European Journal of Applied Physiology (2020) 120:567–577
https://doi.org/10.1007/s00421-020-04313-9

ORIGINAL ARTICLE

Progressions of core stabilization exercises based on postural control challenge assessment

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Received: 7 October 2019 / Accepted: 1 February 2020 / Published online: 11 February 2020

Abstract

Purpose The intensity progression of core stabilization exercises (CSEs) is usually based on personal criteria rather than on objective parameters. To develop exercise progressions for four of the most common CSEs 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.

Methods 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 center of pressure displacement was calculated to assess exercise intensity through the measurement of the participants' body sway (PBS).

Results In general, long bridges produced higher PBS than short bridges, bridging with single leg support produced higher PBS than bridging with double leg support and bridging on a hemisphere ball produced higher PBS than bridging on the floor. The most difficult bridging variations were those performed on a hemisphere ball with single leg support. Regarding the bird-dog, two-point positions produced higher PBS than three-point positions and the positions performed on a hemisphere ball produced higher PBS than those performed on the floor.

Conclusion 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 shows 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

Abbreviations

ANOVA	Analysis of variance
CoP	Center of pressure
CSEs	Core stabilization exercises
EMG	Electromyography
ICC	Intra-class correlation coefficient
MV	Mean velocity
SEM	Standard error of measurement

Introduction

Core stabilization exercises (CSEs) are common elements of training programs in fitness, sports and rehabilitation (Borghuis et al. 2008; Gouttebarge and Zuidema 2018; Khaiyat and 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 et al. 2008).

Bridge or *plank* exercises and *bird-dog* exercises are some of the most commonly used CSEs (Boucher et al. 2016, 2018; El Shemy 2018; Hoglund et al. 2018; Toprak Celenay and 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 and McGill 1997; Kavcic et al. 2004). Bridge exercises consist in maintaining the spine in neutral position

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Communicated by Bénédicte Schepens.

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(with minimal associated trunk motion) while holding the pelvis lifted off the floor, against gravity, in different prone, supine or lateral postures (i.e., front, back and side bridge exercises, respectively) (Bjerkefors et al. 2010; Ekstrom et al. 2007; Garcia-Vaquero et al. 2012; Okubo et al. 2010; Saliba et al. 2010; Vera-Garcia et al. 2013, 2014; Vera-García et al. 2015b). 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-Garcia et al. 2014; Vera-García et al. 2015b).

Many electromyographic studies have been performed to describe the trunk and hip muscle activation during different variations of these CSEs. 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 et al. 2001; Lehman et al. 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 et al. 2013; McGill and Karpowicz 2009; Vera-Garcia et al. 2013, 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 and Karpowicz 2009; Vera-Garcia et al. 2013) and (iv) trunk extensors and rotators, hip extensors and shoulder flexors for bird-dog exercises (Callaghan et al. 1998; Ekstrom et al. 2007; Garcia-Vaquero et al. 2012; Souza et al. 2001; Vera-Garcia et al. 2014). The muscle activation patterns of these CSEs 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 et al. 2017b; 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, hemisphere balls, slings, etc.) increase muscle coactivation; (Atkins et al. 2015; Calatayud et al. 2014, 2017a, b; 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 core stability demands and muscle coactivation (Kim et al. 2013; McGill and Karpowicz 2009; Vera-Garcia et al. 2014).

All these electromyographic studies have provided basic information to help prescribe core stability programs, as for example the intensity of the participants' neuromuscular response that is needed to perform each CSE. With the aim of maximizing the effects of CSE training programs, the electromyographic trunk response has been used as an internal load index to establish CSE progressions (Calatayud et al. 2017a; Garcia-Vaquero et al. 2012; Vera-Garcia et al. 2014). However, the electromyographic signal is very variable and highly dependent on the quality of the EMG normalization procedures (De Luca 1997; Vera-Garcia et al. 2010). In addition, electromyography provides information about the activity of each single muscle individually rather than an overall information of the system's effort to accomplish the exercise demands. On the basis of these limitations, Barbado et al. (2018) proposed the use of the degree of the participant's trunk postural control (assessed by posturographic techniques) during isometric CSEs as an external index to characterize the CSE training load. This index reflects the intensity or effort invested in accomplishing the requirements of each exercise, and therefore, it can be used to establish CSE progressions. In the practical field, the CSE intensity 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, 2018; Chuter et al. 2015; El Shemy 2018; Hoglund et al. 2018; Mills et al. 2005; Parkhouse and Ball 2011). However, the CSE intensity progressions throughout training programs are usually based on subjective evaluations of the participants' trunk postural control during the CSE performance rather than on objective parameters (Chuter et al. 2015; Mills et al. 2005; Parkhouse and Ball 2011). Therefore, some questions arise when a personal trainer, a fitness instructor, a practitioner, a clinician 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 center of pressure (CoP) sway during their execution (Barbado et al. 2018). The main objectives were to develop exercise progressions for these common CSEs analyzing the participants' difficulty to control body posture across the different variations and to analyze the effect of the participants' sex and postural control level on these progressions.

Materials and methods

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 h 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 within the 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).

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 (Fig. 1) on two synchronized force platforms (9287CA, Kistler®, Switzerland). Although the exercise variations and the posturographic protocol have been thoroughly reported elsewhere (Barbado et al. 2018), they are briefly described here.

After warming up, participants performed the following variations of the CSEs in a randomized order: (i) for the bridging exercises (Fig. 1): (A) short bridges, (B) long bridges, (C) bridging with single leg support, (D) bridging with double leg support on a hemisphere ball (Medusa T1, Elksport®, Spain), and (E) bridging with single leg support on a hemisphere ball; (ii) for the bird-dog (Fig. 1): (A) three-point position with an elevated leg, (B) three-point position with an elevated leg and the contralateral knee on a hemisphere ball, (C) classic two-point bird-dog position

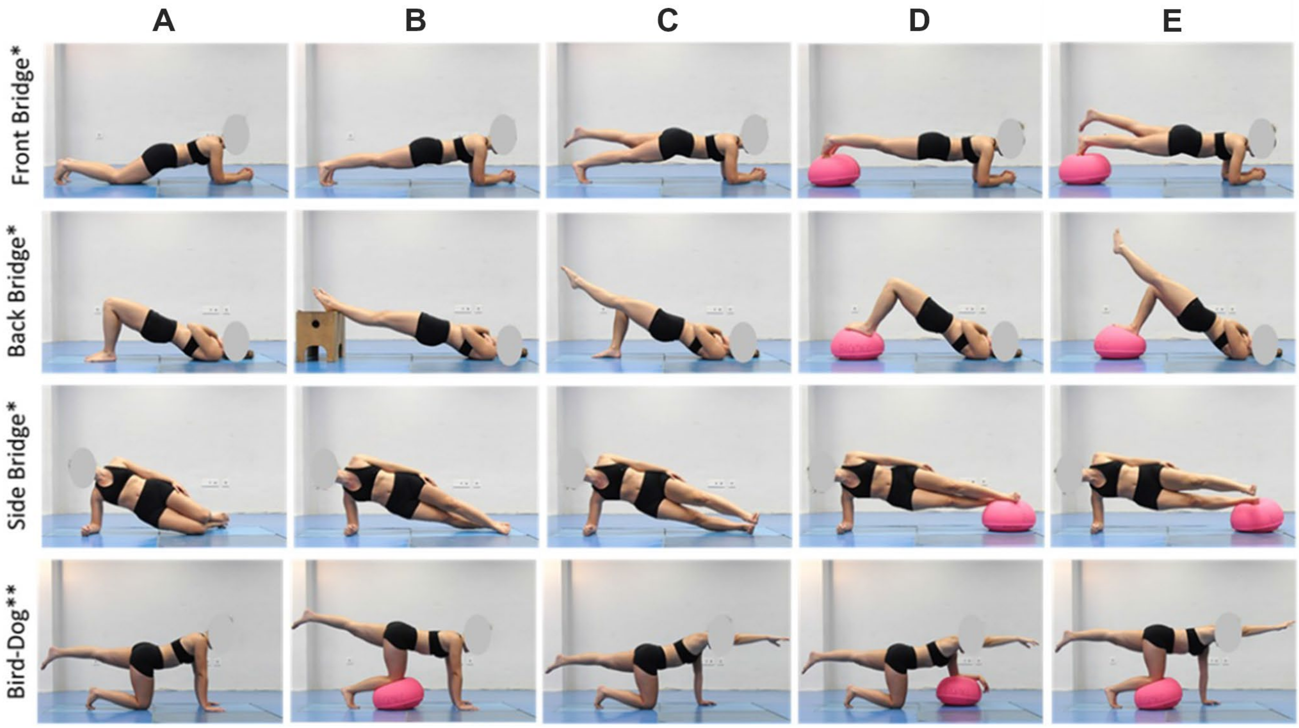

Fig. 1 Core stabilization exercises on two force platforms. *Variations of the front, back and side bridge exercises: A: short bridges; B: long bridges; C: bridging with single leg support; D: bridging with double leg support on a hemisphere ball; E: bridging with single leg support on a hemisphere ball. **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 a hemisphere ball; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball; E: two-point bird-dog position with the knee on a hemisphere ball

with elevated contralateral leg and arm, (D) two-point bird-dog position with the forearm on a hemisphere ball, and (E) two-point bird-dog position with the knee on a hemisphere ball. In the variations in which a hemisphere ball (diameter: 45 cm; height: 23 cm) was used, it was placed on its flattest surface on one of the force platforms (Fig. 1).

In each trial, participants maintained the posture for 6 s (with a 60-s rest between trials) and 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). Participants were instructed to keep their lumbar spine and pelvis in neutral position during the isometric exercises and they were encouraged not to perform a training session at least 12 h before testing.

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 resulting 4 s window was selected for each trial and low-pass filtered at 5 Hz (4th-order, zero-phase-lag, Butterworth). Then, the mean velocity (MV) and the resultant distance of the CoP displacement were computed for each trial (Prieto et al. 1996) with a software developed “ad hoc” by our research team within LabView 9.0 environment (National Instruments, USA).

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.

Considering that a recent posturographic study (performed with a smaller sample; $n = 23$) found low to moderate levels of reliability for the MV of the CoP displacement during the same CSE variations analyzed in this study, (Barbado et al. 2018) the standard error of measurement (SEM = standard deviation of the difference between the two sessions divided by $\sqrt{2}$) and the intra-class correlation coefficient ($\mathrm{ICC}_{3,1}$) were calculated (confidence limits set at 95%) to assess the absolute and relative reliability of the CoP variables. Test–retest reliability analyses were carried out with the best score (lower MV or resultant distance) obtained from each testing session and using a spreadsheet designed by Hopkins (Hopkins 2015). $\mathrm{ICC}_{3,1}$ 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 1999). Based on previous CoP reliability analyses (Santos et al. 2008) and considering that the absolute reliability scores are task dependent (Atkinson and Nevill 1998) a SEM ≤ 20% was considered adequate for the posturographic analysis.

The following analyses were executed using the best repetition (i.e., lower MV) of the four trials performed for each exercise. 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, two separate two-way 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* (2 levels: male and female) and/or *performance level* (2 levels: high and low trunk control) the between-subject factors. To analyze the differences according to the performance level, participants were classified as individuals with high or with low trunk control based on the averaged MV of CoP displacement of the most difficult variation of each exercise. That is, 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 the participants (i.e., participants with moderate trunk control) were not selected to reduce the bias in the results caused by a potential misclassification of those participants with a moderate performance level. To compare between male and female performance in each exercise variation, post-hoc *t* tests with Bonferroni correction for multiple comparisons were 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-variation 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 front bridge, back bridge, side bridge and bird-dog exercise. Following a previous study by Vera-Garcia et al. (2019) only the most reliable variations (those showing an ICC ≥ 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.

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

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 trunk stabilization 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	4.70 ± 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 at 95%, *UCL* upper confidence limit 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 a hemisphere ball; E: bridging with single leg support on a hemisphere ball

**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 a hemisphere ball; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball; E: two-point bird-dog position with the knee on a hemisphere ball of 20 exercise variations obtained $ICC_{3,1}$ values > 0.60) than the resultant distance (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 ($F_{4,296} = 144.91–195.86$, $p < 0.05$; $Power = 1.00$) 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 (Fig. 2). These body sway differences were used to establish difficulty/intensity progressions for the CSEs, which have been illustrated in Fig. 2 using an exercise difficulty scale (based on MV scores) ranging between 0 and 80 mm/s.

When the ANOVA was performed considering the participants' sex, no significant interactions were found between-sex and variations factors for any exercise ($F_{4,188} = 0.54–2.27$; $p > 0.05$; $Power < 0.66$). As Table 2 shows, the differences between the exercise variations for the front and side bridge were similar in the male and female groups, obtaining differences in most exercise variations with the exception of the comparison between variations D and E. However, while the male group showed

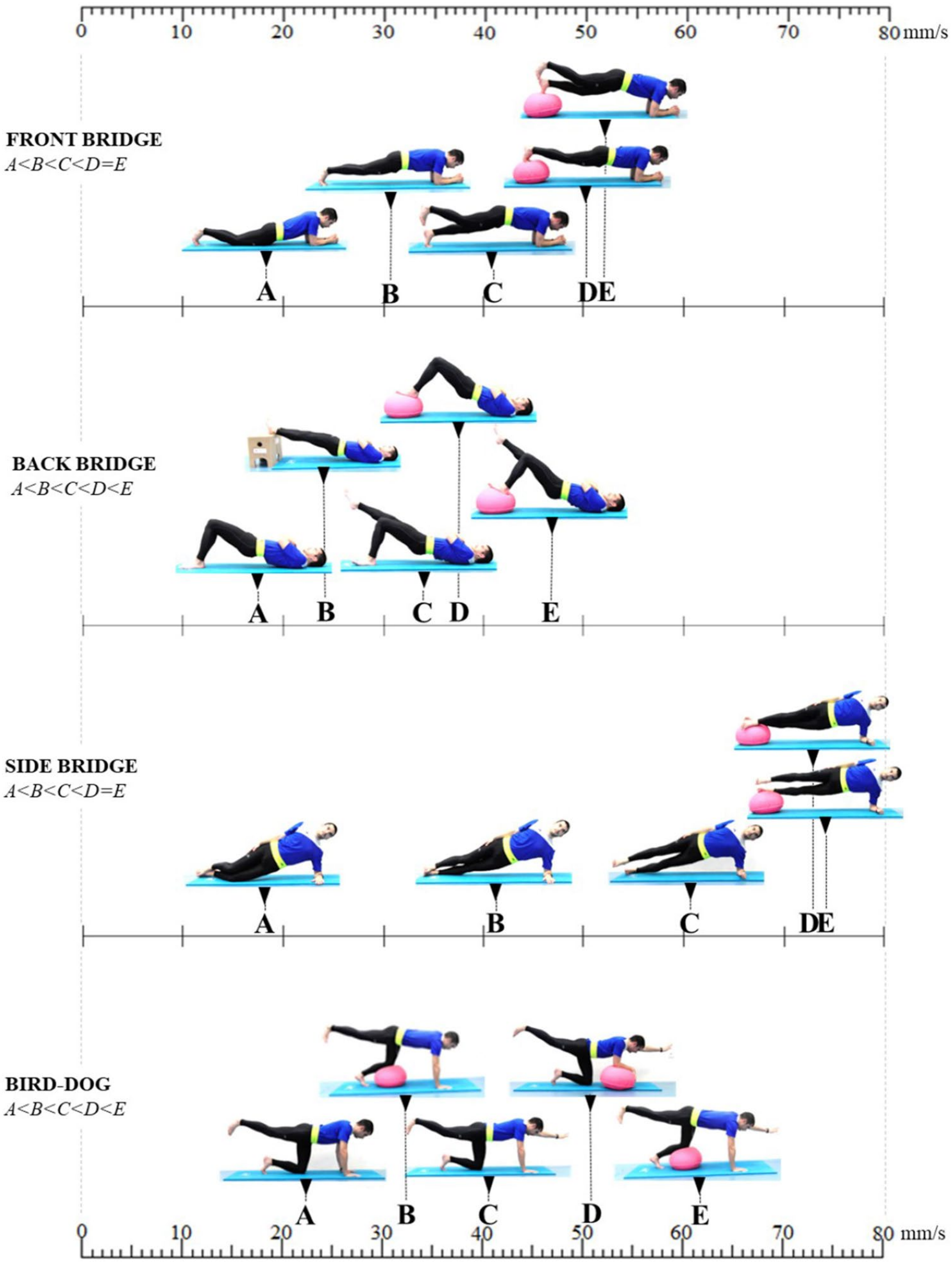

Fig. 2 Difficulty progressions for the core stabilization exercises based on the mean velocity of center of pressure displacement obtained during the different exercise variations. The five variations of each exercise are placed along a difficulty scale (ranging between 0 and 80 mm/s) in those places 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)

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 differences only reached statistical significance for the side bridge ($F_{1,74} = 5.63$; $p < 0.05$; $Power = 0.65$), 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 ($F_{1,74} = 2.73$; $p = 0.10$; $Power = 0.37$), in which a significant paired difference was found for variation E (Table 2).

The trunk control level had a higher influence on CSE progressions than the participants' sex, as significant interactions were found between *performance level* and *variations* factors for all exercises ($F_{4,188} = 11.616–32.561$; $p < 0.05$; $Power = 1.00$). 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).

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 exercise ($0.48 \leq r \leq 0.62$; $p < 0.05$).

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; Mills et al. 2005; Parkhouse and Ball 2011) and, thus, this depends on the experience and criteria of the person who establishes the progression. To guide difficulty progression of the CSEs based on objective criteria, a posturographic protocol was used to develop progressions for some of the most common CSEs through the measurement of the participant's body sway during the exercise execution.

The CSE progressions developed with the entire sample are presented in Fig. 2. 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

Table 2 Mean velocity (mm/s) of center of pressure displacement obtained during the different variations of the trunk stabilization 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 a hemisphere ball; E: bridging with single leg support on a hemisphere ball

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 a hemisphere ball; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball; E: two-point bird-dog position with the knee on a hemisphere ball

*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 ($p < 0.05$)

Table 3 Mean velocity (mm/s) of center of pressure displacement obtained during the different variations of the trunk stabilization 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 a hemisphere ball; E: bridging with single leg support on a hemisphere ball

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 a hemisphere ball; C: classic two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball; E: two-point bird-dog position with the knee on a hemisphere ball

*Results of the comparison between exercise variations showing significant (<) or non-significant (=) differences between them

[a] Significant differences between the non-consecutive variations ($p < 0.05$)

Table 4 Pearson correlations ($p < 0.05$) 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								

Note that only exercise variations with intra-class correlation coefficients higher than 0.6 were used for the correlation analysis

LCL lower confidence limit at 95%, *UCL* upper confidence limit at 95%

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 et al. 2017b; 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 a hemisphere ball compared to bridging on the floor. Although labile surfaces, such as hemisphere balls and fitballs, are commonly used to increase the postural control challenge during CSEs, (Feldwieser et al. 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 hemisphere ball than when bridging with single leg support on the floor. Possibly, these differences were due to the fact that the hemisphere ball 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 (Fig. 2), due to a reduction in the base of support. The use of the hemisphere ball also increased the body sway during these bird-dog variations, mainly when the knee was placed on the hemisphere ball, 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 hemisphere ball.

The CSE progressions presented in Fig. 2 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 specific 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 CSEs (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 with 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 core stability (Barbado et al. 2016; Vera-Garcia et al. 2019) 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 core stability 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 et al. (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 et al. 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. First of all, as some exercise variations have not shown appropriate levels of reliability, future studies must replicate this work to confirm its results. Furthermore, 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. To that purpose, as shown in a study by Barbado et al. (2018) smartphone accelerometers could be used to objectively individualize these CSE progressions due to their low cost, portability, ease of use and reliability (Barbado et al. 2018). Moreover, experimental research will be needed to explore the effectiveness of these individualized progressions to improve core stability in different populations. Finally, it should be noted that, although the bird-dog variations are usually performed with limb motions, only isometric exercises were analyzed in this study to avoid the bias that dynamic movement can induce on CoP parameters.

In conclusion, several difficulty progressions were developed in this study for front bridge, back bridge, side bridge and bird-dog exercise. 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 guide the prescription of core stability programs in young physically active individuals.

Acknowledgements This study was made possible by financial support from the Ministerio de Economía y Competitividad (Plan Nacional de I+D+I; Ref.: DEP2014-55167-R), Spain. Belén Irles-Vidal was supported by a pre-doctoral grant given by the Ministerio de Educación, Cultura y Deporte (FPU), Spain. We would also like to thank the participants who offered their time to take part in this study.

Author contributions FJVG, DBM, CJR, and MPGV conceived and designed research; BIV, APL, CJR, and MPGV conducted experiments; BIV, APL, CJR, and MPGV analyzed data; FJVG, DBM, and BIV, wrote the manuscript. All authors read and approved the manuscript.

Funding This study was made possible by financial support from the Ministerio de Economía y Competitividad (Plan Nacional de I + D + I; Ref.: DEP2014-55167-R), Spain. Belén Irles-Vidal was supported by a pre-doctoral grant given by the Ministerio de Educación, Cultura y Deporte (FPU), Spain.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval 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).

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