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Original article

Smartphone accelerometry for quantifying core stability and developing exercise training progressions in people with multiple sclerosis

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ABSTRACT

Background: Core stability exercise programs have become popular in recent years for preserving balance and functional independence in people with multiple sclerosis (PwMS); however, their real impact is not well-known as the main intervention target (i.e., core stability) theoretically responsible for balance or functional improvements is not measured. The objective of this study was to test the reliability of accelerometers integrated into smartphones for quantifying core stability and developing exercise progressions in PwMS.
Methods: Twenty participants with MS [age: 47.5±8.0 years; height: 1.62±0.07 m; mass: 63.4±10.9 kg; EDSS: 3.0 (1.5-6)] participated voluntarily in this study. CS was assessed in different variations of the front, side, and back bridges and bird-dog exercises by measuring the mean lumbopelvic acceleration in two testing sessions, separated by one week. Relative and absolute reliability of lumbopelvic acceleration of those exercise variations performed by more than 60% of the participants was analyzed by the intraclass correlation coefficient ($ICC_{3,1}$), and the standard error of measurement (SEM) and the minimal detectable change (MDC), respectively. Repeated measures ANOVAs were performed to detect a potential learning effect between test-retest assessments. Statistical significance was set at $p < 0.05$.
Results: Reliability analyses revealed that good to excellent relative and absolute scores (0.85<ICC<0.96; 7.8%≤ SEM≤19.2%; 21.6%≤MDC≤53.2%) for the mean lumbopelvic acceleration obtained during 10 of the 12 CS exercise variations performed by more than 60% of the participants. A non-significant between-session learning effect was detected in all the variables considered (all p values >0.05).
Conclusion: Smartphone accelerometry seems a low cost, portable and easy-to-use tool to objectively and reliably track core stability changes in PwMS through. However, in spite of the popularity of bridging and bird-dog exercises, only the short and long bridges and the three-point bird-dog positions proved feasible for most participants. Overall, this study provides useful information to evaluate and guide the prescription of core stability exercise programs in PwMS with mild-to-moderate impairment.

1. Introduction

People with MS (PwMS) frequently experience balance control deficits (Barbado et al., 2020; Moreno-Navarro et al., 2020) which, together with muscle weakness (Jørgensen et al., 2017) and increased fatigue perception (Rooney et al., 2019), negatively impact functional capacity (Kalron et al., 2016; Kjølhede et al., 2015), compromising the ability to perform daily living activities and increasing the fall risk (Kalron and Achiron 2013). Among the different factors involved in postural control, increasing the stability of the core structures of the body might contribute to preserving balance as, due to the upper body heavy mass, even small trunk disturbances can be enough to loss balance and fall (Van der Burg et al., 2006). Considering that PwMS appear to suffer a progressive decline in CS and core strength over time (Barbado et al., 2020; Moreno-Navarro et al., 2020, 2021), incorporating specific exercises targeting CS in regular training programs designed for this population seems important for managing of the disability progression.

Based on this rationale, lately, CS exercises have been integrated as

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part of the exercise-based rehabilitation strategy to increase trunk postural control in PwMS (Abasıyanık et al., 2020; Freeman et al., 2010; Nilsagård et al., 2014; Fox et al., 2016; Amiri et al., 2019; Arntzen et al., 2019). Commonly, CS programs consist of performing exercises that challenge the participant's ability to maintain the spine and pelvis in a neutral position (Freeman et al., 2010; Nilsagård et al., 2014; Fox et al., 2016; Amiri et al., 2019; Arntzen et al., 2019; Heredia et al., 2021). Some of the most popular CS exercises are *bridge/plank* exercises and *bird-dog* exercises (García-Vaquero et al., 2012; Barbado et al., 2018). Although the use of these CS exercises has become popular in recent years (Freeman et al., 2010; Nilsagård et al., 2014; Fox et al., 2016; Amiri et al., 2019; Arntzen et al., 2019), the real impact of CS training programs is not well-known as the main intervention target (i.e., core stability) theoretically responsible for balance or functional improvements in PwMS is not measured. In addition, as the challenge imposed by each CS exercise is not quantified, little is known about what exercise intensity or difficulty level is the most appropriate according to the PwMS' characteristics or how CS exercise intensity should progress throughout a rehabilitation program.

CS-based interventions in PwMS report that CS exercises should be adapted to the participants' CS level. However, the exercise progressions are generally based on the experience and criteria of the professional who conducts the training program rather than objective criteria and validated CS measurements (Freeman et al., 2010; Fox et al., 2016; Arntzen et al., 2019). Recently, force platforms and accelerometers tools have proven their validity for quantifying the postural control challenge (i.e., training load intensity) imposed by different variations of bridging and bird-dog exercises on young and physically active individuals. (Barbado et al. 2018; Vera-Garcia et al., 2020; Heredia-Elvar et al., 2021). Considering the specificity and reliability of lumbopelvic postural control measurements obtained via smartphone-based accelerometers along with their portability, low cost and the easiness of use (Barbado et al. 2018), they seem more appropriate than force platforms to be used in clinical settings. However, to the best of our knowledge, no studies have analyzed so far, the reliability of this measuring tool in people with neurological conditions as MS, who present variable and unpredictable day-to-day fluctuations in physical symptoms (Greenhalgh et al., 2004; Moreno-Navarro et al., 2021) and motor performance (Albrecht et al., 2001; Feys et al., 2014; Moreno-Navarro et al., 2021).

Therefore, the first aim of this study was to assess the test-retest reliability of smartphone-based accelerometry to assess CS in PwMS with mild-to-moderate impairment during the execution of four variants of the front bridge, back bridge, side bridge and bird-dog exercises. In addition, based on this smartphone-based assessment of the challenge in controlling the lumbopelvic posture imposed by each CS exercise (i.e., exercise intensity), we checked whether smartphone-based accelerometry is a valid tool to develop exercise progressions in PwMS using four of the most popular CS exercises (i.e., front bridge, back bridge, side bridge and bird-dog). Due to the wide range of physical disability that PwMS present, we expected that smartphone accelerometry would show good relative reliability; this is a high ability to classify or rank participants according to their CS level. Conversely, as PwMS usually show a high symptom variability, the absolute reliability would be lower than those shown by a previous study in healthy people (Barbado et al., 2018). In addition, we hypothesized that smartphone accelerometry would be able to track the increased challenge imposed on the core when the exercise variants became more difficult. We also hypothesized that a smaller number of CS exercise variants would be available for PwMS with higher EDSS scores.

2. Material and methods

2.1. Participants

Twenty participants with MS from regional participant associations enrolled in this test-retest cross-sectional study. The sample selection was based on the following inclusion criteria: 1) definite diagnosis of MS according of the McDonald criteria (Mantero et al., 2018); 2) they had to be relapse-free in the previous 3 months; 3) expanded disability status scale ≤6; 4) they had to be able to walk 100 m with or without assistance. Furthermore, PwMS with inguinal hernia, urinary incontinence or any pathology that contraindicated physical exercise practice were excluded from the study. All demographic and clinical data (table 1) were derived from medical records.

At study entry, participants with MS gave written informed consent in accordance with the Declaration of Helsinki. All the study procedures were approved by the local ethics committee (DCD.FBM.01.21). In order to reduce the potential variability caused by the participants' physical condition, all participants participated in a multicomponent physical conditioning program the lasted 3 months (1.5 h/session and 2 sessions/week) focused on improving PwMS' strength and balance. In this program PwMS became familiar with the CS exercise execution, as they performed different bridging and bird-dog variations for 10 to 15 minutes per session approximately.

2.2. Experimental procedure

The participants performed two 60 min testing sessions separated by one week in a quiet and well-illuminated biomechanics laboratory. In each session, the participants performed two trials of four variations of front bridge, back bridge, side bridge and bird-dog exercises, for a total of 32 trials per session. Based on the protocol developed by Heredia-Elvar et al. (2021), the following bridging exercise progressions were executed (Fig. 1): (i) for the front and side bridge exercises: A) short bridge; B) long bridge; C) long bridge with single leg support; and D) long bridge with double leg support on a hemisphere ball (Medusa T1, Elksport®, Spain); (ii) for the back bridge exercise: A) short bridges; B) short bridge with single leg support; C) short bridge with double leg support on a hemisphere ball; and D) short bridge with single leg support on hemisphere ball; (iii) 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 a hemisphere ball; C) conventional two-point bird-dog position with elevated contralateral leg and arm; and D) two-point bird-dog position with the forearm on a hemisphere ball. The bridging and bird-dog variations performed on a single leg were carried out with PwMS' non-affected leg support. The non-affected leg was determined based on each participant' self-perception. The exercise progression order was counterbalanced among participants.

Participants were encouraged not to perform a workout session at least 12 h prior to testing. A 10 min warm-up was performed before the assessments, consisting of: lumbopelvic mobility, cross-crunches, side crunches, trunk extensions and body-weight squats. CS exercise variations were executed under the instructions that trunk motion had to be maintained to a minimum, while holding the spine and pelvis in a

Table 1
Main demographic and clinical characteristics.

Characteristics	PwMS
Age (years)	47.5±8.0
Body mass (kg)	63.4±10.9
Height (m)	1.62±0.07
Female/Male (n)	17/3
Disease Duration (years)	12.2±6.1
EDSS	3.0 (1.5-6.0)
MS Type (n)	
Relapsing remitting	15
Secondary progressive	5
Primary progressive	1

PwMS: people with multiple sclerosis; EDSS: Expanded Disability Status Scale; MS: multiple sclerosis.
Data are presented as mean±SD except for the EDSS, in which the maximum range is presented.

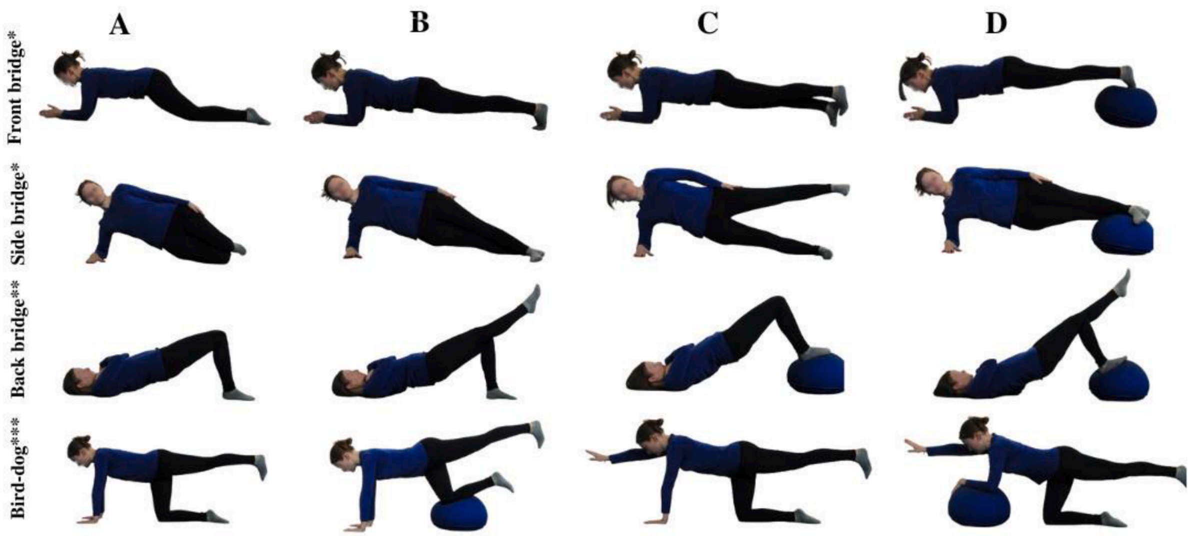

Fig. 1. Variations of the bird-dog, and the front, back and side bridge exercises.

"neutral" position. A researcher specialized in physical exercise placed the participants in the proper position and supervised whether PwMS were able to maintain that required body posture (i.e., minimal trunk motion, lumbar spine and pelvis in neutral position and good body alignment) throughout the whole trial (15 s; 60 s rest between trials).

During the CS exercise performance, lumbopelvic acceleration was recorded to assess the postural control challenge imposed on the participants. Lumbopelvic acceleration was recorded at 100 Hz from a 3-axis accelerometer (model LIS3DH, STMicroelectronics, Switzerland) integrated in a smartphone (Model Huawei G8, Huawei, China), with a free mobile application (Accelerometer Analyzer, Mobile Tools, Poland) from which gravity acceleration was removed. Following the protocol developed by Barbado et al. (2018) the smartphone was placed between the great trochanter and the iliac crest of the non-affected leg using an adjustable belt. A free application (TeamViewer QuickSupport, TeamViewer, Germany) was used to control the smartphone accelerometer remotely.

2.3. Data processing

After removing the first two seconds and the last second of the acceleration data, the resulting 12 s window was selected for each exercise variation in which, according to the investigators' criteria, the participants were able to maintain the required body posture. Using an "ad hoc" software (LabView 9.0, National Instruments, USA), the selected accelerometer data was low-pass filtered at 10 Hz (4th-order, zero-phase-lag, Butterworth) and then, the mean acceleration was calculated as the average of the acceleration data series (Barbado et al., 2018).

2.4. Statistical analysis

Descriptive values (mean±standard deviation) of the mean acceleration were calculated for all exercise variations. The normal distribution of the was tested using the Kolmogorov–Smirnov test with the Lilliefors correction ($p > 0.05$). The statistical analyses were performed only for the exercise variations that could be completed by at least 10 participants.

The intra-class correlation coefficient ($ICC_{3,1}$) and the standard error of measurement (SEM) were calculated (confidence limits set at 95%) to evaluate the relative and absolute test-retest reliability, respectively (Weir 2005). The interpretation of the $ICC_{3,1}$ was based on the following values: low (<0.50), fair (0.50-0.69), good (0.70-0.89), and excellent (0.90-1.00) (Koo and Li 2016). The SEM was calculated as the standard deviation of the difference between the two testing sessions divided by $\sqrt{2}$ (Hopkins 2000). Furthermore, SEM values were also expressed as percentages to facilitate data extrapolation, interpretation and comparison with the pertinent literature. Since the SEM variability is task-dependent (Hopkins 2000), the interpretation of SEM scores was based on previous test-retest studies on posturographic measures (Barbado et al., 2018; Vera-Garcia et al., 2020; Santos et al., 2008), according to which SEM scores lower than 20% were considered acceptable. Reliability analyses were performed with the best score (i.e., lower mean lumbopelvic acceleration) obtained in each testing session and using a spreadsheet designed by Hopkins (2015). Based on the SEM, the minimal detectable change (MDC) was assessed according to the following formula ($MDC = SEM * 1.96 * \sqrt{2}$). MDC represents the minimal differences between individual test results over repeated time points that are needed to be confident that a true change has occurred and that the change is not due to a measurement error or a biological variability (Lexell and Downham, 2005; Weir, 2005).

One-way repeated measures ANOVAs with the *session* as within-subject factor (2 levels: test and retest) were used to compare the mean lumbopelvic acceleration of each exercise variation between both testing sessions in order to explore the possible existence of test-retest learning/repetition effect. The magnitude of the learning effect was assessed through the Cohen's effect size with Hedges' adjustment (Hedges and Olkin 1985). The effect sizes were categorized as follows: trivial ($d_g<0.2$), small ($0.2\leq d_g<0.5$), moderate ($0.5\leq d_g<0.8$) and large ($d_g\geq 0.8$) (Cohen 1988).

The face validity of the smartphone-based accelerometry was examined by analyzing how pelvic acceleration changed as the exercise variations became more difficult. Specifically, one-way repeated-measures ANOVAs were carried out being *variation* the within-subject factor (the four variations of each exercise) to classify the variations of each CS exercise according to the participants' difficulty in maintaining the lumbopelvic posture (i.e., the lumbopelvic acceleration). Post-hoc tests with Bonferroni correction were used for pairwise exercise variation comparisons. These analyses were performed using the best repetition of the four trials (two trials × two testing sessions) performed for each exercise variation. A Pearson correlation and a linear regression analysis were performed to assess the relationship between the disability of PwMS, quantified by the EDSS, and the number of variations performed by each participant.

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

3. Results

As shown in Table 2, the relative reliability values were good-to-excellent for all the exercise variations (0.73<ICC<0.96). Absolute reliability was acceptable (i.e., <20%) in 10 out of 12 analyzed exercise variations (7.8%≤SEM≤19.2%). The front bridge variations showed the lowest SEM scores (≤13.5%). Conversely, the short back bridge and the conventional bird-dog showed SEM values ≥20%. Repeated-measures ANOVAs revealed no significant differences between the mean lumbopelvic acceleration of the two testing sessions for most variables, except for the long front bridge and the front bridge with single leg support, which showed significant differences in scores between the sessions.

As shown in Table 2, most participants were unable to perform (i.e., to maintain the required posture during the 15 s exercise duration) the side bridge with single leg support, the side bridge and the back bridge with double leg support on a hemisphere ball, and the two-point bird-dog position with the forearm on a hemisphere ball. Moreover, no participant was able to perform all the side bridge variations. Only six participants carried out all the back-bridge variations. 14 and 10 participants were able to perform all the front bridge and bird-dog variations, respectively. On the contrary, most of the participants (17 out of 20) could perform the short and long bridging variations and the three-point bird-dog positions. There was observed a negative significant relationship between the EDSS and the number of variations performed by PwMS (r=0.54; y=-0.94*EDSS+15.40).

Regarding the lumbopelvic acceleration comparison between the exercise variations (Table 3), the ANOVA found significant differences between most of the variations for each exercise, except for the comparisons between the long back bridge and the back bridge with single leg support, and between the front bridge with single leg support and the front bridge with double leg support on a hemisphere ball.

Table 3
Exercise progression for different variations of the core stability exercises in PwMS based on the mean pelvic acceleration (m/s^2) obtained from the smartphone accelerometers.

Variation	Back Bridge ($n = 14$)	Front Bridge ($n = 14$)	Side Bridge ($n = 17$)	Bird-Dog ($n = 17$)
A	0.08±0.04	0.08±0.03	0.15±0.06	0.08±0.03
B	0.20±0.12	0.16±0.07	0.24±0.11	0.16±0.07
C	0.22±0.15	0.24±0.10	-	0.24±0.12
D	-	0.23±0.08	-	-
Progression	$A < B = C$	$A < B < D = C$	$A < B$	$A < B < C$

PwMS: People with Multiple Sclerosis; SD: standard deviation.
Variations of the back bridge exercise: A: short bridges; B: short bridge with single leg support; C: short bridge with double leg support on a hemisphere ball; D: short bridge with single leg support on hemisphere ball.
Variations of the front 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.
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: conventional two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball.
*Results of the comparison between exercise variations showing pairwise significant (<) or non-significant (=) differences between them.

4. Discussion

One of the major findings of this study was that measurements of CS as assessed by smartphone accelerometry were associated to high relative (i.e., consistent from test to retest in terms of participants' ranking) and absolute reliability (low between-sessions variability in scores) for most of the exercise variations that proved feasible for at least 10 PwMS. Specifically, most exercise variations obtained ICC values higher than 0.80, and SEM values lower than 20%, in line with previous observations

Table 2
Descriptive statistics (mean±SD) and relative ($ICC_{3,1}$) and absolute (SEM, MDC) one-week test-retest reliability for the mean pelvic acceleration (m/s^2) obtained during the different variations of the core stability exercises in people with multiple sclerosis ($N = 20$).

Exercises	Variations	Participants Test/Retest	Test	Retest	p	$ICC_{3,1}$ (95%CI)		SEM (m/s^2)			MDC (%)
								Mean	(95%CI)	%	
Back Bridge	**A**	**20/20**	0.07±0.03	0.08±0.04	0.36	0.81	(0.57-0.92)	0.02	(0.01-0.03)	25.4	70.4
	B	**19/19**	0.21±0.09	0.20±0.12	0.86	0.87	(0.70-0.95)	0.04	(0.03-0.06)	19.2	53.2
	C	**14/14**	0.22±0.14	0.22±0.15	0.93	0.94	(0.83-0.98)	0.04	(0.03-0.06)	16.8	46.6
	D	**6/9**	0.32±0.16	0.37±0.16	-	-	-	-	-	-	-
Front Bridge	**A**	**20/20**	0.08±0.04	0.08±0.03	0.45	0.90	(0.77-0.96)	0.01	(0.01-0.02)	13.5	37.4
	B	**20/20**	0.16±0.06	0.15±0.06	0.01	0.96	(0.91-0.98)	0.01	(0.01-0.02)	7.8	21.6
	C	**14/14**	0.26±0.10	0.23±0.10	0.02	0.95	(0.86-0.98)	0.02	(0.02-0.04)	9.5	26.3
	D	**17/17**	0.23±0.07	0.22±0.08	0.37	0.91	(0.76-0.97)	0.02	(0.02-0.04)	10.8	29.9
Side Bridge	**A**	**20/20**	0.15±0.08	0.15±0.06	0.65	0.87	(0.69-0.94)	0.03	(0.02-0.04)	18.3	50.7
	B	**17/17**	0.24±0.09	0.24±0.11	0.70	0.90	(0.74-0.96)	0.03	(0.03-0.05)	14.1	39.1
	C	**1/4**	-	0.44±0.28	-	-	-	-	-	-	-
	D	**4/6**	0.34±0.14	0.35±0.11	-	-	-	-	-	-	-
Bird-Dog	**A**	**20/20**	0.08±0.03	0.08±0.03	0.44	0.85	(0.66-0.94)	0.01	(0.01-0.02)	14.9	41.3
	B	**20/20**	0.15±0.07	0.16±0.07	0.68	0.87	(0.71-0.95)	0.03	(0.02-0.04)	16.7	46.3
	C	**16/17**	0.27±0.15	0.24±0.12	0.27	0.73	(0.38-0.90)	0.04	(0.08-0.12)	28.2	78.2
	D	**10/10**	0.36±0.17	0.36±0.17	-	-	-	-	-	-	-

Student t test for repeated measures were used to assess test-retest mean differences.
Absolute and relative reliability was assessed through the standard error of measurement (SEM) and the minimal detectable change (MDC), and the intraclass correlation coefficient ($ICC_{3,1}$), respectively.
Student t test a reliability analyses were carried out with those participants who were able to carry out each exercise variation in both test and retest sessions.
SD: standard deviation; coefficient; CI: confidence interval.
Variations of the back bridge exercise: A: short bridges; B: short bridge with single leg support; C: short bridge with double leg support on a hemisphere ball; D: short bridge with single leg support on hemisphere ball.
Variations of the front 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.
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: conventional two-point bird-dog position with elevated contralateral leg and arm; D: two-point bird-dog position with the forearm on a hemisphere ball.

in healthy young males (Barbado et al., 2018). The high relative consistency showed by smartphone accelerometry in ranking PwMS according to their CS status may help individualize the rehabilitation programs for trunk postural control in this population. In addition, despite the high symptoms fluctuations of PwMS (Greenhalgh et al., 2004; Barbado et al., 2020), the absolute reliability scores provided hallmarks to ascertain if changes in participants' CS level are caused by within-subject day-to-day variability or by real changes. Based on MDC results, lumbopelvic acceleration reductions higher than 0.08 m/s^2 during most CS exercises would indicate a real CS improvement in people with mild-to-moderate MS; nevertheless, based on SEM scores, changes higher than 0.03 m/s^2 would be enough to identify group-changes. These findings along with the low cost, portability and easy-to-use features of smartphone accelerometers suggest that they qualify as suitable tools to assess CS in PwMS, especially in clinical settings.

Regarding the feasibility of the bridging and bird-dog exercise progressions, only the easiest variations of each exercise could be completed by most participants (i.e., the short and long bridging variations and the three-point bird-dog positions). As previously reported by Vera-Garcia et al. (2020), in young and recreationally active individuals, long bridges impose higher postural demands on the participants than short bridges (i.e., higher lumbopelvic acceleration), maybe because they had to maintain more weight lifted off the mat and the arm's weight force was higher. The front-bridge was the easiest CS exercise with 14 participants being able to perform the four variations. Regarding smartphone accelerometry, as a previous study in healthy individuals observed (Barbado et al., 2018), the lumbopelvic increased as the exercise variations became more challenging. Hence, the face validity of the smartphone accelerometry for quantifying core stability in PwMS seems to be confirmed. Based on the lumbopelvic acceleration, the front bridge with single leg support and the front bridge with double leg support on a hemisphere ball were more difficult than the short and long front bridges, supporting the results of previous posturograhic (Vera-Garcia et al., 2020) and electromographic (Lehman et al., 2005; Escamilla et al., 2016; García-Vaquero et al., 2012) studies in healthy individuals. Most of participants (14/20) were able to perform the back bridge with single leg support, however, only six participants could perform the variation with double leg support on a hemisphere ball. This might suggest that perturbed proprioception caused by unstable surfaces would be more determinant to perform back bridge variations than leg weakness. The side bridge was the most difficult exercise, with no participant being able to perform all the variations. Only a few participants could perform the side bridge with single leg support and the side bridge with double leg support on a hemisphere ball, which was probably caused by the reduced muscle strength and endurance (Moreno-Navarro et al., 2021), and/or the impaired coordination/proprioception that PwMS usually show. The challenge imposed by using a single leg and/or an unstable support seems to be more determinant to perform the side-bridge than the front- or back-bridge variations. In this sense, the ability to perform side-bridge variations seems to be a good index of PwMS' disability, but at the same time it limits its use for rehabilitation purposes, as there are fewer variations available. Regarding the bird-dog exercise, the reduction of the number of support limbs and the use of an unstable surface increased the lumbopelvic acceleration and reduced the number of participants that could perform the exercise.

Although the current study does not present data from healthy control individuals, the study by Barbado et al. (2018) showed young and physically active people's lumbopelvic acceleration for all the exercise variations analyzed in the present study using the same protocol. Barbado et al. (2018) did not report any problem or limitation in performing the exercises in healthy subjects; however, as it was expected, not all the PwMS were able to carry out all the CS exercise variations. This reflect how muscle weakness and CS deficits caused by an impaired postural control system limit the exercise variants available for rehabilitation purposes in this population (Moreno-Navarro et al., 2020). This is supported by the fact that the higher the disability observed in the PwMS, the smaller the number of CS exercise variations were performed (i.e., one less variation per 1 point in the EDSS score). However, conversely to what was expected, it must be noted that the lumbopelvic acceleration found in the current study was clearly lower than those obtained by Barbado et al. (2018) in the same exercise variations and using the same posturographic protocol (e.g., PwMS: 0.08-0.22 m/s^2; healthy individuals: 0.17-0.39 m/s^2 for the front bridge variations). From the authors' point of view, these results may indicate that mildly-to-moderately disabled PwMS have a lower neuromuscular ability to make rapid postural adjustments during these isometric exercises, which would have limited their ability to perform the more complex variations in the present study. Nevertheless, future research comparing PwMS at different stages and clinical courses of the disease and healthy controls is needed to confirm this hypothesis.

4.1. Study limitations

The present exploratory, cross-sectional study is not free of limitations, warranting cautious interpretation. Since only mildly or moderately disabled participants were enrolled, the present findings may not apply to PwMS with moderate to severe disability, for whom a more stringent selection of exercises and variations would be advisable. Further research should analyse the test-retest reliability of smartphone accelerometers during CS exercises in PwMS with moderate-to-severe disability, especially in non-ambulant participants, as their trunk postural control seems to be a key point to perform daily life activities (Lanzetta et al., 2004; Van Der Linden et al., 2014). In addition, most of the findings were generated from the subgroup of participants who could maintain the required body posture and accomplish the required tasks, making the sample size too small to analyse the smartphone accelerometer reliability in the most complex exercise variations. While this certainly had an impact on the statistical power of our comparisons and reliability analyses, investigating the feasibility of even more complex CS tasks provides relevant information to guide the prescription of CS exercise programs for PwMS in early stage of the disease.

5. Conclusions

The smartphone accelerometry showed good-to-excellence relative reliability and acceptable absolute reliability to assess the postural control challenge of CS exercises in people with mild-to-moderate MS. Therefore, based on the smartphones' low cost, portability and easiness-to-use, they seem suitable devices to objectively classify PwMS according to their CS status and ascertain the effectiveness of individualized CS exercise programs in clinical and research settings.

In addition, in spite of the popularity of bridging and bird-dog exercises, only the short and long bridges and the three-point bird-dog positions could be performed by most participants. The bridges with single-leg support and with double-leg support on a hemisphere ball (mainly the side bridges) and the two-point bird-dog positions were the most difficult exercise variations for these participants. Overall, this study provides useful information to evaluate CS and guide the prescription of CS exercise programs in PwMS with mild-to-moderate impairment.

Data availability statement

The datasets for this study can be found as Supplementary Material.

Ethics statement

The studies involving human participants were reviewed and approved by the Miguel Hernández University Office for Research Ethics (DCD.FBM.01.21) according to the Declaration of Helsinki. The participants/participants provided their written informed consent to take part in this study.

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CRediT authorship contribution statement

Amaya Prat-Luri: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Pedro Moreno-Navarro:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft. **Carmen Carpena:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **Andrea Manca:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. **Franca Deriu:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. **David Barbado:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Writing – original draft, Writing – review & editing. **Francisco J. Vera-Garcia:** Conceptualization, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.msard.2023.104618.

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