis that neuromuscular control deficits of core stability are contributing factors of injuries of distal segments of the kinetic chains during jumping-landing, cutting, dribbling, kicking, etc. (Zazulak et al., 2007a, b). For example, Zazulak et al. (2007a) measured the neuromuscular control of the trunk against sudden perturbation of 277 athletes and then tracked knee injuries over three years, finding that those athletes with poor kinematic response to sudden perturbation had an increased risk of knee ligament injuries. Likewise, other experimental studies also seem to support this hypothesis. In this way, Whyte et al. (2017) proved the effectiveness of a 6-week trunk stability dynamic exercise program on the biomechanics of different movements, finding a reduction of the risk factors linked to the anterior cruciate ligament injury. In the same line, Araujo et al. (2015) stated how a 6-week core stability static and dynamic exercise program improved the falling position in women that practiced capoeira, therefore reducing the risk of injury in the lower-limbs.

1.2.2. Core stability and athletic performance

According to the definition of core stability suggested by Kibler et al. (2006) in the field of sports medicine, an optimal control of the central elements of most kinetic chains in athletic activities will maximize the upper and lower-limb function. Starting from this hypothesis, cross-sectional and observational cohort studies (Barbado, Barbado, Elvira, van Dieën & Vera-Garcia, 2016; Barbado, López-Valenciano, Juan-Recio, Montero-Carretero, van Dieën & Vera-Garcia, 2016; Cook, Burton & Hoogenboom, 2006; Elvira et al., 2013) and experimental studies (Manchado et al., 2017; Park, Hyun & Jee, 2016; Romero-Franco et al., 2012; Watson et al., 2017) have looked into the possible benefits that a good level of trunk stability can offer on performance in different sports. For example, Barbado, López-Valenciano et al. (2016) compared different trunk performance parameters between national and international level judokas, finding better trunk responses to sudden perturbations for the international athletes. Concerning the experimental studies, Reed et al. (2012) carried out a systematic review of the experimental literature to analyse the association between core stability training and sports-related performance measures, finding controversial results and a lot of difficulties to analyse the literature. The principal limitations of the studies were: i) core stability exercises were normally part of a general training routine, making it difficult to directly isolate their effects on athletic performance; ii) many studies were carried out with amateur or university athletes, and therefore their results are not generalizable to elite or professional sport; iii) there was a lack of standardisation of the protocols used to assess core stability and athletic performance. Regarding this last limitation, sports-specific testing protocols are required to reveal core stability adaptations in high-level athletes (Barbado et al., 2016).

Despite these limitations, several experimental studies have recently been published, which show the possible positive effects of core stability training for the improvement of performance in different sports. In this sense, Manchado et al. (2017) analysed the effect of a core training program on the throw speed in 30 handball players and found that the strengthening of the lumbopelvic region could contribute to the improvement of the kinetic chain of the specific movement of throwing in handball. In a study carried out with archers (Park et al., 2016), a Pilates program based on core stability exercises improved the balance of these athletes. Furthermore, Romero-Franco et al. (2012) analysed the effect of a 6-week specific proprioceptive training program on core stability and centre of gravity control in sprinters, finding improvements in these variables. To conclude, Watson et al. (2017) showed that a 9-week core stability program improved the stability and other performance variables in dancers.

1.3. The assessment of core stability

Due to the potential benefits of core stability for injury prevention and athletic performance presented above, many different tests have been developed to measure core stability in laboratory and field settings. The diversity of these protocols seems to be related to the different definitions of core stability found in the literature, so each of the methodologies presented below is based on one of the concepts of core stability discussed in the first section of this introduction.

What follows are different protocols to assess core stability depending on the setting in which they are normally used, this is to say, biomechanics or engineering labs (laboratory tests) or sports centres, educational centres and rehabilitation clinics (field tests). In general, the laboratory tests stand out due to a higher accuracy in the measurement and the use of very precise instrumental, and on the other hand, the field tests tend to be simpler, more cost-effective and easier to use, not needing expensive equipment or complicated data reduction.

1.3.1. Laboratory tests to measure core stability

There are three main methodologies used in biomechanics and engineering to assess core stability (Vera-Garcia, Barbado, Moreno-Pérez, Hernández-Sánchez, Juan-Recio & Elvira, 2015b): i) *Mathematical modelling*; ii) *Sudden loading/unloading tests*; and iii) *Stable and unstable sitting tests.* The first of them comes from the theoretical and mathematical basis developed by Bergmark (1989), is applicable to static or quasi-static situations, and is based on stiffness calculation. The other two are more empirical methodologies which come from a more operational concept of core stability (Zazulak et al., 2008), which allows an assessment of stability both in static (maintaining or controlling the trunk position against perturbations) and in dynamic situations (maintaining or controlling the trunk trajectory against perturbations).

a) *Mathematical modelling*

Bergmark (1989) mathematically formalized the concepts of energy wells, stiffness and stability, which allowed the development of mathematical models for quantification of spine stability using the elastic potential energy approach (Cholewicki & McGill, 1996). In this sense, Cholewicki & McGill (1996) developed a lumbar spine stability model based on elastic potential energy calculations as a function of stiffness and elastic energy storage. According to this model, the musculoskeletal spine stores potential energy by virtue of its elastic deformation under load, which is recovered when the load disappears. The greater the spinal stiffness, the higher loads would be needed to deform it, and therefore the more stable the spine is.

b) *Sudden loading/unloading tests*

This methodology analyses the trunk kinetic and kinematic response to quick and controlled forces applied to the trunk (sudden or release forces) in different positions: i) in standing, to analyse a whole-body response to perturbation (Cresswell, Oddsson & Thorstensson, 1994); and ii) in sitting or semi-sitting position, to minimize the influence of the lower-limbs, focusing on core stability assessments (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Cholewicki et al., 2005; Cholewicki, Simons & Radebod, 2000; Gardner-Morse & Stokes, 2001; Glofcheskie, 2015; Shahvarpour, Shirazi-Adl, Lariviére & Bazrgari, 2015; Yoshitomi, Tanaka, Duarte, Lima, Morya & Hazime, 2006; Zazulak et al., 2007a). The loads are normally applied using a pneumatic, mechanic or electronic mechanism, previously standardising the point of application, direction, duration and magnitude of the loads.

This type of protocols allows the quantification of three main variables after the perturbation (Cholewicki, McGill, Shah & Lee, 2010; Cholewicki, Simons et al., 2000; Gardner-Morse & Stokes, 2001): i) maximum trunk angular displacement; ii) the coefficient of trunk stiffness, i.e. the relation between applied torque and trunk angular displacement after the perturbation; and iii) the coefficient of trunk damping, which is related with the ability of the trunk to reduce its angular displacement depending on the speed at which the perturbation is applied. Furthermore, electromyographic variables such as intensity and latency of the trunk muscle response after the perturbation and the intensity of the muscle activation prior to the perturbation are also calculated (Brown et al., 2006; Radebold et al., 2000, 2001; Reeves et al., 2005; Vera-Garcia et al., 2006; Vera-Garcia, Elvira, Brown & McGill, 2007). All these variables have allowed the analysis of the effect of different measurement and participant factors or conditions on the trunk kinematic, kinetic and electromyographic response against perturbations. The main factors analysed have been the following: loading directions and magnitudes (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Gardner-Morse & Stokes, 2001; Krajcarski, Potvin & Chiang, 1999; Vera-Garcia et al., 2006), expected/unexpected loads (i.e. when perturbation timing was known/unknown) (Granata, Orishimo & Sanford, 2001; Thomas, Lavender, Corcos & Andersson, 1998; Vera-Garcia et al., 2007; Wilder, Aleksiev, Magnusson, Pope, Spratt & Goel, 1996); mechanical tissue creep (Sánchez-Zuriaga, Adams & Dolan, 2010), vibration (Wilder et al., 1996), fatigue (Granata et al., 2001; Herrmann, Madigan, Davidson & Granata, 2006; Sánchez-Zuriaga et al., 2010; Wilder et al., 1996), low back injury or pain (Cholewicki et al., 2002; Radebold et al., 2001; Reeves et al., 2005), sport specificity (Barbado et al., 2016) and sport performance level (Barbado, López-Valenciano et al., 2016).

Despite the great amount of studies that have used this methodology, few studies have analysed the reliability of this type of tests, obtaining contradictory results (Barbado et al., 2016; Herrmann et al., 2006). On the one hand, Barbado et al. (2016) obtained good relative and absolute intra-session reliability, especially in trunk angular displacement, which showed the best absolute reliability values. On the other hand, Herrmann et al. (2006) obtained low levels of relative reliability, but they did not analyse the absolute reliability, which shows the need to carry out new research on the consistency of these protocols. Regarding repetition or learning effect of these tests, Barbado et al. (2016) found no differences between the different repetitions of the test, possibly because the variables analysed were calculated with the signal of the 110 ms after the perturbation, which show the involuntary response of the passive structures of the trunk and the activation of spinal reflexes (Barbado et al., 2016; Cholewicki et al., 2010; Cholewicki, Simons et al., 2000).

c) *Stable and unstable sitting tests*

This is a posturographic methodology based on the quantification of the participant’s centre of pressure (CoP) fluctuations regarding a desired position or trajectory (also called the body sway). Unlike the conventional posturographic tests performed in upright standing (Hoogvliet, van Duyl, de Bakker, Mulder & Stam, 1997; Nakagawa & Hoffman, 2004; Panzer, Bandinelli & Hallett, 1995; Teasdale, Bard, LaRue & Fleury, 1993), these protocols assess the participant’s ability to control trunk posture and/or motion while sitting on an unstable or a stable seat (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Cholewicki, Polzhofer & Radebold, 2000; Lee & Granata, 2008; Reeves et al., 2006; van Dieën, Koppes & Twisk, 2010). The seat is placed on a force platform to measure CoP fluctuations and has leg and foot supports to reduce the influence of the lower-limbs in the measurement. The stable and the unstable seats have similar characteristics, but the unstable seat has a rigid hemisphere attached to the bottom. Many of these protocols consist of measuring postural sway during quiet sitting on an unstable seat (Cholewicki et al., 2000; Lee & Granata, 2008; Reeves et al., 2006; van Dieën et al., 2010). In addition, authors such as Barbado et al. (2016) and Barbado, López-Valenciano et al. (2016), have developed a protocol with static and dynamic tasks performed on a stable and an unstable seat and visual feedback of the CoP and a target point in real time, which allows an assessment of core stability under 10 different conditions.

The variables that are usually measured in these protocols are the fluctuations and the mean velocity of the CoP (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016), which have been used as a measure of core stability in different populations, such as physically active individuals (Barbado et al., 2016; van Dieën et al., 2010) and athletes of different sport modalities (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016). Furthermore, this methodology has also been used to compare neuromuscular control of core stability among asymptomatic populations and populations with various pathologies, such as people with low back pain (Radebold et al., 2001; van Daele, Hagman, Truijen, Vorlat, van Gheluwe & Vaes, 2010; van Daele, Huyvaert, Hagman, Duquet, van Gheluwe & Vaes, 2007; van Dieën et al., 2010; Willigenburg, Kingma & van Dieën, 2013), with idiopathic scoliosis (Bennett, Abel & Granata, 2004), with Parkinson’s disease (van der Burg, van Wegen, Rietberg, Kwakkel & van Dieën, 2006) and with stroke (Pérennou, Leblond, Amblard, Micallef, Hérisson & Pélissier, 2001). Despite the numerous studies that have used this methodology, there are few investigations that have analysed the reliability of these protocols (Barbado et al., 2016; Lee & Granata, 2008; van Dieën et al., 2010), finding, in general, a moderate to high intra-session relative reliability. Regarding absolute reliability, the study performed by Barbado et al. (2016) also found good consistency, although an increase in test performance was observed with test repetition (i.e. a learning or repetition effect), mainly in the most difficult tasks.

3.2. Field tests to measure core stability

The specificity and the high cost of the laboratory equipment, as well as the complexity both of the protocols and of the calculation and interpretation of the biomechanical variables, have limited the use of the laboratory tests presented in the previous section to certain research centres, to several professional sports clubs and to very specialised clinical centres. This has meant the need to develop field tests to measure core stability in situations in which these technological, economical and/or human resources are not available.

What follows is a revision of the main field tests that have been used in scientific literature to assess core stability, which have been grouped in three different methodologies depending on their characteristics (Vera-Garcia et al., 2015b): i) *Lumbopelvic postural control tests*; ii) *Whole-body stability tests*; and iii) *Trunk muscle fitness tests*. While the first of these methodologies is based on the clinical concept of spine stability/instability (Mills et al., 2005; Panjabi, 2003), the others follow concepts developed in sport science and medicine (Kibler et al., 2006).

a) *Lumbopelvic postural control tests*

These tests are carried out in lying supine and basically consist in controlling the lumbopelvic posture against forces applied by the movement of the lower-limbs. The most known examples of these tests are the *Double-leg Lowering Test* (Krause, Youdas, Hollman & Smith, 2005; Leetun et al., 2004; Sharrock et al., 2011) and the *Sahrmann Core Stability Test* (Chuter, de Jonge, Thompson & Callister, 2015; Mills et al., 2005; Stanton, Reaburn & Humphries, 2004). These protocols are used to identify lumbopelvic control deficits associated to low back instability and/or pain in clinical assessments (Kendall, McCreary & Provance, 1993) although the *Double-leg Lowering Test* has also been used to measure abdominal strength (Ladeira, Hess, Galin, Fradera & Harkness, 2005; Parker et al., 2011; Sharrock et al., 2011). Both tests seem to have moderate to high absolute and relative reliability levels in different populations (physically young, middle-age and elderly individuals) (Haladay, Denegar, Miller & Challis, 2015; Krause et al., 2005; Ladeira et al., 2005; Parker et al., 2011; Stanton et al., 2004), nevertheless some authors have criticised their lack of sensitivity to discriminate between individuals with high physical condition (Jamison, McNeilan, Young, Givens, Best & Chaudhari, 2012; Leetun et al., 2004; Vera-Garcia et al., 2015b). Furthermore, the use of these tests has been limited to clinical environments due to two main reasons: on the one side, because for their correct execution two expert examiners per participant are needed, which makes the assessment of groups of people difficult; and on the other side, some of the protocols use a pressure biofeedback to monitor the pelvic rotation (Mills et al., 2005; Sharrock et al., 2011), which may improve their sensitivity but increasing their cost and complexity.

b) *Whole-body stability tests*

This group includes general dynamic balance tests, normally carried out in single leg stance, which have been used to assess core control in different planes of movement. These tests follow the concept of core stability presented by Kibler et al. (2006), which highlights the importance of controlling the central elements of the kinetic chains to increase athletic performance and reduce injury risk. Among the most important tests we can find the *Three Plane Core Strength Test*, the *One-leg Standing Balance Test* and the *One-leg Squat Test* (Kibler et al., 2006; Weir, Darby, Inklaar, Koes, Bakker & Tol, 2010). Many of these tests are usual in sport medicine, in which an expert examiner must qualitatively score the performance of the participants in the tasks depending on different established criteria. Despite being subjective measurements of the control of core movement and posture, validity and reliability of these protocols have not been analysed in depth. To the best of our knowledge, we are only aware of one study that has analysed the reliability of the *Three Plane Core Strength Test* (Weir et al., 2010), finding low inter and intra-tester reliability.

Another of the tests that we can include in this methodology is the *Star Excursion Balance Test*, as although it is normally used as a general measure of dynamic postural control in single leg stance (Gribble, Kell, Refshauge & Hiller, 2013; Hyong & Kim, 2014; Kinzey & Amstrong, 1998; Lanning, Uhl, Ingram, Mattacola, English & Newom, 2006; Munro & Herrington, 2010; Whyte, Burke, White & Moran, 2015), it has also been used as a measure of core stability (Chuter et al., 2015). Most of the protocols or variations of the *Star Excursion Balance Test* showed good within-session relative and absolute reliability (Gribble et al., 2013; Hyong & Kim, 2014; Lanning et al., 2006; Plisky, Gorman, Butler, Kiesel, Underwood & Elkins, 2009; Plisky, Rauh, Kaminski & Underwood, 2006), but nevertheless, it is necessary to carry out new studies to analyse the between-session reliability and the learning effect of this test. Moreover, the results of the *Star Excursion Balance Test* have mainly been used as indicators of the lower-limb functionality (Ambegaonkar, Caswell, Winchester, Shimokochi, Cortes & Caswell, 2013; Ambegaonkar, Mettinger, Caswell, Burt & Cortes, 2014; Clagg, Paterno, Hewett & Schmitt, 2015; Delahunt et al., 2013; Gribble, Hertel, Denegar & Buckley, 2004; Hertel, Braham, Hale & Olmsted-Kramer, 2006; Nakagawa & Hoffman, 2004; Olmsted, Carcia, Hertel & Shultz, 2002), but the validity of this test as a measure of core stability is unknown. In this sense, the results of the *Whole-body stability tests* shown in this section are clearly influenced by the stance leg performance and stability, fact that casts doubts on their validity as core stability tests (Vera-Garcia et al., 2015b).

c) *Trunk muscle fitness tests*

These tests come from the concept of core strength, which as we have mentioned before has been used as a synonym of core stability in sport science and medicine and encompasses different qualities of the trunk muscles (e.g. strength/power and endurance). Within this methodology, the most widely used protocols have been trunk muscle endurance tests (Calatayud et al., 2017; Chuter et al., 2015; Leetun et al., 2004; Nesser, Huxel, Tincher & Okada, 2008), such as the McGill standardised testing battery (McGill, Childs & Liebenson, 1999), which includes the *Trunk Flexor Test*, the *Biering-Sorensen Test* and the *Side Bridge Test*, developed to assess the isometric endurance of trunk flexor, extensor and lateral muscles, respectively. These tests basically consist in holding a posture against gravity for the longest time possible and are characterised for having a good relative reliability (Chan, 2005; Demoulin, Vanderthommen, Duysens & Crielaard, 2006; Evans, Refshauge & Adams, 2007; Juan-Recio, Barbado, López-Valenciano & Vera-Garcia, 2014), showing their robustness to discriminate different levels of trunk isometric endurance between individuals with similar characteristics. Nevertheless, they don’t have a good absolute reliability (Juan-Recio et al., 2014; Moreland, Finch, Stratford, Balsor & Gill, 1997), which questions their use in certain contexts, for example in high performance sports, in which the athletes have very little margin of improvement and therefore it would be very difficult to know if the changes produced after an intervention program are due to training or to errors in the measurements. Another of their limitations is the learning effect of some of these tests (Juan-Recio et al., 2014), which need to carry out extensive familiarisation periods before their use in training programs or in experimental studies.

In addition to the trunk endurance tests, trunk power/strength tests have also been suggested as measures of core stability, as for example the *Front Abdominal Power Test* and the *Side Abdominal Power Test* (Cowley, Fitzgerald, Sottung & Swensen, 2009; Cowley & Swensen, 2008). These tests consist in reaching the maximum distance when throwing a medicine ball in different positions. Studies that have analysed the reliability of these tests (Cowley et al., 2009; Cowley & Swensen, 2008), found similar results to those obtained during the analysis of the trunk endurance tests, this is to say, good relative reliability values, bad absolute reliability values and an improvement in the performance of the tests due to a learning or repetition effect.

The *Trunk muscle fitness tests* are easy and inexpensive protocols that have been widely used to measure trunk muscle function. Nevertheless, these tests have been questioned as measures of core stability (van Dieën, Luger & van der Eb, 2012; Vera-Garcia et al., 2015b), as trunk muscle power/strength and endurance may be determinants of core stability (like other variables, i.e. mass, age, fatigue, etc.), rather than core stability variables themselves. Therefore, it is necessary to carry out studies that assess the validity of these protocols as stability tests.

4. The edge of knowledge about core stability measurement

Despite the possible benefits of core stability for low back and lower-limb injury prevention and treatment, as well as for athletic performance, there are important limitations in the scientific literature that make the selection and application of core stability tests difficult. What follows is a summary of the most important limitations that have been analysed in this introduction and which were the starting point for this Doctoral Thesis.

- There are numerous definitions of core stability in the literature which have resulted in different methodologies to assess it in biomechanical and field settings. As stated by Reeves et al. (2007), core stability is not likely a one-dimensional concept, so many of the tests showed in this introduction may reflect different dimensions of this capability. However, to the best of our effort, we have not found correlational studies on the relationships between the most common core stability tests, and therefore we do not know if one test scores are related to other test scores (maybe measuring the same dimension of stability) or if they are unrelated (maybe measuring different dimensions of core stability, or even different capabilities, such as endurance or strength).
- There are few studies that have analysed the reliability of the laboratory tests, especially absolute reliability and learning effect of the measurements (Barbado et al., 2016; Herrmann et al., 2006; Lee & Granata, 2008; van Dieën et al., 2010). Furthermore, these tests are not easily accessible to the majority of the population.
- The lack of sensitivity of the *Lumbopelvic postural control tests* to discriminate different performance levels in individuals with high physical condition has been criticized (Jamison et al., 2012; Leetun et al., 2004; Walker, Rothstein, Finucane & Lamb, 1987).
- There are doubts on the reliability of the *Whole-body stability tests* that carry out qualitative valuations of core stability (e.g. *Three Plane Core Strength Test*, *One-leg Standing Balance Test* and *One-leg Squat Test*) (Weir et al., 2010), as these depend among other factors, on the examiner’s experience. Furthermore, it is necessary to perform new studies on the between-session reliability and the learning effect of the *Star Excursion Balance Test*.

- The *Trunk muscle fitness tests* have a moderate to low absolute reliability and an important learning effect (see for example: Evans et al., 2007; Juan-Recio et al., 2014; Juan-Recio, López-Plaza, Barbado, García-Vaquero & Vera-Garcia, 2017; Moreland et al., 1997).
- There are doubts on the validity of the *Whole-body stability tests* as measures of core stability, as the performance of these tests seems to be very influenced by the functionality of the lower-limb (Chaiwanichsiri, Lorprayoon & Noomanoch, 2005; Nakagawa & Hoffman, 2004; Olmsted et al., 2002; Plisky et al., 2006; Vera-Garcia et al., 2015b). Furthermore, the *Trunk muscle fitness tests* are valid to measure muscle strength/power or endurance, but there are also doubts on their validity as core stability tests (Granacher, Schellbach, Klein, Prieske, Baeyens & Muehlbauer, 2014; Tse, McManus & Masters, 2005; Vera-Garcia et al., 2015b).

On the base of these limitations, further research is needed to describe the possible relationships between the most common core stability tests, which may help to understand the generality or specificity of the results of these protocols. Furthermore, future studies must improve the knowledge on some of the most important characteristics of the referred tests, such as reliability and validity of the measurements. To finish, taking into account the limitations of field tests and the difficulties to use the laboratory tests in sport, educational and rehabilitation settings, it is necessary to develop new field protocols that provide us with valid and reliable measures of core stability.

CHAPTER 2

RESEARCH OBJECTIVES AND HYPOTHESES

CHAPTER 2

RESEARCH OBJECTIVES AND HYPOTHESES

2.1. General objectives

Based on the limitations of the literature showed in the previous chapter, the general objectives of this Doctoral Thesis were:

I. *To analyse the reliability and relationship between some of the most representative tests used to assess core stability in biomechanics laboratories and field settings.*

II. *To develop new field tests to measure core stability, and to analyse the main characteristics of these protocols in order to facilitate their adequate use.*

To carry out these objectives, two correlational and reliability test-retest studies were performed:

- Study 1: Protocols to measure core stability in laboratory and field settings: reliability and correlation analyses.
- Study 2: Reliability of the *Star Excursion Balance Test* and two new similar protocols to measure trunk postural control.

2.2. Specific objectives

The specific objectives have been organised depending on the two studies of this Doctoral Thesis:

Study 1:

I. To assess the relative and absolute between-session reliability and the learning effect of some of the most common types of methodologies used to assess core stability in biomechanics laboratories (*Sudden Loading Test* and *Stable and Unstable Sitting Test*) and field settings (*Biering-Sorensen Test*, *Three Plane Core Strength Test* and *Double-leg Lowering Test*).

II. To analyse the relationship among the *Sudden Loading Test*, the *Stable and Unstable Sitting Test*, the *Biering-Sorensen Test*, the *Three Plane Core Strength Test* and the *Double-leg Lowering Test*.

Study 2:

III. To assess the absolute and relative between-session reliability of the *Star Excursion Balance Test* and two variations of this test to assess trunk postural control while sitting, i.e. the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*. In the new protocols, the influence of the lower-limbs was minimized to increase the role of the upper-body in postural control.

IV. To analyse the relationship between the *Star Excursion Balance Test* and the new protocols performed in sitting position, as well as the relationship between the *Star Excursion Sitting Test* and the *Star Excursion Timing Test*.

2.3. Research hypotheses

The following hypotheses were established in the two studies of this Doctoral Thesis:

Study 1:

I. Taking into account the reliability results obtained by the *Sudden Loading Test* and the *Stable and Unstable Sitting Test* in a previous study (Barbado et al., 2016), both laboratory protocols will show good absolute and relative reliability values, although the *Stable and Unstable Sitting Test* will show a significant learning or repetition effect (Barbado, López-Valenciano et al., 2016; Barbado, Moreside & Vera-Garcia, 2017).

II. According to the results obtained in previous studies, we will find a moderate to high relative reliability in the *Biering-Sorensen Test* (Demoulin et al., 2006; Evans et al., 2007; Juan-Recio et al., 2014; Mayer, Quillen, Verna, Chen, Lunseth & Dagenais, 2015), but a low to moderate absolute reliability and a clear learning effect (Juan-Recio et al., 2014; Moreland et al., 1997).

III. Taking into account the results from the study by Weir et al. (2010) and the subjectivity of the evaluations performed in the *Three Plane Core Strength Test* to score the participants, the reliability of this field test will be low.

IV. Taking into consideration the findings of prior studies performed in young physically active individuals, the *Double-leg Lowering Test* will obtain high absolute and relative reliability (Krause et al., 2005; Ladeira et al., 2005), although it will show a significant learning effect.

V. Considering core stability as a multidimensional and context dependent ability (Barbado et al., 2016; Reeves et al., 2007), there will be no significant correlations between the variables of the different protocols used to measure it, since in these tests the results are obtained in very different conditions. Nevertheless, as within each laboratory test the variables are obtained in very similar conditions, the correlations between them will be significant.

Study 2:

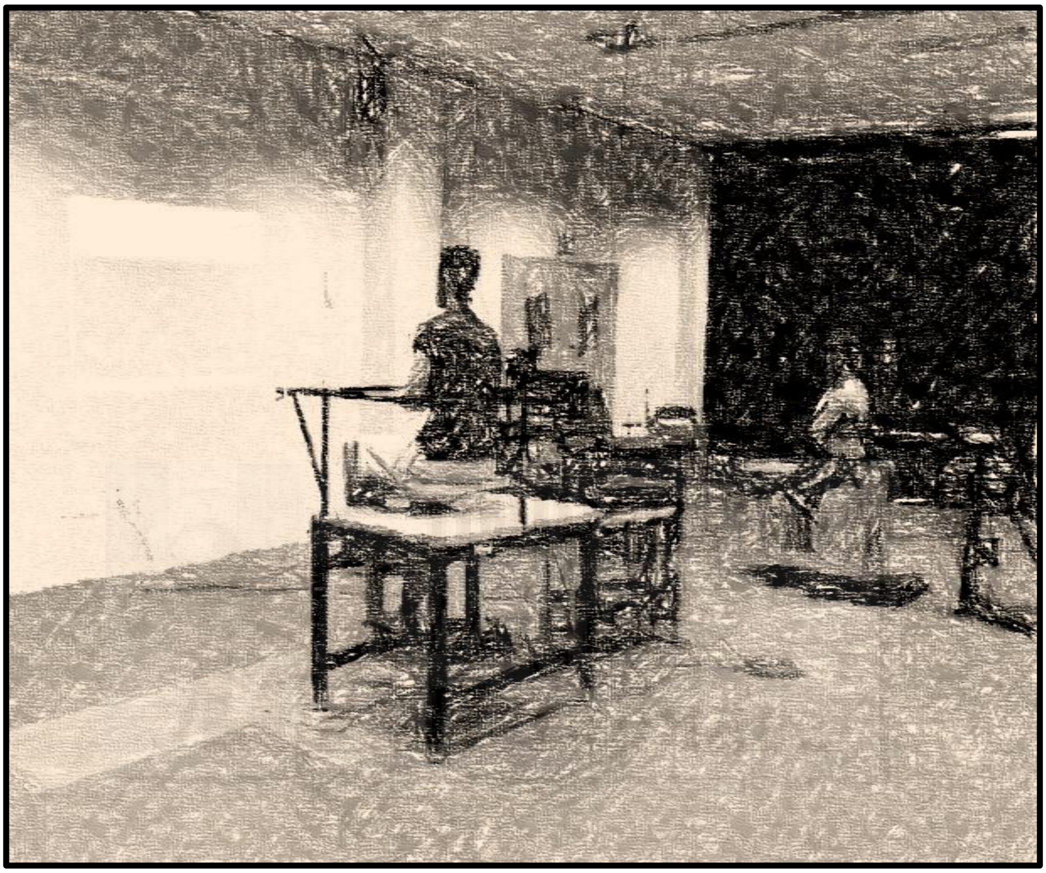
VI. Based on the results found in other studies (Clark, Saxion, Cameron & Gerber, 2010; Hale, Hertel & Olmsted-Kramer, 2007; Hyon & Kim, 2014; Kinzey & Amstrong, 1998; Munro & Herrington, 2010; Plisky et al., 2009, 2006), the *Star Excursion Balance Test* will show a moderate to high reliability. In the same way, considering the similarities between this protocol and its variations to assess trunk postural control, we think that the *Star Excursion Sitting Test* and the *Star Excursion Timing Test* will show similar reliability values to those of the *Star Excursion Balance Test*.

VII. Despite the fact that the *Star Excursion Sitting Test* and the *Star Excursion Timing Test* were developed based on the protocol of the *Star Excursion Balance Test*, significant correlations between the new tests and the original test will not be found, as the *Star Excursion Balance Test* assesses postural control in single-leg stance while its variations measure trunk postural control while sitting, which reduces lower-limb influence and provides field measures more related to core stability.

VIII. Taking into account that the *Star Excursion Sitting Test* and the *Star Excursion Timing Test* have very similar characteristics, a significant correlation will be found between them.

CHAPTER 3

STUDY 1



Submitted to review in American Journal of Sports Medicine.

Protocols to measure core stability in laboratory and field settings: reliability and correlation analyses.

Francisco J. Vera-Garcia, Diego López-Plaza, Casto Juan-Recio & David Barbado.

CHAPTER 3

STUDY 1

Protocols to measure core stability in laboratory and field settings: reliability and correlation analyses

by

Francisco J. Vera-Garcia, Diego López-Plaza, Casto Juan-Recio & David Barbado.

Abstract

Background: Core stability is a current topic that has sparked interest in sport sciences in recent years, so many different tests have been used to assess it. However, the relationships among these tests are currently unknown.

Purpose: The main objective of this study was to analyse the relationship between five representative tests of some of the most common types of protocols used to assess core stability in laboratory (*Sudden Loading Test* and *Stable and Unstable Sitting Test*) and field settings (*Biering-Sorensen Test*, *Three Plane Core Strength Test* and *Double-leg Lowering Test*). In addition, the reliability of these tests was also examined.

Study Design: Correlational and reliability test-retest study.

Methods: Thirty-three recreational active males (age: 24.06±2.89 years; mass: 75.02±9.30 kg; height: 176.58±5.51 cm) performed all the tests twice. The following variables were measured: trunk angular displacement, stiffness and damping after perturbation in the

Sudden Loading Test; centre of pressure displacement in the *Stable and Unstable Sitting Test*; position-holding time in the *Biering-Sorensen Test*; visual scores (from 1-poor, to 4-excellent) of the participants' postural control in the *Three Plane Core Strength Test*; and lumbopelvic displacement in the *Double-leg Lowering Test*. The relationship between all variables was examined using Pearson correlation coefficient in those variables which showed a good reliability (intraclass correlation coefficient (ICC)>0.60).

Results: Stiffness and angular displacement in the *Sudden Loading Test*, dynamic unstable tasks in the *Stable and Unstable Sitting Test* and the holding-time in the *Biering-Sorensen Test* showed a good reliability (ICC: 0.63-0.91; typical error: 9.8%-21.0%); however, the ANOVA showed significant test-retest differences in the *Stable and Unstable Sitting Test* and the *Biering-Sorensen Test*. Few and low correlations were observed between *Sudden Loading Test, Stable and Unstable Sitting Test* and *Biering-Sorensen Test*. In addition, although several significant correlations were found among the dynamic unstable tasks of the *Stable and Unstable Sitting Test* ($r \geq 0.807$; $p < 0.01$), no correlations were found between the loading directions of the *Sudden Loading Test*.

Conclusions: Only both the laboratory tests and the *Biering-Sorensen Test* met the necessary features to provide reliable scores. The absence of correlations between these protocols suggests that core stability measurements are not generalizable, as they probably assess different dimensions of core stability or in the case of *Biering-Sorensen Test*, a different capacity (i.e. trunk extensor endurance).

Key words: *biomechanical test; consistency; field test; trunk stability*.

1. Introduction

Core stability is a popular concept that has attracted the interest of coaches, athletes, clinicians and researchers in the last 20 years because of its potential benefits for injury prevention and athletic performance (Borghuis et al., 2008; Kibler et al., 2006; Vera-Garcia et al., 2015a; Zazulak et al., 2008). Consequently, many different tests have been used to assess core stability in laboratory and field settings. As there is no single accepted definition of this term (Borghuis et al., 2008; Kibler et al., 2006; Reeves et al., 2007; Vera-Garcia et al., 2015a; Zazulak et al., 2008), the characteristics of these protocols and the parameters measured are very different, e.g. trunk/spine stiffness (Brown et al., 2006; Cholewicki, Simons et al., 2010; Vera-Garcia et al., 2006; Vera-Garcia et al., 2007), participant's CoP fluctuations (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Cholewicki et al., 2000; van Dieen et al., 2010), lumbopelvic displacement (Krause et al., 2005; Stanton et al., 2004), visual/qualitative scores (Kibler et al., 2006) and endurance time (Chuter et al., 2015; Leetun et al., 2004; Nesser et al., 2008). In addition, although some of these parameters could be related, the relationships between all these protocols are unknown, hindering the generalization of their results.

Based on the concepts of energy wells, stiffness and stability (mathematically formalized by Bergmark (1989)), Cholewicki & McGill (1996) developed a *mathematical model* to quantify spine mechanical stability in static or quasi-static conditions, which focused on elastic potential energy calculations as a function of stiffness and elastic energy storage (Cholewicki & McGill, 1996). On the other hand, following a more operational biomechanical concept of core stability (i.e. "the capacity of the body to maintain or resume a relative position (static) or trajectory (dynamic) of the trunk following perturbation" (Zazulak et al., 2008)), two laboratory methodologies have generally been used to assess core stability: i) *Sudden loading/unloading tests*, which measure the trunk kinetic and kinematic response to quick and controlled perturbations (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Cholewicki, Simons et al., 2000; Gardner-Morse & Stokes, 2001; Granata et al., 2001; Vera-Garcia, et al., 2006); and ii) *Stable and unstable sitting tests*, which quantify the fluctuations of the participants' CoP regarding a desired position or trajectory (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016; Cholewicki et al., 2000; Lee & Granata, 2008; van Dieën et al., 2010). These two methodologies have been effective in detecting core stability deficits associated to low back disorders (Radebold et al., 2001; Reeves, Cholewicki & Narendra, 2009). In addition, poor trunk response to sudden force release has been related to incidence of lower limb injuries (Zazulak et al., 2007a). However, although both kinds of tests are based on the same biomechanical concept of core stability, they seem to measure different stability features or dimensions. In this sense, Barbado et al. (2016) compared the performance of competitive judokas and kayakers and recreational athletes in representative tests of both methodologies and found that specific-sport training induces specific core stability adaptations, which were only revealed through specific tests. These findings suggest core stability outcomes are not generalizable, but highly dependent on the conditions in which they are measured (i.e. dynamic or static, one-dimensional or two-dimensional, etc.) and on the characteristics of the target population (i.e. level of physical fitness, sport discipline, age, health status, etc.).

Regarding the field tests, many different protocols have been used to assess core stability in field settings. Taking into account their main characteristics, they can be grouped in three different methodologies (Vera-Garcia et al., 2015b): i) *Lumbopelvic postural control tests*, which are based on clinical concepts of spine stability/instability (e.g. "the ability to control motion of the lumbar spine and pelvis relative to an arbitrarily defined neutral position" (Mills et al., 2005)) and measure the ability to maintain a given lumbopelvic position in lying supine, such as the *Double-leg Lowering Test* (Krause et al., 2005; Leetun et al., 2004; Radwan et al., 2014; Sharrock et al., 2011) and the *Sahrmann Core Stability Test* (Mills et al., 2005; Stanton et al., 2004); ii) *Whole-body stability tests*, which follow the definition provided by Kibler et al. (2006) (i.e. the ability to control the trunk motion and position to allow optimum energy transfer through the core to the limbs) and are normally performed in single leg stance, as for example, the *Three Plane Core Strength Test* and the *Star Excursion Balance Test* (Chaudhari, McKenzie, Borchers & Best, 2011; Chuter et al., 2015; Kibler et al., 2006; Radwan et al., 2014; Weir et al., 2010); and iii) *Trunk muscle fitness tests*, which generally measure trunk isometric endurance, such as the *Biering-Sorensen Test* (Chuter et al., 2015), and follow a core stability conception very close to the concept of core strength/strengthening (Akuthota & Nadler, 2004; Leetun et al., 2004; Nesser et al., 2008; Radwan et al., 2014). Therefore, the main field methodologies used to assess core stability seem to measure different dimensions/components of this concept (like the biomechanical tests presented above) or even other related capabilities (e.g. endurance, strength, etc.) that would not fall within many of the stability definitions, hindering the comparison between core stability studies that use different testing protocols. Furthermore, despite their low cost and easy application, some of these field tests have shown several methodological limitations (i.e. low reliability, poor sensitivity, etc.) (Walker et al., 1987; Weir et al., 2010), which make the data interpretation even more difficult. Future studies should analyse the advantages and limitations of these tests, including their validity as core stability measures (Vera-Garcia et al., 2015b; Weir et al., 2010).

Considering the ambiguity of the core stability term in the literature and the wide variety of tests used to measure it in biomechanical and field settings, the selection of the most suitable tests for each individual/situation is an important and complex decision which represents a major challenge for coaches, physical trainers, clinicians and researchers. Further research is needed to understand the characteristics of these tests better and to explore the possible relationships between their scores. This information would facilitate the interpretation and application of the results of these protocols.

Therefore, in order to facilitate the decision-making process when selecting core stability tests, the main objective of this study was to analyse the relationship among five representative tests of some of the most common types of methodologies used to assess core stability in biomechanics laboratories (*Sudden Loading Test* and *Stable and Unstable Sitting Test*) and field settings (*Biering-Sorensen Test*, *Three Plane Core Strength Test* and *Double-leg Lowering Test*). In addition, considering the relevance of the measurement consistency to examine the relationship between variables (Atkinson & Nevill, 1998; Hopkins, 2000), the relative and absolute reliability of these tests were analysed, which also allowed us to discuss about the advantages and disadvantages of their use in different contexts.

2. Methods

2.1. Participants

Thirty-three healthy and recreationally active males (1-3 hours of moderate physical activity; 1-3 days per week) voluntarily took part in this study (age: 24.06±2.89 years; mass: 75.02±9.30 kg; height: 176.58±5.51 cm). Participants completed a questionnaire about their health status and physical activity habits during the year before testing. Exclusion criteria for this study were: known medical problems, especially neurological or musculoskeletal disorders and/or episodes of low back pain, and participating in a trunk muscle conditioning program at the time of the study. All subjects signed an informed consent based on the Helsinki Declaration of 2013. All procedures were approved by the University Office for Research Ethics.

2.2. Experimental procedure

Participants participated in four testing sessions, in which they performed the five tests twice spaced a month apart. In the first and second session they carried out the laboratory tests in this order: *Sudden Loading Test* and *Stable and Unstable Sitting Test*. In the third and fourth session they performed the three field tests in the following order: *Three Plane Core Strength Test*, *Double-leg Lowering Test* and *Biering-Sorensen Test*. The two repetitions of each test (test and retest) were separated by a month with the intention of avoiding the influence of neuromuscular fatigue on test execution and reducing the learning effect of these tests (Juan-Recio et al., 2017). None of the participants had previously carried out these tests, so the initial familiarisation with them was the same for all of them. Before each testing session, all participants performed a warm-up that consisted of 5 min of cycling and 4 sets of standardised trunk exercises: 2 sets of 15 curl-ups and 2 sets of 15 back extensions in a roman chair (the recovery time between sets and exercises was 30 s).

2.3. Testing protocol description

Sudden Loading Test

Following the methodology previously described by Barbado et al. (2016) and Barbado, López-Valenciano et al. (2016), participants were placed in a semi-sitting position (Figure 1) on a stable and rigid wooden chair which limits leg motion and promotes a neutral spine position and an elastic equilibrium for the core structures (Sutarno

& McGill, 1995). Sudden and unexpected loads were applied to the participants' upper-body centre of mass through a pulling mechanism formed by a pneumatic piston (pressure: 4.2 bar; speed: 0.5 m/s), a steel cable tensioner and an adjustable trunk harness (Figure 1). The pneumatic piston was placed in front, behind and at the right side of the participants to apply five sudden loads in anterior, posterior and right-lateral direction, respectively. Each perturbation took place within a 15 s window, in which participants were at rest.

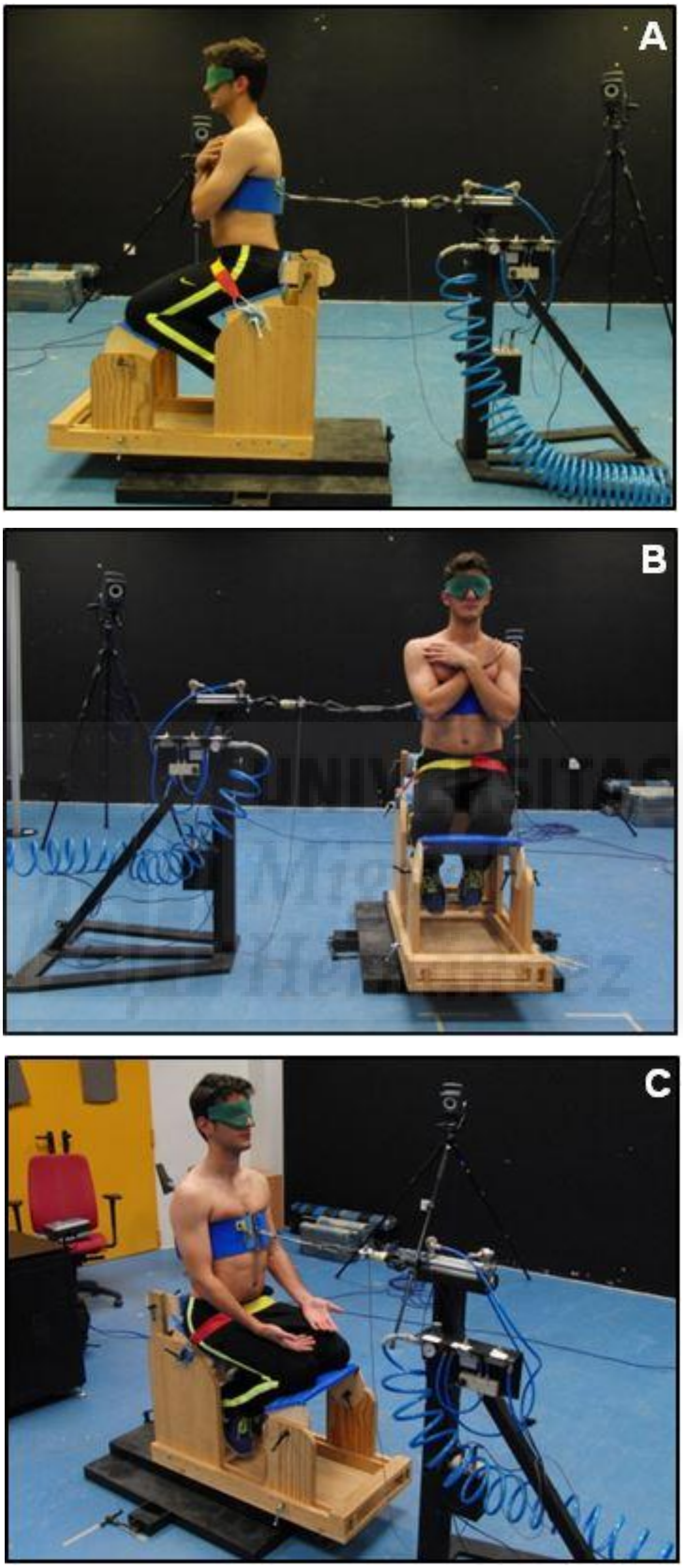
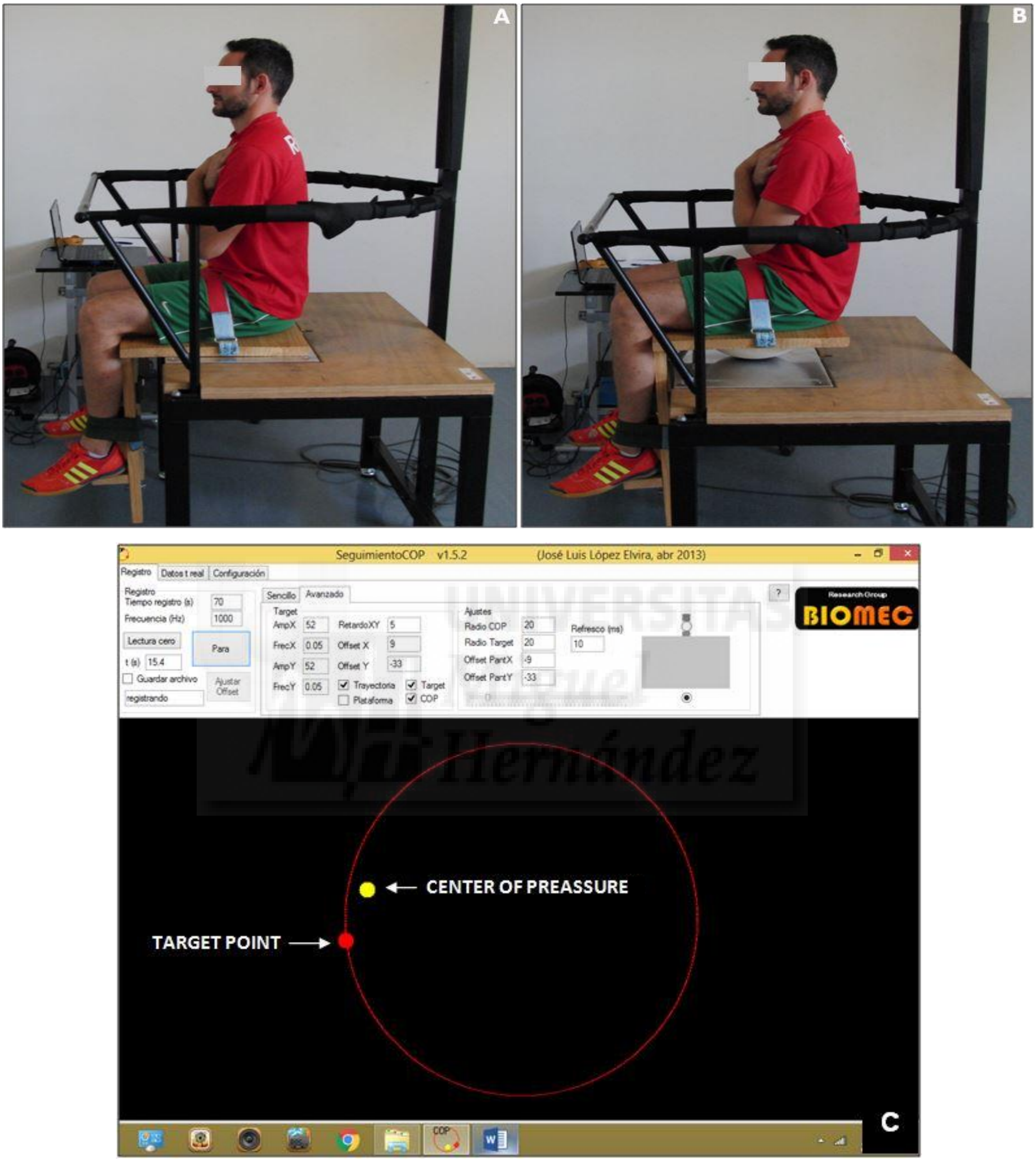


Figure 1. Pictures showing the set-up for applying sudden loads in the *Sudden Loading Test* in the following directions: (A) posterior; (B) lateral; and (C) anterior.

Stable and Unstable Sitting Test

As previously described by Barbado et al. (2016) and Barbado, López-Valenciano et al. (2016), participants performed 10 balance tasks while sitting on a stable or an unstable seat placed on a force-plate (Kistler, Switzerland, Model 9286AA) (Figure 2). The CoP displacement was measured during static and dynamic conditions (sampling frequency: 1000 Hz) in order to quantify trunk postural control. The stable seat was a wooden structure with leg and foot supports to avoid lower limb motion and to control the leg and foot position. A polyester resin hemisphere (radius: 35 cm, height: 12 cm), placed with Velcro® tape in the bottom of the stable seat, was used for the unstable sitting tasks (Figure 2B). Participants performed two statics and three dynamic tasks on each seat (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016). Visual feedback of CoP displacement (X and Y) was provided to participants in real time during the dynamic and one of the static tasks (Figure 2C). In addition, during these tasks, a target point was shown to the participants to assess their ability to adjust their CoP position to the target location. As a result, the following conditions were analysed: stable sitting without feedback (SNF); stable sitting with feedback (SWF); stable sitting while performing medial-lateral displacements with feedback (SML); stable sitting while performing anterior-posterior displacements with feedback (SAP); stable sitting while performing circular displacements with feedback (SCD); unstable sitting without feedback (UNF); unstable sitting with feedback (UWF); unstable sitting while performing medial-lateral displacements with feedback (UML); unstable sitting while performing anterior-posterior displacements with feedback (UAP); and unstable sitting while performing circular displacements with feedback (UCD). The duration of each task was 70 s. A 1 min rest period was set between tasks, which were counterbalanced to reduce a possible learning or fatigue effect. Each task was performed twice and the best result was used for subsequent analyses.



Registro
Tiempo registro (s) 70
Frecuencia (Hz) 1000
t (s) 15.4
☐ Guardar archivo
registrando

Target
AmpX 52
FrecX 0.05
AmpY 52
FrecY 0.05
RetardoXY 5
Offset X 9
Offset Y -33
☑ Trayectoria
☐ Plataforma
☑ Target
☑ COP

Ajustes
Radio COP 20
Radio Target 20
Offset PartX -9
Offset PartY -33
Refresco (ms) 10

Figure 2. Pictures showing: (A) a lateral view of a participant performing the *Stable and Unstable Sitting Test* on a stable seat; (B) a lateral view of a participant performing the *Stable and Unstable Sitting Test* on an unstable seat; and (C) the software used to provide feedback to the participants in real time (unstable sitting circular task).

Three Plane Core Strength Test

According to the methodology described by Kibler et al. (2006), participants' postural control was examined in single leg stance (dominant leg) while their trunk slowly moved in the three planes to lightly touch a wall located 8 cm away from the participants' shoulder/s and then returning to the starting position: i) frontal plane (Figure 3A): participants performed lateral bending motions to touch the wall with their dominant shoulder; ii) sagittal plane (Figure 3B): participants performed extension-flexion motions to touch the wall with the back of their head; iii) transverse plane (Figures 3C and 3D): participants performed twisting motions to touch the wall alternatively with one shoulder and then with the other. After a familiarisation period (i.e. verbal instructions, visual demonstration and six practice repetitions for each testing direction), participants performed two trials of six repetitions for each testing direction. They were instructed to keep the head and pelvis in the neutral position during the movement in the three planes. The same examiner scored the tests for all participants following the criteria established by Chmielewski, Hodges, Horodyski, Bishop, Conrad & Tillman (2007).

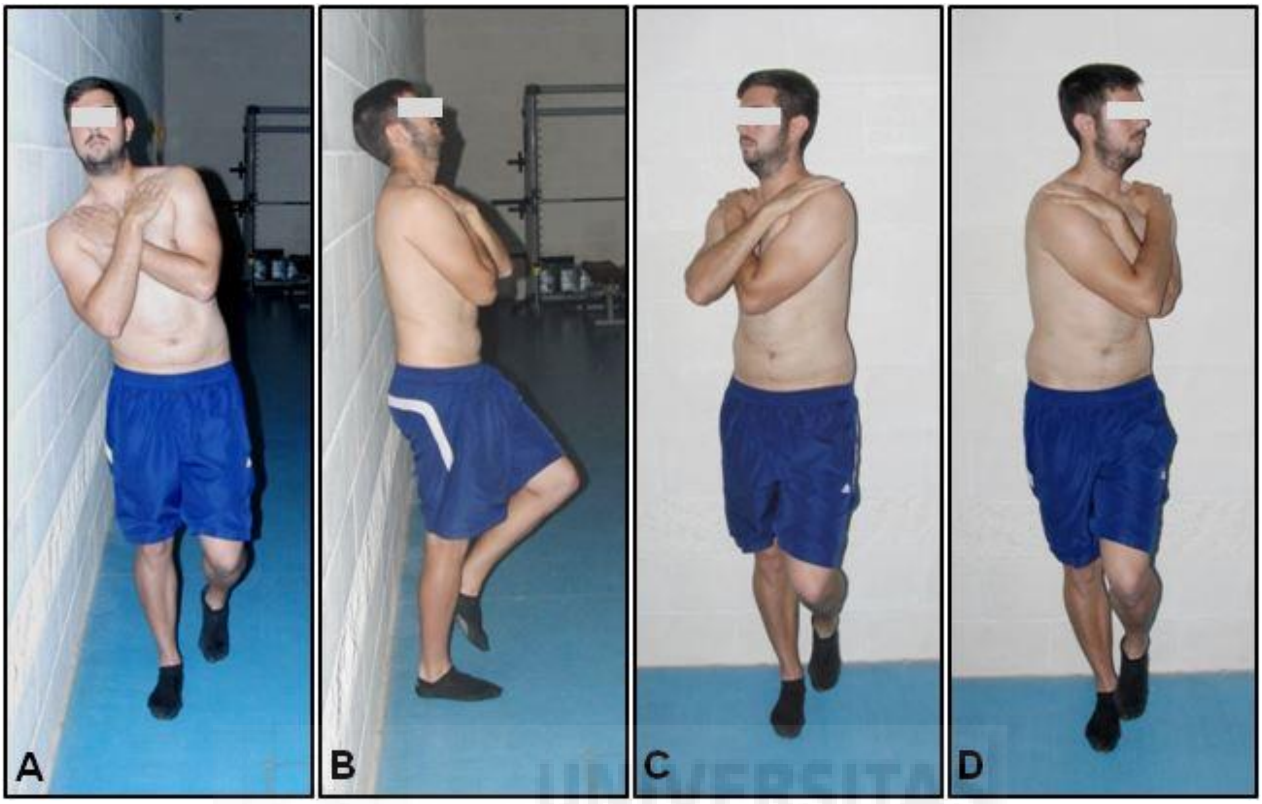


Figure 3. Pictures showing a participant performing the *Three Plane Core Strength Test*: (A) in the frontal plane; (B) in the sagittal plane; (C) and (D) in the transversal plane.

Double-leg Lowering Test

As described by Krause et al. (2005), to perform the *Double-leg Lowering Test* the participants were placed in a laying supine position on a semi-rigid mat with the arms on the chest and an examiner on each of their sides (Figure 4). Examiner 1 helped participants to place their legs as close to the vertical position as possible with the knees extended (depending on the hamstring flexibility) and placed their fingers between the low back and the mat in order to monitor the position of the low back during the test. Participants were asked to keep the pelvis posteriorly rotated, and the lumbar spine held firm to the mat, while slowly lowering both legs from the vertical position to the horizontal position. The time execution for lowering the legs was limited to 10 s and counted aloud using a metronome. Examiner 1 verbally indicated examiner 2 when the participants' back began to lift from the monitoring fingers, which represented the end of the test. Examiner 2 recorded the participant's performance in degrees with a goniometer, which had a 40 cm–long wooden dowel in the top for placement along the axis of the femur. The goniometer remained parallel to the participants' left femur during leg lowering (Figure 4). Two trials were performed with a 1 min rest between them, using the lower value for subsequent analyses.

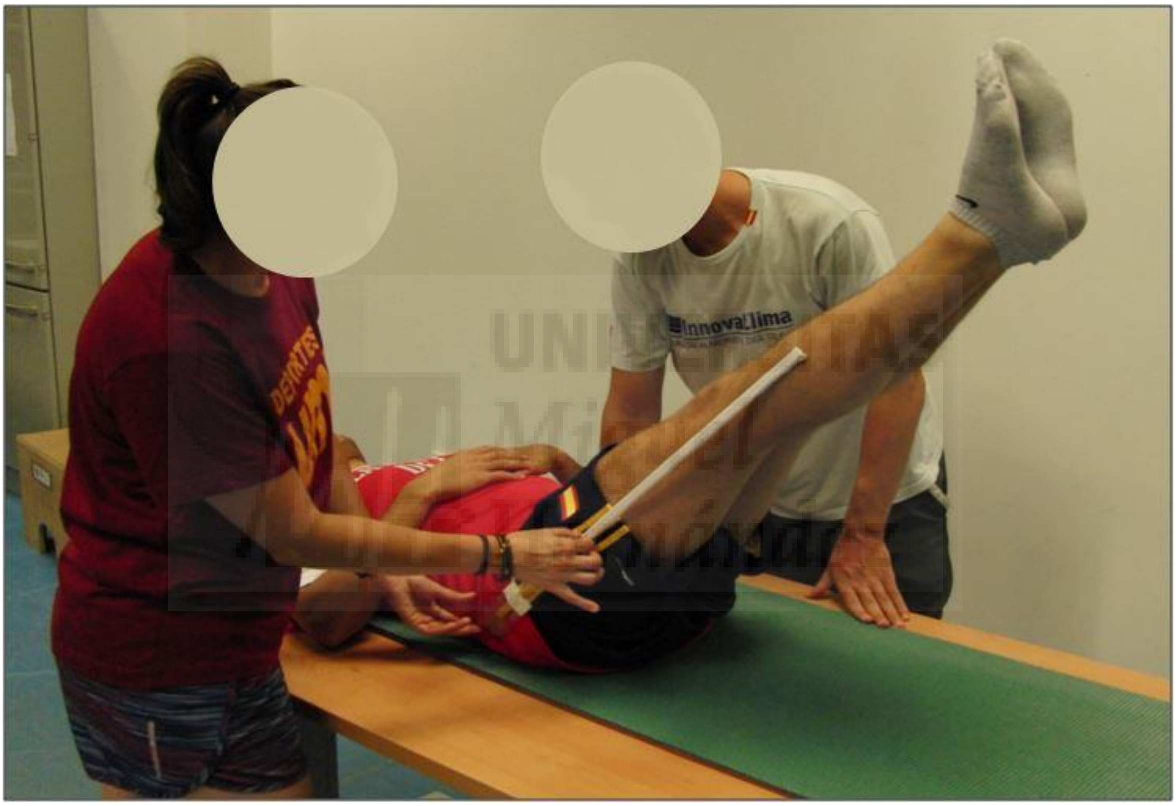


Figure 4. Picture showing a participant performing the *Double-leg Lowering Test*.

Biering-Sorensen Test

As described by Biering-Sorensen (1984), participants were positioned in a prone position with the lower body fastened on a test bench by Velcro® inextensible tape and with the upper body out of the bench (extended horizontally and unsupported), matching the anterior-superior iliac spines with the bench edge (Figure 5). The participants were instructed to maintain the trunk cantilevered in the horizontal position for as long as possible while their arms were crossed over the chest. A digital stopwatch (Casio HS-30W-N1V) was used to record the time execution (seconds).

Figure 5. Picture showing a participant performing the *Biering-Sorensen Test*.

2.4. Data analysis and reduction

Stiffness, damping and angular displacement of the trunk for the Sudden Loading Test

The stiffness, maximum angular displacement and damping of the trunk were calculated in each direction (anterior, posterior and right-lateral) according to Cholewicki, Simons et al. (2000). In order to obtain the highest reliability for these parameters, the calculations were performed for the 110 ms after perturbation (Barbado et al., 2016; Barbado, López-Valenciano et al., 2016), which means that they mainly represent the combination of the passive and reflex response of the trunk following perturbation

(Cholewicki, Simons et al., 2000). The mean of the three best trials of each direction was used for the reliability and the correlation analysis.

Mean radial error of the CoP during the Stable and Unstable Sitting Test

The CoP signal was filtered through a low-pass, 4th-order, zero-phase-lag Butterworth filter with a cut-off frequency of 5 Hz (Lin, Seol, Nussbaumm & Madigan, 2008) and then subsampled at 20 Hz (Rhea et al., 2011). To avoid the influence of the CoP behaviour related to the beginning of the test (non-stationarity), signal from the first 10 s of each 70 s trial was removed from further analyses (van Dieën et al., 2010). In order to quantify trunk postural control while sitting, the mean radial error was calculated as described by Barbado et al. (2016) and Barbado, López-Valenciano et al. (2016). The best trial of each condition (i.e. lower mean radial error) and an unstable dynamic composite index (the averaged mean radial error of the three unstable dynamic tasks) were used for the reliability and correlational analysis.

2.5. Statistical analyses

The descriptive statistics of each variable were presented as mean and standard deviation. The distribution of raw data sets was analysed using the Kolmogorov–Smirnov test (p>.05) and all outliers (±3 standard deviation values) were eliminated. Then, in order to know the relationship between the measurement error and the magnitude of the variables, a homocedasticity analysis was done (Atkinson & Neville, 1998).

The relative reliability was analysed by the intraclass correlation coefficient ($ICC_{2,1}$ & $ICC_{2,k}$) for each direction and for the composite indexes, respectively, calculating their confident limits at 90% (CL: 90%) (Hopkins, 2000). ICC values were interpreted according to the following criteria: <0.1, trivial; 0.1-0.29, small; 0.3-0.49, moderate; 0.5-

0.69, large; 0.7-0.89, very large; 0.9-1, nearly perfect (Hopkins, Marshall, Batterham & Hanin, 2009). In order to detect the agreement of chance for ordinal variables used in the *Three Plane Core Strength Test*, weighted Kappa index (*k*) was estimated, whose confidence limits were calculated at 90% (90% CL). This index was interpreted according to the following scale: 0.00 (poor); 0.01-0.20 (slight); 0.21-0.40 (fair); 0.41-0.60 (moderate); 0.61-0.80 (substantial); 0.81-1.00 (almost perfect) (Landis & Koch, 1977).

Absolute reliability was assessed through the typical error (TE), minimum detectable change (MDC) and change in the mean (CM). The TE was calculated dividing the difference between consecutive pairs of trials by √2 (intra-subject variability); then, the MDC was calculated as 1.5 times the TE (Hopkins, 2000). A one-way ANOVA was performed for each test score to explore the existence of statistically significant differences between sessions (CM).

After analysing the reliability of the test scores, the data obtained in the second testing session was used to perform a Pearson correlation analysis (*r*) between those variables which obtained an acceptable level of relative reliability (Atkinson & Nevill, 1998), i.e. ICC values higher than 0.60. All analyses were performed with SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).

3. Results

Table 1 shows the descriptive statistics and relative and absolute reliability of the test scores. In relation to the *Sudden Loading Test*, while the reliability of the trunk angular displacement and trunk stiffness was moderate to high for most variables ($0.63 \leq ICC \leq 0.91$; $9.80\% \leq TE \leq 20.97\%$), the reliability of the trunk damping was low ($0.25 \leq ICC \leq 0.71$; $34.83\% \leq TE \leq 46.67\%$). In addition, no statistical differences were found for the sudden loading parameters between sessions. Concerning the *Stable and Unstable Sitting Test*, the dynamic unstable sitting tasks (UML, UAP and UCD) and their composite index showed higher reliability ($0.70 \leq ICC \leq 0.81$; $13.42\% \leq TE \leq 15.55\%$) than the static unstable and the static and dynamic stable sitting tasks ($0.08 \leq ICC \leq 0.58$; $12.71\% \leq TE \leq 39.15\%$). On the other hand, all the dynamic conditions (dynamic stable, dynamic unstable and composite index) showed significant increases in test performance between sessions (i.e. lower mean radial error). In relation to the field tests, the *Three Plane Core Strength Test* showed fair Kappa indexes ($0.26 \leq k \leq 0.29$) and TE values higher than 23.6% and the *Double-leg Lowering Test* showed a moderate ICC value (0.55), while the *Biering-Sorensen Test* showed a large ICC value (0.81) and a TE value of 12.3%, with a significant increase of the mean endurance time between both testing sessions. It should be noted that during the *Double-leg Lowering Test*, more than 75% of the sample were able to completely lower both legs until they touched the mat without pelvic anterior rotation (score=0°).

Table 2 shows the Pearson correlation coefficients calculated between those variables which obtained ICC values higher than 0.60. In relation to the *Sudden Loading Test*, only four significant correlations were found between the sudden loading variables, i.e. significant negative correlations among stiffness and angular displacement in frontal (r=-0.694; p<0.01) and posterior (r=-0.857; p<0.01) loading directions, and significant positive correlations between posterior stiffness and lateral angular displacement (r=0.561; p<0.01) and between frontal and lateral angular displacement (r=0.626; p<0.01). On the contrary, for the dynamic unstable conditions of the *Stable and Unstable Sitting Test*, all the analysed correlations were significant, finding high significant positive correlations among UML, UAP and UCD ($r \geq 0.807$; p<0.01) and between these tasks and their composite index ($r \geq 0.927$; p<0.01). Regarding the correlations between different protocols, only two low significant correlations were obtained between the angular displacement after frontal and posterior loading and dynamic unstable sitting tasks. In addition, no significant correlations were found between the biomechanical parameters and the *Biering-Sorensen Test* scores.

Table 1. Descriptive statistics and relative and absolute reliability for the variables obtained in the different tests.

Protocols and variables			Session 1	Session 2	CM (mean - 90% CL)	Typical error (%) (mean - 90% LC)	MDC$_{75}$ (%)	ICC$_{(2,1)}$ (mean - 90% LC)
Sudden Loading Test	θ	**Anterior**	0.087 ± 0.022	0.088 ± 0.025	0.001 (-0.005 - 0.006)	11.46 (9.23 - 15.30)	17.18 (13.84 - 22.95)	0.87 (0.76 - 0.94)†
		Lateral	0.075 ± 0.019	0.072 ± 0.018	-0.003 (-0.010 - 0.003)	18.52 (14.92 - 24.73)	27.78 (22.37 - 37.10)	0.63 (0.28 - 0.81)†
		Posterior	0.207 ± 0.028	0.196 ± 0.025	-0.006 (-0.015 - 0.003)	9.80 (8.01 - 12.74)	14.70 (12.02 - 19.12)	0.72 (0.47 - 0.86)†
	K	**Anterior**	1499.30 ± 589.74	1538.72 ± 772.74	39.42 (-102.73 - 181.57)	19.52 (15.65 - 26.28)	29.28 (23.48 - 39.41)	0.91 (0.82 - 0.95)†
		Lateral	855.00 ± 291.34	938.97 ± 268.70	83.98 (-3.36 - 171.31)	20.97 (16.96 - 27.79)	31.45 (25.43 - 41.69)	0.71 (0.43 - 0.85)†
		Posterior	530.30 ± 135.60	571.45 ± 158.80	41.16 (4.23 - 78.09)	14.66 (11.99 - 19.07)	21.99 (17.98 - 28.60)	0.81 (0.64 - 0.90)†
	β	**Anterior**	362.98 ± 177.40	360.6 ± 188.11	-2.36 (-85.31 - 80.58)	46.67 (37.58 - 62.32)	70.01 (56.38 - 93.48)	0.25 (-0.48 - 0.62)†
		Lateral	712.98 ± 222.14	703.01 ± 349.80	-9.96 (-124.62 - 104.70)	34.83 (28.17 - 46.17)	52.25 (42.25 - 69.26)	0.50 (0.03 - 0.74)†
		Posterior	73.69 ± 37.37	77.85 ± 32.51	8.34 (-4.46 - 21.13)	35.93 (29.38 - 46.72)	53.90 (44.07 - 70.08)	0.71 (0.44 - 0.85)†
Stable and Unstable Sitting Test	**MRE**	**SNF**	1.01 ± 0.45	1.12 ± 0.51	0.11 (-0.08 - 0.31)	39.15 (31.53 - 52.28)	58.72 (47.29 - 78.41)	0.08 (-0.27 - 0.41)
		SWF	0.76 ± 0.44	0.62 ± 0.28	-0.13 (-0.29 - 0.02)	33.47 (27.07 - 44.37)	50.21 (40.60 - 66.56)	0.42 (0.09 - 0.66)
		SML	2.18 ± 0.47	1.89 ± 0.51	-0.29 (-0.49 - -0.09)*	21.01 (17.06 - 27.66)	31.51 (25.58 - 41.49)	0.24 (-0.09 - 0.53)
		SAP	2.07 ± 0.44	1.77 ± 0.32	-0.40 (-0.62 - -0.19)*	12.71 (10.28 - 16.85)	19.07 (15.42 - 25.28)	0.57 (0.30 - 0.76)
		SCD	3.09 ± 0.72	2.51 ± 0.60	-0.58 (-0.79 - -0.36)*	16.27 (13.21 - 21.42)	24.40 (19.81 - 32.13)	0.52 (0.23 - 0.72)
		UNF	5.57 ± 1.71	4.85 ± 1.12	-0.72 (-1.28 - -0.16)	22.93 (18.61 - 30.18)	34.39 (27.92 - 45.28)	0.35 (0.02 - 0.61)
		UWF	4.98 ± 1.12	4.36 ± 1.60	-0.63 (-1.11 - -0.15)	21.87 (17.75 - 28.79)	32.80 (26.63 - 43.18)	0.58 (0.31 - 0.76)
		UML	6.57 ± 1.87	5.88 ± 1.55	-0.54 (-1.04 - -0.03)*	15.55 (12.47 - 20.93)	23.33 (18.70 - 31.40)	0.70 (0.46 - 0.84)
		UAP	7.07 ± 2.01	5.92 ± 1.66	-1.16 (-1.62 - -0.04)*	13.42 (10.85 - 17.78)	20.12 (16.27 - 26.67)	0.72 (0.51 - 0.85)
		UCD	8.55 ± 2.87	7.06 ± 2.05	-1.50 (-2.09 - -0.91)*	14.08 (11.38 - 18.66)	21.11 (17.07 - 27.99)	0.81 (0.64 - 0.90)
		Composite index	7.62 ± 2.49	6.36 ± 1.74	-1.26 (-1.74 - -0.78)*	14.08 11.76 - 19.06)	21.72 (17.63 - 28.59)	0.79 (0.62 - 0.89)
TPCST		**Frontal**	2.04 ± 0.76	2.33 ± 0.88	0.30 (-0.07 - 0.66)	35.69 (29.18 - 46.41)	53.54 (43.78 - 6961.)	0.26 (0.02 - 0.50)¥
		Sagittal	2.56 ± 0.89	2.78 ± 0.70	0.22 (-0.07 - 0.51)	23.64 (19.33 - 30.74)	35.46 (29.00 - 46.11)	0.29 (0.04 - 0.54)¥
		Transverse	2.00 ± 0.83	2.00 ± 0.73	0.00 (-0.30 - 0.30)	32.52 (26.59 - 42.29)	48.78 (39.89 - 63.43)	0.29 (0.04 - 0.55)¥
DLLT			2.19 ± 7.14	3.37 ± 8.35	1.19 (-1.27 - 3.64)	**	**	0.55 (0.28 - 0.74)
BST			138.56 ± 41.90	155.30 ± 49.50	16.74 (5.10 - 28.38)*	12.28 (10.00 - 16.06)	18.41 (15.00 - 24.09)	0.81 (0.66 - 0.90)

θ (rad): trunk angular displacement; K (N*m/rad): trunk stiffness coefficient; β (N*m*s/rad): trunk damping coefficient; MRE (mm): mean radial error; SNF: stable sitting without feedback; SWF: stable sitting with feedback; SML: stable sitting while performing medial-lateral displacements with feedback; SAP: stable sitting while performing anterior-posterior displacements with feedback; SCD: stable sitting while performing circular displacements with feedback; UNF: unstable sitting without feedback; UWF: unstable sitting with feedback; UML: unstable sitting while performing medial-lateral displacements with feedback; UAP: unstable sitting while performing anterior-posterior displacements with feedback; UCD: unstable sitting while performing circular displacements with feedback; TPCST: *Three Plane Core Strength Test*; DLLT (º): *Double-leg Lowering Test*; BST (s): *Biering-Sorensen Test*; CM: Change in mean; ICC: intraclass correlation coefficient; MDC: minimum detectable change; * signification p<.05; †: ICC$_{(2,k);}$ ¥: weighted kappa index; **: Values were not included due to its arbitrary reference system.

Table 2. Relationship between *Sudden Loading Test*, *Stable and Unstable Sitting Test* and *Biering-Sorensen Test*.

Protocols and variables			*Sudden Loading Test*						*Stable and Unstable Sitting Test*			
			Frontal		Lateral		Posterior		MRE			
			K	*θ*	*K*	*θ*	*K*	*θ*	UML	UAP	UCD	Composite index
Biering-Sorensen test			-.161	.122	-.093	.123	-.192	-.267	-.071	-.213	-.143	-143
Sudden Loading Test	**Frontal**	***K***	-	**-.694****	.163	-.282	-.093	.291	.236	.191	.176	.116
		θ		-	-.419	**.626****	.223	-.181	-.227	-.371	**-.439***	-.357
	Lateral	***K***			-	-.189	-.012	-.188	.178	.125	.180	.183
		θ				-	**.561****	-.282	.404	-.053	-.136	-.041
	Posterior	***K***					-	**-.857****	.373	.306	.200	.268
		θ						-	**-.447***	-.322	-.225	-.308
Stable and Unstable Sitting Test	**MRE**	**UML**							-	**.807****	**.850****	**.927****
		UAP								-	**.941****	**.965****
		UCD									-	**.980****
		Composite index										-

θ: trunk angular displacement; *K*: trunk stiffness coefficient; MRE: mean radial error; UML: unstable sitting while performing medial-lateral displacements with feedback; UAP: unstable sitting while performing anterior-posterior displacements with feedback; UCD: unstable sitting while performing circular displacements with feedback; *Signification *p*<.05; **Signification *p*<.001.

4. Discussion

Despite the potential benefits of core stability for injury prevention and sport performance (Borghuis et al., 2008; Kibler et al., 2006; Vera-Garcia et al., 2015a; Zazulak et al., 2008), there is no consensus in research and field settings about which tests should be used to measure core stability, maybe because it is a multidimensional and complex concept which has received many different definitions (Barbado et al., 2016; Reeves et al., 2007). Therefore, in order to assist with the selection and application of core stability measures, this study analysed the reliability and the relationships among five representative tests of the most popular methodologies used to assess core stability in biomechanics laboratories and field settings. The major finding was the lack of relationships between those protocols which obtained an acceptable level of reliability, i.e. *Sudden Loading Test* (trunk angular displacement and stiffness), *Stable and Unstable Sitting Test* (dynamic unstable conditions) and *Biering-Sorensen Test*. Consequently, it seems that the results obtained in one test are not generalizable to other measures of core stability, which highlights the importance of choosing the most appropriate tests for each situation based on their reliability, specificity, cost and availability.

Reliability of core stability measures

Regarding the laboratory protocols, our data showed moderate to high reliability for trunk angular displacement and trunk stiffness after sudden loading (ICC≥0.63; TE≤20.97%) and for the dynamic unstable conditions of the *Stable and Unstable Sitting Test* (ICC≥0.70; TE≤15.55%). However, these 1-month reliability results were lower than those previously obtained by Barbado et al. (2016) (ICC≥0.90; SEM≤14.8%) in the same protocols, perhaps because they examined intra-session reliability. On the other hand, low reliability was found for the damping scores after sudden loading (ICC≥0.25; TE≤46.7%) and for the static unstable conditions and the static and dynamic stable conditions of the *Stable and Unstable Sitting Test* (ICC≥0.08; TE≤39.1%). Interestingly, the relative reliability in the *Stable and Unstable Sitting Test* was higher for the most difficult conditions (dynamic unstable tasks and composite index), maybe because the other conditions did not represent a challenge to our participants (being recreationally active males) and therefore they were not able to discriminate between them (Lee & Granata, 2008). In relation to the comparison between testing sessions, no learning effect (i.e. no statistical test-retest differences) was found for the trunk response to sudden loading in the 110 ms after perturbation, as this response depends mainly on spinal reflexes and passive trunk structures (Cholewicki et al., 2010; Cholewicki, Simons et al., 2000). However, all the dynamic conditions of the *Stable and Unstable Sitting Test* showed significant increases in test performance between sessions, indicating the need of a longer familiarisation period to avoid learning effect in this protocol (Barbado et al., 2016; Barbado et al., 2017).

Concerning the field tests, the *Three Plane Core Strength Test* showed a fair intra-rater agreement (0.26≤*k*≤0.29). These results are consistent with those obtained by Weir et al. (2010), which found a poor inter and intra-tester reliability (0.31≤ICC≤0.55). Possibly, the narrow 4-point scale used to score the participants in this test (from 1-poor, to 4-excellent) provoked that most participants scored in the central values (homogenising the sample), which could affect the correlation index used to assess the relative reliability as it is sensitive to sample homogeneity (Atkinson & Nevill, 1998; Hopkins, 2000). In addition, it should be noted that these test scores may reflect whole-body stability rather than core stability as they are clearly influenced by the stance leg performance. In this sense, although core stability seems to play an important role in whole-body stability (Anderson

& Brhm, 2005; Kahle & Gribble, 2009), this test measures postural control in single-leg stance and therefore it may be strongly affected by lower limb characteristics and capabilities (e.g. muscle strength, joint stability, leg length, etc.).

Regarding the *Double-leg Lowering Test*, the low sensitivity showed for this protocol (>75% of participants obtained a 0º score) affected its reliability and correlation analysis in this study. Although there are conflicting results in the literature (Krause et al., 2005; Leetun et al., 2004; Sharrock et al., 2011; Youdas, Garrett, Harmsen, Suman & Carey, 1996; Walker et al., 1987), it seems that *Double-leg Lowering Test* sensitivity is affected by the age and physical condition of the participants. In this sense, most of our young and recreationally active male participants were able to lower both legs completely without loss of pelvic control, supporting a previous study which showed lack of sensitivity of this protocol to discriminate between individuals with high physical condition (Leetun et al., 2004). Nevertheless, the *Double-leg Lowering Test* scores obtained in the current study could be also influenced by the relatively low experience of the examiner to monitor the position of the low back with his fingers. Possibly, if we had used a pressure biofeedback to monitor the pelvic anterior rotation (Ladeira et al., 2005; Lanning et al., 2006; Mills et al., 2005) we would have made the test more challenging for our participants and therefore more sensitive to discriminate between them.

In comparison to the *Three Plane Core Strength Test* and the *Double-leg Lowering Test*, the *Biering-Sorensen Test* showed a high reliability (ICC=0.80; TE=12.3%), which in general is in agreement with earlier studies (Evans et al., 2007; Juan-Recio et al., 2014; Juan-Recio et al., 2017; Latimer, Maher, Refshauge & Colaco, 1999; McGill et al., 1999). It is important to notice that the mean endurance time of our participants increased with test repetition, showing the need of a familiarisation period to avoid learning effect (Juan-Recio et al., 2014; Juan-Recio et al., 2017).

Correlations between reliable core stability measures

The very few correlations found between the *Sudden Loading Test* and the *Stable and Unstable Sitting Test*, and especially between the different loading directions in the *Sudden Loading Test*, show the complexity of measuring core stability, as different biomechanical parameters seem to assess different features of this multidimensional capability (Barbado et al., 2016, 2017). As previously stated by Reeves et al. (2006, 2007), core stability is context dependent, so the result of its assessment depends on the measurement characteristics (e.g. applied forces magnitude, direction and duration), which may involve different motor control mechanisms. In this sense, trunk performance during the dynamic tasks on the unstable seat are influenced by the feedback mechanisms of the cerebellar-cortical system (Collins & De Luca, 1993; Cholewicki et al., 2000; Jacobs & Horak, 2007); however, trunk responses (i.e. angular displacement and stiffness) in the 110 ms after unexpected sudden perturbations mainly depend on passive trunk structures and spinal reflex responses (Cholewicki et al., 2010; Cholewicki, Simons et al., 2000).

Moreover, the lack of relationship between the posterior, right-lateral and anterior loading directions in the *Sudden Loading Test* suggests that trunk kinetic and kinematic responses to quick perturbations are specific to the plane being evaluated. These results are in line with a biomechanical-epidemiologic study (Zazulak et al., 2007a), which showed that the trunk displacement after sudden force release was a significant predictor of ligament injury in female athletes when the perturbations were applied in lateral direction, but not when they were applied in anterior o posterior direction. In addition, Barbado et al. (2016), showed that competitive judokas displayed higher stiffness after lateral loading than competitive kayakers and recreational athletes, but did not show statistical differences in anterior o posterior directions. Thus, specific sport demands may induce specific core stability adaptations in a plane of motion which are not easily transferable to others.

Regarding the *Stable and Unstable Sitting Test*, high significant correlations were found among all the dynamic unstable conditions (r>0.807; p<0.01), as they have very similar characteristics and may measure the same core stability dimension. Additionally, as a methodological consideration, these high correlations suggest this protocol could be reduced to a single task (for example the most demanding, i.e. the unstable sitting while performing circular displacements) to increase its efficiency.

The *Biering-Sorensen Test* was the only field test that obtained an acceptable level of relative reliability (ICC=0.81), and consequently the relationship between this test and the laboratory tests were analysed, not finding significant correlations between them (r≤-0.267; p>0.05). During the *Biering-Sorensen Test*, participants must maintain the trunk cantilevered in the horizontal position against gravity, which probably requires a certain level of stability. However, participants' performance in this test is quantified as the longest time they are able to keep in the horizontal position (Demoulin et al., 2006), which seems an endurance index rather than a stability parameter (Juan-Recio et al., 2017; van Dieën et al., 2012; Vera-Garcia et al., 2015b). Therefore, although the lack of relationship between this protocol and the laboratory tests might suggest that the *Biering-Sorensen Test* measures a different dimension of core stability, in our opinion it really measures trunk extensor endurance. Overall, taking into account the limitations of the three field test analysed in this study, it seems necessary to develop new protocols to assess core stability in field settings.

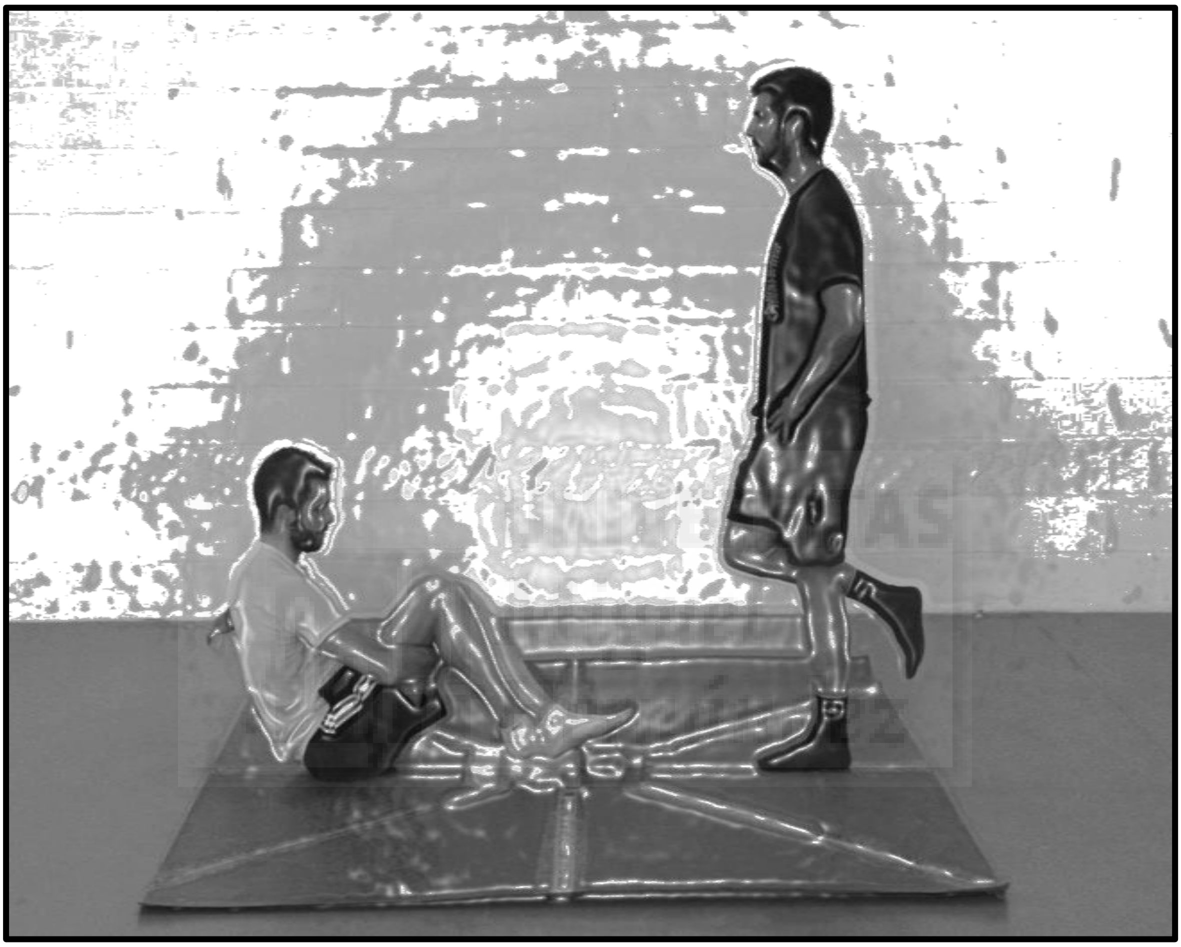
As in any research, it is important to note some limitations which could bias the data presented above and their analysis. Although a sample of 25 participants has been considered a sufficient sample size in reliability studies (Springate, 2012), a much larger sample would be desirable for minimizing the random change for the measurements (Hopkins, 2000). Secondly, our results could only be applied to a healthy, young and recreationally active population. Future studies should explore the reliability and the relationships of these and other protocols in different populations (e.g. competitive athletes, low back pain patients, etc.). Finally, even though we analysed three representative tests of some of the most popular types of field methodologies used to measure core stability, there are many different field tests in the literature, so we could have chosen other tests, and therefore, have obtained different results.

5. Conclusions

Sudden Loading Test, *Stable and Unstable Sitting Test* and *Biering-Sorensen Test* were the only tests which provided reliable parameters; however, with the exception of the *Sudden Loading Test*, the test-retest design used in this study was not enough to avoid learning effect in these protocols. In relation to the correlation analysis, the absence of correlations between the laboratory protocols, and even between the loading directions of the *Sudden Loading Test*, indicate that the results of core stability measurements are not easily generalizable, as they change depending on test conditions. Additionally, as the *Biering-Sorensen Test* is a timed measure and no correlations were found between this and the laboratory protocols, this field test seems to measure trunk extensor endurance instead of core stability. Overall, the results of this study show the complexity of core stability assessment and provide information about some popular tests used to assess core stability, which may help coaches, clinicians and researchers to choose the most appropriate tests for each situation and to interpret their results.

CHAPTER 4

STUDY 2



Submitted to review in Journal of Sport Sciences

Reliability of the *Star Excursion Balance Test* and two new similar protocols to measure trunk postural control.

Diego López-Plaza, Casto Juan-Recio, David Barbado, Iñaki Ruiz-Pérez & Francisco J. Vera-Garcia.

CHAPTER 4

STUDY 2

Reliability of the *Star Excursion Balance Test* and two new similar protocols to measure trunk postural control

by

Diego López-Plaza, Casto Juan-Recio, David Barbado, Iñaki Ruiz-Pérez & Francisco J. Vera-Garcia.

Abstract

Objective: The aims of this study were: i) to assess the absolute and relative between-session reliability of the *Star Excursion Balance Test* (SEBT) and two variations of this test to assess trunk postural control while sitting, i.e. the *Star Excursion Sitting Test* (SEST) and the *Star Excursion Timing Test* (SETT); ii) to analyse the relationships between these three test scores.

Design: Correlational and reliability test-retest study.

Setting: Controlled laboratory environment.

Participants: Twenty-seven recreational active males (24.54±3.05 years; mass: 75.30±9.96 kg; height: 176.81±6.03 cm).

Main Outcome Measures: Maximum normalised reach distances were assessed for different SEBT and SEST directions. Additionally, composite indexes were calculated for SEBT, SEST and SETT.

Results: SEBT directions and SEBT, SEST and SETT composite indexes showed moderate-to-large 1-month reliability (0.61≤ICC≤0.87; 1.27%≤TE≤5.94%). A learning effect was detected for some SEBT and SEST directions, and for SEST and SETT composite indexes. No significant correlations were found between the SEBT and its two variations ($r \leq 0.366$; $p > 0.05$). A significant correlation was found between the SEST and SETT composite indexes ($r = 0.520$; $p > 0.01$).

Conclusions: SEBT, SEST and SETT are reliable field protocols to measure postural control. However, while SEBT assesses postural control in single-leg stance, SEST and SETT provide trunk postural control measures with lower influence of the lower-limbs.

Key words: *balance; consistency; core stability; field test.*

1. Introduction

The *Star Excursion Balance Test* (SEBT) is a field test widely used to assess the dynamic postural control (Gribble et al., 2013; Hyong & Kim, 2014; Kinzey & Amstrong, 1998; Lanning et al., 2006; Munro & Herrington, 2010; Whyte et al., 2015), which is expressed as the maximum distance that participants can reach with their feet in several directions while maintaining a single-leg stance (Gribble et al., 2013). The SEBT has been normally performed either in eight or four directions, and even simplified to three directions (a SEBT variation known as *Y-Balance Test*).

The popularity of the different SEBT protocols is mainly based on their relative low cost and ease of use in comparison to posturographic tests, as well as on their within-session reliability (Gribble et al., 2013; Hyong & Kim, 2014; Lanning et al., 2006; Plisky et al., 2009, 2006) and their applications to injury prevention in clinical, sport and research settings (Ambegaonkar et al., 2013, 2014; Clagg et al., 2015; Delahunt et al., 2013; Ganesh, Chhabra & Mrityunjay**,** 2015; Gribble et al., 2004; Hertel et al., 2006; Olmsted et al., 2002). In this sense, low SEBT scores have been related with several injuries, such as recurrent ankle sprain and chronic instability (Gribble et al., 2004; Hertel et al., 2006; Nakagawa & Hoffman, 2004; Olmsted et al., 2002), anterior cruciate ligament injury (Ambegaonkar et al., 2013, 2014; Clagg et al., 2015; Delahunt et al., 2013; Herrington Hatcher, Hatcher & McNicholas, 2009) and chronic low-back pain (Ganesh et al., 2015).

Regarding the reliability of the SEBT protocols, most studies have examined the within-session consistency, reporting moderate to good intra-rater reliability ($0.67<ICC<0.97$; $2.29\%<SEM<5.43\%$) (Hyong & Kim, 2014; Lanning et al., 2006; Plisky et al., 2009, 2006) and poor to good inter-rater reliability ($0.35<ICC<0.95$; $2.41\%<SEM<4.60\%$) (Gribble et al., 2013; Hyong & Kim, 2014; Plisky et al., 2009, 2006). However, there are not many studies (Calatayud, Borreani, Colado, Martin & Flandez, 2014; Hertel, Miller & Denegar, 2000; Kinzey & Amstrong, 1998; Munro & Herrington, 2010; Whyte et al., 2015) which have studied the between-session reliability of the SEBT scores in depth, which is an important factor to know, for example, if the changes in the scores of this test in longitudinal studies are (or not) caused by within-subject variability. In this sense, although a minimum of four (Herrington et al., 2009; Robinson & Gribble, 2008) or six (Gribble & Hertel, 2003; Gribble et al., 2004; Hertel et al., 2000; Plisky et al., 2006) practice trials for each direction seem needed to obtain consistent SEBT scores in a single testing session, there is no agreement about the number of practice trials/sessions that are necessary to obtain consistent between-session scores in this test, avoiding learning effect (Calatayud et al., 2014; Hertel et al., 2000; Munro & Herrington, 2010).

In addition, despite SEBT protocols have been widely used as dynamic postural control measures in single-leg stance (Gribble et al., 2013; Kinzey & Amstrong, 1998; Whyte et al., 2015), some researchers have used them to evaluate the effect of core stability programs (which are normally based on trunk exercises performed in lying positions) (Chuter et al., 2015; Filipa, Byrnes, Paterno, Myer & Hewett, 2010; Imai, Kaneoka, Okubo & Shiraki, 2014; Sandrey & Mitzel, 2013); furthermore, in one of these studies a SEBT protocol was used as a core stability test (Chuter et al., 2015). However, although the upper-body may have an influence in the SEBT performance, the scores of this protocol reflect whole body balance in single-leg stance rather than stability of the trunk structures.

Therefore, although much information exists about the SEBT characteristics and applications, there are important limitations in the scientific literature that must be addressed, especially the between-session reliability analysis of the protocol and the application of this or similar field tests to assess core stability. Based on these limitations, the aim of this study was to analyse the absolute and relative between-session reliability of the SEBT and two variations of this test developed to assess trunk postural control while sitting: the *Star Excursion Sitting Test* (SEST), expressed as the maximum distance that participants can reach with their hands while sitting, and the *Star Excursion Timing Test* (SETT), a similar protocol to the SEST with time constraint. In both SEBT variations the influence of the lower-limbs was minimized to increase the role of the upper-body in postural control and to obtain field measures related to core stability. The correlations between the three test scores were also analysed to examine the relationships between protocols.

2. Methods

2.1. Participants

Twenty-seven recreationally active males volunteered to participate in this study (age: 24.54±3.05 years; mass: 75.30±9.96 kg; height: 176.81±6.03 cm). Participants with known medical problems, histories of trunk, ankle, knee or hip injury requiring treatment in the previous year and participants with neurological or musculoskeletal disorders that might adversely affect balance control were excluded. All participants signed an informed consent approved by the Ethics Committee of the University in accordance with the Declaration of Helsinki 2013.

2.2. Test description

Star Excursion Balance Test (SEBT)

The test was performed following the Kinzey & Amstrong (1998) protocol, with participants standing in the middle of a grid with eight millimetre lines extending at 45º angles from the centre of the grid (Figure 6). The heel of the participant's stance foot was aligned with the centre of the grid and his big toe was aligned with the anterior line. The participant was asked to reach with his reaching leg as far as possible along the four diagonal directions: posterior-medial (PM), posterior-lateral (PL), anterior-medial (AM) and anterior-lateral (AL). This subject had to make a light touch on the line and return to the centre, while maintaining a single-leg stance with the opposite leg (stance leg) in the centre of the grid and keeping his hands on his waist. Standard tape measures were placed on the grid lines to quantify the distance (cm) that each participant reached. Three consecutive repetitions were made in each direction in the following order: PM, PL, AM and AL. A repetition was considered as null whether the participant lost his balance, let go of his waist or moved his foot.

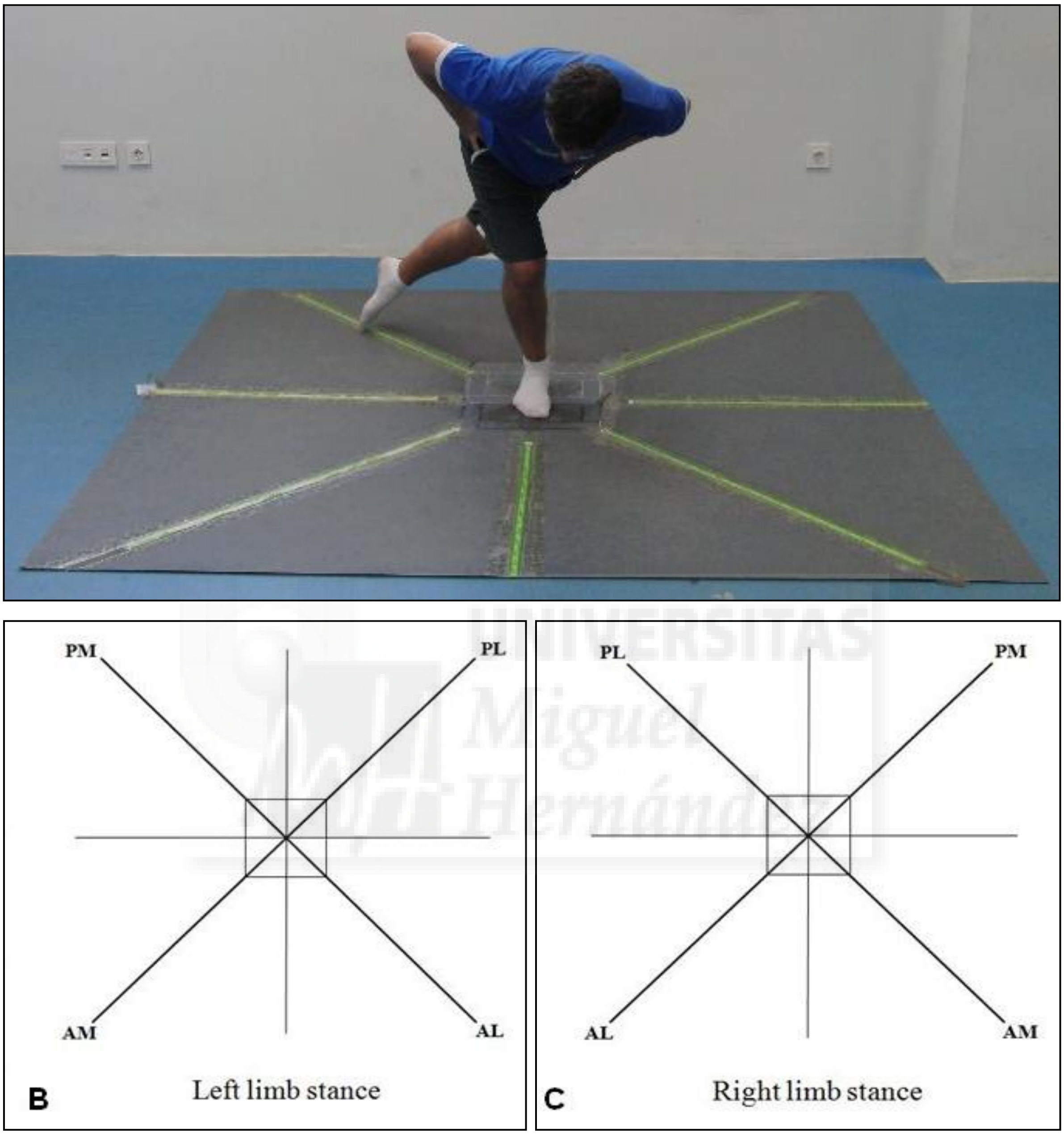


Figure 6. Pictures showing: (A) a participant performing the *Star Excursion Balance Test* (SEBT) along the posterior-lateral direction; (B) zenithal view of the 8-line grid used to perform the SEBT on the left limb; and (C) zenithal view of the 8-line grid used to perform the SEBT on the right limb. Test directions: AL, anterior-lateral; PL, posterior-lateral; PM, posterior-medial; AM, anterior-medial.

Star Excursion Sitting Test (SEST)

The test was performed with participants sitting in the centre of the above mentioned grid, but directions were renamed (Figure 7A). Several cones were placed in the grid over the standard tape measure lines in the four diagonal directions: right-anterior (RA), right-posterior (RP), left-anterior (LA), left-posterior (LP); and in the two lateral directions: right-lateral (RL) and left-lateral (LL).

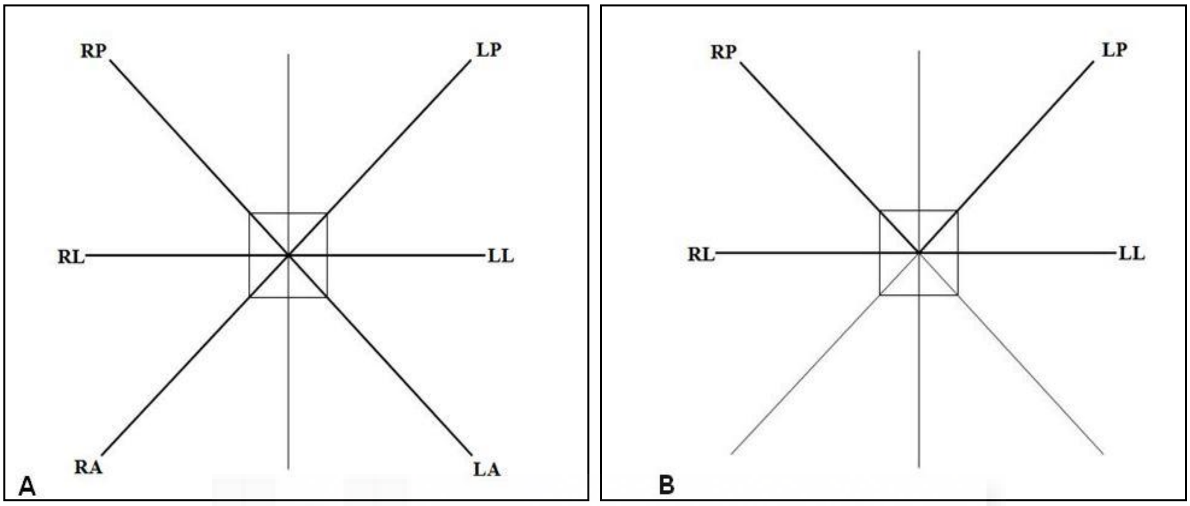


Figure 7. Pictures showing: (A) zenithal view of the 8-line grid used to perform the *Star Excursion Sitting Test*; and (B) zenithal view of the 8-line grid used to perform the *Star Excursion Timing Test*. Test directions: RA, right-anterior; RL, right-lateral; RP, right-posterior; LA, left-anterior; LL, left-lateral; LP, left-posterior.

Participants grabbed their legs with one arm, placing their hand under the popliteal area of the opposite leg, while maintaining the balance sitting on their buttocks without touching the ground with their feet (Figure 8). In this position, they were asked to touch the cones with the middle finger of the other hand and displace them as far as possible along each line. For left directions the right hand grabbed the legs and the left hand displaced the cones, and vice versa. Three consecutive repetitions were performed in each direction in the following order: RA, RL, RP, LA, LL and LP. A repetition was considered as null if the participant knocked the cone over, let go of his legs or leaned on his hand.

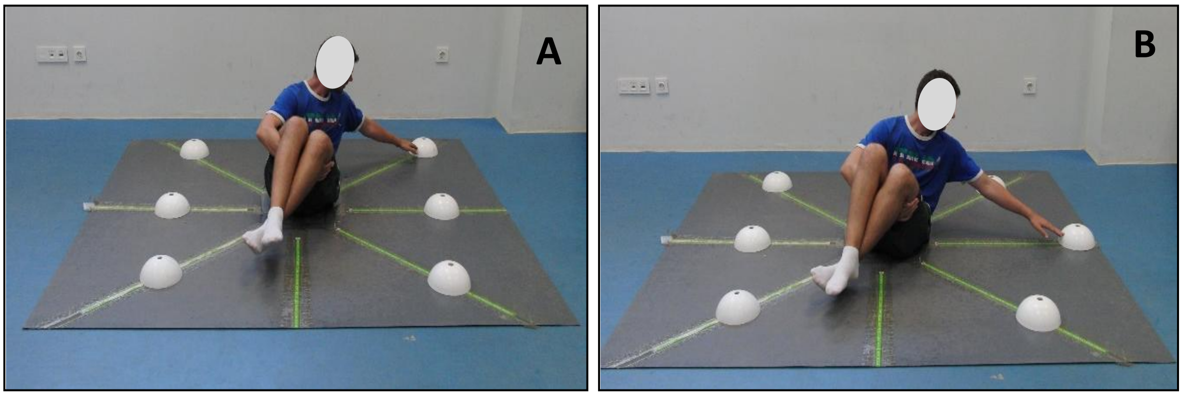


Figure 8. Pictures showing a participant performing the *Star Excursion Sitting Test* along: (A) the left-posterior reach direction; and (B) the left-lateral reach direction.

Star Excursion Timing Test (SETT)

This test is a timed protocol performed in the same initial position described for the SEST (Figure 9). Cones were placed over four of the grid lines, i.e. RL, LL, RP and LP (Figure 7B). Participants performed five consecutive trials in which they had to move the cones as far as possible along the four lines (order: RL, RP, LL and LP) in 8 s, without touching the ground with their feet. During each trial, after displacing the cones in the right directions (RL and RP), participants had to change the hand with which they grabbed their legs to move the cones in the left directions (LL and LP). The initial distance of the cones regarding the centre of the grid was normalised for each participant calculating the adjacent side length of a hypothetic right triangle formed by this side, the hypotenuse (distance between C7 and their middle finger) and the opposite side (distance between trochanter and acromion). An acoustic recorded countdown was provided to the participants as verbal feedback about the time remaining to the end of the test. The criteria for null repetition were the same as for the SEST or to not displace the four cones in the 8 s time period.

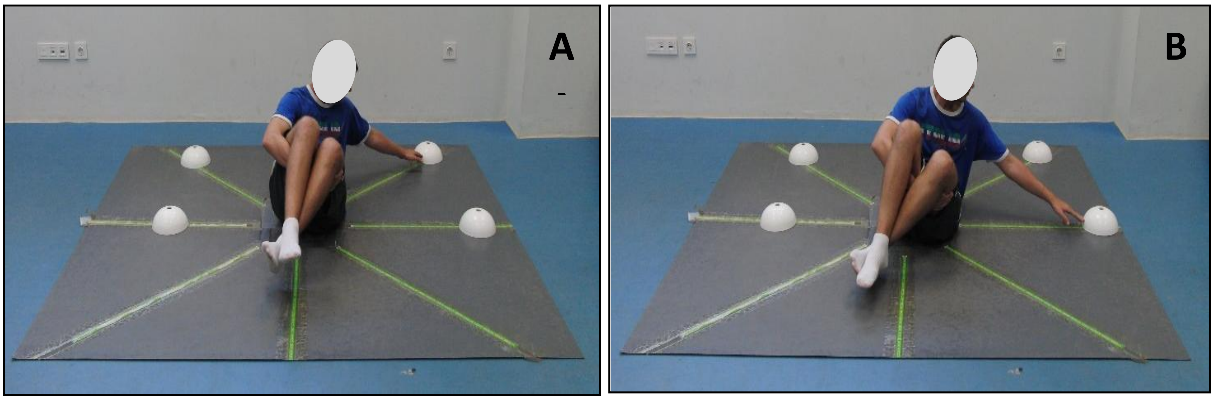


Figure 9. Pictures showing a participant performing the *Star Excursion Timing Test* along: (A) the left-posterior reach direction; and (B) the left-lateral reach direction.

2.3. Procedure

Participants performed the three tests in two testing sessions spaced one month apart. At the beginning of each testing session, several body anthropometric measurements were carried out (following the protocol previously described by Cabañas & Esparza (2009)) to analyse their influence on test scores: height, sitting height, mass, trochanter-acromion length, wing span, arm length (C7-middle finger distance), leg length (anterior superior iliac spine-external malleolus distance), biliocrestal diameter and biacromial diameter. After the anthropometric assessment, participants carried out a warm-up consisting of 5 min of static-cycling and performed a familiarisation period to learn the proper technique and procedure of each test. In this period, the following strategies were explained to each participant to reach the maximum possible distance during the SEBT performance: a) for posterior directions, to flex the ankle, knee and hip of the stance leg as much as possible while bending the upper-body forward to counteract lower-limb elevation; b) for anterior directions, to flex the ankle and knee of the stance leg as much as possible while extending the hip and leaning the upper-body backward to counteract lower-limb elevation. After this information, participants practiced each test direction during 30 s. Finally, they performed the tests in the following order: SEBT, SEST and SETT.

2.4. Data analysis

For each SEBT direction, the maximal reach distance (cm) of the three trials were normalised by dividing it by participant's length leg (cm) and multiplying it by 100 (score expressed in leg length percentage) (Gribble et al., 2013). Additionally, the normalised results of the four directions (AL, PL, AM and PM) were averaged to create a composite normalised score for each dominant and non-dominant leg (Gribble, Robinson, Hertel & Denegar, 2009; Plisky et al., 2009).

The maximal reach distance (cm) of the three SEST trials was selected for each testing direction (RA, RL, RP, LA, LL and LP). In addition, a composite normalised score was calculated for the six direction scores of this test. Regarding the SETT, the reach distance obtained in the four directions (RL, RP, LL and LP) were averaged in each of the five trials, and then the highest average was selected as composite index of this test.

Because arm length was highly correlated with SEST ($r \geq 0.609$; $p > 0.01$) and SETT ($r = 0.890$; $p > 0.01$) scores, these scores were quantified as the residual values of the regression analysis between raw values of these tests and arm length, avoiding anthropometric influence on trunk postural control measures. To facilitate the SEST and SETT score interpretation, normalised values for each participant were expressed as the sum of the regression-predicted value of the averaged participants' arm length of this study and the individual's residual scores (Figure 10).

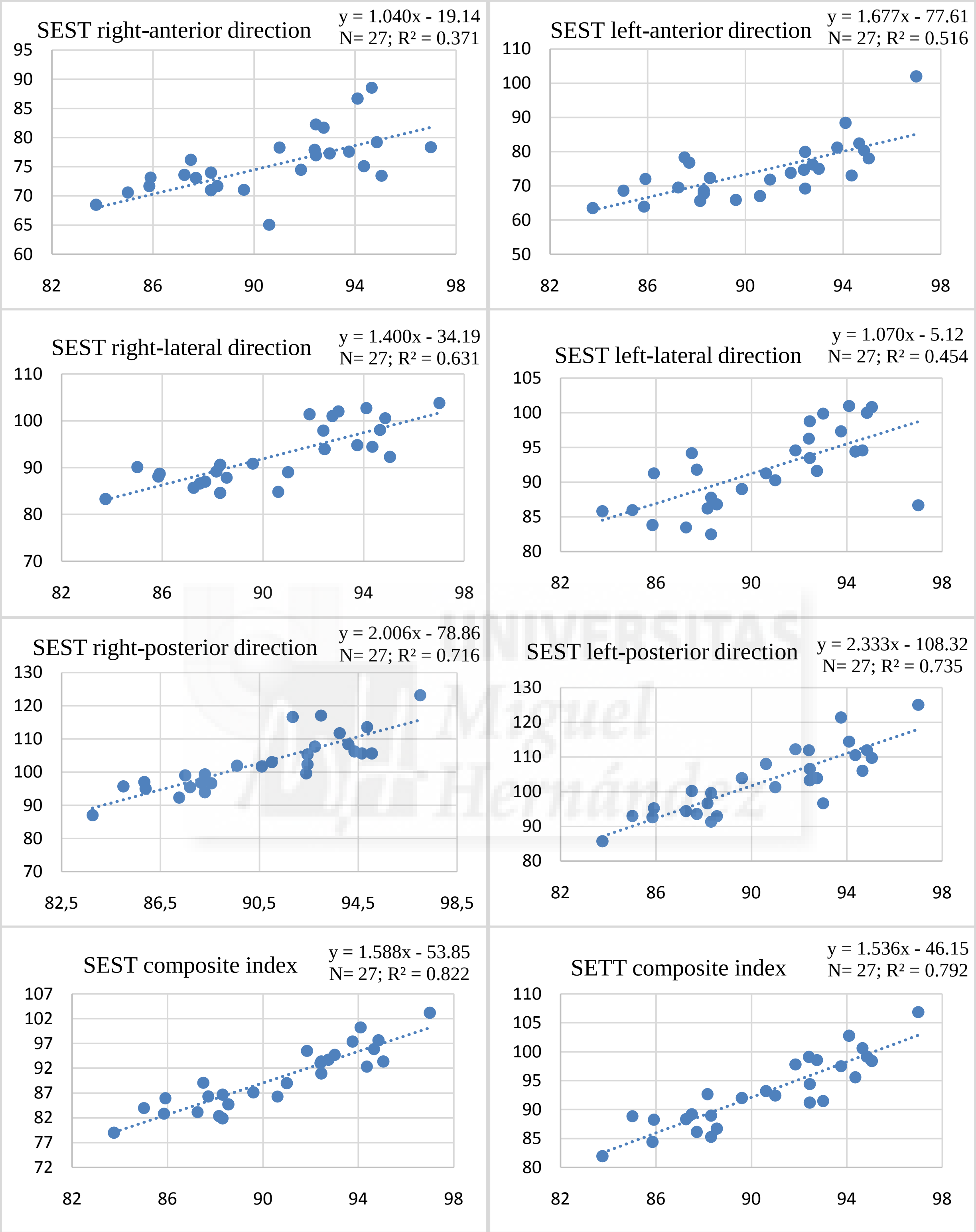


Figure 10. Regression analysis between arm length (cm) and raw scores of each *Star Excursion Sitting Test* (SEST) direction (cm), SEST composite index (cm) and *Star Excursion Timing Test* (SETT) composite index (cm). The axis *x* in the graphs represents the limb-length; the axis *y* represents the reach distance.

2.5. Statistical analysis

The means and standard deviations of the normalised scores of each direction of the SEBT and SEST and the composite normalised scores of the SEBT, SEST and SETT were calculated for each testing session. Normality of the data distribution was verified using the Kolmogorov-Smirnov test.

To evaluate the between-session relative reliability, the ICC (model 2, 1) was used for each direction and for the composite indexes, calculating their CL (90%) (Hopkins, 2000). ICC values were interpreted according to the following criteria: <0.1, trivial; 0.1-0.29, small; 0.3-0.49, moderate; 0.5-0.69, large; 0.7-0.89, very large; 0.9-1, nearly perfect (Hopkins et al., 2009).

Absolute reliability was assessed through the TE, MDC and CM. The TE was calculated dividing the difference between consecutive pairs of trials by √2 (intra-subject variability); then, the MDC was calculated as 1.5 times the TE (Hopkins, 2000). A one-way ANOVA was performed for each test score to explore the existence of statistically significant differences between sessions (CM). In addition, in order to interpret the CM in a qualitative way, an inference analysis (CL: 90%) based on the magnitude of the tests was carried out using a spreadsheet designed by Hopkins et al. (2009). This analysis determines the probability that the true effects will be substantial or trivial when a value is introduced for the smallest substantial change. The probability that the CM was positive, negative or trivial was interpreted according to the following scale: <0.5%, most unlikely; 0.5-5%, very unlikely; 6-25%, unlikely; 26-75%, possibly; 76-95%, likely; 96-99%, very likely; >99%, most likely. Inference was classified as "unclear" when the 90% CM interval coincided with both levels (beneficial and harmful) (Batterham & Hopkins, 2006; Hopkins et al., 2009).

A Pearson correlation analysis (*r*) was used to examine the relationships between those SEBT, SEST and SETT variables which obtained an acceptable level of relative reliability (Atkinson & Nevill, 1998), i.e. ICC values higher than 0.60. All data analyses were conducted using Statistical Package for Social Sciences (PASW statistics 22.0 Inc., Chicago, IL, USA).

3. Results

Table 3 shows relative and absolute reliability values for the normalised SEBT, SEST and SETT scores. For SEBT diagonal directions and the SEBT composite indexes, the relative reliability was moderate to large (0.62≤ICC≤0.87). Regarding absolute reliability, TE values ranged from 2.12% to 5.94% and MDC values ranged from 3.18% to 8.91%, being lower for the composite indexes than for most directions. Furthermore, the PL, AM and PM SEBT scores for the dominant leg and the PL score for non-dominant leg, showed a significant CM (2.56%, -2.94%, 2.21% and 3.11% respectively), interpreted through a magnitude-based inference (Hopkins et al., 2009) as very likely negative for AM direction and likely positive for PL and PM directions in the dominant leg, as well as for PL direction in the non-dominant leg.

The relative reliability of SEST directions (Table 3) was in general low to moderate with ICC values ranging from 0.35 to 0.68. Nonetheless, SEST composite index showed a high relative reliability score (ICC=0.85). Regarding absolute reliability, the composite index of this test also showed better values (TE=1.27%; MDC=1.91%) than its diagonal and lateral directions (2.41%≤TE≤5.31%; 3.62%≤MDC≤7.97%). Furthermore, the LP direction and the composite index of the SEST showed significant CM (2.03% and 1.50%, respectively), which were interpreted qualitatively as likely positive and very likely positive, respectively. Because the reliability of most SEST directions was not very large (only LL direction obtained an ICC value higher than 0.60) in comparison to the SEST composite reliability, only this global index was used in the correlational analysis.

Concerning the SETT composite index (Table 3), the relative reliability was moderate with an ICC value of 0.61, while the TE was 2.31% and the MDC was 3.47%. A significant CM (1.94%) was observed for the SETT score, being interpreted as a likely positive change.

Table 4 shows Pearson's correlation analyses between SEBT, SEST and SETT variables. Each direction of the SEBT significantly correlated with the composite indexes ($r \geq 0.483$; $p > 0.05$) and with several of the other directions of this test. However, no relationships were found between any SEBT score and the composite indexes of SEST and SETT. On the other hand, a significant correlation was found between SEST and SETT composite indexes ($r = 0.520$; $p > 0.01$).

Table 3. Descriptive statistics and relative and absolute reliability of *Star Excursion Balance Test* (SEBT), *Star Excursion Sitting Test* (SEST) and *Star Excursion Timing Test* (SETT).

VARIABLES			Session 1 (mean ± SD)	Session 2 (mean ± SD)	Typical Error (%) (mean - 90% CL)	CM (%) (mean - 90% CL)	Minimum Detectable Change (%)	Qualitative Inference in the CM	ICC$_{(2,1)}$ (mean - 90% CL)
SEBT (cm)	**Dominant Leg**	**AL**	72.83 ± 7.06	72.62 ± 6.85	5.94 (4.85 - 7.72)	-1.08 (-3.83 - 1.68)	8.91 (7.28 - 11.58)	Unlikely negative	0.63 (0.40 - 0.79)
		PL	96.36 ± 7.34	99.45 ± 8.50	4.68 (3.79 - 6.21)	2.56 (0.25 - 4.88)*	7.02 (5.68 - 9.31)	Likely positive	0.68 (0.45 - 0.82)
		AM	92.12 ± 5.96	89.42 ± 6.14	3.41 (2.78 - 4.46)	-2.94 (-4.55 - -1.32)**	5.12 (4.17 - 6.69)	Very likely negative	0.75 (0.57 - 0.86)
		PM	101.56 ± 6.58	103.96 ± 8.00	2.74 (2.22 - 3.61)	2.21 (0.88 - 3.53)**	4.11 (3.34 - 5.41)	Likely positive	0.86 (0.74 - 0.93)
	Non-dominant Leg	**AL**	73.60 ± 6.36	74.76 ± 7.54	5.89 (4.81 - 7.66)	1.56 (-1.17 - 4.29)	8.83 (7.22 - 11.48)	Possibly positive	0.62 (0.38 - 0.79)
		PL	94.08 ± 7.38	97.05 ± 8.46	5.25 (4.29 - 6.82)	3.11 (0.67 - 5.55)	7.87 (6.44 - 10.24)	Likely positive	0.62 (0.37 - 0.78)
		AM	90.77 ± 5.25	89.16 ± 6.93	3.50 (2.84 - 4.61)	-1.83 (-3.52 - -0.13)	5.25 (4.26 - 6.92)	Possibly negative	0.75 (0.56 - 0.86)
		PM	103.27 ± 6.42	102.89 ± 8.16	3.91 (3.18 - 5.11)	0.45 (-1.40 - 2.30)	5.86 (4.77 - 7.66)	Unclear	0.71 (0.51 - 0.84)
	Composite DL		90.65 ± 5.00	91.22 ± 5.25	2.12 (1.73 - 2.77)	0.90 (-0.11 - 1.90)	3.18 (2.59 - 4.16)	Likely trivial	0.87 (0.76 - 0.93)
	Composite NDL		90.43 ± 4.98	90.97 ± 6.17	3.23 (2.63 - 4.22)	0.50 (-1.03 - 2.03)	4.84 (3.94 - 6.33)	Possibly positive	0.74 (0.55 - 0.86)
SEST (cm)	**Right Arm**	**RA**	73.93 ± 6.31	75.23 ± 4.80	4.88 (3.99 - 6.34)	1.75 (-0.51 - 4.02)	7.31 (5.98 - 9.51)	Possibly positive	0.60 (0.34 - 0.77)
		RL	91.81 ± 3.10	92.93 ± 3.81	2.41 (1.97 - 3.13)	1.20 (0.09 - 2.33)	3.62 (2.96 - 4.69)	Likely positive	0.60 (0.36 - 0.77)
		RP	102.24 ± 4.07	103.16 ± 4.49	3.39 (2.78 - 4.41)	0.90 (-0.68 - 2.47)	5.08 (4.16 - 6.62)	Possibly positive	0.35 (0.04 - 0.60)
	Left Arm	**LA**	73.20 ± 5.82	74.56 ± 5.76	5.31 (4.35 - 6.91)	1.84 (-0.62 - 4.30)	7.97 (6.52 - 10.37)	Possibly positive	0.56 (0.29 - 0.74)
		LL	90.86 ± 3.52	92.00 ± 4.17	2.43 (1.98 - 3.18)	1.88 (0.73 - 3.03)	3.64 (2.97 - 4.77)	Possibly positive	0.68 (0.46 - 0.82)
		LP	101.32 ± 4.60	103.40 ± 4.97	3.29 (2.69 - 4.28)	2.03 (0.50 - 3.56)*	4.94 (4.03 - 6.42)	Likely positive	0.52 (0.24 - 0.72)
	Composite		88.87 ± 3.01	90.21 ± 2.62	1.27 (1.05 - 1.66)	1.50 (0.91 - 2.09)*	1.91 (1.58 - 2.50)	Very likely positive	0.85 (0.72 - 0.92)
SETT (cm)	**Composite**		91.44 ± 3.80	93.23 ± 2.80	2.31 (1.89 - 3.01)	1.94 (0.87 - 3.02)*	3.47 (2.84 - 4.51)	Likely positive	0.61 (0.36 - 0.77)

SD: standard deviation; CL: confidence limits; CM: change in the mean; ICC$_{(2,1)}$: intraclass correlation coefficient; * Signification CM$_{(2-1)}$: $p \leq 0.05$; AL: anterior-lateral direction; PL: posterior-lateral direction; AM: anterior-medial direction; PM: posterior-medial direction; RA: right-anterior direction; RL: right-lateral direction; RP: right-posterior direction; LA: left-anterior direction; LL: left-lateral direction; LP: left-posterior direction; DL: dominant leg; NDL: non-dominant leg.

Table 4. Correlations between *Star Excursion Balance Test* (SEBT), *Star Excursion Sitting Test* (SEST) and *Star Excursion Timing Test* (SETT) scores.

			SEBT										SEST	SETT
			Dominant Leg				**Non-Dominant Leg**				**Composite DL**	**Composite NDL**	**Composite**	**Composite**
			AL	**PL**	**AM**	**PM**	**AL**	**PL**	**AM**	**PM**				
SEBT	**Dominant Leg**	**AL**	-	.122	.693**	.451*	.743**	.431*	.761**	.425*	.749**	.729**	.210	-.233
		PL		-	-.055	.518**	.199	.593**	.207	.603**	.625**	.521**	.111	-.048
		AM			-	.346	.619**	.066	.673*	.250	.627**	.483*	.070	-.119
		PM				-	.306	.600**	.344	.514**	.838**	.566**	.360	.044
	Non-Dominant Leg	**AL**					-	.337	.725**	.444*	.620**	.771**	.037	-.353
		PL						-	.385*	.574**	.628**	.743**	.366	-.170
		AM							-	.607**	.659**	.835**	.009	-.262
		PM								-	.651**	.833**	-.016	-.341
	Composite DL										-	.805**	.271	-.113
	Composite NDL											-	.134	-.352
SEST	**Composite**												-	.520**
SETT	**Composite**													-

AL: anterior-lateral direction; PL: posterior-lateral direction; AM: anterior-medial direction; PM: posterior-medial direction; DL: dominant leg; NDL: non-dominant leg; * Signification: $p \leq 0.05$; ** Signification: $p \leq 0.01$.

4. Discussion

With the intention of improving the use and interpretation of the SEBT scores and providing reliable field measures of trunk postural control, this study analysed the correlations and the absolute and relative between-session reliability of the SEBT and two variations of this test (SEST and SETT) performed in sitting position to reduce the influence of lower-limbs in postural control.

SEBT between-session relative reliability was moderate to large with ICC values ranging from 0.62 to 0.87. Previous studies have shown ICC values slightly higher ($0.67<ICC<0.99$) in healthy males and females (Kinzey & Armstrong, 1998; Munro & Herrington, 2010; Whyte et al., 2015), showing the robustness of SEBT protocols to categorise the dynamic postural control in homogeneous samples. In addition, the absolute reliability was good for SEBT diagonal directions and composite indexes (Table 3), supporting the results obtained in previous research (Ambegaonkar et al., 2013; Calatayud et al., 2014; Filipa et al., 2010; Kinzey & Armstrong, 1998; Munro & Herrington, 2010; Whyte et al., 2015). Considering the MDC, SEBT composite index increases of at least 3.18% for the dominant leg and 4.84% for the non-dominant leg would be necessary (e.g. in an intervention study) to be confident with a 75% chance that a real change has happened in the dynamic postural control. Overall, these results show the SEBT consistency to assess this variable over time, for example during training and rehabilitation programs. However, PL and PM SEBT directions showed a significant between-session score increase (i.e. a learning effect) in the dominant leg and PL SEBT direction also showed this increase in the non-dominant leg (Table 3). In this sense, according to the magnitude-based inference (Hopkins et al., 2009), the three score increases showed a probability between 76% and 95% of being positive. Therefore, although several strategies were explained to the participants to facilitate the learning of the SEBT, the familiarisation period (30-s practice for each direction) was not long enough to avoid the learning effect in the aforementioned directions. Based on the study by Calatayud et al. (2014), four practice trials for each direction seem effective to avoid between-session differences in the SEBT scores. However, further research is needed to establish high efficiency familiarisation protocols which improve SEBT learning with lower time cost.

In relation to SEST and SETT, the reliability analysis showed the consistency of these protocols to discriminate between participants with similar trunk postural control. In this sense, the relative reliability was large for the SEST composite index (ICC=0.85) and moderate for SEST directions (0.35≤ICC≤0.68) and SETT composite index (ICC=0.61). Regarding absolute reliability, some authors have indicated that TE values lower than 10% represent adequate levels of absolute reliability (Flansbjer, Holmbäck, Downham, Patten & Lexell, 2005; Hyon & Kim, 2014; Liaw, Hsieh, Lo, Chen, Lee & Lin, 2008). Although this criterion seems arbitrary (Atkinson & Neville, 1998), SEST and SETT data showed TE values clearly lower than this reference value, especially for the composite indexes (1.27% and 2.31%, respectively). The TE values of the SEST directions were slightly higher (2.41%≤TE≤5.31%), but similar to those obtained in the SEBT directions. The MDC showed similar results, with lower values for the composite indexes (SEST=1.91%; SETT=3.47%) than for the SEST directions (3.62%≤MDC≤7.97%). Regarding the between session differences, a significant CM was detected for the LP direction of the SEST (2.03%) and for the composite indexes of SEST (1.50%) and SETT (1.94%). As commented before for SEBT, a longer familiarisation period seems needed to learn these protocols properly.

Despite SEST and SETT were developed based on the SEBT protocol and carried out in the 45º spaced 8-line grid developed to perform this protocol, no significant correlations were found between the SEBT and its variations (Table 4). Therefore, although the three tests measure postural control, our results indicate that the ability to control body balance while standing on one leg is different from the ability to control balance while sitting with leg motion restriction. Considering that SEBT variations analysed in this study increase the role of the upper-body in test performance, they seem more appropriate than SEBT to measure core stability in field settings. In this sense, although SEBT has been used to assess the effect of core stability programs (Chuter et al., 2015; Filipa et al., 2010; Imai et al., 2014; Sandrey & Mitzel, 2013), the lower-limb may have more influence on test performance than trunk structures, especially in people with ankle chronic instability, leg extensor muscle weakness or lower-limb motion deficits. However, further research is needed to establish which tests are more suitable to measure core stability in clinical, sport, fitness and research settings. In this sense, future studies must explore the advantages and disadvantages of using SEST and SETT to measure trunk postural control, for example, possible limitations of their use in some populations like elderly people, overweight people or individuals with hip and/or back mobility impairments (e.g. patients who are sensitive to lumbar flexion).

Because of the similarity between the SEST and SETT, their composite indexes showed a significantly moderate correlation (r=0.520; p>0.01). However, although both tests are related, this relationship doesn’t seem high enough to use them interchangeably. Possibly, the time restriction of the SETT involves higher postural control demands than the SEST, which (although it should be confirmed in future studies) is a remarkable characteristic in this type of protocols. On the other hand, the SEST composite index showed better reliability data than the SETT score, which must also be taken into account when choosing a test to measure trunk postural control.

5. Conclusions

This study confirms the between-session consistency of the SEBT to measure dynamic postural control in single-leg stance, and provides two reliable field tests (mainly the composite indexes) to measure trunk postural control in sitting position. Although the three tests are similar, SEBT scores did not correlate with SEST and SETT scores, maybe because the new protocols minimize the influence of the lower-limbs on test performance (i.e. obtaining measures of postural control more related to core stability). The three protocols are easy to use and inexpensive, but they need a longer familiarisation period than the one used in this study (30-s of practice for each direction) to avoid learning effect.

CHAPTER 5

EPILOGUE

CHAPTER 5

EPILOGUE

5.1. Conclusions

This Doctoral Thesis provides valuable information about the main characteristics and the relationships between some of the most representative tests used to assess core stability in laboratory and field settings. In addition, it also presents two new field tests to measure trunk postural control in healthy and recreationally active individuals, which were developed based on the SEBT, a well-known protocol normally used to assess whole-body postural control in single-leg stance.

The Doctoral Thesis includes two correlational and reliability test-retest studies. The first one analysed the inter-session reliability and the relationship between several representative tests of some of the most common types of methodologies used to assess core stability: *Sudden Loading Test*, *Stable and Unstable Sitting Test*, *Biering-Sorensen Test*, *Three Plane Core Strength Test* and *Double-leg Lowering Test*. Furthermore, the second study examined the inter-session reliability and the relationships between the SEBT and its two new variations, i.e. SEST and SETT; both protocols were carried out in sitting position to increase the role of the upper-body in postural control.

A summary of the main contributions of this Doctoral Thesis is shown hereafter on the basis of the research hypothesis:

Study 1:

Hypothesis I. *Taking into account the results of previous studies, the Sudden Loading Test and the Stable and Unstable Sitting Test will show good absolute and relative* *reliability, although the Stable and Unstable Sitting Test will show a significant learning or repetition effect.*

?. The hypothesis was partially confirmed. The trunk stiffness and angular displacement of the *Sudden Loading Test* and the dynamic unstable sitting conditions of the *Stable and Unstable Sitting Test* showed moderate to high reliability, while the reliability of the trunk damping after perturbation and of the static unstable and the static and dynamic stable sitting conditions was low to moderate. In addition, the dynamic unstable sitting conditions of the *Stable and Unstable Sitting Test* showed significant increases in test performance between sessions, which confirms the learning effect of this test.

Hypothesis II. *Based on earlier studies, the Biering-Sorensen Test will show a moderate to high relative reliability, but a low to moderate absolute reliability and a clear learning effect.*

OK. The hypothesis was confirmed. The relative reliability obtained for the *Biering-Sorensen Test* was high; however, it did not present a good absolute reliability. On the other hand, this field test showed a significant learning effect.

Hypothesis III. *Taking into account the results of a previous study and the subjectivity of the evaluations performed in the Three Plane Core Strength Test to score the participants, the reliability of this field test will be low.*

OK. The hypothesis was confirmed. The *Three Plane Core Strength Test* showed low relative and absolute reliability.

Hypothesis IV. *Considering the findings of prior studies performed in young physically active individuals, the Double-leg Lowering Test will obtain high absolute and relative reliability, although it will show a significant learning effect.*

NO. The hypothesis was not confirmed. The *Double-leg Lowering Test* was not sensitive enough to discriminate between most of our young and recreationally active participants, as more than 75% of them obtained a 0º score. This did not allow to perform a proper reliability analysis.

Hypothesis V. *Considering core stability as a multidimensional and context dependent ability, there will be no significant correlations between the variables of the different protocols used to measure it, since in these tests the results will be obtained in very different conditions. Nevertheless, as within each laboratory test the variables will be obtained in very similar conditions, the correlations between them will be significant.*

?. The hypothesis was partially confirmed. As expected, no relationship was found between the laboratory protocols; however, only few correlations were found between the loading directions of the *Sudden Loading Test*, indicating that the results of core stability measurements largely depend on test conditions. In addition, the laboratory protocols did not correlate with the *Biering-Sorensen Test*, which seems to measure trunk extensor endurance rather than core stability. Overall, these findings highlight the difficulty of measuring core stability and the importance of choosing the most appropriate tests for each situation.

Study 2:

Hypothesis VI. *Based on the results of other studies, the SEBT will present moderate to high reliability. In the same way, considering the similarities between this protocol and* *its variations to assess trunk postural control, we think that the SEST and the SETT will show similar reliability values to those of the SEBT.*

OK. The hypothesis was confirmed. The SEBT, the SEST and the SETT showed moderate to high reliability, especially the composite scores.

Hypothesis VII. *Despite the fact that the SEST and the SETT were developed based on the protocol of the SEBT, significant correlations between the new tests and the original test will not be found, as the SEBT assesses postural control in single-leg stance while its variations measure trunk postural control while sitting, which reduces lower-limb influence and provides field measures more related to core stability.*

OK. The hypothesis was confirmed. No significant correlations were found between the SEBT and its two variations performed in sitting position.

Hypothesis VIII. *Taking into account that the SEST and the SETT have very similar characteristics, a significant correlation will be found between them.*

OK. The hypothesis was confirmed. The correlation analysis showed a significant and moderate correlation between the SEST and the SETT.

5.2. Conclusiones

Esta Tesis Doctoral proporciona información valiosa sobre las principales características y las posibles relaciones entre algunos de los test más representativos para medir la estabilidad del core en ámbitos de laboratorio y de campo. Además, presenta también dos nuevos test de campo para medir el control postural del tronco en individuos sanos y recreacionalmente activos; test que han sido desarrollados a partir del SEBT, un protocolo muy conocido que normalmente se utiliza para valorar el control postural general en apoyo monopodal.

La Tesis Doctoral incluye dos estudios correlacionales y de fiabilidad test-retest. El primero de estos estudios analizó la fiabilidad entre sesiones y la relación entre varios test representativos de algunas de las metodologías más comúnmente utilizadas para valorar la estabilidad del core: *Sudden Loading Test*, *Stable and Unstable Sitting Test*, *Biering-Sorensen Test*, *Three Plane Core Strength Test* y *Double-leg Lowering Test*. Además, el segundo estudio examinó la fiabilidad entre sesiones y las relaciones entre el SEBT y sus dos nuevas variaciones, es decir, el SEST y el SETT. Ambos protocolos fueron realizados en sedestación para incrementar el rol del tren superior en el control postural.

A continuación, se presenta un resumen de las principales contribuciones de esta Tesis Doctoral en función de las hipótesis de investigación:

Estudio 1:

Hipótesis I. *Teniendo en cuenta los resultados de estudios previos, el Sudden Loading Test y el Stable and Unstable Sitting Test mostrarán una buena fiabilidad absoluta y relativa, aunque el Stable and Unstable Sitting Test presentará un efecto de aprendizaje o de repetición significativo.*

¿?. Se confirmó la hipótesis parcialmente. La rigidez y el desplazamiento angular del tronco en el *Sudden Loading Test* y las tareas dinámicas sobre asiento inestable en el *Stable and Unstable Sitting Test* mostraron una fiabilidad de moderada a alta. Sin embargo, el coeficiente de amortiguamiento del tronco tras las perturbaciones y las tareas estáticas realizadas sobre asiento inestable, así como las tareas estáticas y dinámicas realizadas sobre un asiento estable, presentaron una fiabilidad de baja a moderada. Además, las tareas dinámicas sobre asiento inestable del *Stable and Unstable Sitting Test*, mostraron incrementos significativos en el rendimiento del test entre sesiones, lo que confirma el efecto de aprendizaje de este test.

Hipótesis II. *Basándonos en estudios anteriores, el Biering-Sorensen Test mostrará una fiabilidad relativa de moderada a alta, pero una fiabilidad absoluta de baja a moderada y un claro efecto aprendizaje.*

OK. Se confirmó la hipótesis. La fiabilidad relativa obtenida por el *Biering-Sorensen Test* fue alta, sin embargo, su fiabilidad absoluta no fue buena. Por otra parte, este test de campo mostró un efecto de aprendizaje significativo.

Hipótesis III. *Teniendo en cuenta los resultados de un estudio previo y la subjetividad de las evaluaciones realizadas en el Three Plane Core Strength Test para puntuar a los participantes, la fiabilidad de este test será baja.*

OK. Se confirmó la hipótesis. El *Three Plane Core Strength Test* mostró una baja fiabilidad absoluta y relativa.

Hipótesis IV. *Considerando los hallazgos de estudios previos realizados con individuos jóvenes y físicamente activos, el Double-leg Lowering Test obtendrá una fiabilidad absoluta y relativa alta, aunque mostrará un efecto de aprendizaje significativo.*

NO. No se confirmó la hipótesis. El *Double-leg Lowering Test* no fue suficientemente sensible para discriminar entre la mayoría de los participantes (jóvenes y físicamente activos), ya que más del 75% de la muestra obtuvo una puntuación de 0º. Esto no permitió realizar un análisis de fiabilidad adecuado.

Hipótesis V. *Considerando la estabilidad del core como una capacidad multidimensional y dependiente del contexto, no se obtendrán correlaciones significativas entre las variables de los diferentes protocolos utilizados para su medición, ya que en estos test los resultados se obtendrán en condiciones muy diferentes. Sin embargo, puesto que dentro de cada test de laboratorio las variables se obtendrán en condiciones muy similares, las correlaciones entre ellas serán significativas.*

¿?. Se confirmó la hipótesis parcialmente. Como se esperaba, no se encontró relación entre los protocolos de laboratorio; sin embargo, sólo se encontraron unas pocas correlaciones entre las direcciones de aplicación de la carga del *Sudden Loading Test*, indicando que los resultados de las medidas de estabilidad del core dependen en gran medida de las condiciones de la evaluación. Además, los protocolos de laboratorio no correlacionaron con el *Biering-Sorensen Test*, el cual parece medir la resistencia de la musculatura extensora de tronco más que la estabilidad del core. En general, estos resultados destacan la dificultad que entraña la medición de esta habilidad y la importancia de elegir el test más apropiado para cada situación.

Estudio 2:

Hipótesis VI. *En función de los resultados de otros estudios, el SEBT presentará una fiabilidad de moderada a alta. Además, considerando las similitudes entre este protocolo y sus variaciones para valorar el control postural del tronco, creemos que el SEST y el SETT mostrarán valores de fiabilidad similares a aquellos obtenidos por el SEBT.*

OK. Se confirmó la hipótesis. El SEBT, el SEST y el SETT presentaron una fiabilidad de moderada a alta, especialmente en las puntuaciones globales.

Hipótesis VII. *A pesar de que el SEST y el SETT fueron desarrollados en base al protocolo del SEBT, no se encontrarán correlaciones significativas entre los test nuevos y el original, ya que el SEBT valora el control postural en apoyo monopodal, mientras que sus dos variaciones miden el control postural del tronco en sedestación, lo que reduce la influencia de los miembros inferiores y proporciona medidas de campo más relacionadas con la estabilidad del core.*

OK. Se confirmó la hipótesis. No se encontraron correlaciones significativas entre el SEBT y sus dos variaciones realizadas en sedestación.

Hipótesis VIII. *Teniendo en cuenta que el SEST y el SETT tienen características muy similares, se encontrará una correlación significativa entre ambos test.*

OK. Se confirmó la hipótesis. El análisis correlacional de Pearson mostró una correlación moderada y significativa entre el SEST y el SETT.

5.3. Study limitations and future research

Like any study, this Doctoral Thesis is not exempt of limitations, which should be considered for the interpretation and application of the results. In addition, some of them have been the starting points of new studies in the Biomechanics and Health Laboratory of the Sports Research Center of Miguel Hernández University of Elche. Although some of the limitations of this Doctoral Thesis have been discussed in the studies included in chapters 3 and 4, what follows are the main limitations:

1. *The sample size and characteristics*. Although a sample size of 25 participants could be considered adequate for some reliability studies (Springate, 2012), a greater number of participants would be advisable to minimize the random change of the measure (Hopkins, 2000). In addition, the sample of the studies of this Doctoral Thesis consisted of

young and recreationally active males, so it is not possible to generalize their conclusions to other populations, such as females, patients with low back pain, elderly people, sedentary individuals, high performance athletes, etc. Future research on core stability tests should overcome these limitations and analyse different populations using a larger sample size.

2. *The time period between testing sessions*. The studies of this Doctoral Thesis followed a reliability test-retest design in which each protocol was performed twice, spaced a month apart to reduce the learning effect. Thus, the reliability results of the eight tests analysed can only be interpreted in this context. Future studies should analyse the consistency of these tests with different time periods between testing sessions for a better knowledge of their characteristics and application in experimental studies.

3. *The repetition or learning effect of some tests*. In the scientific literature, it is generally recommended to perform a reliability analysis after the repetition or learning effect has plateaued (Hopkins, 2000). In this Doctoral Thesis, although several repetitions of each test were performed in each testing session (selecting the best repetition), the participants' performance significantly increased between testing sessions in several tests (e.g. *Stable and Unstable Sitting Test, Biering-Sorensen Test*, etc.). These results confirm the need of a familiarisation session or more practice trials to make the learning effect negligible, which is not usual in practical settings, in which participants are normally evaluated once in a short testing session. In order to overcome this limitation, our research group is currently modifying some protocols to reduce their learning effect and facilitate their use in a single testing session. For example, we have reduced the number of conditions analysed in the *Stable and Unstable Sitting Test* (e.g. removing the unreliable conditions) to increase the practice trials in the remaining ones.

4. *The field tests selected for the first study*. Despite the three field tests selected to carry out the first study represent the most common methodologies used to assess core stability in field settings, there are many other field tests used for this purpose. Therefore, we cannot ignore the possibility of obtaining different results with other measurements. Future research should analyse the reliability and relationship between the many different core stability tests, especially including those that are very different from the protocols analysed in this study.

5. *The high relationship between the new field tests developed in the second study and the participants' arm length*. Due to this relationship, the raw data of the SEST and the SETT was normalized to reduce the effect of participants' anthropometry on test scores. The need of performing this normalization could hinder the applicability of these tests in some settings. In addition, the correlational analysis may suggest that the scores of the SEST and the SETT depend on the participants' anthropometry rather than on their neuromuscular control of the trunk posture. Therefore, future studies could modify these tests to increase the trunk neuromuscular control demands, for example performing them on an unstable surface. Moreover, considering the possible difficulties of using these tests in some individuals with problems to bend their trunk, grab their legs or sit on the floor (such as elderly people, overweight individuals or patients with low back pain), at present, our research group is working in the use of smartphone accelerometers to develop new field protocols to assess core stability. This accessible technology may provide quantitative measures of the body sway that could be used outside of research laboratories to evaluate and prescribe core stability programs.

REFERENCES

REFERENCES

Abt, J. P., Smoliga, J. M., Brick, M. J., Jolly, J. T., Lephart, S. M., & Fu, F. H. (2007). Relationship between cycling mechanics and core stability. *Journal of Strength & Conditioning Research*, *21*(4), 1300-1304.

Akuthota, V., Ferreiro, A., Moore, T., & Fredericson, M. (2008). Core Stability Exercise Principles. *Current Sports Medicine Reports*, *7*(1), 39-44.

Akuthota, V., & Nadler, S. F. (2004). Core strengthening. *Archives of Physical Medicine and Rehabilitation*, *85*(3 Suppl 1), 86-92.

Ambegaonkar, J. P., Caswell, S. V., Winchester, J. B., Shimokochi, Y., Cortes, N., & Caswell, A. M. (2013). Balance comparisons between female dancers and active nondancers. *Research Quarterly for Exercise and Sport*, *84*(1), 24-29.

Ambegaonkar, J. P., Mettinger, L. M., Caswell, S. V., Burtt, A., & Cortes, N. (2014). Relationships between core endurance, hip strength, and balance in collegiate female athletes. *International Journal of Sports Physical Therapy*, *9*(5), 604-616.

Anderson, K., & Brhm, D. G. (2005). Trunk muscle activity increases with unstable squat movements. *Canadian Journal of Applied Physiology*, *30*(1), 33-45.

Araujo, S., Cohen, D., & Hayes, L. (2015). Six weeks of core stability training improves landing kinetics among female capoeira athletes: a pilot study. *Journal of Human Kinetics, 45*, 27-37.

Arendt, E. A. (2007). Core Strengthening. *Instructional Course Lectures*, *56*, 379-384.

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.

Barbado, D., Barbado, L. C., Elvira, J. L., van Dieën, J. H., & Vera-Garcia, F. J. (2016). Sports-specific testing protocols are required to reveal trunk stability adaptations in high-level athletes. *Gait & Posture, 49*, 90-96.

Barbado, D., López-Valenciano, A., Juan-Recio, C., Montero-Carretero, C., van Dieën, J. H., & Vera-Garcia, F. J. (2016). Trunk Stability, Trunk Strength and Sport Performance Level in Judo. *PloS One*, *11*(5), e0156267.

Barbado, D., Moreside, J., & Vera-Garcia, F. J. (2017). Reliability and repetition effect of the center of pressure and kinematics parameters that characterize trunk postural control during unstable sitting test. *PM&R, 9*(3), 219-230.

Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance, 1*(1), 50-57.

Bennett, B. C., Abel, M. F., & Granata, K. P. (2004). Seated postural control in adolescents with idiopathic scoliosis. *Spine (Phila Pa 1976)*, *29*(20), E449-E454.

Bergmark, A. (1989). Stability of the lumbar spine: a study in mechanical engineering. *Acta Orthopaedica Scandinavica*, *60* (230 Suppl1), 1-54.

Biering-Sørensen, F. (1984). Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine, 9,* 106–119.

Borghuis, J., Hof, A. L., & Lemmink, K. A. (2008). The importance of sensory-motor control in providing core stability: implications for measurement and training. *Sports Medicine*, *38*(11), 893-916.

Brown, S. H., Vera-Garcia, F. J., & McGill, S. M. (2006). Effects of abdominal muscle coactivation on the externally preloaded trunk: variations in motor control and its effect on spine stability. *Spine*, *31*(13), E387-E393.

Cabañas, M. D., & Esparza, F. (2009). *Compendio de cineantropometria*. Madrid: CTO Editorial, 2.

Calatayud, J., Borreani, S., Colado, J. C., Martin, F., & Flandez, J. (2014). Test-retest reliability of the Star Excursion Balance Test in primary school children. *The Physician and Sportsmedicine*, *42*(4), 120-124.

Calatayud, J., Casaña, J., Martín, F., Jakobsen, M. D., Colado, J. C., Gargallo, P., ... Andersen, L. L. (2017). Trunk muscle activity during different variations of the supine plank exercise. *Musculoskeletal Science and Practice*, *28*, 54-58.

Chaiwanichsiri, D., Lorprayoon, E., & Noomanoch, L. (2005). Star excursion balance training: effects on ankle functional stability after ankle sprain. *Journal of the Medical Association of Thailand= Chotmaihet thangphaet*, *88*, 90-94.

Chan, R. H. (2005). Endurance times of trunk muscles in male intercollegiate rowers in Hong Kong. *Archives of Physical Medicine and Rehabilitation*, *86*(10), 2009-2012.

Chaudhari, A. M., McKenzie, C. S., Borchers, J. R., & Best, T. M. (2011). Lumbopelvic control and pitching performance of professional baseball pitchers. *Journal of Strength & Conditioning Research*, *25*(8), 2127-2132.

Chevidikunnan, M. F., Al Saif, A., Gaowqzeh, R. A., & Mamdouh, K. A. (2016). Effectiveness of core muscle strengthening for improving pain and dynamic balance among female patients with patellofemoral pain syndrome. *Journal of Physical Therapy in Science*, *28*(5), 1518-1523.

Chmielewski, T. L., Hodges, M. J., Horodyski, M., Bishop, M. D., Conrad, B. P., & Tillman, S. M. (2007). Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *Journal of Orthopaedic and Sports Physical Therapy*, *37*(3), 122-129.

Cholewicki, J., Greene, H. S., Polzhofer, G. K., Galloway, M. T., Shah, R. A., & Radebold, A. (2002). Neuromuscular function in athletes following recovery from a recent acute low back injury. *Journal of Orthopaedic & Sports Physical Therapy, 32*(11), 568-575.

Cholewicki, J., & McGill, S. M. (1996). Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clinical Biomechanics (Bristol, Avon), 11*(1), 1-15.

Cholewicki, J., McGill, K. C., Shah, K. R., & Lee, A. S. (2010). The effects of a three-week use of lumbosacral orthoses on trunk muscle activity and on the muscular response to trunk perturbations. *BMC Musculoskeletal Disorders, 11*, 154.

Cholewicki, J., Polzhofer, G. K., & Radebold, A. (2000). Postural control of trunk during unstable sitting. *Journal of Biomechanics, 33*(12), 1733-1737.

Cholewicki, J., Silfies, S. P., Shah, R. A., Greene, H. S., Reeves, N. P., Alvi, K., & Goldberg, B. (2005). Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976), 30*(23), 2614-2620.

Cholewicki, J., Simons, A. P. D., & Radebold, A. (2000). Effects of external trunk loads on lumbar spine stability. *Journal of Biomechanics, 33*(11), 1377-1385.

Chuter, V. H., de Jonge, X. A., Thompson, B. M., & Callister, R. (2015). The efficacy of a supervised and a home-based core strengthening programme in adults with poor core stability: a three-arm randomised controlled trial. *British Journal of Sports Medinice, 49*(6), 395-399.

Clagg, S., Paterno, M. V., Hewett, T. E., & Schmitt, L. C. (2015). Performance on the modified star excursion balance test at the time of return to sport following anterior cruciate ligament reconstruction. *Journal of Orthopaedic & Sports Physical Therapy, 4*5(6), 444-452.

Clark, A. W., Goedeke, M. K., Namvong, R., Rockwell, D. E., Lehecka, B. J., Manske, R. C., & Smith B. S. (2016). Effects of Pelvic and Core Strength Training on High School Cross-Country Race Times. *Journal of Strength & Conditioning Research*.

Clark, R. C., Saxion, C. E., Cameron, K. L., & Gerber, J. P. (2010). Associations between three clinical assessment tools for postural stability. *North American Journal of Sports Physical Therapy*, *5*(3), 122-130.

Collins, J. J., & De Luca, C. J. (1993). Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research 95*, 308-318.

Cook, G., Burton, L., & Hoogenboom, B. (2006). Pre-participation screening: the use of fundamental movements as an assessment of function–part 1. *North American Journal of Sports Physical Therapy*, *1*(2), 62.

Cowley, P. M., Fitzgerald, S., Sottung, K., & Swensen, T. (2009). Age, weight, and the front abdominal power test as predictors of isokinetic trunk strength and work in young men and women. *Journal of Strength & Conditioning Research*, *23*(3), 915-925.

Cowley, P. M., & Swensen, T. C. (2008). Development and reliability of two core stability field tests. *Journal of Strength and Conditioning Research*, *22*(2), 619-624.

Cresswell, A. G., Oddsson, L., & Thorstensson, A. (1994). The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research*, *98*(2), 336-341.

Delahunt, E., Chawke, M., Kelleher, J., Murphy, K., Prendiville, A., Sweeny, L., & Patterson, M. (2013). Lower limb kinematics and dynamic postural stability in anterior cruciate ligament-reconstructed female athletes. *Journal of Athletic Training*, *48*(2), 172-185.

Demoulin, C., Vanderthommen, M., Duysens, C., & Crielaard, J. M. (2006). Spinal muscle evaluation using the Sorensen test: a critical appraisal of the literature. *Joint, Bone, Spine: Revue du Rhumatisme*, *73*(1), 43-50.

Elvira, J. L. L., Barbado, D., Juan-Recio C, García-Vaquero M. P., López-Valenciano, A., López-Plaza, D., & Vera-García, F. J. (2013). Diferencias en la estabilización del tronco sobre un asiento inestable entre piragüistas, judocas y sujetos físicamente activos. *Kronos*, *12*(2), 63-72.

Escamilla, R. F., Lewis, C., Bell, D., Bramblet, G., Daffron, J., Lambert, S., ... Andrews, J. R. (2010). Core muscle activation during Swiss ball and traditional abdominal exercises. *Journal of Orthopaedic & Sports Physical Therapy, 40*(5), 265-276.

Esser, M. (2017). Effects of Core Stability Training on Masters Swimmers. *Sportverletzung Sportschaden*, *31*(2), 93-102.

Evans, K., Refshauge, K. M., & Adams, R. (2007). Trunk muscle endurance tests: reliability, and gender differences in athletes. *Journal of Science and Medicine in Sport*, *10*(6), 447-455.

Filipa, A., Byrnes, R., Paterno, M. V., Myer, G. D., & Hewett, T. E. (2010). Neuromuscular training improves performance on the star excursion balance test in young female athletes. *Journal of Orthopaedic & Sports Physical Therapy*, *40*(9), 551-558.

Flansbjer, U. B., Holmbäck, A. M., Downham, D., Patten, C., & Lexell, J. (2005). Reliability of gait performance tests in men and women with hemiparesis after stroke. *Journal of Rehabilitation Medicine, 37*(2), 75-82.

Ganesh, G. S., Chhabra, D., & Mrityunjay, K. (2015). Efficacy of the star excursion balance test in detecting reach deficits in subjects with chronic low back pain. *Physioterapy Research International*, *20*(1), 9-15.

Gardner-Morse, M. G., & Stokes, I. A. (2001). Trunk stiffness increases with steady-state effort. *Journal of Biomechanics*, *34*(4), 457-463.

Glofcheskie, G. (2015). *Comparison of trunk proprioceptive ability, postural control, and neuromuscular responses to sudden trunk perturbations between athletes and non-athletes*. Master’s Thesis, Universidad of Guelph, Ontario, Canada.

Granacher, U., Schellbach, J., Klein, K., Prieske, O., Baeyens, J. P., & Muehlbauer, T. (2014). Effects of core strength training using stable versus unstable surfaces on physical fitness in adolescents: a randomized controlled trial. *BMC Sports Science, Medicine and Rehabilitation*, *6*(1), 40.

Granata, K. P., & England, S. A. (2006). Stability of dynamic trunk movement. *Spine*, *31*(10), E271.

Granata, K. P., Orishimo, K. F., & Sanford, A. H. (2001). Trunk muscle coactivation in preparation for sudden load. *Journal of electromyography and kinesiology: official journal of the International Society of Electrophysiological Kinesiology*, *11*(4), 247-254.

Gribble, P. A., & Hertel, J. (2003). Considerations for Normalizing Measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science*, *7*(2), 89-100.

Gribble, P. A., Hertel, J., Denegar, C. R., & Buckley, W. E. (2004). The effects of fatigue and chronic ankle instability on dynamic postural control. *Journal of Athletic Training*, *39*(4), 321-329.

Gribble, P. A., Kelly, S. E., Refshauge, K. M., & Hiller, C. E. (2013). Interrater reliability of the star excursion balance test. *Journal of Athletic Training*, *48*(5), 621-626.

Gribble, P. A., Robinson, R. H., Hertel, J., & Denegar, C. R. (2009). The effects of gender and fatigue on dynamic postural control. *Journal of Sport Rehabilitation*, *18*(2), 240-257.

Haladay, D. E., Denegar, C. R., Miller, S. J., & Challis, J. (2015). Electromyographic and kinetic analysis of two abdominal muscle performance tests. *Physiotherapy Theory and Practice*, *31*(8), 587-593.

Hale, S. A., Hertel, J., & Olmsted-Kramer, L. C. (2007). The effect of a 4-week comprehensive rehabilitation program on postural control and lower extremity function in individuals with chronic ankle instability. *Journal of Orthopaedic & Sports Physical Therapy*, *37*(6), 303-311.

Herrington, L., Hatcher, J., Hatcher, A., & McNicholas, M. (2009). A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *Knee*, *16*(2), 149-152.

Herrmann, C. M., Madigan, M. L., Davidson, B. S., & Granata, K. P. (2006). Effect of lumbar extensor fatigue on paraspinal muscle reflexes. *Journal of Electromiography & Kinesiology*, *16*(6), 637-641.

Hertel, J., Braham, R. A., Hale, S. A., & Olmsted-Kramer, L. C. (2006). Simplifying the Star Excursion Balance Test: analyses of subjects with and without chronic ankle instability. *Journal of Orthopaedic & Sports Physical Therapy*, *36*(3), 131–137.

Hertel, J., Miller, S. J., & Denegar, C. R. (2000). Intratester and intertester reliability during the Star Excursion Balance Test. *Journal of Sport Rehabilitation*, *9*(2), 104–116.

Hides, J. A., Jull, G. A., & Richardson, C. A. (2001). Long-term effects of specific stabilizing exercises for first-episode low back pain. *Spine (Phila Pa 1976)*, *26*(11), E243-248.

Hodges, P. W., & Richardson, C. A. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominis. *Spine*, *21*(22), 2640-2650.

Hodges, P. W., & Richardson, C. A. (1997). Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy in Sport*, *77*(2), 132-142.

Hodges, P. W., & Richardson, C. A. (1998). Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. *Clinical Spine Surgery*, *11*(1), 46-56.

Hoogvliet, P., van Duyl, W. A., de Bakker, J. V., Mulder, P. G., & Stam, H. J. (1997). Variations in foot breadth: effect on aspects of postural control during one-leg stance. *Archives of Physical Medicine and Rehabilitation*, *78*(3), 284-289.

Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine+Science in Sports+Exercise*, *41*(1), 3.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*(1), 1-15.

Hoppes, C. W., Sperier, A. D., Hopkins, C. F., Griffiths, B. D., Principe, M. F., Schnall, B. L., Bell, J. C., & Koppenhaver, S. L. (2016). The efficacy of an eight-week core stabilization program on core muscle function and endurance: a randomized trial. *International Journal of Sports Physical Therapy*, *11*(4), 507-519.

Hyong, I. H., & Kim, J. H. (2014). Test of intrarater and interrater reliability for the star excursion balance test. *Journal or Physical Therapy Science*, *26*(8), 1139-1141.

Imai, A., Kaneoka, K., Okubo, Y., & Shiraki, H. (2014). Effects of two types of trunk exercises on balance and athletic performance in youth soccer players. *International Journal of Sports Physical Therapy*, *9*(1), 47-57.

Jacobs, J. V., & Horak, F. B. (2007). Cortical control of postural responses. *Journal of Neural Transmission*, *114*(10), 1339-1348.

Jamison, S. T., McNeilan, R. J., Young, G. S., Givens, D. L., Best, T. M., & Chaudhari, A. M. (2012). Randomized controlled trial of the effects of a trunk stabilization program on trunk control and knee loading. *Medicine and Science in Sports and Exercise*, *44*(10), 1924-1934.

Javadian, Y., Akbari, M., Talhebi, G., Taghipour-Darzi, M., & Janmohammadi, N. (2015). Influence of core stability exercise on lumbar vertebral instability in patients presented with chronic low back pain: A randomized clinical trial. *Caspian Journal of Internal Medicine*, *6*(2), 98-102.

Juan-Recio, C., Barbado, D., López-Valenciano, A., & Vera-Garcia, F. J. (2014). Test de campo para valorar la resistencia de los músculos del tronco. *Apunts. Educación física y deportes*, *117*, 59.

Juan-Recio, C., López-Plaza, D., Barbado, D., García-Vaquero, M. P., & Vera-Garcia, F. J. (2017). Reliability assessment and correlation analysis of 3 protocols to measure trunk muscle strength and endurance. *Journal of Sports Sciences*, *30*, 1-8.

Kahle, N. L., & Gribble, P. A. (2009). Core Stability Training in Dynamic Balance Testing Among Young, Healthy Adults. *Athletic Training & Sports Health Care*, *1*(2), 65-73.

Kang, K. Y. (2015). Effects of core muscle stability training on the weight distribution and stability of the elderly. *Journal of Physical Therapy in Science*, *27*(10), 3163-3165.

Kendall, F. P., McCreary, E. K., & Provance, P. G. (1993). Muscles, testing and function. 4th ed. Baltimore, Md: Williams & Wilkins.

Ketelhut, N. B., Kindred, J. H., Manago, M. M., Hebert, J. R., & Rudroff, T. (2015). Core muscle characteristics during walking of patients with multiple sclerosis. *Journal of Rehabilitation Research and Development*, *52*(6), 713.

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sport Medicine*, *36*(3), 189-198.

Kinzey, S. J., & Armstrong, C. W. (1998). The reliability of the Star-Excursion test in assessing dynamic balance. *Journal of Orthopaedic & Sports Physical Therapy*, *27*(5), 356–360.

Kliziene, I., Sipaviciene, S., Klizas, S., & Imbrasiene, D. (2015). Effects of core stability exercises on multifidus muscles in healthy women and women with chronic low-back pain. *Journal of Back and Musculoskeletal Rehabilitation*, *28*(4), 841-847.

Ko, E. J., Chun, M. H., Kim, D. Y., Yi, J. H., Kim, W., & Hong, J. (2016). The Additive Effects of Core Muscle Strengthening and Trunk NMES on Trunk Balance in Stroke Patients. *Annals of Rehabilitation Medicine*, *40*(1), 142-151.

Krajcarski, S. R., Potvin, J. R., & Chiang, J. (1999). The in vivo dynamic response of the spine to perturbations causing rapid flexion: effects of pre-load and step input magnitude. *Clinical Biomechanics (Bristol, Avon)*, *14*(1), 54-62.

Krause, D. A., Youdas, J. W., Hollman, J. H., & Smith, J. (2005). Abdominal muscle performance as measured by the double leg-lowering test. *Archives of Physical Medicine and Rehabilitation*, *86*(7), 1345-1348.

Ladeira, C. E., Hess, L. W., Galin, B. M., Fradera, S., & Harkness, M. A. (2005). Validation of an abdominal muscle strength test with dynamometry. *Journal of Strength & Conditioning Research*, *19*(4), 925-930.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 159-174.

Lanning, C. L., Uhl, T. L., Ingram, C. L., Mattacola, C. G., English, T., & Newsom, S. (2006). Baseline values of trunk endurance and hip strength in collegiate athletes. *Journal of Athletic Training*, *41*(4), 427-434.

Latimer, J., Maher, C. G., Refshauge, K., & Colaco, I. (1999). The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine (Phila Pa 1976)*, *24*(20), 2085-2089.

Lee, H., & Granata, K. P. (2008). Process stationarity and reliability of trunk postural stability. *Clinical Biomechanics (Bristol, Avon)*, *23*(6), 735-742.

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine and Science in Sports and Exercise*, *36*(6), 926-934.

Liaw, L. J., Hsieh, C. L., Lo, S. K., Chen, H. M., Lee, S., & Lin, J. H. (2008). The relative and absolute reliability of two balance performance measures in chronic stroke patients. *Disability and Rehabilitation*, *30*(9), 656-661.

Lin, D., Seol, H., Nussbaum, M. A., & Madigan, M. L. (2008). Reliability of COP-based postural sway measures and age-related differences. *Gait & Posture*, *28*(2), 337-342.

Manchado, C., García-Ruiz, J., Cortell-Tormo, J. M., & Tortosa-Martínez, J. (2017). Effect of Core Training on Male Handball Players' Throwing Velocity. *Journal of Human Kinetics*, *56*, 177-185.

Mayer, J. M., Quillen, W. S., Verna, J. L., Chen, R., Lunseth, P., & Dagenais, S. (2015). Impact of a supervised worksite exercise program on back and core muscular endurance in firefighters. *American Journal of Health Promotion, 29*(3), 165-172.

McGill, S. M., Childs, A., & Liebenson, C. (1999). Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Archives of Physical Medicine and Rehabilitation*, *80*(8), 941-944.

McGill, S. M., & Cholewicki, J. (2001). Biomechanical basis for stability: an explanation to enhance clinical utility. *Journal of Orthopaedic and Sports Physical Therapy, 31*(2), 96-100.

McGill, S. M, Grenier, S., Kavcic, N., & Cholewicki, J. (2003). Coordination of muscle activity to measure stability of the lumbar spine. *Journal of Electromyography and Kinesiology*, *13*(4), 353-359.

Mills, J. D., Taunton, J. E., & Mills, W. A. (2005). The effect of a 10-week training regimen on lumbo-pelvic stability and athletic performance in female athletes: A randomized controlled trial. *Physical Therapy in Sport*, *6*(2), 60-66.

Moreland, J., Finch, E., Stratford, P., Balsor, B., & Gill, C. (1997). Interrater reliability of six tests of trunk muscle function and endurance. *Journal of Orthopaedic and Sports Physical Therapy, 26*(4), 200-208.

Munro, A. G., & Herrington, L. C. (2010). Between-session reliability of the Star Excursion Balance Test. *Physical Therapy in Sport, 11*(4), 128-132.

Nakagawa, L., & Hoffman, M. (2004). Performance in static, dynamic, and clinical tests of postural control in individuals with recurrent ankle sprains. *Journal of Sport Rehabilitation, 13*(3), 255–268.

Nesser, T. W., Huxel, K. C., Tincher, J. L., & Okada, T. (2008). The relationship between core stability and performance in division I football players. *Journal of Strength & Conditioning Research*, *22*(6), 1750-1754.

Olmsted, L. C., Carcia, C. R., Hertel, J., & Shultz, S. J. (2002). Efficacy of the Star Excursion Balance Tests in detecting reach deficits in subjects with chronic ankle instability. *Journal of Athletic Training*, *37*(4), 501–506.

Panjabi, M. M. (1992). The stabilizing system of the spine, part 1: function, dysfunction, adaptation, and enhancement. *Journal of Spinal Disorders*, *5*(4), 383-389.

Panjabi, M. M. (2003) Clinical spinal instability and low back pain. *Journal of Electromyography and Kinesiology*, *13*(4), 371-379.

Panzer, P., Bandinelli, S., & Hallett, M. (1995). Biomechanical assessment of quiet standing and changes associated with aging. *Archives of Physical Medicine and Rehabilitation*, *76*(2), 151-157.

Park, J. M., Hyun. G. S., & Jee, Y. S. (2016). Effects of Pilates core stability exercises on the balance abilities of archers. *Journal of Exercise Rehabilitation*, *12*(6), 553-558.

Parker, M., Goldberg, R. F., Dinkins, M. M., Asbun, H. J., Smith, C. D., Preissler, S., & Bowers, S. P. (2011). Pilot study on objective measurement of abdominal wall strength in patients with ventral incisional hernia. *Surgical Endoscopy*, *25*(11), 3503-3508.

Pérennou, D. A., Leblond, C., Amblard, B., Micallef, J. P., Herisson, C., & Pelissier, J. Y. (2001). Transcutaneous electric nerve stimulation reduces neglect-related postural instability after stroke. *Archives of Physical Medicine and Rehabilitation*, *82*(4), 440-448.

Plisky, P. J., Gorman, P. P., Butler, R. J., Kiesel, K. B., Underwood, F. B., & Elkins, B. (2009). The reliability of an instrumented device for measuring components of the star excursion balance test. *North American Journal of Sports Physical Therapy*, *4*(2), 92-99.

Plisky, P. J., Rauh, M. J., Kaminski, T. W., & Underwood, F. B. (2006). Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic & Sports Physical Therapy*, *36*(12), 911-919.

Radebold, A., Cholewicki, J., Panjabi, M. M., & Patel, T. C. (2000). Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. *Spine (Phila Pa 1976)*, *25*(8), 947-954.

Radebold, A., Cholewicki, J., Polzhofer, G. K., & Greene, H. S. (2001). Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976)*, *26*(7), 724-730.

Radwan, A., Francis, J., Green, A., Kahl, E., Maciurzynski, D., Quartulli, A., . . . Weiss, B. (2014). Is there a relation between shoulder dysfunction and core instability? *International Journal of Sports Physical Therapy*, *9*(1), 8.

Reed, C. A., Ford, K. R., Myer, G. D., & Hewett, T. E. (2012). The effects of isolated and integrated 'core stability' training on athletic performance measures: a systematic review. *Sports Medicine*, *42*(8), 697-706.

Reeves, N. P., Cholewicki, J., & Milner, T. E. (2005). Muscle reflex classification of low-back pain. *Journal of Electromyography and Kinesiology*, *15*(1), 53-60.

Reeves, N. P., Cholewicki, J., & Narendra, K. S. (2009). Effects of reflex delays on postural control during unstable seated balance. *Journal of Biomechanics*, *42*(2), 164-170.

Reeves, N. P., Everding, V. Q., Cholewicki, J., & Morrisette, D. C. (2006). The effects of trunk stiffness on postural control during unstable seated balance. *Experimental Brain Research*, *174*(4), 694-700.

Reeves, N. P., Narendra, K. S., & Cholewicki, J. (2007). Spine stability: the six blind men and the elephant. *Clinical Biomechanics (Bristol, Avon)*, *22*(3), 266-274.

Rhea, C. K., Silver, T. A., Hong, S. L., Ryu, J. H., Studenka, B. E., Hughes, C. M., & Haddad, J. M. (2011). Noise and complexity in human postural control: interpreting the different estimations of entropy. *PloS One*, *6*(3), e17696.

Robinson, R. H., & Gribble, P. A. (2008). Support for a Reduction in the Number of Trials Needed for the Star Excursion Balance Test. *Archives of Physical Medicine and Rehabilitation*, *89*(2), 364-370.

Romero-Franco, N., Martínez-López, E., Lomas-Vega, R., Hita-Contreras, F., & Martínez-Amat, A. (2012). Effects of proprioceptive training program on core stability and center of gravity control in sprinters. *Journal of Strength & Conditional Research*, *26*(8), 2071-2077.

Sánchez-Zuriaga, D., Adams, M. A., & Dolan, P. (2010). Is activation of the back muscles impaired by creep or muscle fatigue? *Spine (Phila Pa 1976)*, *35*(5), 517-525.

Sandrey, M. A., & Mitzel, J. G. (2013). Improvement in dynamic balance and core endurance after a 6-week core-stability-training program in high school track and field athletes. *Journal of Sport Rehabilitation*, *22*(4), 264-271.

Shahvarpour, A., Shirazi-Adl, A., Larivère, C., & Bazrgari, B. (2015). Computation of trunk stability in forward perturbations: effects of preload, perturbation load, initial flexion and abdominal preactivation. *Journal of Biomechanics*, *48*(1), 44-52.

Shamsi, M. B., Rezaei, M., Zamanlou, M., Sadeghi, M., & Pourahmadi, M. R. (2016). Does core stability exercise improve lumbopelvic stability (through endurance tests) more than general exercise in chronic low back pain? A quasi-randomized controlled trial. *Physiotherapy Theory and Practice*, *32*(3), 171-178.

Shamsi, M., Sarrafzadeh, J., Jamshidi, A., Zarabi, V., & Pourahmadi, M. R. (2016). The effect of core stability and general exercise on abdominal muscle thickness in non-specific chronic low back pain using ultrasound imaging. *Physiotherapy Theory and Practice*, *32*(4), 277-283.

Sharma, A., Geovinson, S. G., & Singh, S. J. (2012). Effects of a nine-week core strengthening exercise program on vertical jump performances and static balance in volleyball players with trunk instability. *Journal of Sports Medicine and Physical Fitness*, *52*(6), 606-615.

Sharma, V., & Kaur, J. (2017). Effect of core strengthening with pelvic proprioceptive neuromuscular facilitation on trunk, balance, gait, and function in chronic stroke. *Journal of Exercise Rehabilitation*, *13*(2), 200-205.

Sharrock, C., Cropper, J., Mostad, J., Johnson, M., & Malone, T. (2011). A pilot study of core stability and athletic performance: is there a relationship? *International Journal of Sports Physical Therapy*, *6*(2), 63-74.

Silfies, S. P., Ebaugh, D., Pontillo, M., & Butowicz, C. M. (2015). Critical review of the impact of core stability on upper extremity athletic injury and performance. *Brazilian Journal of Physical Therapy*, *19*(5), 360-368.

Smith, B. E., Littlewood, C., & May, S. (2014). An update of stabilisation exercises for low back pain: a systematic review with meta-analysis. *BMC Musculoskeletal Disorders*, 15, 416.

Springate, S. D. (2012). The effect of sample size and bias on the reliability of estimates of error: a comparative study of Dahlberg's formula. *European Journal of Orthodontics*, *34*(2), 158-163.

Stanton, R., Reaburn, P. R., & Humphries, B. (2004). The effect of short-term Swiss ball training on core stability and running economy. *Journal of Strength & Conditioning Research*, *18*(3), 522-528.

Stilwell, P., & Harman, K. (2017). Contemporary biopsychosocial exercise prescription for chronic low back pain: questioning core stability programs and considering context. *Journal of the Canadian Chiropractic Association*, *61*(1), 6-17.

Stuber, K. J., Bruno, P., Sajko, S., & Hayden, J. A. (2014). Core stability exercises for low back pain in athletes: a systematic review of the literature. *Clinical Journal of Sport Medicine*, *24*(6), 448-456.

Sutarno, C. G., & McGill, S. M. (1995). Isovelocity investigation of the lengthening behaviour of the erector spinae muscles. *European Journal of Applied Physiology and Occupational Physiology*, *70*(2), 146-153.

Teasdale, N., Bard, C., LaRue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research*, *19*(1), 1-13.

Thomas, J. S., Lavender, S. A., Corcos, D. M., & Andersson, G. B. (1998). Trunk kinematics and trunk muscle activity during a rapidly applied load. *Journal of Electromyography and Kinesiology*, *8*(4), 215-225.

Tinto, A., Campanella, M., & Fasano, M. (2017). Core strengthening and synchronized swimming: TRX® suspension training in young female athletes. *Journal of Sports Medicine and Physical Fitness*, *57*(6), 744-751.

Tse, M. A., McManus, A. M., & Masters, R. S. (2005). Development and validation of a core endurance intervention program: implications for performance in college-age rowers. *Journal of Strength and Conditioning Research*, *19*(3), 547.

Van Daele, U., Hagman, F., Truijen, S., Vorlat, P., Van Gheluwe, B., & Vaes, P. (2010). Decrease in postural sway and trunk stiffness during cognitive dual-task in nonspecific chronic low back pain patients, performance compared to healthy control subjects. *Spine (Phila Pa 1976), 35*(5), 583-589.

Van Daele, U., Huyvaert, S., Hagman, F., Duquet, W., Van Gheluwe, B., & Vaes, P. (2007). Reproducibility of postural control measurement during unstable sitting in low back pain patients. *BMC Musculoskeletal Disorders, 8*, 44.

Van der Burg, J. C., van Wegen, E. E., Rietberg, M. B., Kwakkel, G., & van Dieën, J. H. (2006). Postural control of the trunk during unstable sitting in Parkinson's disease. *Parkinsonism & Related Disorders, 12*(8), 492-498.

van Dieën, J. H., Koppes, L. L., & Twisk, J. W. (2010). Postural sway parameters in seated balancing; their reliability and relationship with balancing performance. *Gait & Posture, 31*(1), 42-46.

van Dieën, J. H., Luger, T., & van der Eb, J. (2012). Effects of fatigue on trunk stability in elite gymnasts. *European Journal of Applied Physiology, 112*(4), 1307-1313.

van Dieën, J. H., Selen, L. P., & Cholewicki, J. (2003). Trunk muscle activation in low-back pain patients, an analysis of the literature. *Journal of Electromyography and Kinesiology, 13*(4), 333-351.

Vera-Garcia, F. J., Barbado, D., Moreno-Pérez, V., Hernández-Sánchez, C., Juan-Recio, C., & Elvira, J. L. L. (2015). Core Stability. Concepto y aportaciones al entrenamiento y la prevención de lesiones. *Revista Andaluza de Medicina del Deporte, 8*(2), 79–85.

Vera-Garcia, F. J., Barbado, D., Moreno-Pérez, V., Hernández-Sánchez, C., Juan-Recio, C., & Elvira, J. L. L. (2015). Core Stability. Evaluación y criterios para su entrenamiento. *Revista Andaluza de Medicina del Deporte, 8*(3), 130–137.

Vera-Garcia, F. J., Brown, S. H., Gray, J. R., & McGill, S. M. (2006). Effects of different levels of torso coactivation on trunk muscular and kinematic responses to posteriorly applied sudden loads. *Clinical Biomechanics (Bristol, Avon)*, *21*(5), 443-455.

Vera-Garcia, F. J., Elvira, J. L., Brown, S. H., & McGill, S. M. (2007). Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. *Journal of Electromyography and Kinesiology*, *17*(5), 556-567.

Walker, M. L., Rothstein, J. M., Finucane, S. D., & Lamb R. L. (1987). Relationships between lumbar lordosis, pelvic tilt, and abdominal muscle performance. *Physical Therapy*, *67*(4), 512-516.

Wang, X. Q., Zheng, J. J., Yu, Z. W., Bi, X., Lou, S. J., Liu, J., … Chen, P. J. (2012). A meta-analysis of core stability exercise versus general exercise for chronic low back pain. *PloS One*, *7*(12), e52082.

Watson, T., Graning, J., McPherson, S., Carter, E., Edwards, J., Melcher, I., & Burgess, T. (2017). Dance, balance and core muscle performance measures are improved following a 9-week core stabilization training program among competitive collegiate dancers. *International Journal of Sports Physical Therapy*, *12*(1), 25-41.

Weir, A., Darby, J., Inklaar, H., Koes, B., Bakker, E., & Tol, J. L. (2010). Core stability: inter-and intraobserver reliability of 6 clinical tests. *Clinical Journal of Sport Medicine*, *20*(1), 34-38.

White, A. A., & Panjabi, M. M. (1990). Biomechanical considerations in surgical management of the spine. *Clinical Biomechanics of the Spine*, 528-568.

Whyte, E., Burke, A., White, E., & Moran, K. (2015). A high-intensity, intermittent exercise protocol and dynamic postural control in men and women. *Journal of Athletic Training*, *50*(4), 392-399.

Whyte, E. F., Richter, C., O'Connor, S., & Moran, K. A. (2017). Effects of a dynamic core stability programme on the biomechanics of cutting manoeuvres: a randomised controlled trial. *Scandinavian Journal of Medicine & Science in Sports*.

Wilder, D. G., Aleksiev, A. R., Magnusson, M. L., Pope, M. H., Spratt, K. F., & Goel, V. K. (1996). Muscular response to sudden load. A tool to evaluate fatigue and rehabilitation. *Spine (Phila Pa 1976)*, *21*(22), 2628-2639.

Willigenburg, N. W., Kingma, I., & van Dieën, J. H. (2013). Center of pressure trajectories, trunk kinematics and trunk muscle activation during unstable sitting in low back pain patients. *Gait & Posture*, *38*(4), 625-630.

Wirth, K., Hartmann, H., Mickel, C., Szilvas, E., Keiner, M., & Sander, A. (2017). Core stability in athletes: a critical analysis of current guidelines. *Sports Medicine*, *47*(3), 401-414.

Yoshitomi, S. K., Tanaka, C., Duarte, M., Lima, F., Morya, E., & Hazime, F. (2006). Respostas posturais à perturbação externa inesperada em judocas de diferentes níveis de habilidade. *Revista Brasileira de Medicina do Esporte*, *12*, 159-163.

Youdas, J. W., Garrett, T. R., Harmsen, S., Suman, V. J., & Carey, J. R. (1996). Lumbar lordosis and pelvic inclination of asymptomatic adults. *Physical Therapy*, *76*(10), 1066-1081.

Zazulak, B. T., Cholewicki, J., & Reeves, N. P. (2008). Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *Journal of the American Academy of Orthopaedic Surgeons*, *16*(9), 497-505.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *American Journal of Sports Medicine, 35*(7), 1123-1130.

Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *American Journal of Sports Medicine*, *35*(3), 368-373.