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How should we quantify intensity load to design core stability training programs?

Doctoral thesis

A dissertation presented by

Belén Irles Vidal

Directed by

Dr. Francisco José Vera García and Dr. Francisco David Barbado Murillo

Elche, septiembre 2019

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El Dr. Francisco José Vera García, Titular de la Universidad Miguel Hernández de Elche, junto con el Dr. Francisco David Barbado Murillo, Ayudante Doctor en la Universidad Miguel Hernández de Elche, hacen constar que el trabajo de investigación titulado "How should we quantify intensity load to design core stability training programs?" realizado por la doctoranda Dña. Belén Irles Vidal, ha sido supervisado bajo su dirección y autorizado para su defensa de Tesis Doctoral en esta Universidad ante el tribunal correspondiente.

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HOW SHOULD WE QUANTIFY INTENSITY LOAD TO DESIGN CORE STABILITY TRAINING PROGRAMS?

Tesis Doctoral presentada por:

Dña. Belén Irles Vidal

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

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A dissertation presented by Belén Irles Vidal

Director: Dr. Francisco José Vera García

Codirector: Dr. Francisco David Barbado Murillo

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ABBREVIATION GLOSSARY

ANOVA: Analysis of variance.

CCI: Cociente de correlación intra-clase.

CS: Core stability.

CSE: Core stability exercises.

CdP: Centro de presiones.

CoP: Center of pressure.

EEM: Error estándar de la medida.

EET: Ejercicios de estabilización del tronco.

ICC: Intra-class correlation coefficient.

LCL: Lower confidence limit.

MV: Mean velocity.

RD: Resultant distance.

SEM: Standard error of measurement.

SD: Standard deviation.

UCL: Upper confidence limit.

V_{BD}: Variations of the bird-dog exercise.

V_{Br}: Variations of the front, back and side bridge exercises.

ABSTRACT

Many biomechanical studies have been performed to select the most effective and safest core stability exercises (CSE). However, although most of these exercises are commonly used to enhance motor performance and to prevent and treat musculoskeletal injuries, little is known and understood about how CSE intensity should be quantified and modulated to optimize the benefits of CSE training programs. Based on this limitation, two descriptive studies were performed in this doctoral thesis with the main objectives of *1) analyzing the reliability of different posturographic methodologies to assess the intensity of CSE in research and field settings* and of *2) establishing difficulty progressions for CSE in young physically active males and females.* In both studies, the intensity of some of the most common isometric CSE (*bird-dog*, *front bridge*, *back bridge* and *side bridge* exercises) was quantified through the evaluation of the postural control demands imposed on the participants when they tried to maintain their spine in neutral position during the exercise execution. In the *First Study*, 48 males (age: 23.4 ± 3.3 years, mass: 72.4 ± 8.2 kg, height: 175.2 ± 4.8 cm) and 28 females (age: 24.5 ± 2.7 years, mass: 62.2 ± 10.7 kg, height: 163.8 ± 8.6 cm) performed five variations of each of the aforementioned CSE on two synchronized force platforms. The mean velocity and the resultant distance of the center of pressure (CoP) displacement were calculated to assess exercise intensity through the measurement of the participants' body sway. Unlike the reliability scores of the resultant distance of CoP displacement, the standard error of measurement (SEM) and the intra-class correlation coefficient ($ICC_{3,1}$) scores obtained by the mean velocity of the CoP displacement were acceptable (most exercise variations obtained SEM values < 21% and $ICC_{3,1}$ values > 0.60) to establish intensity progressions for the CSE. The exercise progressions obtained by males and females were very similar. However, the participants with high trunk control showed less significant differences between exercise variations than the participants with low trunk control, which highlights the need to

individualize these progressions according to the participants' training level. In the *Second Study*, 12 males (age: 23.5 ± 3.6 years; mass: 73.9 ± 6.3 kg; height: 173.9 ± 4.7 cm) and 11 females (age: 24.1 ± 1.5 years; mass: 63.1 ± 8.8 kg; height: 165.0 ± 11.5 cm) performed the same exercise variations also on the two force platforms, but in this case we placed a smartphone accelerometer on the participants' pelvis to assess pelvic acceleration. Most CSE variations obtained moderate-to-high reliability scores for the pelvic acceleration (0.71 < ICC < 0.88; 13.23% ≤ SEM ≤ 22.99%) and low-to-moderate reliability scores for the mean velocity of the CoP sway (0.24 < ICC < 0.89; 9.88% ≤ SEM ≤ 35.90%). In addition, correlations between these two variables were moderate-to-high (0.52 ≤ *r* ≤ 0.81). Based on these results, smartphone accelerometers placed on the pelvis provide a more reliable and local measure of postural control during CSE than the MV of CoP sway. Moreover, considering these results and the low-cost, portability and usability of the smartphone accelerometers, these devices seem adequate to quantify the intensity of the CSEs in research and field settings. Overall, this doctoral thesis provides useful information both to guide the design and to control the training intensity of CSE training programs in young physically active individuals.

RESUMEN

En la actualidad, varios estudios biomecánicos han analizado qué ejercicios de estabilización del tronco (EET) son los más eficaces y seguros. Sin embargo, aunque la mayoría de esos ejercicios se utilizan habitualmente para mejorar el rendimiento motriz, así como la prevención y tratamiento de lesiones músculo esqueléticas, en realidad se sabe poco sobre cómo la intensidad de los EET debería ser cuantificada y manipulada para optimizar los beneficios de los programas de entrenamiento basados en estos ejercicios.

En base a esta limitación, en esta tesis se llevaron a cabo dos estudios descriptivos con los objetivos principales de *1) analizar la fiabilidad de distintas metodologías posturográficas para evaluar la intensidad de los EET tanto en laboratorio como en campo y 2) establecer progresiones de dificultad para esos ejercicios en hombres y mujeres físicamente activas.* En ambos estudios se cuantificó la intensidad de algunos de los EET isométricos más comunes (*perro de muestra*, *puente frontal*, *puente dorsal* y *puente lateral*) a través de la evaluación del control postural mostrado por los participantes al intentar mantener la columna vertebral en posición neutra durante la ejecución de dichos ejercicios. En el *Primer Estudio*, 48 hombres (edad: 23.4 ± 3.3 años, peso: 72.4 ± 8.2 kg, altura: 175.2 ± 4.8 cm) y 28 mujeres (edad: 24.5 ± 2.7 años, peso: 62.2 ± 10.7 kg, altura: 163.8 ± 8.6 cm) realizaron cinco variaciones de cada uno de los ejercicios mencionados anteriormente sobre dos plataformas de fuerzas sincronizadas. Para evaluar la intensidad de los ejercicios, se analizó la oscilación corporal de los participantes mediante el cálculo de la velocidad media y la distancia resultante de la oscilación del centro de presiones (CdP). Contrariamente a lo observado para la distancia resultante, los valores del error estándar de la medida (EEM) y del coeficiente de correlación intra-clase ($CCI_{3,1}$) mostrados por la velocidad media fueron adecuados (la mayoría de las variaciones de los ejercicios obtuvieron valores de EEM $<$ 21% y

de $CCI_{3,1} > 0.60$) para establecer progresiones de intensidad para los EET. Las progresiones obtenidas por hombres y mujeres fueron muy similares. Sin embargo, aquellos participantes con mayor control de tronco mostraron menos diferencias significativas entre las variaciones de los ejercicios que los participantes con menos control de tronco, lo cual destaca la necesidad de individualizar estas progresiones de acuerdo al nivel de entrenamiento de los participantes. En el *Segundo Estudio*, 12 hombres (edad: 23.5 ± 3.6 años; peso: 73.9 ± 6.3 kg; altura: 173.9 ± 4.7 cm) y 11 mujeres (edad: 24.1 ± 1.5 años; peso: 63.1 ± 8.8 kg; altura: 165.0 ± 11.5 cm) realizaron los mismos ejercicios descritos en el primer estudio sobre dos plataformas de fuerzas, pero en este caso se colocó en un smartphone en la pelvis de los participantes para evaluar la aceleración pélvica a través del acelerómetro que lleva integrado dicho dispositivo. La fiabilidad de la mayoría de las variaciones de los EET fue moderada-alta para la aceleración pélvica ($0.71 < CCI < 0.88$; $13.23\% \leq EEM \leq 22.99\%$) y baja-moderada para la velocidad media del CdP ($0.24 < CCI < 0.89$; $9.88\% \leq EEM \leq 35.90\%$). Además, las correlaciones entre estas dos variables fueron moderadas-altas ($0.52 \leq r \leq 0.81$). En base a estos resultados, los acelerómetros integrados en los smartphones colocados en la pelvis aportan una medida más fiable y local del control postural durante los EET que la oscilación del CdP medida a través de la velocidad media. Asimismo, teniendo en cuenta estos resultados, así como el bajo coste, portabilidad y facilidad de uso de los acelerómetros integrados en los smartphones, estos dispositivos podrían ser una herramienta adecuada para cuantificar la intensidad de los EET tanto en el ámbito de la investigación como en el campo profesional. En general, esta tesis ofrece información útil para guiar en el diseño y control de la intensidad de los programas de entrenamiento de EET en hombres y mujeres jóvenes físicamente activos.

CHAPTER 1

GENERAL INTRODUCTION

Chapter 1
Introduction

1.1. The concept of *core stability*

The *core* of the body includes all the muscles and osteoarticular structures surrounding the lumbo-pelvic complex (Axler & McGill, 1997; Kibler, Press, & Sciascia, 2006; McGill, 1997; McGill, Juker, & Kropf, 1996). As a functional concept, the passive and active structures of the core work as a unit, being the center of the functional kinetic chain and providing local strength and stability (Kibler et al., 2006; McGill, Grenier, Kavcic, & Cholewicki, 2003; Panjabi, 1992), which has been related to optimization of the force transmission to the extremities and spine stabilization (Escamilla et al., 2010; Kibler et al., 2006; Vera-García et al., 2015a).

In Biomechanics, *core stability* (CS) has been defined as *the ability of the osteoarticular and muscle structures, coordinated by the motor control system, to maintain or resume a trunk position or trajectory while it is being challenged by internal or external perturbations* (Vera-García et al., 2015a). This concept has attracted considerable attention in the last 20 years as it has been related to: a) injury prevention and rehabilitation (Hides, Jull, & Richardson, 2001; Whyte, Richter, O'Connor, & Moran, 2018; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007a); b) sport performance optimization (Manchado, Garcia-Ruiz, Cortell-Tormo, & Tortosa-Martinez, 2017; Romero-Franco, Martinez-Lopez, Lomas-Vega, Hita-Contreras, & Martinez-Amat, 2012; Watson et al., 2017); and c) improvement of functional capacity for everyday tasks (Kang, 2015; Ketelhut, Kindred, Manago, Hebert, & Rudroff, 2015). Therefore, CS exercises (CSE) are common elements in sports, fitness and clinical settings.

1.2. Biomechanical assessment of core stability

Based on the concepts of energy wells, stiffness and stability (mathematically formalized by Bergmark), Cholewicki & McGill (1996) developed a *mathematical model* to quantify spine mechanical stability in static or quasi-static conditions (Bergmark, 1989; Cholewicki & McGill, 1996) which focused on elastic potential energy calculations as a function of stiffness and elastic energy storage. On the other hand, following a more operational biomechanical concept of CS (as the concept presented in the previous section of this Introduction), two laboratory methodologies have generally been used to assess this capability:

1. The *sudden loading/unloading methodology*, which measures the trunk mechanical response (i.e. trunk displacement, stiffness and damping) (Barbado, Barbado, Elvira, Dieen, & Vera-Garcia, 2016; Cholewicki, Simons, & Radebold, 2000; Gardner-Morse & Stokes, 2001; Vera-Garcia, Brown, Gray, & McGill, 2006; Vera-Garcia, Elvira, Brown, & McGill, 2007) and/or the trunk muscular response (i.e. amplitude and timing of the muscle response) (Glofcheskie & Brown, 2017; Ishida, Suehiro, Kurozumi, & Watanabe, 2016; Shahvarpour, Shirazi-Adl, Lariviere, & Bazrgari, 2015) to quick and controlled perturbations.
2. The *unstable sitting methodology*, which quantifies the fluctuations of the participants' center of pressure (CoP) regarding a desired position or trajectory while sitting on an unstable seat placed on a force platform (Barbado, Barbado, et al., 2016; Cholewicki, Simons, et al., 2000; Elvira et al., 2013; Lee & Granata, 2008; Reeves, Cholewicki, & Milner, 2005; van Dieen, Koppes, & Twisk, 2010).

These two methodologies have been useful in clarifying some CS roles in injury prevention and rehabilitation and in sport performance. In this sense, they have been effective in detecting CS deficits associated to low back disorders (Arab, Shanbehzadeh, Rasouli, Amiri, & Ehsani, 2018; Cyr, Wilson, Mehyar, & Sharma, 2019; Radebold, Cholewicki, Polzhofer, & Greene, 2001; Reeves, Cholewicki, & Narendra, 2009; Shahvarpour, Gagnon, Preuss, Henry, & Lariviere, 2018). In addition, poor trunk response to sudden forces release has been related to higher incidence of lower limb injuries (Zazulak et al., 2007a; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007b). In sport context, the sudden loading/unloading and the unstable sitting methodologies have also been useful to reveal that specialization in sports with large balance demands (i.e. kayaking and judo) induces specific CS adaptations, which are not revealed through nonspecific tests (Barbado, Barbado, et al., 2016; Glofcheskie & Brown, 2017). In addition, both methodologies have been used to measure CS in international and national level judokas, which has allowed to determine which CS parameters seem more important to improve judo performance (Barbado, Lopez-Valenciano, et al., 2016).

Despite the utility of these methodologies, their high economic cost and their difficulty of use make them hard to employ outside the laboratory settings by health and sport professionals without a biomechanical background. Furthermore, although the outcomes obtained from these methodologies (i.e. trunk stiffness, CoP sway, etc.) can help to differentiate and classify participants according to their CS status, they are not easily applicable to training load quantification, as these outcomes are not obtained during the execution of the exercises used in the CS training programs.

To solve some of these problems, a variety of field based tests have been used in sport, fitness, school, clinical and research settings to measure CS (Vera-García et al., 2015b; Vera-Garcia, Lopez-Plaza, Juan-Recio, & Barbado, 2019b), as for example: the *Double-leg Lowering Test* (Krause, Youdas, Hollman, & Smith, 2005; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; Sharrock, Cropper, Mostad, Johnson, & Malone, 2011), the *Sahrmann Core Stability Test* (Mills, J. D., Taunton, J. E., & Mills, W. A., 2005; Stanton, Reaburn, & Humphries, 2004), the *Three Plane Core Strength Test* (Chuter, de Jonge, Thompson, & Callister, 2015; Kibler et al., 2006; A. Weir et al., 2010), the *Star Excursion Balance Test* (Chuter et al., 2015; Kibler et al., 2006; A. Weir et al., 2010), and the *Biering-Sorensen Test* (Chuter et al., 2015; Leetun et al., 2004; Nesser, Huxel, Tincher, & Okada, 2008). However, despite the low cost and the easy application of these tests, most of them do not follow a mechanical concept of CS, and they even measure other related capabilities, such as trunk isometric endurance (e.g. *Biering-Sorensen Test*) or whole-body balance in single leg stance (e.g. *Three Plane Core Strength Test* and *Star Excursion Balance Test*) (Vera-García et al., 2015b; Vera-Garcia et al., 2019b). Other limitations of these tests are their low reliability (e.g. *Three Plane Core Strength Test*) (Chuter et al., 2015; Kibler et al., 2006; A. Weir et al., 2010) and their lack of sensitivity to discriminate between individuals with high physical condition (e.g. *Double-leg Lowering Test*) (Walker, Rothstein, Finucane, & Lamb, 1987; A. Weir et al., 2010).

Considering both, the methodological limitations of the field based tests and the difficulty of applying the biomechanical methodologies to perform experimental interventions in field settings, future studies should provide practitioners, coaches, physical trainers and researchers with more functional and ecological biomechanical measures of CS. These measures may help to address one of the main limitations when designing and conducting CS training programs, i.e. the lack of methodologies to quantify and control the training load.

1.3. Core stability training programs

The design of CS training programs depends on the combination of a variety of factors that can be modified to optimize CS adaptations: the type of exercises, the length of the program, the duration of the exercises and rest periods, the number of repetitions, the type of contraction, the speed of execution, etc. (Cissik, 2002; Hatfield et al., 2006; Vera-Garcia, Monfort Pañego, & Sarti-Martínez, 2005). Among them, research has traditionally focused on studying the trunk muscle activation and the spinal loading during core exercises in order to select the most effective and safest exercises for trunk conditioning (Axler & McGill, 1997; Juker, McGill, Kropf, & Steffen, 1998; Kavcic, Grenier, & McGill, 2004). In this sense, different variation of *bridges* or *planks* and *bird-dog* exercises are some of the most commonly used exercises in CS training programs (Boucher, Preuss, Henry, Dumas, & Lariviere, 2016; Boucher, Preuss, Henry, Nugent, & Lariviere, 2018; El Shemy, 2018; Hoglund, Pontiggia, & Kelly, 2018; Toprak Celenay & Ozer Kaya, 2017; Watson et al., 2017), as they challenge the neuromuscular system while imposing non-excessive loads on the lumbar spine (Axler & McGill, 1997; Kavcic et al., 2004).

Despite the large number of investigations that have been performed to select the most effective and safest CSE, little is known and understood about how other training factors should be modulated to optimize the benefits of CS training programs. For example, the training intensity and the training volume of these programs are commonly modified by changing the difficulty (manipulating the body posture, the base of support, etc.) (Chuter et al., 2015; Jonathan D Mills et al., 2005; Parkhouse & Ball, 2011; Whyte et al., 2018) as well as the duration and/or the number of repetitions and sets (Clark et al., 2017; Chuter et al., 2015; Jonathan D Mills et al., 2005; Moon et al., 2013; Parkhouse & Ball, 2011; Sato & Mokha, 2009) of the CSE, respectively. However, the modification of these training characteristics is normally based on the experience and criteria of the person who designs and/or conducts the training program rather than on objective parameters (Chuter et al., 2015; Jonathan D Mills et al., 2005; Parkhouse & Ball, 2011). The training volume can be quantified by the time that the trunk posture is maintained during the repetitions and sets of the isometric CSE (such as *front bridge*, *back bridge* or *side bridge* exercises) (Jonathan D Mills et al., 2005; Moon et al., 2013; Sato & Mokha, 2009). However, to the best of the authors' knowledge, no methodology has been used to quantify the intensity of the CSE based on objective parameters. Considering that the training intensity of these exercises reflects the participants' difficulty to control the trunk posture during their execution, posturographic measurements could be used to quantify the intensity of the CSE. However, although posturography has been used to develop the unstable sitting methodology presented above (Barbado, Barbado, et al., 2016; Cholewicki, Simons, et al., 2000; Elvira et al., 2013; Lee &

Granata, 2008; Reeves et al., 2005; van Dieen et al., 2010), it still has not been applied to the quantification of the postural control challenge imposed on each participant during the execution of CSE.

The most conventional posturographic methodologies found in the literature are based on the use of force platforms (Chaudhry, Bukiet, Ji, & Findley, 2011; M. Duarte & Freitas, 2010; Dufvenberg, Adeyemi, Rajendran, Öberg, & Abbott, 2018; Lopez Panos, Ortiz-Gutierrez, Chana Valero, & Felipe Concepcion, 2019). However, nowadays the use of more accessible technology to measure postural control is currently increasing, as for example the use of accelerometers embedded in smartphones (Chiu, Tsai, Lin, Hou, & Sung, 2017; Han, Lee, & Lee, 2016). The assessment of the participants' postural control during the execution of CSE through these posturographic methodologies may provide objective data to quantify the intensity of the CS training programs, which is crucial to describe the dose-response relationships between training characteristics and CS adaptations. Further research is needed to explore the potential and limitations of posturographic methodologies based on both traditional and more modern technology to quantify the intensity of these programs.

CHAPTER 2

RESEARCH AIMS AND HYPOTHESES

Chapter 2

Research aims and hypotheses

2.1. General objectives

Based on the limitations of the literature presented in the previous chapter, the general objectives of this doctoral thesis were *1) to analyze the reliability of different posturographic methodologies to assess the intensity of CSE in research and field settings and 2) to establish difficulty progressions for those exercises in young physically active males and females*.

To carry out our objectives we designed two descriptive posturographic studies in which the intensity of some of the most common isometric CSE (i.e. bird-dog, front bridge, back bridge and side bridge exercises) was quantified through the evaluation of the postural control demands imposed to the participants when they tried to maintain the posture during the exercise performance. In the first study, the participants performed the exercises on two synchronized force platforms to observe the CoP displacement (i.e. whole-body sway) while performing several variations of these exercises. The oscillation of the body was used to establish different exercise intensity progressions. In the second study, the same exercise variations were performed again on the two force platforms, but in this case, a smartphone accelerometer was also placed on the participants' pelvis to assess pelvic accelerations. The reliability and correlations between both methodologies were analyzed. The two research studies were named as follows:

- Study 1: Progressions of core stability exercises based on postural control challenge assessment.
- Study 2: Training intensity quantification of core stability exercises based on a smartphone accelerometer.

2.2. Specific objectives

The specific objectives have been organized depending on the two studies of this doctoral thesis:

Study 1:

1. To analyze the absolute and relative reliability of the CoP sway to assess the intensity of different variations of bird-dog, front bridge, back bridge and side bridge exercises.
2. To develop intensity progressions for bird-dog, front bridge, back bridge and side bridge exercises based on the postural control challenge imposed on the participants during the different isometric variations of these exercises.
3. To analyze the effect of the participants' sex and postural control level on these progressions.

Study 2:

4. To analyze the reliability of the pelvic acceleration (obtained from a smartphone accelerometer): a) to classify individuals (i.e. relative reliability) according to their pelvic postural control in different variations of bird-dog, front bridge, back bridge and side bridge exercises; and b) to provide reference scores (i.e. absolute reliability) which would allow to identify if changes during training are caused by treatment or by within-subject variability.
5. To explore the relationship between local (pelvic acceleration) and global stability (whole-body sway) while performing CSE.

2.3. Research hypotheses

The following hypotheses were established in the two studies of this doctoral thesis:

Study 1:

1. Considering the fact that posturography is a reliable methodology to assess both, whole-body balance in standing position (Chiu et al., 2017; Han et al., 2016) and trunk postural control while sitting (Barbado, Lopez-Valenciano, et al., 2016; Barbado, Moreside, & Vera-Garcia, 2017; Cholewicki, Polzhofer, & Radebold, 2000; Lee & Granata, 2008; Reeves, Everding, Cholewicki, & Morrisette, 2006; van Dieen et al., 2010), the reliability of force platforms to quantify the intensity of the CSE (through measuring the participants' CoP displacement) will be high.
2. Although we have not found any posturographic assessment of CSE in the literature, based on mechanical criteria and on the results of different electromyographic studies (Atkins et al., 2015; Calatayud, Borreani, Colado, Martin, & Rogers, 2014; Calatayud, Casana, Martin, Jakobsen, Colado, & Andersen, 2017; Calatayud, Casana, Martin, Jakobsen, Colado, Gargallo, et al., 2017; Czaprowski et al., 2014; Escamilla, Lewis, Pecson, Imamura, & Andrews, 2016; Garcia-Vaquero, Moreside, Brontons-Gil, Peco-Gonzalez, & Vera-Garcia, 2012; Kim, Oh, & Park, 2013; McGill & Karpowicz, 2009; Vera-Garcia, Barbado, & Moya, 2014), the participants' body sway will be higher in those exercise variations in which: i) the weight lifted off the floor and/or the lever arm is higher; ii) the base of support is lower and/or the number of limbs supported is less; and/or iii) the surface of support is more unstable.
3. Considering that some electromyographic studies have found little or no significant differences in muscle activation between males and females

during CSE (see for example: Garcia-Vaquero et al., 2012), sex will not have a significant effect on the CSE progressions.

4. Based on the experience of our research group in designing and conducting CSE programs, trunk postural control level will have an influence on the CSE progressions. In this sense, participants with low trunk control will not show differences between the most difficult variations of the exercises (i.e. floor effect), while participants with high trunk control will not show differences between the easiest variations (i.e. ceiling effect).

Study 2:

5. Taking into account that previous studies have shown that smartphone-based accelerometry is a reliable methodology to assess ankle stability and whole-body dynamic balance (Chiu et al., 2017; Han et al., 2016), the reliability of the smartphone accelerometers to quantify the intensity of the CSE (measuring the participants' pelvic acceleration) will be high.
6. Considering the important role of trunk motor control to guarantee a proper whole-body stability (Park, Hyun, & Jee, 2016; Watson et al., 2017), pelvic accelerations and CoP sway will show high correlations.

2.4. Objetivos generales

En base a las limitaciones mostradas en la literatura que han sido expuestas en el capítulo anterior, los objetivos generales de esta tesis doctoral fueron *1) analizar la fiabilidad de las distintas metodologías posturográficas para evaluar la intensidad de los ejercicios de estabilización del tronco, tanto en laboratorio como en campo y 2) establecer progresiones de dificultad para esos ejercicios en hombres y mujeres físicamente activas.*

Para llevar a cabo nuestros objetivos se diseñaron dos estudios posturográficos descriptivos en los que se cuantificó la intensidad que producen algunos de los ejercicios isométricos de estabilización del tronco más comunes (perro de muestra, puente frontal, puente dorsal y puente lateral) a través del análisis del control postural mostrado por los participantes al intentar mantener la postura durante la ejecución de dichos ejercicios. En el primer estudio, los participantes realizaron los ejercicios sobre dos plataformas de fuerzas sincronizadas para observar la oscilación corporal a través del análisis del desplazamiento del centro de presiones (CdP) al realizar diversas variaciones de cada ejercicio. Dicha oscilación corporal fue utilizada para establecer las progresiones de intensidad de estos ejercicios. En el segundo estudio, esos mismos ejercicios fueron nuevamente realizados sobre dos plataformas de fuerzas, pero en este caso, se colocó en la pelvis de los participantes un smartphone, el cual dispone de un acelerómetro integrado que permitió registrar la aceleración pélvica. En este estudio se analizó la fiabilidad y las correlaciones entre ambas metodologías posturográficas. Los títulos de los dos trabajos de investigación se presentan a continuación:

- Estudio 1: Progresiones de ejercicios de estabilización del tronco basadas en el análisis del control postural.

- Estudio 2: Cuantificación de la intensidad de entrenamiento producida por los ejercicios de estabilización del tronco a través de acelerómetros integrados en smartphones.

2.5. Objetivos específicos

A continuación se presentan los objetivos específicos de los dos estudios que forman parte de esta tesis doctoral:

Estudio 1:

1. Analizar la fiabilidad absoluta y relativa de las oscilaciones del CdP para medir la intensidad de distintas variaciones de los ejercicios perro de muestra, puente frontal, puente dorsal y puente lateral.
2. Desarrollar progresiones de intensidad para los ejercicios perro de muestra, puente frontal, puente dorsal y puente lateral, en función de la dificultad de los participantes para controlar la postura durante la ejecución de diversas variaciones isométricas de estos ejercicios.
3. Analizar el efecto del sexo y del nivel de control postural de los participantes sobre estas progresiones.

Estudio 2:

4. Analizar la fiabilidad de la aceleración de la pelvis (obtenida mediante un acelerómetro integrado en un smartphone) para: a) clasificar individuos (i.e. fiabilidad relativa) en función del control postural pélvico mostrado en diferentes variaciones del perro de muestra, puente frontal, puente dorsal y puente lateral; y b) proporcionar valores de referencia (i.e. fiabilidad absoluta) que permitan identificar si los cambios durante el entrenamiento son causados por una intervención o por la variabilidad intra-sujeto.

5. Explorar la relación entre la estabilidad local (aceleración de la pelvis) y la estabilidad global (oscilación de todo el cuerpo) al realizar los ejercicios de estabilización del tronco.

2.6. Hipótesis de investigación

A continuación se presentan las hipótesis de los dos estudios de esta tesis doctoral:

Estudio 1:

1. Diversos estudios han mostrado que la posturografía es una metodología fiable para evaluar tanto el equilibrio corporal en posición de bipedestación (Chiu et al., 2017; Han et al., 2016), como el control postural del tronco en posición de sedestación (Barbado, Lopez-Valenciano, et al., 2016; Barbado et al., 2017; Cholewicki, Polzhofer, et al., 2000; Lee & Granata, 2008; Reeves et al., 2006; van Dieen et al., 2010). Considerando los resultados obtenidos por estos trabajos, las plataformas de fuerza mostrarán una alta fiabilidad para cuantificar la intensidad de los ejercicios de estabilización del tronco a través de la medición del desplazamiento del CdP de los participantes.
2. No hemos encontrado en la literatura ningún estudio que haya llevado a cabo una evaluación posturográfica de los ejercicios de estabilización del tronco. No obstante, teniendo en cuenta diversos criterios mecánicos y los resultados obtenidos por varios estudios electromiográficos (Atkins et al., 2015; Calatayud et al., 2014; Calatayud, Casana, Martin, Jakobsen, Colado, & Andersen, 2017; Calatayud, Casana, Martin, Jakobsen, Colado, Gargallo, et al., 2017; Czaprowski et al., 2014; Escamilla et al., 2016; Garcia-Vaquero et al., 2012; Kim et al., 2013; McGill & Karpowicz, 2009; Vera-Garcia et al., 2014), la oscilación corporal será mayor en aquellas variaciones en las que: i) haya mayor masa suspendida en el aire y/o mayor brazo de palanca; ii)

haya menor base de sustentación y/o menor número de apoyos; y/o iii) la superficie de apoyo sea más inestable.

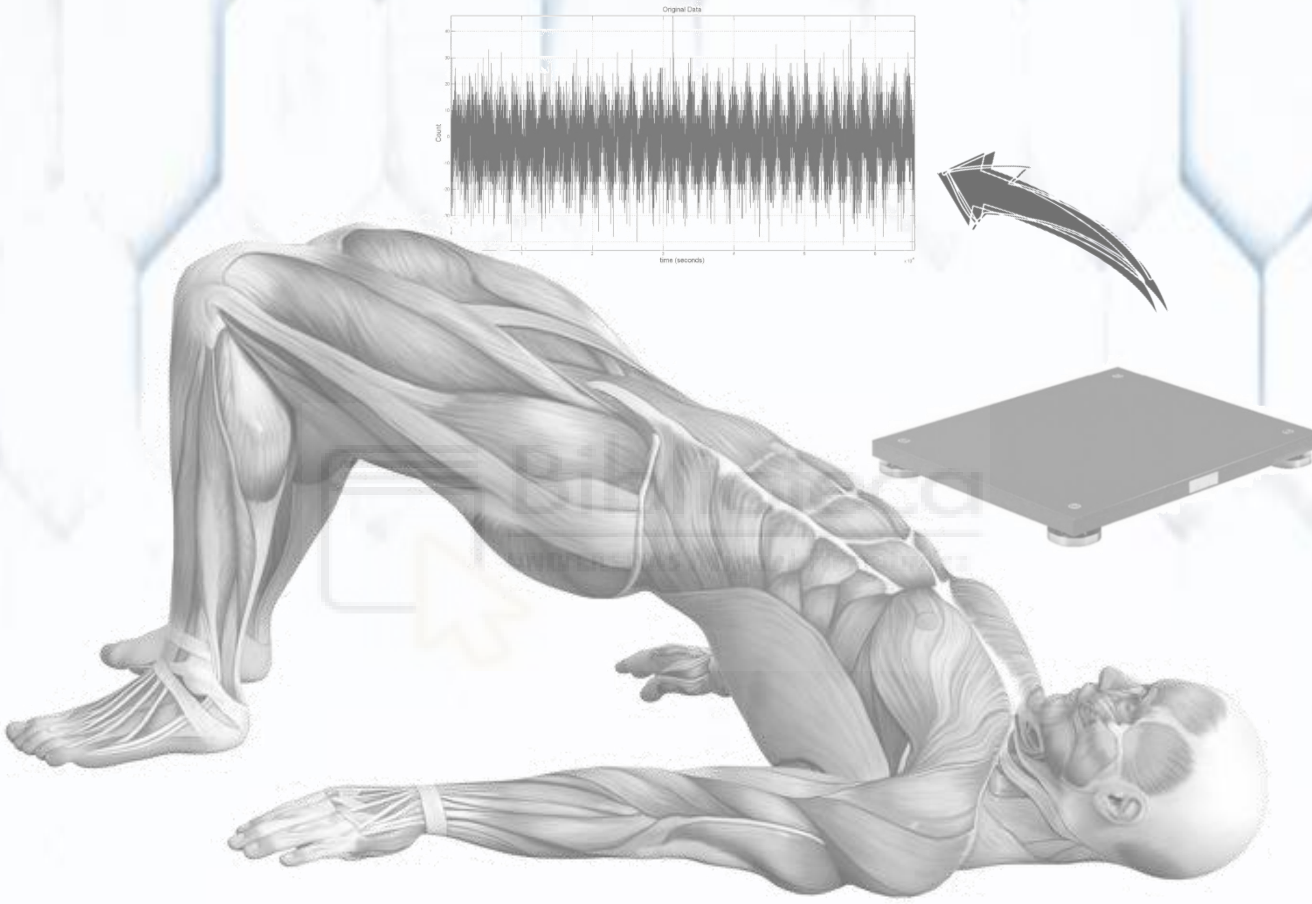
3. Considerando que algunos estudios electromiográficos han encontrado diferencias pequeñas o no significativas en la activación muscular entre hombres y mujeres durante los ejercicios de estabilización del tronco (ver por ejemplo: Garcia-Vaquero et al., 2012), el sexo no tendrá un efecto significativo en las progresiones de ejercicios de estabilización del tronco.
4. Basándonos en la experiencia de nuestro grupo de investigación en el diseño y aplicación de programas de ejercicios de estabilidad del tronco, pensamos que el nivel de control postural tendrá un efecto significativo sobre las progresiones de los ejercicios de estabilización del tronco. Nuestra hipótesis es que los participantes con menor control de tronco no mostrarán diferencias entre las variaciones más difíciles de los ejercicios (i.e. efecto suelo), mientras que los participantes con alto control de tronco no mostrarán diferencias entre las variaciones más fáciles (i.e. efecto techo).

Estudio 2:

5. Teniendo en cuenta algunos estudios previos que han mostrado que la acelerometría integrada en smartphones como una metodología fiable para evaluar tanto la estabilidad de tobillo como el equilibrio dinámico corporal (Chiu et al., 2017; Han et al., 2016), estos instrumentos mostrarán una fiabilidad alta para cuantificar la intensidad de los ejercicios de estabilización del tronco a través de la medición de la aceleración pélvica de los participantes.
6. Considerando el importante papel del control motor del tronco para garantizar una adecuada estabilidad corporal (Park et al., 2016; Watson et al., 2017), las correlaciones entre las aceleraciones de la pelvis y la oscilación del CdP serán altas.

CHAPTER 3

STUDY 1



Based on the following article submitted to *Journal of Orthopaedic & Sports Physical Therapy*:

Progressions of core stability exercises based on postural control challenge assessment.

Belen Irles-Vidal, David Barbado, Amaya Prat-Luri, María Pilar García-Vaquero, Casto Juan-Recio, Francisco J. Vera-Garcia.

Chapter 3

Study 1

Progressions of core stability exercises based on postural control challenge assessment.

by

Belen Irles-Vidal, David Barbado, Amaya Prat-Luri, María Pilar García-Vaquero, Casto Juan-Recio, Francisco J. Vera-Garcia.

3.1. ABSTRACT

The intensity progression of core stability exercises (CSE) is usually based on personal criteria rather than on objective parameters. This study aimed to analyze the reliability of the center of pressure (CoP) sway to assess the intensity of the CSE, to develop exercise progressions for four of the most common CSE based on the postural control challenge imposed on the participants and to analyze the effect of participants' sex and postural control level on these progressions. Seventy-six males and females performed five variations of front bridge, back bridge, side bridge and bird-dog exercises on two force platforms. The mean velocity of the CoP displacement was calculated to assess exercise intensity through the measurement of the participants' body sway. In general, long bridges produced higher body sway than short bridges, bridging with single leg support produced higher body sway than bridging with double leg support and bridging on an inflated rubber hemisphere produced higher body sway than bridging on the floor. The most difficult bridging variations were those performed on an inflated rubber hemisphere with single leg support. Regarding the bird-dog, two-point positions produced higher body sway than three-point positions and the positions performed on an inflated rubber hemisphere produced higher body sway than those performed on the floor. The CSE progressions obtained by males and females were very similar. However, the

participants with high trunk control showed less significant differences between exercise variations than the participants with low trunk control, which highlights the need to individualize the progressions according to the participants' training level. Overall, this study provides useful information to guide the prescription of CSE progressions in young physically active individuals.

Keywords: core stability, training intensity, trunk control, load progression, posturography.

3.2. INTRODUCTION

CSE are common elements of training programs in fitness, sports and rehabilitation (Borghuis, Hof, & Lemmink, 2008; Gouttebarge & Zuidema, 2018; Khaiyat & Norris, 2018; Slomka et al., 2018) which challenge the capacity of the motor control system to maintain or resume a relative position or trajectory of the trunk under internal and/or external loads (Vera-García et al., 2015a; Zazulak, Cholewicki, & Reeves, 2008).

Bridge or plank exercises and bird-dog exercises are some of the most commonly used CSE (Boucher et al., 2016; Boucher et al., 2018; El Shemy, 2018; Hoglund et al., 2018; Toprak Celenay & Ozer Kaya, 2017; Watson et al., 2017). They are isometric trunk exercises that challenge the participants' postural control in a way that spares the spine of excessive compressive forces (Axler & McGill, 1997; Kavcic et al., 2004). Bridge exercises consist in maintaining the spine in neutral position (with minimal associated trunk motion) while holding the pelvis lifted off the floor, against gravity, in different prone, supine or lateral positions (i.e. front, back and side bridge exercises, respectively) (Bjerkefors, Ekblom, Josefsson, & Thorstensson, 2010; Ekstrom, Donatelli, & Carp, 2007; Garcia-Vaquero et al., 2012; Okubo et al., 2010; Saliba et al., 2010; Vera-Garcia, Barbado, Flores-Parodi, Alonso-Roque, & Elvira, 2013; Vera-García et al., 2015b; Vera-Garcia et al., 2014). Similarly, bird-dog exercises consist in holding the spine in neutral position while performing different limb movements in quadruped positions (Bjerkefors et al., 2010; Garcia-Vaquero et al., 2012; Vera-García et al., 2015b; Vera-Garcia et al., 2014).

Many electromyographic studies have been performed to describe the trunk and hip muscle activation during different variations of these CSE. As these studies have shown, bridge and bird-dog exercises produce muscle activation patterns characterized by low-moderate muscle activation levels (Bonino et al., 2010; Ekstrom et al., 2007; Imai et al., 2010; Konrad, Schmitz, & Denner, 2001; Lehman, Hoda, & Oliver, 2005; Okubo et al., 2010; Willardson et al., 2010), in which the main agonists are the muscles that counteract gravity: i) trunk and hip flexors for front bridges (Ekstrom et al., 2007; Escamilla et al., 2016; Garcia-Vaquero et al., 2012; Imai et al., 2010; Maeo, Takahashi, Takai, & Kanehisa, 2013; McGill & Karpowicz, 2009; Vera-Garcia et al., 2013; Vera-Garcia et al., 2014); ii) trunk and hip extensors for back bridges (Bjerkefors et al., 2010; Ekstrom et al., 2007; Garcia-Vaquero et al., 2012; Imai et al., 2010; Maeo et al., 2013; Vera-Garcia et al., 2013); iii) trunk lateral flexors and hip abductors for side bridges (Ekstrom et al., 2007; Escamilla et al., 2016; Garcia-Vaquero et al., 2012; Imai et al., 2010; Maeo et al., 2013; McGill & Karpowicz, 2009; Vera-Garcia et al., 2013); and iv) trunk extensors and rotators, hip extensors and shoulder flexors for bird-dog exercises (Callaghan, Gunning, & McGill, 1998; Ekstrom et al., 2007; Garcia-Vaquero et al., 2012; Souza, Baker, & Powers, 2001; Vera-Garcia et al., 2014). The muscle activation patterns of these CSE change when the conventional form of the exercise technique is modified, for example: i) bridge exercises with single leg support (raising a leg) increase trunk rotators activation (Calatayud, Casana, Martin, Jakobsen, Colado, Gargallo, et al., 2017; Escamilla et al., 2016; Garcia-Vaquero et al., 2012; Vera-Garcia et al., 2014); ii) bridge or bird-dog exercises on unstable support surfaces (fitballs or Swiss balls, inflated rubber hemispheres, slings, etc.) increase muscle coactivation (Atkins et al., 2015; Calatayud et al., 2014; Calatayud, Casana, Martin, Jakobsen, Colado, & Andersen, 2017; Calatayud, Casana, Martin, Jakobsen, Colado, Gargallo, et al., 2017; Czaprowski et al., 2014; Escamilla et al., 2016; Vera-Garcia et al., 2014); iii) front or side bridge exercises kneeling on the floor (short bridges) and/or with extended elbows reduce muscle activation (Escamilla et al., 2016; Vera-Garcia et al., 2014); and iv) bridge or bird-dog exercises with limb motions increase CS demands and muscle coactivation (Kim et al., 2013; McGill & Karpowicz, 2009; Vera-Garcia et al., 2014).

Although all these studies have provided basic information to prescribe CS programs (i.e. main muscles recruited, muscle coactivation patterns, etc.), electromyography does not allow the assessment of the postural control challenge imposed on each participant during the CSE, which is necessary to quantify the training intensity (Barbado, Irles-Vidal, Prat-Luri, Garcia-Vaquero, & Vera-Garcia, 2018). CSE intensity is a key factor for the prescription of CS programs, which is normally modulated by modifying the exercise difficulty through variations in the exercise technique (i.e. modifying the lever arm and/or the base of support, performing the exercises on different surfaces/devices, etc.) (Boucher et al., 2016; Boucher et al., 2018; Chuter et al., 2015; El Shemy, 2018; Hoglund et al., 2018; Jonathan D Mills et al., 2005; Parkhouse & Ball, 2011). However, the progression of the CSE intensity/difficulty throughout training programs is usually based on personal criteria rather than on objective parameters (Chuter et al., 2015; Jonathan D Mills et al., 2005; Parkhouse & Ball, 2011). Therefore, some questions arise when a coach, a personal trainer, a fitness instructor, a practitioner or a researcher modifies the exercise technique to increase the CSE intensity: Does this modification entail a real change of intensity for the participant? Is this technique modification more appropriate than other techniques to increase the CSE intensity? Further research is needed to answer these and other questions and to ultimately establish CSE progressions based on objective measurements of CSE intensity rather than on the subjective criteria of those professionals who design and/or conduct the training program.

In the present study, five variations of the front bridge, back bridge, side bridge and bird-dog exercises were performed on two force platforms to assess the difficulty of each variation based on the CoP sway during their execution (Barbado et al., 2018). The main objectives were: i) to analyze the absolute and relative reliability of the CoP sway to assess the intensity of the different variations of the CSE; ii) to develop exercise progressions for bird-dog, front bridge, back bridge and side bridge exercises based on the participants' difficulty to control body posture across the different variations; and iii) to analyze the effect of the participants' sex and postural control level on these progressions.

3.3. MATERIALS AND METHODS

3.3.1. Participants

Seventy-six asymptomatic young volunteers took part in this study: 48 males (age: 23.4 ± 3.3 years, mass: 72.4 ± 8.2 kg, height: 175.2 ± 4.8 cm) and 28 females (age: 24.5 ± 2.7 years, mass: 62.2 ± 10.7 kg, height: 163.8 ± 8.6 cm). All participants were physically active individuals who performed 1–3 hours of moderate physical activity 2–3 days per week. The exclusion criteria were: i) to be taller than 1.85 m, as it was observed before testing that individuals taller than this height did not fit on the total surface of the two force platforms (placed in series) when they were lying on them; ii) to have been involved in core training programs in the 6 months prior to this study; and iii) to have history of spinal, abdominal, hip or shoulder surgery, inguinal hernia, neurological disorders or episodes of back pain which required medical treatment 6 months before this study began. Participants were informed of the risks of this study and filled out a written informed consent in accordance with the Declaration of Helsinki and approved by the University Office for Research Ethics (DPS.FVG.02.14).

3.3.2. Instrumentation and data collection

Participants carried out two testing sessions (60 min each) spaced one week apart. In each session, participants performed two trials of five variations of front bridge, back bridge, side bridge and bird-dog exercises (Figure 1 and 2) on two synchronized force platforms (9287CA, Kistler®, Switzerland). The CoP sway was recorded (1000 samples/s) in anterior-posterior and medial-lateral directions with the BioWare software (version 5.2.1.3, Kistler®, Switzerland).

Prior to testing, participants performed a warm-up, which consisted of 10 repetitions of the following exercises: lumbo-pelvic mobility (i.e. pelvic circles, pelvic anteversion and retroversion, and cat-camel), cross crunch, side crunch, trunk extension and free-weight squat. During the testing trials, CSE variations were performed under the instruction that trunk motion was to be maintained to a minimum, while keeping the lumbar spine and pelvis in a neutral position. In each trial, a researcher placed the participants in the proper position, which they had to hold for 6 s, with a 60-second rest between trials. This short exercise was chosen to reduce the influence of muscle fatigue on postural control throughout the 40 trials performed in each testing session. The order of the four exercise progressions (front bridges, back bridges, side bridges and bird-dogs) was randomized between participants. Additionally, in each progression half of the sample performed the five exercise variations from the easiest to most difficult condition and vice versa.

For the bridging exercises, the following variations were performed based on a progression established through changes in the gravitational torque on the trunk, the number of supporting limbs and/or the use of an inflated rubber hemisphere (Medusa T1, Elksport®, Spain) (Figure 1): (A) short bridges, (B) long bridges, (C) bridging with single leg support, (D) bridging with double leg support on the inflated rubber hemisphere, and (E) bridging with single leg support on the inflated rubber hemisphere. As the bird-dog has different characteristics, the following progression was performed (Figure 2): (A) three-point position with an elevated leg, (B) three-point position with an elevated leg and the contralateral knee on the inflated rubber hemisphere, (C) classic two-point bird-dog position with elevated contralateral leg and arm, (D) two-point bird-dog position with the forearm on the inflated rubber hemisphere, and (E) two-point bird-dog position with the knee on the inflated rubber hemisphere. In the variations in which the inflated rubber hemisphere (diameter: 45 cm; height: 23 cm) was used, it was placed on its flattest surface on one of the force platforms (Figures 1 and 2).

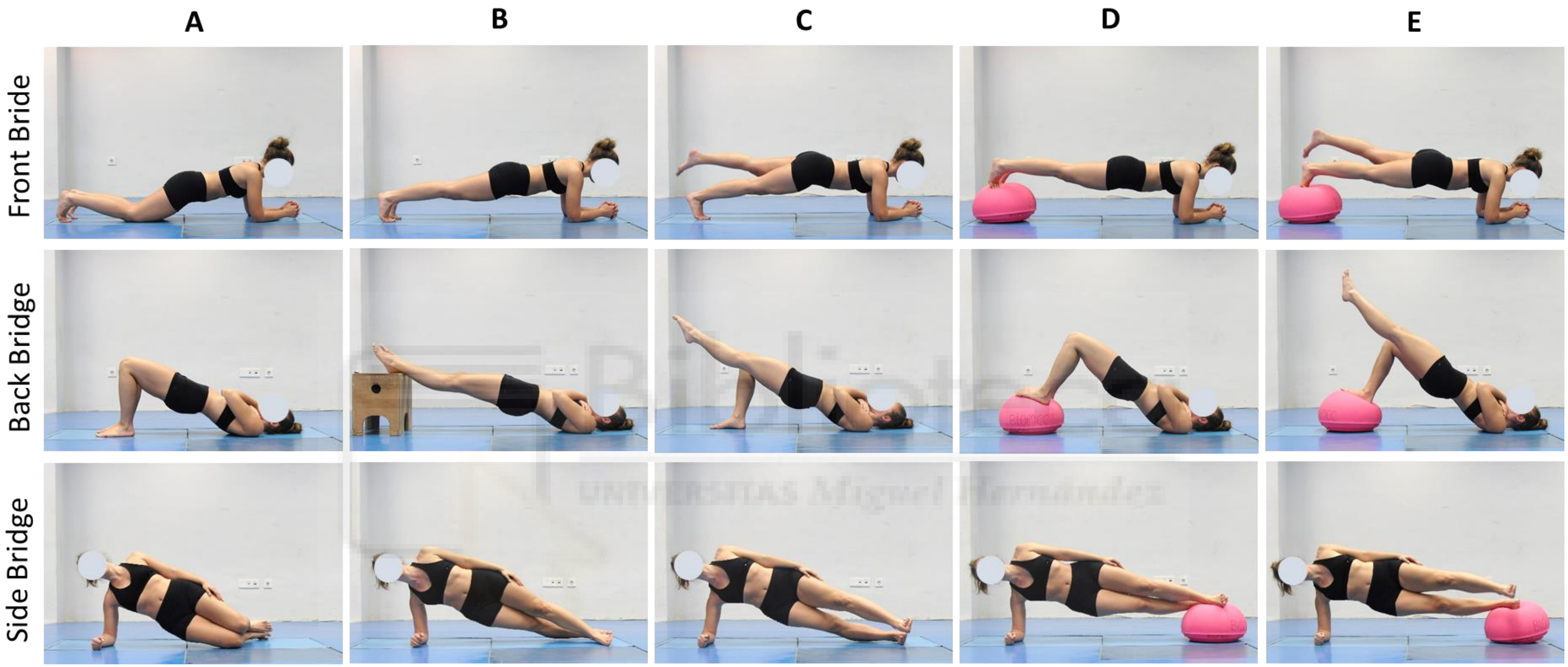


Figure 1. Bridging exercise variations on two force platforms: (A) short bridges; (B) long bridges; (C) bridging with single leg support; (D) bridging with double leg support on an inflated rubber hemisphere; (E) bridging with single leg support on an inflated rubber hemisphere.

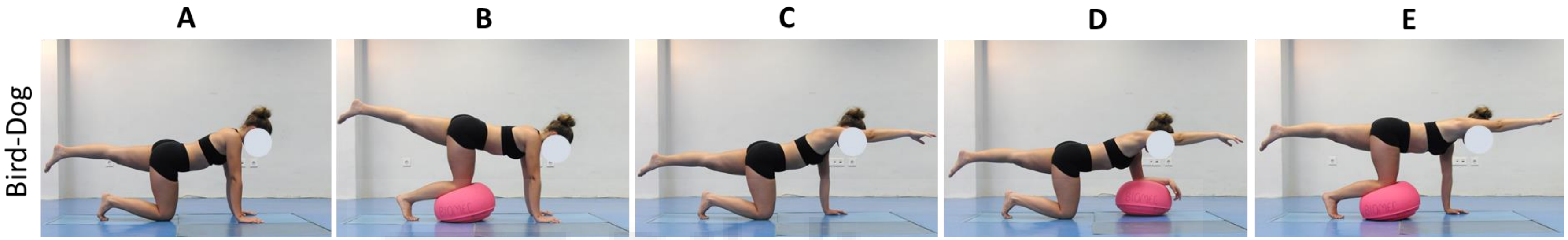


Figure 2. Bird-dog exercise variations on two force platforms: (A) three-point position with an elevated leg; (B) three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; (C) classic two-point bird-dog position with elevated contralateral leg and arm; (D) two-point bird-dog position with the forearm on an inflated rubber hemisphere; (E) two-point bird-dog position with the knee on an inflated rubber hemisphere.

3.3.3. Data processing

The CoP signals of both force platforms were unified through the algorithm proposed by the product supplier. After removing the first and the last second of the CoP data, the remaining 4 s window was selected for each trial and low-pass filtered at 5 Hz (4^{th}-order, zero-phase-lag, Butterworth). Then, the mean velocity (MV) and the resultant distance of the CoP displacement were computed for each trial (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996) with a software developed "ad hoc" by our research team within LabView 9.0 environment (National Instruments, USA).

3.3.4. Statistical analysis

The normal distribution of the CoP data was confirmed using the Kolmogorov–Smirnov test with the Lilliefors correction ($p > 0.05$). Descriptive statistics including mean and standard deviations were calculated for each variable.

To analyze the relative and absolute reliability, the intra-class correlation coefficient ($ICC_{3,1}$) and the standard error of measurement (SEM) were calculated, respectively (J. P. Weir, 2005). $ICC_{3,1}$ values were interpreted according to the following criteria: excellent (0.90-1.00), good (0.70-0.89), fair (0.50-0.69), low (< 0.50) (Fleiss, 1986). The SEM was calculated as the standard deviation of the difference between the two sessions divided by √2 (Hopkins, 2000). This method was employed to reduce the impact of the sample heterogeneity and the influence of systematic error. SEM was expressed as both absolute values and percentages to facilitate data extrapolation. Based on previous CoP results (Santos, Delisle, Lariviere, Plamondon, & Imbeau, 2008) and considering that the SEM is task dependent (Atkinson & Nevill, 1998), a SEM below 20% was considered adequate for the posturographic analysis. The interval confidence limits were calculated at 90% for $ICC_{3,1}$ and SEM. Reliability analyses were carried out using a spreadsheet designed by Hopkins (Hopkins, 2015).

The following analyses were carried out using the best repetition of the four trials performed for each exercise in the two testing sessions. One-way repeated-measures ANOVAs were carried out to classify the CSE variations according to the postural control challenge imposed on the participant (i.e. CoP sway), being *variations* (the five variations of each exercise) the within-subject factor. Moreover, mixed ANOVAs were carried out to analyze if differences between exercise variations were dependent on sex or performance level, being *variations* (the five variations of each exercise) the within-subject factor and *sex* (male and female) and/or *performance level* (high and low trunk control) the between-subject factors. In order to select the participants with high and with low trunk control, the MV of CoP displacement of the most difficult variation of each exercise was averaged between exercises and then, the sample was ordered from less to more averaged CoP sway and divided into three groups of 25-26 participants. The group with less averaged CoP sway and the group with more averaged CoP sway were selected as participants with high and low trunk control, respectively. The rest of participants (i.e. participants with moderate trunk control) were not selected with the intention of comparing only those participants with a significant difference in performance level. In order to compare between male and female performance in each exercise variation, a t-test with Bonferroni correction for multiple comparisons was performed. Participants' body mass and height were used as covariates to explore if these anthropometric variables had an effect on the differences between exercise variations. Nevertheless, as these covariates did not affect the between-variations differences significantly (height: F = 2.12-1.36, $p > 0.05$; mass: F = 0.69-0.14, $p > 0.05$), they were removed from the statistical analysis.

Pearson correlation moments (r) were used to describe the relationships of the postural control challenge imposed by the exercises between the front bridge, back bridge, side bridge and bird-dog exercise. Following a previous study by Vera-Garcia et al. (Vera-Garcia, Lopez-Plaza, Juan-Recio, & Barbado, 2019a), only the most reliable variations (those showing an $ICC_{3,1} \geq 0.60$) were used to carry out this correlational analysis.

The SPSS package (version 22, SPSS Chicago, Illinois, USA) was used to perform the ANOVA and correlation analysis, with the significance level set at 0.05.

3.4. RESULTS

As Table 1 shows, the MV of CoP displacement obtained better absolute and relative reliability results (13 out of 20 exercise variations obtained SEM values < 21% and 15 out of 20 exercise variations obtained $ICC_{3,1}$ values > 0.60) than the resultant distance of CoP displacement (8 out of 20 exercise variations obtained SEM values < 21% and 9 out of 20 exercise variations obtained $ICC_{3,1}$ values > 0.60). Based on these results, the MV was used to perform the ANOVA and the correlation analysis.

Analyzing the whole sample, ANOVA main effect ($F_{4, 296}$ = 144.91-195.86, $p < 0.05$) showed significant differences in MV between exercise variations. Specifically, multiple comparisons showed that most of the exercise variations were significantly different between each other, with the exception of the comparison between variations D and E for the front and side bridge (Figure 3). These body sway differences were used to establish difficulty/intensity progressions for the CSE, which have been illustrated in Figure 3 using an exercise difficulty scale (based on MV scores) ranging between 0 and 80 mm/s.

Table 1. Descriptive statistics (mean ± SD) and absolute (SEM) and relative ($ICC_{3,1}$) reliability for the resultant distance (RD) and the mean velocity (MV) of center of pressure displacement obtained during the different variations of the core stability exercises.

	Exercise Variations		Session 1	Session 2		SEM			$ICC_{3,1}$
			Mean ± SD	**Mean ± SD**	***p***	**Mean**	**LCL – UCL**	**%**	**Mean (LCL – UCL)**
RD (mm)	**Front Bridge***	**A**	1.50 ± 0.65	1.45 ± 0.61	0.550	0.48	0.41 – 0.57	32.32	0.43 (0.27 – 0.57)
		B	2.04 ± 0.81	2.29 ± 0.81	0.001	0.46	0.39 – 0.55	21.22	0.68 (0.56 – 0.77)
		C	3.28 ± 1.00	3.50 ± 1.34	0.045	0.67	0.58 – 0.80	19.81	0.68 (0.56 – 0.77)
		D	3.58 ± 1.30	3.56 ± 1.35	0.804	0.66	0.57 – 0.79	18.62	0.75 (0.66 – 0.82)
		E	4.69 ± 1.50	4.47 ± 1.42	0.073	0.73	0.63 – 0.86	15.84	0.76 (0.66 – 0.83)
	Back Bridge*	**A**	1.84 ± 0.79	1.95 ± 0.77	0.220	0.52	0.45 – 0.62	27.36	0.57 (0.42 – 0.68)
		B	2.02 ± 0.74	2.23 ± 0.90	0.031	0.57	0.50 – 0.68	26.98	0.52 (0.37 – 0.65)
		C	3.50 ± 1.15	3.80 ± 1.24	0.016	0.74	0.64 – 0.88	20.27	0.62 (0.49 – 0.73)
		D	3.49 ± 1.07	3.67 ± 1.34	0.178	0.84	0.72 – 1.00	23.43	0.53 (0.38 – 0.65)
		E	4.7 0± 1.67	4.72 ± 1.63	0.934	0.90	0.77 – 1.07	19.06	0.71 (0.60 – 0.79)
	Side Bridge*	**A**	2.38 ± 0.87	2.56 ± 1.00	0.098	0.68	0.58 – 0.81	27.46	0.48 (0.32 – 0.62)
		B	2.92 ± 0.90	3.13 ± 1.10	0.049	0.66	0.57 – 0.79	21.96	0.55 (0.40 – 0.67)
		C	4.79 ± 1.49	4.70 ± 1.38	0.554	0.93	0.80 – 1.11	19.66	0.58 (0.44 – 0.70)
		D	6.24 ± 1.92	5.79 ± 1.94	0.027	1.22	1.05 – 1.45	20.22	0.61 (0.47 – 0.72)
		E	7.04 ± 1.91	6.62 ± 2.04	0.061	1.34	1.15 – 1.59	19.57	0.55 (0.40 – 0.67)
	Bird-Dog**	**A**	3.03 ± 1.24	3.07 ± 1.19	0.721	0.69	0.59 – 0.82	22.50	0.69 (0.57 – 0.78)
		B	3.81 ± 1.38	3.93 ± 1.30	0.358	0.82	0.73 – 0.95	21.27	0.63 (0.50 – 0.73)
		C	4.98 ± 1.57	4.95 ± 1.76	0.899	1.20	1.06 – 1.38	24.10	0.49 (0.33 – 0.62)
		D	6.50 ± 2.50	6.30 ± 2.40	0.509	1.89	1.67 – 2.19	29.33	0.41 (0.24 – 0.56)
		E	6.81 ± 1.84	6.72 ± 1.98	0.698	1.45	1.25 – 1.72	21.41	0.43 (0.56 – 0.57)
MV (mm/s)	**Front Bridge***	**A**	18.05 ± 8.00	18.00 ± 7.25	0.962	6.17	5.31 - 7.36	34.25	0.35 (0.17 - 0.51)
		B	29.45 ± 10.96	30.03 ± 10.55	0.531	5.70	4.91 - 6.78	19.15	0.72 (0.62 - 0.80)
		C	39.44 ± 12.71	41.07 ± 14.82	0.238	8.45	7.24 -10.05	20.98	0.63 (0.50 - 0.73)
		D	55.41 ± 24.85	50.75 ± 20.61	0.152	12.20	10.76 - 14.15	23.19	0.70 (0.59 - 0.79)
		E	56.54 ± 20.45	51.53 ± 16.78	0.001	9.18	7.91 - 10.92	16.99	0.76 (0.67 - 0.83)
	Back Bridge*	**A**	17.18 ± 6.35	17.98 ± 5.93	0.255	4.26	3.67 - 5.08	24.25	0.52 (0.37 - 0.65)
		B	22.52 ± 8.90	23.84 ± 8.99	0.178	5.90	5.07 - 7.04	25.44	0.57 (0.43 - 0.69)
		C	32.75 ± 11.38	34.01 ± 10.56	0.263	6.91	5.96 - 8.22	20.71	0.61 (0.47 - 0.72)
		D	37.70 ± 13.73	37.35 ± 12.85	0.775	7.60	6.55 - 9.04	20.26	0.68 (0.56 - 0.77)
		E	47.30 ± 18.18	46.07 ± 15.24	0.394	8.84	7.62 - 10.52	18.93	0.73 (0.62 - 0.81)
	Side Bridge*	**A**	27.61 ± 10.07	28.61 ± 11.03	0.373	6.92	5.97 - 8.24	24.63	0.58 (0.43 - 0.69)
		B	38.45 ± 12.90	41.66 ± 14.93	0.013	7.72	6.64 - 9.19	19.26	0.70 (0.59 - 0.78)
		C	61.95 ± 21.10	60.67 ± 20.52	0.528	12.43	10.72 - 14.79	20.28	0.65 (0.52 - 0.75)
		D	78.16 ± 28.40	73.52 ± 27.62	0.019	11.71	10.07 - 14.00	15.45	0.83 (0.76 - 0.88)
		E	79.25 ± 22.14	74.53 ± 23.24	0.016	11.64	10.02 - 13.89	15.14	0.74 (0.64 - 0.82)
	Bird-Dog**	**A**	24.36 ± 10.22	22.93 ± 8.69	0.139	5.85	5.04 - 6.97	24.75	0.62 (0.49 - 0.73)
		B	33.85 ± 11.93	32.22 ± 11.97	0.142	6.74	5.81 - 8.04	20.42	0.69 (0.57 - 0.78)
		C	41.88 ± 14.94	40.34 ± 13.22	0.177	6.88	5.93 – 8.21	16.75	0.77 (0.67 - 0.84)
		D	52.30 ± 19.35	50.71 ± 21.10	0.475	13.56	11.68 - 16.15	26.32	0.56 (0.41 - 0.68)
		E	62.37 ± 20.45	61.04 ± 18.57	0.468	11.12	9.57 - 13.26	18.01	0.68 (0.56 - 0.77)

SD: standard deviation; SEM: standard error of measurement; %: SEM mean expressed in percentage; $ICC_{3,1}$: intra-class correlation coefficient; LCL: lower confidence limit set at 95%; UCL: upper confidence limit set at 95%.

**Variations of the front, back and side bridge exercises*: A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.

***Variations of the bird-dog exercise*: A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.

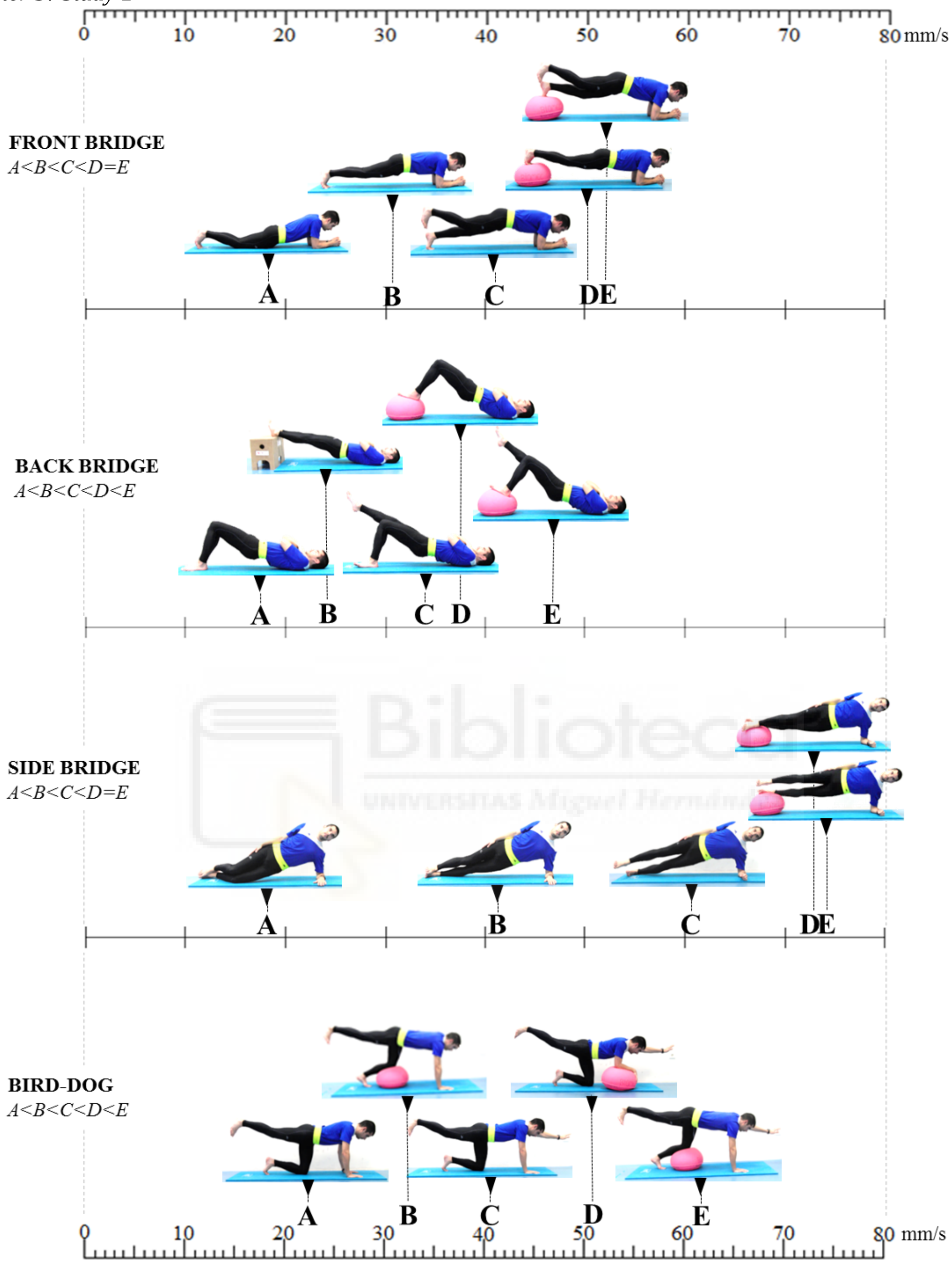


Figure 3. Difficulty progressions for the core stability exercises based on the mean velocity of center of pressure displacement (i.e. body sway) obtained during the different exercise variations. The five variations of each exercise have been placed along a difficulty scale (ranging between 0 and 80 mm/s) in those places which represent the mean levels of body oscillation measured during their execution (while participants tried to stay still). Results of the statistical comparison between exercise variations are shown *in italics* below each exercise name (< indicates "significant differences" and = indicates "non-significant differences" between exercise variations).

When the ANOVA was performed considering the participants' sex (Table 2), the differences between the exercise variations for the front and side bridge were similar in the male and female groups, showing differences in most exercise variations with the exception of the comparison between variations D and E. However, while the male group showed significant differences between all variations for the back bridge and the bird-dog, the differences in the female group did not find statistical significance for the comparison between variations C and D of the back bridge and for the comparison between variations C and D and variations D and E of the bird-dog. Regarding the comparison of CSE performance between males and females, females showed better postural control than males in most exercises, although the differences only reached statistical significance for the side bridge ($F_{1,74} = 5.63$; $p < 0.05$), with significant paired differences for variations A, D and E (Table 2). In addition, between sex differences almost reached statistical significance for the front bridge ($F_{1,74} = 2.73$; $p = 0.10$), in which a significant paired difference was found for variation E (Table 2).

Table 2. Mean velocity of center of pressure displacement (mm/s) obtained during the different variations of the core stability exercises for males and females.

	V_{Br}	**Front Bridge (mean ± SD)**	V_{Br}	**Back Bridge (mean ± SD)**	V_{Br}	**Side Bridge (mean ± SD)**	V_{BD}	**Bird-Dog (mean ± SD)**
Males (n=48)	**A**	15.44 ± 5.93	**A**	16.14 ± 5.12	**A**	26.06 ± 10.50[F]	**A**	21.66 ± 8.70
	B	27.59 ± 9.75	**B**	19.44 ± 6.93	**B**	38.03 ± 13.93	**B**	30.67 ± 10.90
	C	36.75 ± 11.68	**C**	30.09 ± 10.19	**C**	56.58 ± 21.19	**C**	36.02 ± 13.45
	D	48.69 ± 22.28	**D**	34.95 ± 12.48	**D**	75.10 ± 30.72[F]	**D**	43.18 ± 18.11
	E	51.52 ± 18.63[F]	**E**	44.99 ± 18.19	**E**	73.26 ± 22.39[F]	**E**	58.14 ± 18.79
Paired comparisons*		***A<B<C<D=E***		***A<B<C<D<E***		***A<B<C<E=D***		***A<B<C<D<E***
Females (n=28)	**A**	14.00 ± 5.39	**A**	14.24 ± 5.40	**A**	21.64 ± 6.40	**A**	17.95 ± 6.42
	B	24.43 ± 8.42	**B**	20.40 ± 8.63	**B**	32.13 ± 10.11	**B**	27.14 ± 9.86
	C	33.34 ± 13.17	**C**	28.51 ± 9.25	**C**	50.71 ± 16.41	**C**	39.83 ± 13.91
	D	42.84 ± 17.00	**D**	31.38 ± 10.92	**D**	58.61 ± 14.47	**D**	44.82 ± 14.14
	E	43.33 ± 12.02	**E**	39.06 ± 11.72	**E**	62.93 ± 15.82	**E**	51.60 ± 14.32
Paired comparisons*		***A<B<C<D=E***		***A<B<C=D<E***		***A<B<C<D=E***		***A<B<C=D=E[a]***

SD: standard deviation.
V_{Br}: *Variations of the front, back and side bridge exercises:* A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.
V_{BD}: *Variations of the bird-dog exercise:* A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.
[*]Results of the comparison between exercise variations showing significant (<) or non-significant (=) differences between them.
[a]Significant differences between the non-consecutive variations ($p < 0.05$).
[F]Significant differences between males and females ($p < 0.05$).

As Table 3 shows, the trunk control level had a higher influence on CSE progressions than the participants' sex. In general, the high trunk control group showed less significant differences between exercise variations than the low trunk control group, mainly for the back bridge and the front bridge progressions (Table 3). No significant interactions were found between *sex*, *performance level* and *variations* factors for any exercise ($F_{4,188} = 0.96 – 2.38$; $p > 0.05$).

Table 3. Mean velocity of center of pressure displacement (mm/s) obtained during the different variations of the core stability exercises for the participants with low and high trunk control.

	V_{Br}	Front Bridge (mean ± SD)	V_{Br}	Back Bridge (mean ± SD)	V_{Br}	Side Bridge (mean ± SD)	V_{BD}	Bird-Dog (mean ± SD)
Low trunk control (n=25)	**A**	17.91 ± 5.01	**A**	18.59 ± 4.14	**A**	31.33 ± 8.35	**A**	25.12 ± 5.98
	B	34.04 ± 8.62	**B**	22.47 ± 8.26	**B**	46.51 ± 12.11	**B**	36.73 ± 9.16
	C	45.73 ± 10.40	**C**	36.70 ± 8.18	**C**	69.71 ± 17.27	**C**	43.99 ± 12.03
	D	64.84 ± 19.26	**D**	44.00 ± 10.99	**D**	91.84 ± 27.30	**D**	50.22 ± 16.07
	E	65.19 ± 12.94	**E**	58.23 ± 13.78	**E**	89.48 ± 15.99	**E**	72.65 ± 13.02
Paired comparisons*		***A<B<C<D=E***		***A=B<C<D<E***		***A<B<C<E=D***		***A<B<C<D<E***
High trunk control (n=25)	**A**	11.28 ± 3.30	**A**	12.45 ± 5.42	**A**	17.54 ± 4.43	**A**	14.56 ± 3.42
	B	19.97 ± 7.12	**B**	16.43 ± 6842	**B**	25.89 ± 8.03	**B**	20.29 ± 5.85
	C	24.79 ± 7.15	**C**	21.32 ± 6.89	**C**	39.58 ± 9.93	**C**	28.33 ± 8.94
	D	30.89 ± 12.34	**D**	23.75 ± 7.23	**D**	47.45 ± 10.94	**D**	34.42 ± 7.33
	E	32.98 ± 7.96	**E**	27.49 ± 7.98	**E**	50.20 ± 10.41	**E**	40.96 ± 10.37
Paired comparisons*		***A<B=C=D=E***[a]		***A=B=C=D=E***[a]		***A<B<C=D=E***[a]		***A<B<C<D=E***

SD: standard deviation.
V_{Br}: *Variations of the front, back and side bridge exercises:* A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.
V_{BD}: *Variations of the bird-dog exercise:* A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.
[*]Results of the comparison between exercise variations showing significant (<) or non-significant (=) differences between them.
[a]Significant differences between the non-consecutive variations ($p < 0.05$).

To finish, the correlation analysis (Table 4) showed significant and moderate mean correlations in body sway between front bridge, back bridge, side bridge and bird-dog exercises ($0.48 \leq r \leq 0.62$; $p < 0.05$).

Table 4. Pearson correlation moments ($p < 0.05$) of the mean velocity of center of pressure displacement between exercises.

	Bird-Dog		Back Bridge		Front Bridge		Side Bridge	
	Mean	**LCL - UCL**	**Mean**	**LCL - UCL**	**Mean**	**LCL - UCL**	**Mean**	**LCL - UCL**
Bird-Dog			0.49	0.43 - 0.56	0.50	0.44 - 0.56	0.48	0.43 - 0.53
Back Bridge					0.62	0.59 - 0.65	0.58	0.56 - 0.61
Front Bridge							0.62	0.59 - 0.66
Side Bridge								

LCL: lower confidence limit set at 95%; UCL: upper confidence limit set at 95%.
Note that only exercise variations with intra-class correlation coefficients higher than 0.6 were used for the correlation analysis.

3.5. DISCUSSION

The progression of the exercise training load is one of the main training principles (Kasper, 2019). It is usually professional expertise which guides decision making for the CSE progression (Chuter et al., 2015; Jonathan D Mills et al., 2005; Parkhouse & Ball, 2011) and, thus, this depends on the experience and criteria of the person who establishes the progression. In order to guide difficulty progression of the CSE based on objective criteria, a posturographic protocol was used to develop progressions for some of the most common CSE through the measurement of the participant's body sway during the exercise execution.

The absolute and relative reliability scores obtained by the MV of the CoP displacement were acceptable to establish intensity progressions for the CSE. The progressions developed with the entire sample are presented in Figure 3. In general, participants showed higher body sway during long bridges in comparison to short bridges. These greater postural demands explain the higher trunk muscular activation observed in previous studies during different variations of long bridges (Escamilla et al., 2016; Vera-Garcia et al., 2014), as in these variations participants have to maintain more weight lifted off the floor and the arm's weight force is higher than in short bridges. In addition, bridging with single leg support produced higher body sway than bridging with double leg support, which may be due to the greater rotational torque and the lower base of support while bridging with an elevated leg.

These differences in rotational torque seem to explain the higher activation of the trunk rotators (mainly internal oblique) observed in electromyographic studies during the execution of bridges with single leg support (Calatayud, Casana, Martin, Jakobsen, Colado, Gargallo, et al., 2017; Escamilla et al., 2016; Garcia-Vaquero et al., 2012; Vera-Garcia et al., 2014). Moreover, most participants in the current study showed higher body sway during bridging with double or single leg support on an inflated rubber hemisphere compared to bridging on the floor. Although labile surfaces, such as inflated rubber hemispheres and fitballs, are commonly used to increase the postural control challenge during CSE (Feldwieser, Sheeran, Meana-Esteban, & Sparkes, 2012; Lehman et al., 2005; Stevens et al., 2006), bridging on unstable surfaces does not always increase neuromuscular demands (Imai et al., 2010; Lehman et al., 2005; Vera-Garcia et al., 2014). Interestingly, participants in this study showed higher body sway during bridging with double leg support on the inflated rubber hemisphere than when bridging with single leg support on the floor. Possibly, these differences were due to the fact that the inflated rubber hemisphere used in this study was a very unstable surface, as its "flat" surface was neither rigid nor was it completely flat. In this sense, if a more stable surface had been used, the results might have been different, which must be taken into consideration when prescribing CSE progressions.

Regarding the bird-dog variations, participants showed greater body sway during the two-point positions in comparison to the three-point positions (Figure 3), due to a reduction in the base of support. The use of the inflated rubber hemisphere also increased the body sway during these bird-dog variations, mainly when the knee was placed on the inflated rubber hemisphere, as this raised the center of gravity and placed more body-weight on the labile surface in comparison to the variation with the forearm on the inflated rubber hemisphere.

The CSE progressions presented in Figure 3 show the general results of the participants of this study, as they are based on average values. However, each participant should have his/her own exercise progressions depending on his/her particular characteristics. In this sense, although the participants' sex did not modify the front and side bridge progressions, it had some influence on the back bridge and bird-dog progressions (Table 2). Moreover, the participants' trunk control had a higher influence on the CSE progressions, since the participants with high trunk control showed less significant differences between variations in the four CSE (Table 3). Possibly, the difficulty level of some of the CSE variations (mainly the front and back bridge variations, which showed less body sway) was not a sufficient stimulus to reveal significant differences between variations in participants with higher trunk control, perhaps showing a ceiling effect on the assessment of these CSE variations. Therefore, although the CSE progressions presented here seem useful to be used in young physically active males and females, they should be adapted to each participant's characteristics, principally to their CSE training level. In this sense, progressions with more difficult exercise variations should be developed for those participants with high trunk control.

Regarding the correlation analysis, the moderate correlations ($r \leq 0.62$) obtained between the four exercises analyzed in this study (Table 4) indicate that some participants with a good performance in one CSE could have a low or moderate performance in a different CSE. These findings support those of previous biomechanical studies on CS (Barbado, Barbado, et al., 2016; Vera-Garcia et al., 2019b) which showed that the trunk response after sudden perturbations in one direction was not related to the trunk response after sudden perturbations in other directions. Overall, these results emphasize the importance of a proper selection of the most suitable tests and exercises for each individual and situation, showing the complexity of CS assessment and training.

In relation to the trunk control during the CSE performance, females tended to show lower levels of body sway than males, although these between-sex differences only reached statistical significance in four exercise variations (Table 2). Although the origin of these differences is difficult to explain, they could be due to differences in CSE training experience between females and males. In addition, although the participants' height and mass did not affect the between-sex comparison (height: F = 2.12-1.36, $p > 0.05$; mass: F = 0.69-0.14, $p > 0.05$), the best CSE performance of females could be related to anthropometric characteristics. In this sense, a previous study by Juan-Recio (2014) showed that, besides the mass, other anthropometric features, such as the pelvic and shoulder width and the acromial-iliac index, negatively correlated with the *Side Bridge Test* performance (Juan-Recio, Barbado, Lopez-Valenciano, & Vera-Garcia, 2014). Further research is needed to understand the effect of sex and anthropometry on trunk control during CSE performance better.

To the best of our knowledge, this is the first study using posturography to develop CSE progressions. However, several limitations exist as to the interpretation of the current results. In this sense, the progressions presented here have been developed for young physically active individuals, so other progressions could be more appropriate for other populations. In addition, as mentioned above, these progressions are based on average values of the CoP sway, so it is necessary to adapt them to the characteristics of each person. Moreover, it should be noted that, although the bird-dog variations are usually performed with limb motions, only isometric exercises were analyzed in this study in order to avoid the bias that dynamic movement can induce on CoP parameters.

In conclusion, reliable measures of CoP sway were used in this study to develop several difficulty progressions for front bridge, back bridge, side bridge and bird-dog exercises. Although, these CSE progressions only showed small changes depending on the participants' sex, participants' trunk control had a higher impact on CSE progressions, which shows the need to individualize them according to the participants' training level. Overall, this study provides useful information to measure the CSE intensity and to guide the prescription of CS programs in young physically active individuals.

CHAPTER 4

STUDY 2

Based on the article published in PLOS One as:

Training intensity quantification of core stability exercises based on a smartphone accelerometer.

David Barbado, Belen Irles-Vidal, Amaya Prat-Luri, Maria Pilar Garcia-Vaquero, Francisco J. Vera-Garcia.

Chapter 4

Study 2

Training intensity quantification of core stability exercises based on a smartphone accelerometer.

by

David Barbado, Belen Irles-Vidal, Amaya Prat-Luri, Maria Pilar Garcia-Vaquero, Francisco J. Vera-Garcia.

4.1. ABSTRACT

Although core stability training is largely used to enhance motor performance and prevent musculoskeletal injuries, the lack of methods to quantify core stability training intensity hinders the design of core stability programs and the comparison and generalization of their effects. The main aim of this study was to analyze the reliability of smartphone accelerometers to quantify the intensity of several isometric core stability exercises. Additionally, this study analyzed to what extent the pelvic acceleration data represent the local stability of the core structures or the whole-body postural control. Twenty-three male and female physically active individuals participated in this study. Participants performed two testing-sessions spaced one week apart, each consisting of two 6-second trials of five variations of front bridge, back bridge, side bridge and bird-dog exercises. In order to assess load intensity based on the postural control challenge of core stability exercises, a smartphone accelerometer and two force platforms were used to measure the mean pelvic linear acceleration and the mean velocity of the center of pressure displacement, respectively. Reliability was assessed through the intra-class correlation coefficient ($ICC_{3,1}$) and the standard error of measurement (SEM). Pearson coefficient was used to analyze the correlation between parameters. Most core stability exercise variations obtained moderate-to-high reliability scores for pelvic acceleration ($0.71 < ICC_{3,1} < 0.88$; $13.23\% \leq SEM \leq 22.99\%$) and low-to-moderate reliability scores for center of pressure displacement ($0.24 < ICC_{3,1} < 0.89$; $9.88\% \leq SEM \leq 35.90\%$). Finally, correlations between center of pressure displacement and pelvic acceleration were moderate-to-high ($0.52 \leq r \leq 0.81$). Based on the result of this study, smartphone accelerometers seem reliable devices to quantify isometric core stability exercise intensity, which is useful to identify the individuals' core stability status and to improve the dose-response characterization of core stability programs.

Keywords: load, dose-response, training intensity, core stability testing.

4.2. INTRODUCTION

CS training is nowadays largely used in several fields, mainly to enhance athletic performance and to prevent and rehabilitate musculoskeletal injuries (Kibler et al., 2006; Willardson, 2007; Zazulak et al., 2007a). However, in several experimental studies CS training programs have not delivered as positive results as could be expected (Jamison et al., 2012; Sato & Mokha, 2009; Shamsi, Sarrafzadeh, & Jamshidi, 2015). One of the main reasons which could explain these poor results is the limited modulation and quantification of the training load parameters, especially the training intensity. In CS programs, training volume has been modulated through easily quantifiable parameters, i.e. exercise duration, number of repetitions and sets, etc. (Jonathan D Mills et al., 2005; Moon et al., 2013; Sato & Mokha, 2009). However, although training intensity has been manipulated by modifying the CSE difficulty through variations in different mechanical constraints (i.e. participant posture, lever arms, base of support, unstable surfaces, etc.) (Chuter et al., 2015; Mills, J. D., Taunton, J. E., & Mills, W. A., 2005; Parkhouse & Ball, 2011), to the best of the authors' knowledge no experimental study has quantified the CS training intensity based on objective parameters.

The quantification of the load intensity is essential to analyze the dose-response relationships between training and CS adaptations. Coaches, fitness instructors, practitioners and researchers usually manipulate the CSE intensity based on their personal criteria but they do not use any field-based methodology or technique to assess whether the level of difficulty of the CSE is sufficient to challenge the stability of the core structures and thus, to induce CS adaptations (Hibbs, Thompson, French, Wrigley, & Spears, 2008). In laboratory settings, the participants' difficulty to maintain or resume a desired posture or trajectory of the trunk is accurately evaluated using biomechanical methodologies, such as sudden loading/unloading (Barbado, Barbado, et al., 2016; Barbado, Lopez-Valenciano, et al., 2016; Cholewicki, Simons, et al., 2000; Vera-Garcia et al., 2007) and/or unstable sitting (Barbado, Barbado, et al., 2016; Barbado, Lopez-Valenciano, et al., 2016; Barbado et al., 2017; Cholewicki, Reeves, Everding, & Morrisette, 2007; Reeves et al., 2009). However, these methodologies do not seem to be suitable to quantify CS training load, as they have a high-cost and complex data processing, and especially because their outcomes are not obtained during the execution of the CSE and therefore they are not easily applicable to training prescription. Among the different laboratory instruments, accelerometers might be able to overcome these drawbacks, as they have some features that make them a potential tool to assess CS while performing these exercises. Nowadays, accelerometers are integrated into electronic devices such as smartphones and iPods (del Rosario, Redmond, & Lovell, 2015; Kosse, Caljouw, Vervoort, Vuillerme, & Lamoth, 2015), which has turned them into suitable devices that can be used in professional and scientific applications because of their low cost, portability and ease of use. In addition, smartphone accelerometers have already proven their reliability quantifying stability in different balance conditions (Chiu et al., 2017; Han et al., 2016). However, to the authors' knowledge there are no studies on the suitability of these accelerometers to quantify the CSE training intensity based on the postural control challenge of the exercises.

In the current study, several of the most common CSE employed in fitness, sports and rehabilitation (front bridge, back bridge, side bridge and bird-dog) (Garcia-Vaquero et al., 2012) were performed with a smartphone accelerometer placed on the pelvis while carrying out the exercises on two force platforms. The main objective was to evaluate the reliability of the smartphone accelerometer to quantify the intensity of these CSE. Additionally, the relationship between pelvic acceleration and whole-body postural control (i.e. CoP sway) was also analyzed to enable a discussion about local and global stability. Overall, the obtainment of an accurate and reliable tool to quantify the intensity of CSE would allow both to identify the individuals' CS level and to manipulate training loads during CS interventions. This may be helpful for a dose-response characterization of CSE training programs.

4.3. MATERIALS AND METHODS

4.3.1. Participants

Twenty-three healthy male (n = 12; age: 23.5±3.6 years; mass: 73.9±6.3 kg; height: 173.9±4.7 cm) and female (n = 11; age: 24.1±1.5 years; mass: 63.1±8.8 kg; height: 165.0±11.5 cm) volunteers participated in the study. In an attempt to minimize the potential variability caused by individuals' physical condition, all participants were physically active with a work-out frequency of 2–3 days per week and their age ranged from 18 to 30 years. Additionally, due to the dimensions of the force platforms the participants' height was limited to a maximum of 1.85 m, which also helped to reduce the influence of the anthropometry on the posturographic data. People with a history of spinal, abdominal, hip or shoulder surgery, inguinal hernia, neurological disorders or episodes of back pain which required medical treatment 6 months before this study began were excluded from the study. Participants filled out a written informed consent in accordance with the Declaration of Helsinki and approved by the University Office for Research Ethics (DPS.FVG.02.14).

4.3.2. Instrumentation and data collection

To analyze whole-body postural control during the CSE, each trial was carried out on two synchronized force platforms (9287CA, Kistler, Switzerland) using the same methodology employed in the previous chapter (Study 1). At the same time, to assess lower-trunk postural control, pelvic linear accelerations were recorded at 100 samples/s from a 3-axis accelerometer (model LIS3DH, STMicroelectronics, Switzerland) embedded in a smartphone (Motorola Moto G, 2013, USA), using a free mobile application (Accelerometer Analyzer, Mobile Tools, Poland) from which earth gravity was removed. An adjustable belt was used to place the smartphone on the dominant side of the pelvis, between the iliac crest and the great trochanter. This location was chosen to reduce accelerometer motions caused by muscle contractions. Accelerometer onset was remotely controlled from a computer through a free application (TeamViewer QuickSupport, TeamViewer, Germany). This computer was also used to collect the CoP data simultaneously.

4.3.3. Data processing

The first and last second of each trial was discarded, analyzing a 4 s window for both CoP and acceleration time series. CoP data of both force platforms were unified through the algorithm proposed by the product supplier and low-pass filtered at 5 Hz (4^{th}-order, zero-phase-lag, Butterworth) (Lin, Seol, Nussbaum, & Madigan, 2008). Then, the MV of CoP displacement was computed (Prieto et al., 1996). Regarding the pelvic linear acceleration, the smartphone accelerometer signal was low-pass filtered at 10 Hz (4^{th}-order, zero-phase-lag, Butterworth) (Oba, Sasagawa, Yamamoto, & Nakazawa, 2015) and the mean acceleration was calculated as the average of the acceleration magnitude data series (F. Duarte, Lourenço, & Abrantes, 2014; Zhao & Zhou, 2017). The computation of the CoP and acceleration variables was carried out with “ad hoc” software, developed by our research group within LabView 9.0 environment (National Instruments, USA).

4.3.4. Statistical analysis

The descriptive data of each variable were presented as mean and standard deviations. The normal distribution of the data was confirmed using the Kolmogorov–Smirnov test with the Lilliefors correction.

To analyze the relative and absolute reliability, the $ICC_{3,1}$ and the SEM were calculated, respectively (J. P. Weir, 2005). The interpretation of the $ICC_{3,1}$ and SEM scores was based on similar criteria used in the previous chapter. In general, $ICC_{3,1}$ scores ≥ 0.70 and SEM scores ≤ 20% were considered acceptable for this study.

To assess the possible existence of learning effect in the measurements, a one-way repeated-measures ANOVA was employed to compare the CoP and acceleration variables between testing sessions. The practical significance of the learning effect was assessed by calculating Cohen's effect size (*d*) with Hedges' adjustment (Hedges & Olkin, 1985). Effect sizes > 0.8, 0.8-0.5, 0.5-0.2 and < 0.2 were considered large, moderate, small, and trivial, respectively (Cohen, 1988).

Finally, the possible relationships between the CoP and acceleration variables were evaluated calculating the Pearson correlation moment. SPSS package (version 22, SPSS Chicago, Illinois, USA) was used to perform the ANOVA and correlational analysis, with the significance level set at 0.05.

4.4. RESULTS

Overall, the absolute and relative reliability shown by the MV of CoP displacement ranged from low to moderate for most CSE variations (Table 5). In this sense, only 8 out of 20 exercise variations displayed an adequate reliability ($ICC_{3,1}$ ≥ 0.70; SEM ≤ 20%). On the other hand, as shown in Table 6, the mean pelvic acceleration presented moderate to high absolute and relative reliability scores for all CSE variations ($0.71 < ICC_{3,1} < 0.88$; 13.23% ≤ SEM ≤ 22.99%), except for the three-point bird-dog position with an elevated leg which obtained worse values ($ICC_{3,1} = 0.62$; SEM = 25.36%). Concerning the learning effect analysis, MV of CoP displacement and mean pelvic acceleration showed no significant differences ($p > 0.05$) between days for most CSE variations.

Finally, moderate to high correlations ($0.52 \leq r \leq 0.81$) were found between MV of CoP displacement and mean pelvic acceleration during the CSE variations (Table 7).

Table 5. Descriptive statistics (mean ± SD) and relative ($ICC_{3,1}$) and absolute (SEM) between-session reliability for the mean velocity of center of pressure displacement (mm/s) obtained during the different variations of the core stability exercises.

							SEM (mm/s)			$ICC_{3,1}$	
Exercises	**Variations**	**Session 1**	**Session 2**	**t**	***p***	***d***	**Mean**	**(LCL - UCL)**	**%**	**Mean**	**(LCL - UCL)**
Back Bridge*	**A**	17.18 ± 5.71	17.36 ± 4.16	-0.14	0.89	0.04	4.39	3.52 - 5.91	25.42	0.24	-0.12 - 0.55
	B	27.30 ± 8.43	27.06 ± 8.72	0.12	0.91	-0.03	7.22	5.79 - 9.72	26.56	0.31	-0.05 - 0.59
	C	32.09 ± 9.95	32.22 ± 8.17	-0.07	0.95	0.01	6.14	4.94 - 8.20	19.09	0.56	0.27 - 0.76
	D	36.32 ± 10.71	33.58 ± 11.23	1.68	0.11	-0.25	5.54	4.46 - 7.40	15.86	0.76	0.57 - 0.88
	E	46.38 ± 15.18	46.31 ± 14.49	0.05	0.97	-0.01	5.70	4.59 - 7.61	12.30	0.86	0.74 - 0.93
Front Bridge*	**A**	15.80 ± 7.46	15.50 ± 6.11	0.18	0.86	-0.04	5.62	4.50 - 7.56	35.90	0.34	-0.02 - 0.61
	B	26.88 ± 8.59	28.99 ± 10.25	-1.35	0.19	0.22	5.31	4.28 - 7.10	19.02	0.70	0.47 - 0.84
	C	40.73 ± 13.46	39.30 ± 13.71	0.54	0.60	-0.11	9.02	7.26 - 12.05	22.54	0.58	0.29 - 0.77
	D	47.72 ± 16.32	44.84 ± 14.44	1.25	0.22	-0.19	7.78	6.27 - 10.39	16.82	0.76	0.57 - 0.88
	E	50.54 ± 14.16	48.70 ± 14.24	0.68	0.50	-0.13	9.16	7.38 - 12.23	18.46	0.60	0.33 - 0.78
Side Bridge*	**A**	27.56 ± 8.18	24.05 ± 8.41	2.04	0.53	-0.42	5.82	4.68 - 7.77	22.54	0.53	0.22 - 0.74
	B	39.73 ± 9.21	40.00 ± 11.15	-0.14	0.89	0.03	6.49	5.23 - 8.67	16.28	0.62	0.35 - 0.79
	C	62.15 ± 18.82	59.35 ± 23.00	0.80	0.43	-0.13	11.81	9.51 - 15.77	19.44	0.70	0.47 - 0.84
	D	73.93 ± 25.09	65.63 ± 21.35	2.73	0.01	-0.36	10.31	8.30 - 13.77	14.78	0.82	0.66 - 0.91
	E	81.36 ± 22.96	71.74 ± 21.49	4.22	0.00	-0.43	7.56	6.06 - 10.18	9.88	0.89	0.79 - 0.95
Bird-Dog**	**A**	20.38 ± 6.87	19.39 ± 5.85	0.76	0.46	-0.16	4.45	3.59 - 5.95	22.39	0.53	0.16 - 0.77
	B	31.37 ± 9.22	29.22 ± 10.92	0.93	0.36	-0.21	7.84	6.32 - 10.47	25.89	0.41	0.42 - 0.86
	C	42.14 ± 11.99	40.19 ± 12.96	0.94	0.36	-0.16	7.01	5.65 - 9.37	17.04	0.70	-0.11 - 0.64
	D	54.36 ± 12.55	48.66 ± 12.61	1.80	0.87	-0.45	10.52	8.44 - 14.17	20.43	0.31	0.01 - 0.70
	E	55.50 ± 16.38	56.60 ± 14.57	-0.34	0.74	0.07	10.73	8.60 - 14.44	19.14	0.54	0.16 - 0.78

**Variations of the front, back and side bridge exercises:* A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.

***Variations of the bird-dog exercise:* A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.

SD: standard deviation; *d*: effect size; SEM: standard error of measurement; %: SEM mean expressed in percentage; $ICC_{3,1}$: intra-class correlation coefficient; LCL: lower confidence limit set at 90%; UCL: upper confidence limit set at 90.

Table 6. Descriptive statistics (mean ± SD) and relative ($ICC_{3,1}$) and absolute (SEM) between-session reliability for the mean acceleration (m/s^2) of smartphone accelerometer obtained during the different variations of the core stability exercises.

							SEM (m/s^2)			$ICC_{3,1}$	
Exercise	**Variations**	**Session 1**	**Session 2**	**t**	***p***	***d***	**Mean**	**(LCL - UCL)**	**%**	**Mean**	**(LCL - UCL)**
Back Bridge*	**A**	0.25 ± 0.11	0.25 ± 0.09	0.03	0.98	0.00	0.05	0.04 - 0.07	20.93	0.76	0.52 - 0.89
	B	0.22 ± 0.07	0.23 ± 0.09	-0.32	0.76	0.05	0.04	0.03 - 0.06	18.57	0.77	0.54 - 0.90
	C	0.60 ± 0.21	0.54 ± 0.16	2.29	0.04	-0.33	0.08	0.06 - 0.11	13.23	0.84	0.67 - 0.93
	D	0.43 ± 0.20	0.39 ± 0.17	1.01	0.33	-0.18	0.10	0.07 - 0.14	22.50	0.76	0.51 - 0.89
	E	0.57 ± 0.23	0.57 ± 0.21	0.01	0.99	0.00	0.08	0.06 - 0.12	14.42	0.88	0.74 - 0.95
Front Bridge*	**A**	0.17 ± 0.05	0.18 ± 0.05	-0.49	0.63	0.07	0.02	0.02 - 0.03	12.21	0.85	0.68 - 0.93
	B	0.31 ± 0.14	0.35 ± 0.18	-1.33	0.20	0.21	0.07	0.06 - 0.10	22.99	0.82	0.62 - 0.92
	C	0.57 ± 0.25	0.53 ± 0.24	1.18	0.26	-0.18	0.11	0.08 - 0.15	18.63	0.83	0.64 - 0.92
	D	0.39 ± 0.17	0.38 ± 0.14	0.50	0.63	-0.07	0.06	0.05 - 0.09	15.94	0.86	0.70 - 0.94
	E	0.65 ± 0.27	0.61 ± 0.23	1.38	0.19	-0.17	0.09	0.07 - 0.13	14.22	0.88	0.74 - 0.95
Side Bridge*	**A**	0.29 ± 0.09	0.27 ± 0.08	1.39	0.18	-0.24	0.04	0.03 - 0.06	14.50	0.77	0.54 - 0.90
	B	0.51 ± 0.20	0.48 ± 0.17	0.97	0.35	-0.17	0.09	0.07 - 0.13	18.60	0.77	0.53 - 0.89
	C	0.57 ± 0.21	0.58 ± 0.22	-0.14	0.89	0.02	0.11	0.09 - 0.16	19.39	0.75	0.51 - 0.89
	D	0.58 ± 0.20	0.59 ± 0.22	-0.26	0.80	0.04	0.10	0.08 - 0.15	17.95	0.78	0.55 - 0.90
	E	0.75 ± 0.29	0.66 ± 0.20	1.97	0.07	-0.36	0.13	0.10 - 0.19	17.61	0.74	0.48 - 0.88
Bird-Dog**	**A**	0.26 ± 0.11	0.26 ± 0.09	0.37	0.72	-0.08	0.07	0.05 - 0.10	25.36	0.62	0.21 - 0.84
	B	0.35 ± 0.12	0.34 ± 0.14	0.22	0.83	-0.04	0.07	0.05 - 0.10	21.32	0.71	0.40 - 0.89
	C	0.33 ± 0.12	0.34 ± 0.12	-0.45	0.66	0.08	0.07	0.07 - 0.14	19.97	0.73	0.41 - 0.90
	D	0.52 ± 0.20	0.47 ± 0.14	1.81	0.09	-0.33	0.09	0.06 - 0.11	17.97	0.74	0.36 - 0.88
	E	0.57 ± 0.21	0.57 ± 0.21	0.10	0.92	-0.02	0.12	0.09 - 0.18	20.85	0.71	0.36 - 0.88

**Variations of the front, back and side bridge exercises:* A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.

***Variations of the bird-dog exercise:* A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.

SD: standard deviation; *d*: effect size; SEM: standard error of measurement; %: SEM mean expressed in percentage; $ICC_{3,1}$: intra-class correlation coefficient; LCL: lower confidence limit set at 90%; UCL: upper confidence limit set at 90.

Table 7. Pearson correlation moment between mean acceleration of smartphone accelerometer (m/s^2) and mean velocity of center of pressure displacement (mm/s) obtained during the different variations of the core stability exercises.

Variations	Back Bridge	Front Bridge	Side Bridge	Bird-Dog
A	0.58	0.56	0.79	0.85
B	0.76	0.83	0.64	0.80
C	0.47	0.76	0.67	0.82
D	0.60	0.69	0.83	0.75
E	0.77	0.84	0.78	0.67
Mean ± SD	0.63 ± 0.13	0.74 ± 0.12	0.74 ± 0.08	0.78 ± 0.06

SD: standard deviation.
Variations for the bridge exercises: A: short bridge; B: long bridge; C: bridging with single leg support; D: bridging with double leg support on an inflated rubber hemisphere; E: bridging with single leg support on an inflated rubber hemisphere.
Variants for the bird-dog exercise: A: three-point position with an elevated leg; B: three-point position with an elevated leg and the contralateral knee on an inflated rubber hemisphere; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on an inflated rubber hemisphere; E: two-point bird-dog position with the knee on an inflated rubber hemisphere.

4.5. DISCUSSION

One of the main limitations of CS training programs is the lack of methods to quantify the intensity of the CSE, which hinders the design of these programs and the comparison and generalization of their effects. The aim of this study was to examine the relative and absolute reliability of smartphone accelerometers for the quantification of CS training intensity based on the postural control challenge of the exercises. Additionally, acceleration data were correlated to CoP parameters to analyze to what extent smartphone accelerometer measures reflect the local stability of the core structures or the whole-body postural control.

4.5.1. Reliability of the smartphone accelerometer and the force platforms to quantify CSE intensity

The main results of our study showed that smartphone accelerometers are reliable tools to quantify the postural control challenge of the CSE, displaying high reliability scores in most exercises (ICC ≥ 0.70; SEM ≤ 20%) and supporting the use of the accelerometers in balance studies (Alberts et al., 2015; Heebner, Akins, Lephart, & Sell, 2015; Kamen, Patten, Du, & Sison, 1998; Kosse et al., 2015). These results together with the low-cost and portability of smartphones could lead the design of CS training programs to a more quantitative approach. In this sense, the high relative reliability displayed by the acceleration data shows the smartphone consistency to objectively rank individuals (J. P. Weir, 2005), which would facilitate the individualization of intervention programs according to each person's CS status. Additionally, absolute reliability scores provided reference cut-offs to discriminate if longitudinal changes on pelvic sway during CSE are caused by within-subject day-to-day variability or by real changes in CS status (W. G. Hopkins, 2000). Specifically, based on the SEM scores (Table 6), reductions higher than 0.1 m/s^2 would reflect a real improvement caused by CS interventions.

Although force platforms have been successfully applied for postural control evaluation in different conditions (Prieto et al., 1996; Ruhe, Fejer, & Walker, 2010), the MV of the CoP in this study mostly displayed moderate to low reliability results (Table 5). Interestingly, some of the most challenging exercise variations (e.g. side bridge with single leg support on an unstable surface) displayed the best reliability scores, probably because the increase of neuromuscular control demands reduced outcome variability (Barbado, Barbado, et al., 2016; Lee & Granata, 2008). Probably, the low reliability of many of the CoP variables was caused by the short duration of the trials performed in the current study (6 s), leading to non-stationary behavior of CoP displacements, which could cause the capture of only part of the individuals' dynamic oscillations (Lee & Granata, 2008), consequently resulting in high within-subject variability (Caballero, Barbado, & Moreno, 2015; Ruhe et al., 2010). Considering the good reliability displayed by the smartphone accelerometer, acceleration data seemed to be less influenced by the non-stationarity of postural control in the short-term (Lee & Granata, 2008), which allows to obtain a reliable short time assessment of CS without the influence of muscle fatigue on postural control. Moreover, this short exercise duration reduced the data collection period, which additionally helped to minimize the learning effect of the exercises, as was confirmed by the low differences in the amplitude of pelvis accelerations between testing session 1 and 2 (Table 6).

4.5.2. Relationship between smartphone accelerometer and force platform outcomes

The results of the correlational analysis reinforce the use of smartphone accelerometers for quantifying CS (Table 7). Although the correlations between CoP and acceleration parameters were moderate to high ($0.52 \leq r \leq 0.81$), the explained variance between variables only ranged from 27.0% to 65.6% and therefore both parameters probably do not measure the same postural control capability (del Rosario et al., 2015). Thus, taking into account that CoP displacement during static balance tasks is associated to the neuromuscular responses derived from the body's center of mass motion (Winter, 1990), CoP parameters would reflect the individuals' whole-body postural control. Conversely, as the smartphone accelerometer was placed on the pelvis, acceleration data (i.e. pelvic sway) would be more related to the local postural control (del Rosario et al., 2015) of the core structures and consequently more useful to quantify the intensity of CSE.

4.5.3. Practical applications of smartphone accelerometer results

One of the most interesting applications of the results of this study is that smartphone accelerometers allow an objective and reliable assessment of the participants' performance during some of the most popular CSE, which may facilitate the training intensity quantification during CS programs. For example, as shown in Figure 4, the acceleration values provided by the smartphone may help to individually quantify the intensity of several variations of the front bridge according to the magnitude of pelvic accelerations, which reflect the postural control challenge imposed on each participant. This information could be used to establish CSE progressions and to choose those exercises that produce the desired intensity level for each participant. Interestingly, as Figure 4 shows, similar intensity levels (e.g. 0.2-0.3 m/s^2) can be achieved using different exercises depending on the participant's characteristics. However, in most CS training programs found in the literature all participants performed the same exercises (Clark et al., 2017; Prieske et al., 2016; Sato & Mokha, 2009), while the exercise intensity was not quantified; consequently, many participants could have trained at different intensity levels, eliciting different neural and/or physiological responses and inducing different adaptations (Hibbs et al., 2008). In order to obtain a proper dose-response characterization of CS training programs, future studies may use smartphone accelerometers to explore the effects of different training intensities and progressions in several populations. Possibly, the use of high intensity CSE (i.e. exercises that mainly challenge the participants' postural control) would produce higher stability adaptations than longer CSE performed at low-moderate intensity levels (i.e. exercises that mainly challenge the participants' endurance). However, further research is needed to test this hypothesis and to determine which acceleration levels are the most suitable to increase CS in each population.

To our knowledge, this is the first study using a smartphone accelerometer to quantify the CS training intensity based on the postural control challenge of the exercises. Nonetheless, the current results have to be interpreted with caution as this study has some limitations. For instance, generalization of the data in our study is limited because our participants were young and physically active. In this sense, although the accelerometer showed good reliability to measure pelvic sway during several CSE, future studies should analyze this device consistency in other populations and CSE. In addition, even though accelerometers offer an objective CS assessment, they do not provide information about the spine position, so it is possible that in some trials participants did not maintain the spine in neutral position. It should be noted that smartphone accelerometers can help, but not replace, trainers' labor, as during their use in CSE it necessary to check individuals' exercise technique.

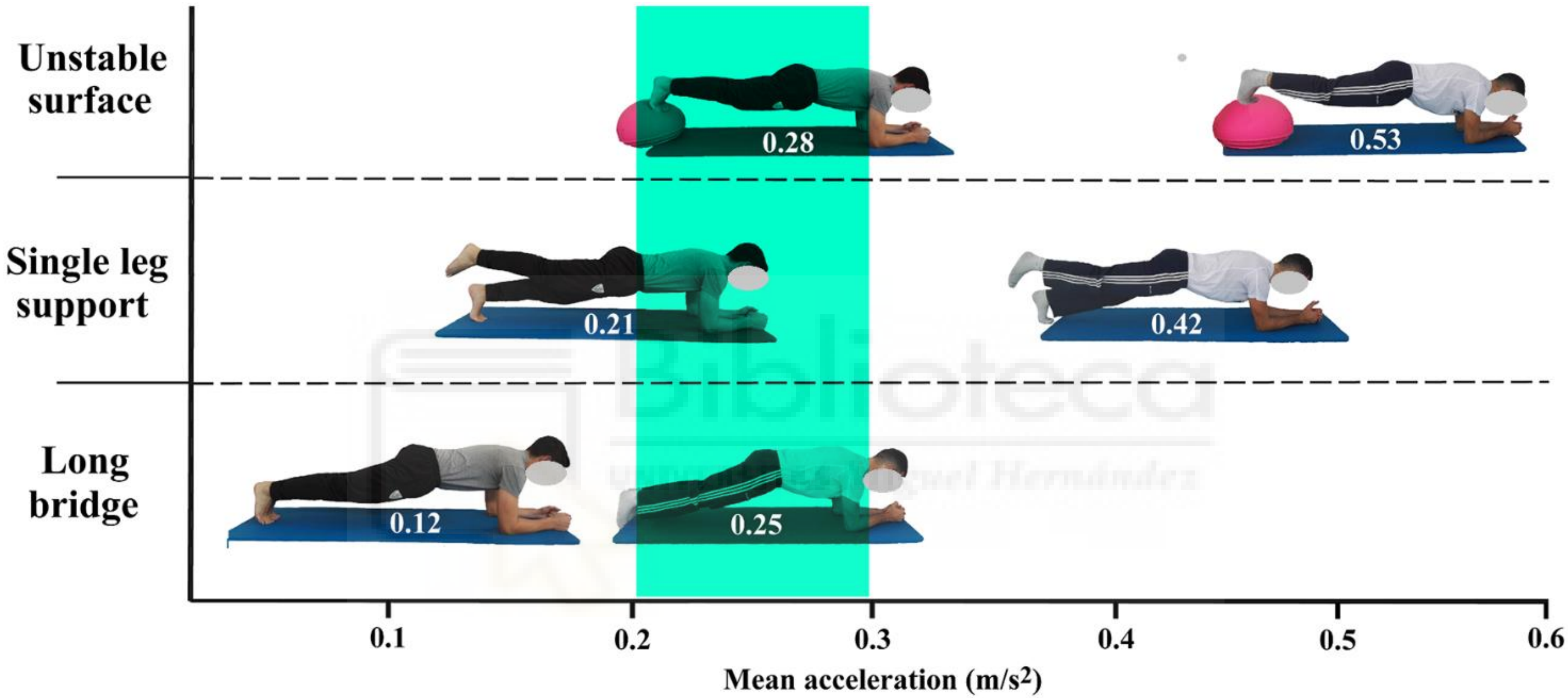


Figure 4: Pelvic mean acceleration values obtained with a smartphone accelerometer in two participants during the execution of three variations of the frontal bridge.

CHAPTER 5

EPILOGUE

Chapter 5
Epilogue

5.1. Conclusions

This doctoral thesis analyzed the reliability of two posturographic methodologies to assess the motor control challenge (i.e. exercise intensity) imposed by five variations of bird-dog, front bridge, back bridge and side bridge exercises and it developed different intensity progressions for those exercises in young physically active males and females.

The doctoral thesis includes two descriptive studies which provide useful information to design and conduct CSE training programs. The first study analyzed the reliability of the participants' CoP sway to quantify the intensity of the aforementioned CSE, it developed intensity progressions for these exercises and it analyzed the effect of the participants' sex and postural control level on these progressions. The second study explored if a cheaper, more portable and easier to use methodology, i.e. the smartphone-based accelerometry, allowed a reliable quantification of the CSE intensity and assessed the relationship between the pelvic acceleration and the CoP sway during the exercises.

The major contributions of this doctoral thesis are presented in the next paragraphs:

Study 1:

1- Unlike the reliability scores of the resultant distance of CoP displacement, the absolute and relative reliability scores obtained by the MV of the CoP displacement helped to establish several intensity progressions for front bridge, back bridge, side bridge and bird-dog exercises in young physically active males and females.

2- In general, long bridges produced higher CoP sway than short bridges, bridging with single leg support produced higher CoP sway than bridging with double leg support and bridging on an inflated rubber hemisphere produced higher CoP sway than bridging on the floor. The most difficult bridging variations were those performed on an inflated rubber hemisphere with a single leg support.

3- For the bird-dog exercise, two-point positions produced higher CoP sway than three-point positions and the positions performed on an inflated rubber hemisphere produced higher CoP sway than those performed on the floor.

4- The CSE progressions obtained by males and females were very similar. However, the participants with high trunk control showed less significant differences between exercise variations than the participants with low trunk control, which highlights the need to individualize these progressions according to the participants' training level.

Study 2:

5- Most CSE variations obtained moderate-to-high reliability scores for the pelvic acceleration and low-to-moderate reliability scores for the CoP sway. Based on these results and on the low-cost, portability and usability of the smartphone accelerometers, these devices seem adequate to quantify the intensity of the CSE in research and field settings.

6- The correlations between pelvic acceleration and CoP sway were moderate-to-high, showing that both parameters are measures of postural control. However, considering that smartphone accelerometers placed on the pelvis provide a more local measure of postural control, they would be more useful to quantify the intensity of CSE.

5.2. Conclusiones

En esta tesis doctoral se analizó la fiabilidad de dos metodologías posturográficas para evaluar cómo cinco variaciones de los ejercicios perro de muestra, puente frontal, puente dorsal y puente lateral retan el control postural (i.e. la intensidad del ejercicio). Además, en base a ello, se desarrollaron distintas progresiones de intensidad de los ejercicios para hombres y mujeres jóvenes físicamente activos.

La tesis doctoral incluye dos estudios descriptivos los cuales aportan información de utilidad para diseñar y aplicar programas de entrenamiento orientados a mejorar la estabilidad del tronco. En el primer estudio se analizó la fiabilidad de las oscilaciones del CdP de los participantes para cuantificar la intensidad de los ejercicios de estabilidad del tronco anteriormente mencionados; posteriormente, se desarrollaron progresiones de intensidad para dichos ejercicios, analizándose el efecto del sexo y el nivel de control postural sobre esas progresiones. En el segundo estudio se exploró si una metodología más económica, portátil y fácil de utilizar, es decir, la acelerometría integrada en smartphones, permitía una cuantificación fiable de la intensidad de los ejercicios de estabilización del tronco y además, se analizó la relación entre la aceleración pélvica registrada con los smartphones y la oscilación del CdP registrada mediante plataforma de fuerzas durante la ejecución de los diversos ejercicios.

Las principales contribuciones de esta tesis doctoral se presentan en los párrafos siguientes:

Estudio 1:

1- A diferencia de la distancia resultante del desplazamiento del CdP, los valores de fiabilidad absoluta y relativa de la velocidad media del CdP fueron adecuados para establecer progresiones de intensidad para el puente frontal, puente dorsal, puente lateral y perro de muestra en mujeres y hombres jóvenes y físicamente activos.

2- En general, los puentes largos produjeron mayor oscilación del CdP que los puentes cortos, los puentes con apoyo monopodal provocaron mayor oscilación del CdP que los puentes con apoyo bipodal y los puentes con apoyo sobre una superficie inestable (balón con forma de semiesfera o casquete esférico) causaron mayor oscilación del CdP que los puentes con apoyo en el suelo. Las variaciones más difíciles de los puentes fueron aquellas ejecutadas sobre la superficie inestable y con apoyo monopodal.

3- Para el ejercicio perro de muestra, las variaciones con dos puntos de apoyo produjeron mayor oscilación de CdP que las variaciones con tres puntos de apoyo y las variaciones ejecutadas sobre la superficie inestable produjeron mayor oscilación del CdP que las realizadas sobre el suelo.

4- Las progresiones de ejercicios de estabilización del tronco obtenidas por hombres y mujeres fueron muy similares. Sin embargo, los participantes con mayor nivel de control de tronco mostraron menos diferencias significativas entre las variaciones de cada ejercicio que los participantes con menor control de tronco, lo que muestra la necesidad de individualizar estas progresiones en función del nivel de entrenamiento de los participantes.

Estudio 2:

5- La mayoría de las variaciones de los ejercicios de estabilización del tronco obtuvieron valores de fiabilidad moderados-altos para la aceleración de la pelvis y bajos-moderados para la oscilación del CdP. Teniendo en cuenta estos resultados y el bajo coste, portabilidad y facilidad de uso de los acelerómetros integrados en los smartphones, estos dispositivos parecen una herramienta adecuada para cuantificar la intensidad de los ejercicios de estabilización del tronco tanto en el ámbito de la investigación como en el campo profesional.

6- Las correlaciones entre la aceleración de la pelvis y la oscilación del CdP fueron moderadas-altas, lo cual demuestra que ambos parámetros miden el control postural. Sin embargo, teniendo en cuenta que los acelerómetros de los smartphone colocados en la pelvis aportan una medida local del control postural, la aceleración pélvica parece ser una medida de mayor utilidad para cuantificar la intensidad de los ejercicios de estabilización del tronco.

5.3. Study limitations and future research

As in any research, the studies included in this doctoral thesis show some limitations, which should be taken into consideration for the interpretation of the results. Most of these limitations have been discussed in each study (chapters 3 and 4). In addition, this section presents some limitations which have been the starting point of new studies and research projects performed in the Biomechanics and Health Laboratory of the Sports Research Center of the Miguel Hernández University of Elche:

1- The CSE progressions presented in the first study of this doctoral thesis have been established through the data of whole-body sway recorded by force platforms; nevertheless the variable provided by the smartphone accelerometer (pelvic acceleration) showed better reliability values than the variables obtained from the force platforms (resultant distance and MV of the CoP displacement). In addition, pelvic acceleration provides more local information about postural control, which would possibly be more related with the core stabilization than with the whole-body sway. Therefore, it would be interesting to assess the CS exercise progressions developed in this doctoral thesis (as well as to develop new ones) based on the pelvic acceleration measurement. In this sense, our research group has carried out a posturographic study, similar to the first study of this doctoral thesis but with a larger sample size and more exercise variations, to establish CSE progressions using smartphone-based accelerometry.

2- The use of electromyography together with the posturographic measurements during the CSE execution would have allowed to obtain a comprehensive understanding of the neuromuscular effort needed to control the core structures in this type of exercises. In order to face the limitation of not using electromyography, we have recently performed a study in which several CSE were performed on two synchronized force platforms while the electromyographic signal of different trunk muscles was recorded. Nowadays we are processing the electromyographic and posturographic data in order to describe and analyze the relationships between the activation of the trunk muscles and the CoP displacement.

3- Smartphone-based accelerometry allows to quantify and compare the intensity of different CSE in quite a functional and easy way. However, which would be the minimal intensity level required to improve CS or which intensity level would be the optimal to obtain adaptations depending on the individuals' features is still unknown. Our research group has developed a study that will be part of another PhD student's doctoral thesis, in which we aimed to match the observational evaluation (based on technical criteria) of some experts on CSE training to the objective and numerical values given by a smartphone accelerometer. Through *Receiver Operator Curves* we are trying to obtain reference values for each CSE that could be considered the minimum stimulus to obtain adaptations according to the expert criteria. Although coaches, physical trainers and practitioners cannot be replaced by accelerometers (the execution technique is crucial), those reference values could help to optimize the modulation and control of training loads during CS training programs.

4- Although the studies included in this doctoral thesis provide methodologies that can be useful to train CS, they are descriptive studies in nature, so it is necessary to develop experimental studies in sport, fitness and clinical settings to assess if they are really useful to design and conduct CSE training programs in these contexts. Our research group has recently developed an experimental study (which is currently in the data analysis process), in which two CSE training programs have been performed during 6 weeks by young physically active males. The main purpose of this study was to analyze the dose-response relationships between training and CS adaptations. The exercise progressions followed by the participants were similar to those developed in this doctoral thesis and the exercise intensity was individualized and controlled using a smartphone accelerometers placed on the pelvis. The characteristics of both programs were similar except for the intensity and volume of the training load, as the exercise intensity was higher in one program and the training volume was higher in the other.

5- The participants in both studies were healthy young physically active males and females, without any motor deficit or physical limitation. Consequently, our results cannot be extended to populations with poor physical condition, illnesses or frailty (e.g. older people, patients with low back pain, sedentary population, etc.), which might obtain more benefits from this kind of exercise training. To address this limitation, our research group has recently been funded by the *Ministerio de Ciencia, Innovación y Universidades* of Spain to carry out the project titled "*Assessment protocols and trunk exercise programs to improve balance, functional capacity and quality of life in older people*" (reference: RTI2018-098893-B-I00). In this project our research group will perform several studies similar to those presented in this doctoral thesis but with different samples of older people.

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