



Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

How much trunk control is affected in adults with moderate-to-severe cerebral palsy?

David Barbado^a, Raúl Reina^a, Alba Roldan^a, Katina McCulloch^b, María Campayo-Piernas^a, Francisco J. Vera-García^{a,*}

^a Sports Research Centre, Miguel Hernández University, Spain

^b Faculty of Kinesiology and Rehabilitation Sciences, Research Group for Adapted Physical Activity and Psychomotor Rehabilitation, University of Leuven, Belgium



ARTICLE INFO

Article history:

Accepted 7 November 2018

Keywords:

Posturography
Reliability
Biofeedback
Trunk control
Adult cerebral palsy

ABSTRACT

Trunk control (TC) impairment is a typical feature in individuals with cerebral palsy (CP), but there are lack of methods that allow to quantify the extent to which static and dynamic TC is impaired in adults with moderate-to-severe CP. Thus, the aims of this study were to analyze the reliability of a posturography protocol to assess TC in adults with CP, and quantify their degree of TC impairment compared to a control sample of adults without CP. Forty-seven adults with moderate-to-severe CP and nineteen control participants were assessed via a protocol of static and dynamic seated trunk tasks, performed on a stable and an unstable surface placed on a force-plate. The mean radial error was the primary variable measured. A large percentage of CP participants successfully completed the static and dynamic conditions on the stable surface (static: 93.6%; dynamic: 91.5–72.3%); however, this percentage decreased considerably on the unstable surface (51.1–34.0%). The posturography protocol displayed good reliability in adults with CP ($0.89 \leq ICC \leq 0.95$; $15.2\% \leq SEM \leq 20.7\%$). Adults with CP displayed significantly decreased TC in 4/5 tasks on the stable seat, particularly in dynamic conditions ($1.71 \leq d_g \leq 1.91$). Our results confirmed that TC is significantly affected in CP adults compared with controls without CP of similar age, but they present more difficulties to perform dynamic tasks. Thus, it would be recommend including dynamic in addition to static conditions to obtain a comprehensive assessment of TC impairment in adults with moderate-to-severe CP. Additional, these results encourage practitioners to design dynamic activities that challenge trunk control for rehabilitations/training programs.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Optimal trunk control (TC) is crucial in order to develop basic activities of day living like sitting or reaching (van der Heide et al., 2005), particularly in individuals with neurological disorders, such as individuals with cerebral palsy (CP) (Desloovere and Heyrman, 2015; Westcott et al., 1997). Cerebral Palsy is defined as a “group of permanent disorders that affect the development of movement and posture, causing activity limitation attributed to non-progressive disturbance” (Rosenbaum et al., 2007). The relevance of TC in this population has been emphasized in the literature with a particular focus on childrens (Sahinoglu et al., 2017). Evidence indicates that impaired TC impacts on developmental milestones, such as social engagement with others, understanding of spatial relationships, and the use of the upper-body motor func-

tions to explore objects (Brundavanam et al., 2015; Ryalls et al., 2016). However, despite CP being a life-long condition, very little is known about the impact of impaired TC during adulthood (Jahnsen, 2004), and far less in adults with moderate-to-severe CP (Goodworth et al., 2017).

Because of the TC impact on childhood motor development, posturography tests (Kyvelidou et al., 2010) and visual assessment scales (Saether et al., 2013) have been used in laboratory and clinical settings to assess TC in children with CP. Some scales, such as the Trunk Control Measurement Scale or the Trunk Impaired Scale, have been specifically designed to assess TC in adult populations with different neurological conditions, such as stroke or Parkinson. However, none of these scales have yet been validated through an objective method. In correspondence with balance assessment in upright stance (Santos et al., 2008), TC has been assessed through the analysis of center of pressure (CoP) fluctuations, measured by force platforms (Barbado et al., 2016a, 2016b, 2017; Cholewicki et al., 2000). This methodology consists of maintaining a trunk

* Corresponding author at: Miguel Hernández University, Sport Research Center, Avda. de la Universidad s/n, 03202 Elche, Spain.

E-mail address: fvera@umh.es (F.J. Vera-García).

position or trajectory, whilst sitting on stable or unstable surfaces with leg motion restriction. It has been used to both: (a) identify trunk control deficits in individuals with lower back injuries (Willigenburg et al., 2013), Parkinson's disease (van der Burg et al., 2006) or multiple sclerosis (Verheyden et al., 2006); and (b) to assess the relationship of TC with sport specialization (Barbado et al., 2016a) and sport performance level (Barbado et al., 2016a). Similar sitting protocols have been applied on children with CP under static conditions (Kyvelidou et al., 2010; Szopa and Domagalska-Szopa, 2015) or whilst performing functional reach/grasp tasks (Cherng et al., 2009). However, to the best of the authors' knowledge, posturography sitting assessment of TC through force platform has not been performed in adults with severe CP.

Based on the literature limitations, a battery of static and dynamic balance tasks was performed by adults with moderate-to-severe CP while sitting on a stable and an unstable seat placed over a force platform. The aims of this study were to: (1) assess the reliability of the measurements in this population, and (2) to describe TC deficits in adults with CP compared to adults without CP. The relationships between the static and dynamic balance tasks were also analyzed to enable a discussion around the objective of better evaluating TC deficits in adults with CP.

2. Methods

2.1. Subjects

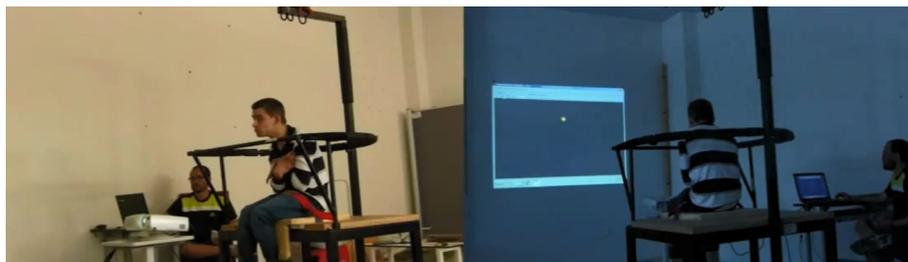
Forty-seven adults with CP were recruited via purposeful sampling from eight special care centers to participate in this study (age: 36.58 ± 14.14 yrs; weight: 49.47 ± 11.32 kg; trunk height: 52.0 ± 7.95 cm; 27 men and 20 women); and 19 control participants (age: 27.89 ± 7.08 yrs; weight: 83.60 ± 11.55 kg; trunk height: 55.74 ± 3.52 cm; 12 men and 7 women). The inclusion criteria for CP individuals were: (1) medical diagnosis of CP; (2) classified as class CP1 ($n=18$, 38.30%) (severe spastic or athetoid tetraplegia) or CP2 ($n=29$, 61.70%) (moderate-to-severe spastic athetoid tetraplegia) by CP-ISRA classification scale (Moore et al., 2016); (3) no surgeries or Botulinum toxin-A injections in the six months prior to testing; (4) able to follow the pertinent test instructions given by the researchers; and (5) classified according to the Gross Motor Function Classification Scale -GMFCS- (Palisano et al., 2008) as level II ($n=6$, 12.77%), III ($n=15$, 31.91%) or IV ($n=26$, 55.32%). The level V was not included as they were not able to perform the test. Inclusion criteria for controls were: (1) no pain in the hip or back; (2) no past pathology in these regions; and (3) neurologic or musculoskeletal problems. Ethics approval was obtained through the local University Ethics Committee (reference# DPS-RVV-001-10).

2.2. Procedures

To assess the participant's TC, they performed different tasks while sitting on a stable or an unstable seat (Fig. 1a and b) using a previously designed protocol (Barbado et al., 2016a, 2016b). Participants were seated in a stable and an unstable wooden chair with leg and foot supports. The unstable seat was built adding a polyester-resin hemisphere to the bottom (diameter: 40 cm; height: 12 cm). The seats were placed on a force-plate (9286AA, Kistler, Switzerland) in appropriate tasks as a yellow dot onto a screen (106×138 cm) in front of the participant (Barbado et al., 2016a, 2016b). In addition, a target point (i.e. red dot) was presented to participants in several tasks, to assess the subject's ability to adjust his/her CoP position to the target location. The radius of yellow and red dots (i.e. CoP and target point position) were 60 mm. To limit the impact that arm positioning had on the outcome of performance, participants were instructed to keep their arms firmly crossed over their chest or as close to this position as possible.

Participants performed two static and three dynamic tasks on both the stable and unstable surface, in a laboratory setting without any external distractor. The first static task was performed without visual feedback; therefore, the participants were instructed to sit still in their preferred seated position. The second static task and the three dynamic tasks were carried out with visual feedback. During the static task, the participants were instructed to align their CoP position with the target point located in the center of the screen. During the dynamic tasks, participants were asked to track the target, which moved through three possible trajectories (anterior-posterior, medial-lateral and circular) (see complementary video). During the dynamic tasks, the target point took 20 s to complete a cycle (0.05 Hz). In order to reduce body size influence on task performance, amplitude of the target point displacement during the dynamic tasks corresponded to the upper-body centre of mass (COM) inclination angle of 4° . The height of the upper-body COM was calculated according to Winter (1990) at 62.6% of the distance between the greater trochanter and the glenohumeral joint. Correlational analyses between anthropometrics and trunk control motor performance carried out in this study did not showed any significant association ($-0.36 \leq r \leq 0.12$).

The task performance was always performed in the same sequential order (from less to higher demanding tasks): (1) stable sitting without feedback (SNF); (2) stable sitting with feedback



Video 1.



Fig. 1. Settings for trunk control evaluation throughout posturography on stable (A) and unstable (B) surfaces. This figure shows a participant with CP, who is unable to perform the unstable conditions.

(SWF); (3) stable sitting while performing medial-lateral displacements with feedback (SML); (4) stable sitting while performing anterior-posterior displacements with feedback (SAP); (5) stable sitting while performing circular displacements with feedback (SCD); (6) unstable sitting without feedback (UNF); (7) unstable sitting with feedback (UWF); (8) unstable sitting while performing medial-lateral displacements with feedback (UML); (9) unstable sitting while performing anterior-posterior displacements with feedback (UAP); (10) unstable sitting while performing circular displacements with feedback (UCD). Familiarization was provided prior to each situation (case dependent). Each assessed task was performed twice, with a 70 s trial duration and 60 s rest interval between trials. A trial ‘failure’ criteria was established when the participant lost control or required assistance >3 times or lost control or required assistance for >15 s during the total 70 s period. If both trials of a given task were deemed unsuccessful, then the assessment was terminated at that stage, i.e. successful completion of each task determined the progression onto the following task (see Fig. 2).

2.3. Data reduction and parameter extraction

Firstly, the CoP signal was low-pass filtered (4th-order, zero-phase-lag, Butterworth, 5 Hz cut-off frequency) according to (Lin et al., 2008). Then, taking into account there is little physiological significance to the CoP signal frequencies above 10 Hz (Borg and Laxaback, 2010), the CoP time series were subsampled at 20 Hz. In addition, the first 10 s of each trial were discarded to avoid non-stationarity related to the beginning of the trial (van Dieen et al., 2010).

The mean radial error (MRE) was used as a global measure to quantify TC during the trials, and it was calculated as the average of vector distance magnitude (mm) of the CoP from the target point or from the participant’s own mean CoP position (Hancock

et al., 1995) for trials with and without visual feedback, respectively. Both trials of each task were used for a within-session reliability analysis. The best trial performed for each condition (lower MRE) was used for the correlational analysis. It was chosen the best trial in order to reduce warm up influence, and consequently, reduce learning effect on task performance (Barbado et al., 2016a).

2.4. Statistical analysis

Descriptive statistics (mean and standard deviation) were calculated for all variables. The normality of the data was examined using Kolmogorov-Smirnov statistical test. As the main aim of this study was to check that the test battery is reliable and feasible for trunk control performance assessment moderate-to-severe CP population, the whole CP sample was used for the subsequent reliability analysis (Pham et al., 2016; van der Linden et al., 2018). However, as a heterogeneous sample can overestimate relative reliability outcomes (Weir, 2005), it was also checked if there were differences in TC between CP individuals according to the Gross Motor Function scale, not finding any significant result. To analyze the within-session absolute reliability of each task, standard error of measurement (SEM) was calculated as the standard deviation of the difference between trial 1 and 2 divided by $\sqrt{2}$ (Hopkins, 2000). This SEM method was selected to avoid the influence of sample heterogeneity and to reduce the effect of systematic error (i.e. learning effect). SEM was expressed as a percentage of the mean of the scores, facilitating extrapolation of the results to other individuals and reliability comparisons between different protocols. The relative reliability of the different measures was analyzed using the intraclass correlation coefficient ($ICC_{3,1}$), calculating 90% confidence limits (90% CL). The ICC values were categorized as follows: excellent (0.90–0.99), high (0.70–0.89), moderate (0.50–0.69) and low (<0.50) (Fleiss, 1986). Reliability analyses were carried out using a spreadsheet designed by Hopkins (2015).

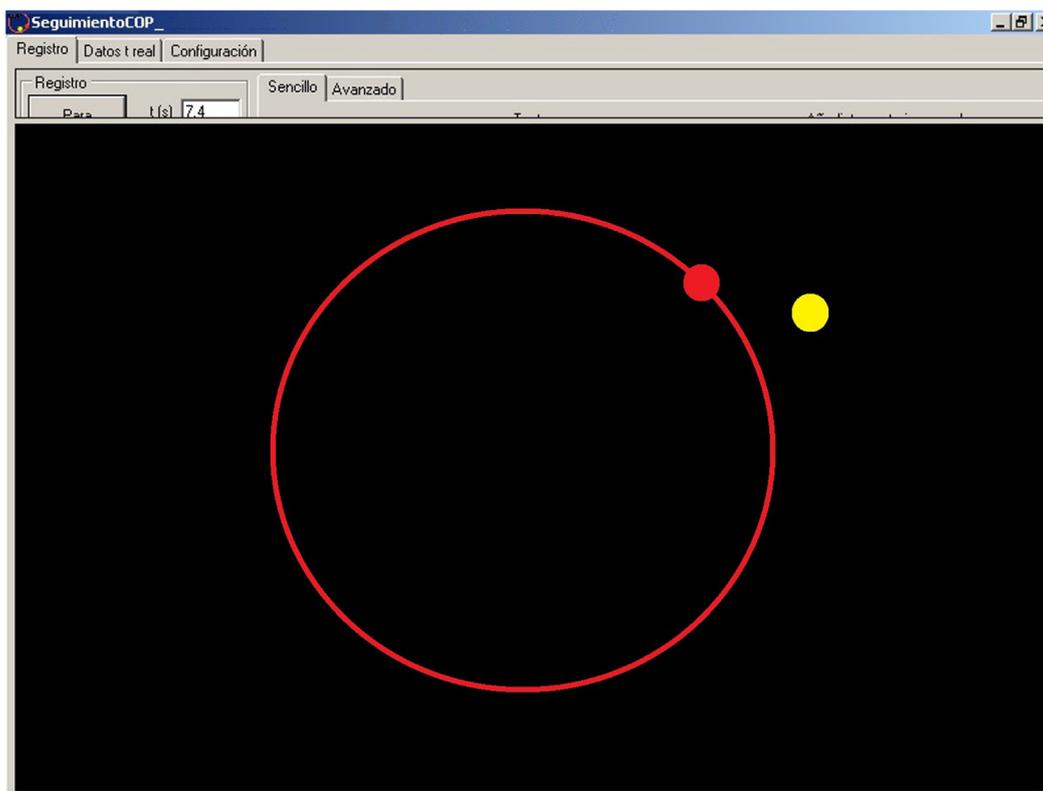


Fig. 2. Screen feedback with the red dot representing the target and its trajectory (circular task), and the yellow dot representing participants' CoP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

One-way repeated-measures ANOVAs were performed to assess repetition effect, being the *trial* as a within-subject factor (trial 1 and 2). A one-way ANOVA was calculated to compare task performance between the control group and adults with CP. To estimate the effect size of between-group differences, Hedges' g index (d_g) was used (Hedges and Olkin, 1985). This index is based on Cohen's d index; however, it provides an effect size estimation reducing the bias caused by small samples ($n < 20$). Effect sizes were interpreted as trivial ($d_g < 0.20$), small ($0.20 \leq d_g < 0.50$), moderate ($0.50 \leq d_g < 0.80$), and large ($d_g \geq 0.80$). Finally, the Pearson correlation coefficient (r) was used to analyze the relationship between test conditions for the participants with CP. All analyses were performed with the SPSS statistics software (version 20.0; SPSS Inc., Chicago, IL, USA), establishing significance at $p < .05$.

3. Results

Kolmogorov-Smirnov test revealed that both groups had a normal distribution of their scores in all the TC variables, so parametric techniques were used for statistical analyses. However, the control group was able to perform the static and dynamic trials on the stable and unstable seat, while three participants with CP were unable to perform any task of the whole battery given their physical limitations. The remaining forty-four participants with CP (93.6%) were able to complete the stable static trials (SNF and SWF). Regarding the stable dynamic trials, 43 (91.5%), 40 (85.1%) and 34 (72.3%) participants with CP were able to perform the SML, SAP and SCD conditions respectively. On the contrary, only 24 and 16 participants with CP (51.1% and 34.0%) were able to perform the static and dynamic conditions over the unstable seat. Therefore, unstable sitting data was not used for further analysis.

Table 1 outlines the descriptive statistics and the intra-session absolute and relative reliability values for each sitting task on the stable seat in the sample of adults with CP. SEM were less than 20% in all tasks, with the exception of SNF condition (SEM = 24.6%). Excellent relative reliability was observed, with ICC values higher than 0.88 for all tasks. Regarding ANOVA results, only the MRE of the SWF and SML tasks showed a significant decrease between trial 1 and 2.

As Table 2 shows, the means and the standard deviations differed considerably between both groups (adults with CP vs. control sample), with all tasks showing high significance differences ($p < .01$) except for the SNF condition ($p < .12$; $d_g = 0.42$). Effect sizes increased according to task complexity, with the SWF task displaying the smallest between-group differences ($d_g = 1.12$), and the SCD the highest between-group difference ($d_g = 1.95$).

For the participants with CP (Table 3), there were highly significant correlations between the static tasks ($r = 0.84$) and between the dynamic tasks ($0.80 \leq r \leq 0.87$). Also, moderate significant correlations were seen between the static and dynamic tasks ($0.37 \leq r \leq 0.58$).

4. Discussion

Trunk control has a major impact on activities of daily living in adults with CP (Westcott et al., 1997). Due to the lack of reliable methods for assessing TC in this population, this study attempts to provide a reliable assessment of TC for adults with moderate-to-severe CP that overcomes clinical scales limitations, describing the extent to which TC is impaired in comparison with adults without CP. To address these objectives, this study has used a protocol based on previous studies in other populations (Barbado et al., 2016a, 2016b) where individuals' TC was evaluated in a seated

Table 1
Descriptive statistics and relative and absolute reliability of mean radial error showed by the participants with Cerebral Palsy during the different tasks of the sitting protocol.

Task	N	Trial 1		Trial 2		F	p	d_g	ICC _(3,1) (mean–90% CL)	SEM (%) (mean–90% CL)
		Mean	(SD)	Mean	(SD)					
SNF	44	5.96	(4.05)	5.99	(3.13)	0.001	0.976	–0.007	0.95 (0.89–0.99)	24.6 (20.0–32.9)
SWF	44	4.99	(3.64)	4.40	(3.15)	5.681	0.027	0.159	0.95 (0.91–0.97)	19.7 (17.3–23.3)
SML	43	10.29	(5.07)	9.18	(4.83)	10.445	0.002	0.215	0.90 (0.85–0.93)	16.4 (14.5–19.2)
SAP	40	9.32	(4.71)	9.33	(5.07)	0.001	0.971	–0.002	0.92 (0.88–0.95)	15.2 (13.0–17.8)
SCD	34	12.19	(5.79)	11.57	(5.41)	1.868	0.181	0.105	0.89 (0.83–0.93)	16.0 (13.9–19.1)

d_g = standardized mean difference with Hedge's adjustment; ICC = intra-class correlation coefficient; CL = confidence limits; SEM = standard error of measurement. Trunk sitting tasks: stable sitting without feedback (SNF); stable sitting with feedback (SWF); stable sitting while performing medial-lateral displacements with feedback (SML); stable sitting while performing anterior-posterior displacements with feedback (SAP); stable sitting while performing circular displacements with feedback (SCD).

Table 2
Difference in the mean radial error of the stable sitting conditions between participants with Cerebral Palsy and the control group.

	N	Control		N	Cerebral Palsy		F	p	d_g (mean–95% CL)
		Mean	(SD)		Mean	(SD)			
SNF	19	3.62	(2.05)	44	5.38	(4.69)	2.477	0.120	0.42 (–0.12–0.97)
SWF	19	0.65	(0.18)	44	4.29	(3.81)	17.188	<0.001	1.12 (0.55–1.69)
SML	19	2.12	(0.66)	43	8.77	(4.58)	39.332	<0.001	1.71 (1.09–2.33)
SAP	19	1.91	(0.49)	40	8.66	(4.65)	39.460	<0.001	1.73 (1.10–2.36)
SCD	19	2.91	(1.05)	34	10.92	(4.98)	47.640	<0.001	1.95 (1.27–2.62)

d_g = standardized mean difference with Hedge's adjustment; CL = confidence limit. Trunk sitting tasks: stable sitting without feedback (SNF); stable sitting with feedback (SWF); stable sitting while performing medial-lateral displacements with feedback (SML); stable sitting while performing anterior-posterior displacements with feedback (SAP); stable sitting while performing circular displacements with feedback (SCD).

Table 3
Pearson correlation moment the mean radial error showed during the different trunk control sitting tasks in the participants with Cerebral Palsy.

	SNF	SWF	SML	SAP	SCD
SNF		0.835 (0.82)	0.476**	0.529**	0.371*
SWF			0.498**	0.580**	0.419*
SML				0.868**	0.797**
SAP					0.805**
SCD					

Trunk sitting tasks: stable sitting without feedback (SNF); stable sitting with feedback (SWF); stable sitting while performing medial-lateral displacements with feedback (SML); stable sitting while performing anterior-posterior displacements with feedback (SAP); stable sitting while performing circular displacements with feedback (SCD).

* $p < .05$.

** $p < .01$.

position during different static and dynamic tasks utilizing real-time biofeedback of the CoP.

A common concern with new test development is the floor and ceiling effects, which are of particular importance when considering a population sample with a wide range of trunk capabilities. In particular, we have assessed the suitability of a test battery to assess TC in participants classified as having moderate to severe gross motor function impairments (GMFCS levels 2–4). The suitability of the unstable sitting methodology has been demonstrated not only in individuals without disabilities and competitive athletes (Barbado et al., 2016a, 2016b) but also, in populations with impaired TC (Verheyden et al., 2006; Willigenburg et al., 2013). However, although the hemisphere radius used in this study was higher than that used in previous studies, reducing task difficulty (Barbado et al., 2016a, 2016b), only 51.1% and 34.0% of our participants with CP were able to complete the unstable static and unstable dynamic conditions respectively. This suggests that seated tasks on an unstable surface might not be appropriate to evaluate individuals with moderate or severe trunk control impairments. On the contrary, the results of this study seem to indicate a good stable surface success rate among participants with CP, with more

than 70% successfully completing the SCD condition (the most difficult task) and the 93.6% completing the static conditions (SNF and SWF).

Most of the stable sitting tasks displayed adequate between trials consistency ($15.2\% \leq TE \leq 19.7\%$). Therefore, they allow us to identify if the difference between separate measures of an individual is, or not, caused by within-subject variability (Hopkins, 2000; Weir, 2005). Relative consistency within these stable sitting tasks was high for both, static and dynamic conditions ($0.89 \leq TE \leq 0.95$), showing an excellent ability to rank (Hopkins, 2000; Weir, 2005) individuals with moderate to severe CP according to their TC.

Comparing our results to a previous study using CoP analysis in CP children (Kyvelidou et al., 2010), our results displayed higher ICC values than those shown by scattering variables used in posturography studies which have assessed TC while stable sitting. One explanation might be related to the fact that our participants received a real-time biofeedback. Thus, those studies that did not offer such biofeedback may have achieved different equilibrium points throughout each trial making the CoP displacement non-stationary; therefore, reducing the reliability of scattering variables (Barbado et al., 2017; Caballero et al., 2015; van Dieen et al., 2010). The TE differences found between SWF and SNF seems to support this hypothesis; and therefore, the use of biofeedback appears to be useful to improve the absolute reliability of TC tests using force platforms. Another point of interest was to assess if the protocol is suitable to assess populations with different levels of trunk control; avoiding as much as possible, floor and ceiling effects. Barbado et al. (2016a) utilized the same protocol presented here and found that the most difficult tasks on the unstable surface displayed better reliability than those on the stable seat in young recreational athletes, whilst for individuals with CP we found the greatest reliability in the static tasks conducted on the stable seat. The results of both studies provide initial indications that this protocol allows for the assessment of a large range of individuals with TC disparity.

It is also important to consider the learning effect when assessing balance tasks. Unlike previous studies (Barbado et al., 2016a,

2017) which showed a performance improvement with practice, CP individuals displayed an increase in performance (decreased MRE) only in two (SWF and SML) of the five sitting conditions. These findings suggest that TC is less susceptible to task learning (or less susceptible to change) in adults with moderate-to-severe CP impairments than in healthy individuals. However, taking into account that a learning effect was found in SWF and SML conditions, it would be necessary to perform at least one familiarization trial before testing.

Posturography revealed a significantly lower performance in adults with moderate-to-severe CP in four of the five static trials compared to healthy adults (Table 2). Interestingly, as the effect sizes showed, when the complexity of the tasks increased (i.e. adding visual biofeedback and motion to increase motor demands), differences in trunk performance became more evident between groups. In this sense, dynamic tasks seem to be adequate than static tasks to assess impaired TC in adults with CP (SWF: $p < 0.001$, $d_g = 1.17$; SCD: $p < 0.001$; $d_g = 1.95$), which indicates that trunk performance in this population is task-specific. The moderate correlations found between conditions seems to support that static and dynamic TC although related, could not reflect the same ability. These results agree with those of Liao et al. (2003), which showed that in more challenging tasks (i.e. dynamic), children with CP presented a greater sway index, which could be due to the fact that these children commonly show problems in (co)activation and coordination of the postural trunk muscles (Chen and Woollacott, 2007). Although both young and adult people with CP have an important TC deficit, future studies are needed to describe how age could affect TC.

Differences found between adults with and without CP in dynamic posturography could be related not solely to individuals' health condition, but to other factors, such as lifestyle, physical activity or technical aids. Adults with CP usually present a high risk of chronic conditions that lead them towards a very sedentary lifestyle (Verschuren et al., 2016). In addition, increasing physical condition is difficult when the therapeutic supports, commonly received during childhood, decrease dramatically with the age and when access to a sports/fitness center or household-related physical activity is limited for these individuals (Reina, 2014). Additionally, adults with moderate-to-severe CP tend to move around with powerchairs, whose typical configuration includes a high seat and other devices that fully support the wheelchair user. These supports might be reinforced by the use of straps in order to facilitate individuals' trunk function. However, the continued use of these support aids might end up having a negative result. For example, these aids could hinder individuals' trunk and head control capacities, which are crucial for maintaining an adequate body posture (da Costa et al., 2016) when performing static and dynamic tasks (Saavedra et al., 2009, 2010).

In spite of the high-reliability results found in this study, some limitations should be considered for future studies, as well as its potential practical applications. In this study, only the intra-session reliability was evaluated. Therefore, further works should evaluate the consistency of this assessment between sessions. In addition, although no differences were found in TC according to the GMFCS classification or age, future studies should increase the number of participants to assess the reliability of this protocol in more homogenous individuals with CP, e.g.: hemiplegia or diplegia. It could be also interesting to use a less severe group of individuals with CP (GMFCS < III), in order to check if the differences between CP and healthy adults are similar to those found in this study. Finally, although our experimental set-up was able to reduce anthropometric influence on trunk performance, future studies should develop easy-to-implement methods to calculate upper-body COM height taking into account body size parameters, characteristics of the wooden chair, etc.

5. Conclusion

This study provides a reliable battery of posturography test to assess TC in adults with moderate-to-severe CP. Because the static and dynamic tasks displayed a high intra-correlation, it might be possible to reduce to one static and one dynamic task, in order to achieve a quick description of trunk postural and movement control in this population. This assessment has shown that TC is significantly affected in CP adults compared with a group without CP of similar age, demonstrating they present more difficulties to perform dynamic tasks on stable surfaces than static ones. For that reason, this study encourages physical activity practitioners to design dynamic activities that challenge trunk control to develop activities of daily living in this population.

Acknowledgements

This study was supported by the Economy and Competitiveness Ministry of Spain, project cod. MINECO DEP2014-55167-R (National Plan I+D+I (Investigation, Development and Innovation), and the Research Project supported by Bancaja – UMH (Ref. 11859/2011).

Conflict of interest statement

The authors declare that they have no conflicts of interest concerning this article.

References

- Barbado, D., Barbado, L.C., Elvira, J.L., Dieen, J.H., Vera-Garcia, F.J., 2016a. Sports-related testing protocols are required to reveal trunk stability adaptations in high-level athletes. *Gait & Posture* 49, 90–96.
- Barbado, D., Lopez-Valenciano, A., Juan-Recio, C., Montero-Carretero, C., van Dieen, J.H., Vera-Garcia, F.J., 2016b. Trunk stability, trunk strength and sport performance level in judo. *PLoS One* 11, e0156267.
- Barbado, D., Moreside, J., Vera-Garcia, F.J., 2017. Reliability and repetition effect of the center of pressure and kinematics parameters that characterize trunk postural control during unstable sitting test. *PM&R* 9, 219–230.
- Borg, F.G., Laxaback, G., 2010. Entropy of balance—some recent results. *J. Neuroeng. Rehabil.* 7, 38.
- Brundavanam, I., Gadde, L.P., Balne, N.K., Purohit, A., 2015. Effect of dynamic sitting balance on upper extremity motor skills in children having spastic diplegia: a correlational study. *Indian J. Cerebral Palsy* 1, 70.
- Caballero, C., Barbado, D., Moreno, F.J., 2015. What COP and kinematic parameters better characterize postural control in standing balance tasks? *J. Motor Behav.* 47, 550–562.
- Chen, J., Woollacott, M.H., 2007. Lower extremity kinetics for balance control in children with cerebral palsy. *J. Motor Behav.* 39, 306–316.
- Cheng, R.J., Lin, H.C., Ju, Y.H., Ho, C.S., 2009. Effect of seat surface inclination on postural stability and forward reaching efficiency in children with spastic cerebral palsy. *Res. Dev. Disabil.* 30, 1420–1427.
- Cholewicki, J., Polzhofer, G.K., Radebold, A., 2000. Postural control of trunk during unstable sitting. *J. Biomech.* 33, 1733–1737.
- da Costa, C.S., Saavedra, S.L., Rocha, N.A., Woollacott, M.H., 2016. Effect of biomechanical constraints on neural control of head stability in children with moderate to severe cerebral palsy. *Phys. Therapy*.
- Desloovere, K., Heyrman, L., 2015. Trunk control in children with cerebral palsy: where are we now? *Dev. Med. Child Neurol.* 57, 310–311.
- Fleiss, J.L., 1986. Analysis of data from multiclinic trials. *Controlled Clin. Trials* 7, 267–275.
- Goodworth, A.D., Wu, Y.H., Felmlee, D., Dunkleberger, E., Saavedra, S., 2017. A trunk support system to identify posture control mechanisms in populations lacking independent sitting. *IEEE Tran. Neural Syst. Rehabil. Eng.* 25, 22–30. a publication of the IEEE Engineering in Medicine and Biology Society.
- Hancock, G.R., Butler, M.S., Fischman, M.G., 1995. On the problem of two-dimensional error score: measures and analyses of accuracy, bias, and consistency. *J. Motor Behav.* 27, 241–250.
- Hedges, L.V., Olkin, I., 1985. *Statistical Methods for Meta-analysis*. Academic Press, Orlando.
- Hopkins, W.G., 2000. Measures of reliability in sports medicine and science. *Sports Med.* 30, 1–15.
- Hopkins, W.G., 2015. *Spreadsheets for analysis of validity and reliability*. *Sports Science* 19, 36–42.
- Jahnsen, R., 2004. Being adult with a 'childhood disease'—a survey on adults with cerebral palsy in Norway (Thesis). Faculty of Medicine, University of Oslo.

- Kyvelidou, A., Harbourne, R.T., Shostrom, V.K., Stergiou, N., 2010. Reliability of center of pressure measures for assessing the development of sitting postural control in infants with or at risk of cerebral palsy. *Arch. Phys. Med. Rehabil.* 91, 1593–1601.
- Liao, S.F., Yang, T.F., Hsu, T.C., Chan, R.C., Wei, T.S., 2003. Differences in seated postural control in children with spastic cerebral palsy and children who are typically developing. *Am. J. Phys. Med. Rehabil.* 82, 622–626. Association of Academic Physiatrists.
- Lin, D., Seol, H., Nussbaum, M.A., Madigan, M.L., 2008. Reliability of COP-based postural sway measures and age-related differences. *Gait & Posture* 28, 337–342.
- Moore, G., Durstine, J.L., Painter, P., Medicine, A.C.o.S., 2016. ACSM's Exercise Management for Persons with Chronic Diseases and Disabilities, 4E. Human Kinetics.
- Palisano, R.J., Rosenbaum, P., Bartlett, D., Livingston, M.H., 2008. Content validity of the expanded and revised gross motor function classification system. *Dev. Med. Child Neurol.* 50, 744–750.
- Pham, H.P., Eidem, A., Hansen, G., Nyquist, A., Vik, T., Sæther, R., 2016. Validity and responsiveness of the trunk impairment scale and trunk control measurement scale in young individuals with cerebral palsy. *Phys. Occup. Therapy Pediatrics* 36 (4), 440–452.
- Reina, R., 2014. Adapted Physical Activity: the journey to Ithaca goes ahead: [Actividad Física Adaptada: el viaje a Ítaca continua]. *RICYDE. Revista Internacional de Ciencias del Deporte* 10, 177–179.
- Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., Dan, B., Jacobsson, B., 2007. A report: the definition and classification of cerebral palsy April 2006. *Dev. Med. Child Neurol. Supplement* 109, 8–14.
- Ryalls, B.O., Harbourne, R., Kelly-Vance, L., Wickstrom, J., Stergiou, N., Kyvelidou, A., 2016. A perceptual motor intervention improves play behavior in children with moderate to severe cerebral palsy. *Front. Psychol.* 7, 643.
- Saavedra, S., Joshi, A., Woollacott, M., van Donkelaar, P., 2009. Eye hand coordination in children with cerebral palsy. *Exp. Brain Res.* 192, 155–165.
- Saavedra, S., Woollacott, M., van Donkelaar, P., 2010. Head stability during quiet sitting in children with cerebral palsy: effect of vision and trunk support. *Exp. Brain Res.* 201, 13–23.
- Sæther, R., Helbostad, J.L., Riphagen, I.L., Vik, T., 2013. Clinical tools to assess balance in children and adults with cerebral palsy: a systematic review. *Dev. Med. Child Neurol.* 55, 988–999.
- Sahinoglu, D., Coskun, G., Bek, N., 2017. Effects of different seating equipment on postural control and upper extremity function in children with cerebral palsy. *Prosthet. Orthot. Int.* 41, 85–94.
- Santos, B.R., Delisle, A., Larivière, C., Plamondon, A., Imbeau, D., 2008. Reliability of centre of pressure summary measures of postural steadiness in healthy young adults. *Gait & Posture* 27, 408–415.
- Szopa, A., Domagalska-Szopa, M., 2015. Postural stability in children with hemiplegia estimated for three postural conditions: standing, sitting and kneeling. *Res. Dev. Disabil.* 39, 67–75.
- van der Burg, J.C., van Wegen, E.E., Rietberg, M.B., Kwakkel, G., van Dieen, J.H., 2006. Postural control of the trunk during unstable sitting in Parkinson's disease. *Parkinsonism Related Disorders* 12, 492–498.
- van der Heide, J.C., Fock, J.M., Otten, B., Stremmelaar, E., Hadders-Algra, M., 2005. Kinematic characteristics of postural control during reaching in preterm children with cerebral palsy. *Pediatric Res.* 58, 586–593.
- van der Linden, M.L., Jahed, S., Tennant, N., Verheul, M.H., 2018. The influence of lower limb impairments on RaceRunning performance in athletes with hypertonia, ataxia or athetosis. *Gait & Posture* 61, 362–367.
- van Dieen, J.H., Koppes, L.L., Twisk, J.W., 2010. Postural sway parameters in seated balancing; their reliability and relationship with balancing performance. *Gait & Posture* 31, 42–46.
- Verheyden, G., Nuyens, G., Nieuwboer, A., Van Asch, P., Ketelaer, P., De Weerd, W., 2006. Reliability and validity of trunk assessment for people with multiple sclerosis. *Phys. Therapy* 86, 66–76.
- Verschuren, O., McPhee, P., Rosenbaum, P., Gorter, J.W., 2016. The formula for health and well-being in individuals with cerebral palsy: physical activity, sleep, and nutrition. *Dev. Med. Child Neurol.* 58, 989–990.
- Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J. Strength Condition. Res.* 19, 231–240. National Strength & Conditioning Association.
- Westcott, S.L., Lowes, L.P., Richardson, P.K., 1997. Evaluation of postural stability in children: current theories and assessment tools. *Phys. Therapy* 77, 629–645.
- Willigenburg, N.W., Kingma, I., van Dieen, J.H., 2013. Center of pressure trajectories, trunk kinematics and trunk muscle activation during unstable sitting in low back pain patients. *Gait & Posture*.
- Winter, D.A., 1990. *Biomechanics and Motor Control of Human Movement*. Wiley, New York, p. 86.