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Assessment of postural control in children with cerebral palsy: A review

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Abstract

This paper aimed to review studies that assessed postural control (PC) in children with cerebral palsy (CP) and describe the methods used to investigate postural control in this population. It also intended to describe the performance of children with CP in postural control. An extensive database search was performed using the keywords: postural control, cerebral palsy, children, balance and functionality. A total of 1065 papers were identified and 25 met the inclusion criteria. The survey showed that PC is widely studied in children with CP, with reliable methods. The link between postural control and functionality was also evident. However, a lack of studies was observed assessing postural control in these children by means of scales and functional tests, as well as exploring postural control during daily functional activities. Thus research addressing these issues can be a promising field for further research on postural control.

Keywords

Postural control; Cerebral palsy; Children; Balance; Functionality

1. Introduction

Postural control is the ability to control the body position in space to achieve orientation and stability (Duarte & Freitas, 2010; Hass, Diener, Rapp, & Dichgans, 1989; Massion, 1998; Shumway-Cook & Woollacott, 2011). Stability could be defined as the maintenance of the center of body mass (COM) within the limits of the base of support during static or dynamics activities (Corrêa, Corrêa, Franco, & Bigongiari, 2007; Massion, 1998; Pollock, Durward, & Rowe, 2000). There is a strong relationship between the base of support (BoS), the projection of the center of mass into this the BoS and the center of pressure (Cumberworth, Patel, Rogers, & Kenyon, 2007; Winter, 1995); since the BoS is defined as the possible range of the center of pressure (COP), the origin of the ground reaction vector (Hof, Gazendam, & Sinke, 2005; Pai & Patton, 1997).

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Moreover the COM is known to continually move within these limits, especially during the performance of daily functional activities such as mobility, transfer, and self-care tasks. Thus, postural control mechanisms should be constantly active in order to recover balance as the COM is displaced (MacKinnon & Winter, 1993; Pollock et al., 2000).

In fact, maintaining a stable posture, even during daily functional activities, is challenging because stability demands complex interactions between sensory system, central nervous system (CNS), and muscle skeletal system (Corrêa et al., 2007; Newell, Slobounov, Slobounova, & Molenaar, 1997; Shumway-Cook & Woollacott, 2011; Woollacott, Jenssen, Jasiewicz, Roncesvalles, & Sveistrup, 1998).

In patients with cerebral palsy (CP), these interactions are known to be affected, which may be a reason why postural control is impaired and the maintenance of stability is critical (Woollacott & Shumway-Cook, 2005). In children with CP, the major postural dysfunction is the inability to coordinate the activation of postural muscles in the right sequence, especially during the performance of functional activities (Brogren, Hadders-Algra, & Forssberg, 1998; Graaf-Peters et al., 2007). This impairment leads to important functional constraints.

Considering the role of postural control in the performance of motor skills (Chen & Woollacott, 2007; Näslund, Sundelin, & Hirschfeld, 2007) and in the adaptation of an individual to changing environmental demands (Barela, 2000),it is important to understand how these factors interact in the CP population. Moreover, knowing the advantages and disadvantages of methodological approaches and gaps in literature may guide future research that improves the quality of life of children with CP in the long run. Thus, this study aims to review papers assessing postural control in children with CP, with a focus on describing methods to assess it and characterizing the children's motor responses.

2. Method

2.1. Study identification and selection

Scientific articles were obtained by means of an extensive search in electronic databases, including PubMed, Science Direct, Scielo, and Lilacs. Papers published between January of 1983 and July of 2012 were considered for inclusion. The search was performed by using the following keywords in combination: postural control, cerebral palsy, children, balance, and functionality.

The papers were pre-selected by reading the titles and abstracts. The selection was completed after reading the full text, considering as inclusion criteria: studies using experimental design with a focus on postural control assessment in children with CP aged less than 18 years old. Studies assessing children classified as any levels of gross motor function classification system (GMFCS) were included.

Papers with other focus than postural control in children with CP, and studies assessing participants older than 18 years were excluded from the review. Clinical trials, case reports and review studies were excluded as well.

The methodological quality of studies was not taken into account in order to gather as much information as possible regarding research in this subject.

2.2. Data extraction and analysis

Data were extracted from the studies and summarized based on: (1) experimental design and characteristics of the research participants (e.g. sample size, age, and GMFCS level); (2) the body posture (e.g. standing or sitting posture) and activity used for assessing postural control (e.g. static postures, functional activities such as gait, manual reaching, and sit-to-stand movement); (3) the measurement tools used for postural control assessment (e.g. kinematics and dynamics analysis, dynamometry, electromyography) and outcome variables (e.g. joint angle, displacement of the center of pressure, and muscle onset latency); (4) factors that may influence postural control (e.g. manipulation of extrinsic factors: postural perturbation; sensory and visual manipulation); and (5) description of the performance of postural control in children with CP.

3. Results and discussion

The database search initially resulted in 1065 studies. 463 of them were retrieved from PubMed, 575 from Science Direct, 6 from Scielo, and 21 from Lilacs. After reading the titles and abstracts, 1040 studies were excluded. The reasons for exclusion were: studies did not aim to assess postural control in children with CP as main objective (n = 142); studies were clinical trials (n = 111); case reports (n =372), and review papers (n = 415). Among the 415 review papers found, only 10 addressed postural control in CP and none of them had the same goal of the present review. Table 1 shows year of publication, experimental design, and characteristics of the sample of the included papers. Table 2 shows data on posture and activity used the studies, extrinsic task factors, measurement tools, and outcome variables.

3.1. Experimental design and research participants

All the included papers consisted of cross-sectional studies. This kind of study is important for identification and characterization of postural control strategies used by children (Thelen & Smith, 1998). This is especially important in children with CP, because a better knowledge of the strategies used for balance control should lead to more effective rehabilitation programs (Ju, Hwang, & Cherng, 2012).

The sample size ranged from 8 to 115 children in the studies (mean = 29.35; SD =21.5), and the mean number of the participants with CP in the studies was 12.1 (SD = 6.4). The large amount of studies with small sample sizes reflects the difficulties researchers face in recruiting a large and homogeneous sample from this population as there is a high variability of clinical features in CP. Analysis of standing postural control also requires a high level of motor control for the maintenance of standing posture for at least 20 s (Ferdjallah, Harris, Smith, & Wertsch, 2002), which cannot always be attained by severely impaired children. Thus, conducting studies assessing postural control in large samples of children with CP is a challenge that still needs to be met by researchers.

The age of the participants ranged from 9 months to 18 years-old. Some studies split the sample into age groups (Rose et al., 2002; Saavedra, Woollacott, & van Donkelaar, 2010).

Splitting the sample according to age is a way to investigate the relationship between age and postural control in both children with CP and controls. However, longitudinal design has not been used to investigate developmental changes in postural control, which points to the need of future studies addressing this issue.

The survey revealed that the studies generally classified children regarding their level of motor function rather than cognitive function, which gives more emphasis to the postural control performance. We suggest that adding a cognitive classification to studies of postural control would contribute to understand the impact of cognitive impairments in postural control modulation.

With regard to the level of impairment, all studies, with the exception of Näslund et al. (2007), evaluated mildly to moderately impaired children. Participants with mild impairment were more likely to be chosen by studies on standing postural control. This is clearly related to the fact that children must be able to perform certain tasks independently so that these studies can be carried out. This classification was based either on GMFCS levels (Burtner, Woollacott, Craft, & Roncesvalles, 2007; Chen & Woollacott, 2007; Corrêa et al., 2007; Girolami, Shiratory, & Aruin, 2011; Ju et al., 2012; Liu, Zaino, & McCoy, 2007; Reilly, Woollacott, & Donkelaar, 2008; Rha, Kim, & Park, 2010; Saavedra et al., 2010; Zaino & McCoy, 2008) or other criteria, such as topography of the lesion (Barela et al., 2011; Bigongiari et al., 2011; Burtner, Qualls, & Woollacott, 1998; Cherng, Su, Chen, & Kuan, 1999; Liao, Jeng, Lai, Cheng, & Hu, 1997; Rose et al., 2002).

The GMFCS was used in several papers studying postural control in children with CP. The GMFCS is important to classify current performance in gross motor function (Palisano et al., 1997). Its wide use confirms the relevance of this system to research and provides insights onto the relation between postural control and functionality by means of a prediction of functioning in daily life (Ostensjo, Carlber, & Vollestad, 2003). The data related to research participants are shown in Table 1.

3.2. Analysis of postures and activities

In the present review, the majority of studies assessed postural control in static standing posture (Barela et al., 2011; Burtner et al., 1998; Burtner, Woollacott, & Qualls, 1999; Burtner et al., 2007; Chen & Woollacott, 2007; Cherng et al., 1999; Corrêa et al., 2007; Donker, Ladebt, Roerdink, Savelsbergh, & Beek, 2008; Ferdjallah et al., 2002; Reilly et al., 2008; Rha et al., 2010; Rose et al., 2002), whereas only four studies investigated static sitting position (Cherng, Lin, Ju, & Ho, 2009; Saavedra et al., 2010). Moreover, few studies had assessed postural control during daily functional activities in children with CP (Bigongiari et al., 2011; Cherng et al., 2009; Girolami et al., 2011; Hsue, Miller, & Su, 2009; Ju et al., 2012; Liao et al., 1997; Liu et al., 2007; Näslund et al., 2007; Zaino & McCoy, 2008).

Regarding the use of functional activities to assess postural control, some authors investigated anticipatory adjustments prior to manual reaching performed in sitting (Bigongiari et al., 2011; Ju et al., 2012) and standing postures (Girolami et al., 2011; Liu et al., 2007). Other studies investigated the reliability of center of pressure (COP) measurement during manual activities (Zaino & McCoy, 2008); the postural response to perturbations during reaching (Cherng et al., 2009); the relationship between static standing postural control and dynamic postural control during gait (Liao et al., 1997); and the relationship between balance deficits and COP/COM measurements during gait (Hsue et al., 2009). However, there are still few studies assessing postural control during the performance of functional activities, as evidenced by the small amount of papers (n = 8) that met the inclusion criteria for this review, and the focus limited to gait and reaching tasks.

We suggest that assessing postural control during functional tasks is important to understand balance adjustments adopted by these children in their daily live specially because of the significant balance perturbations occurring during the performance of functional tasks. Exploring the postural control during functional activities in future research will contribute to understand the relationship between structural impairment and activity performance in the organism, which in turn will lead to better understanding of children's capabilities and of the specific consequences of brain injury on functionality. Moreover, such information will contribute to the creation of rehabilitation programs aimed at improving postural and functional skills according to each child's needs.

The study of other functional skills than gait and reaching only is important because there are many other sources of sensory and balance conflicts in the daily routine. Thus, the characteristics of postural control during functional activities still need to be further investigated.

3.3. Measurement tools and outcome variables

Some of the tools used to assess sitting and standing postural control included electromyography (Bigongiari et al., 2011; Burtner et al., 1998; Cherng et al., 2009; Girolami et al., 2011), infrared emitter (Barela et al., 2011) and magnetic tracking (kinematics analysis) of the head movements in space (Saavedra et al., 2010).

However, most studies employed force platforms to evaluate moments of force around the joints (Chen & Woollacott, 2007), amplitude of ground reaction force (Cherng et al., 2009; Ferdjallah et al., 2002; Näslund et al., 2007), and COP displacement within a given period of time (Burtner et al., 2007; Cherng et al., 1999, 2009; Corrêa et al., 2007; Donker et al., 2008; Girolami et al., 2011; Hsue et al., 2009; Ju et al., 2012; Liao et al., 1997; Liu et al., 2007; Reilly et al., 2008; Rha et al., 2010; Rose et al., 2002; Zaino & McCoy, 2008).

Despite the large number of instruments mentioned above, it is important to highlight the lack of studies using tests and scales that can be used to assess postural control in children with CP such as Pediatric Reach Test (Bartlett & Birmingham, 2003) and Berg Balance Scale (Franjoine, Gunther, & Taylor, 2003). These tests are reliable, easy to handle and involve the performance of functional tasks to be completed. Their low cost makes them valuable tools to be used in clinical practice. Thus, the assessment of postural control by means of refined instruments associated with these tests may provide a better understanding of the functional impairments in postural control, being a wide field of research in literature concerning CP.

3.4. Manipulation of extrinsic factors

With regard to the influence of extrinsic factors on postural control, studies were found on visual (Barela et al., 2011; Cherng et al., 1999, 2009; Donker et al., 2008; Ferdjallah et al., 2002; Liao et al., 1997; Rose et al., 2002; Saavedra et al., 2010) and proprioceptive manipulation (Corrêa et al., 2007), dual-task effects on postural control (Reilly et al., 2008), postural perturbation (Burtner et al., 1999; Burtner et al., 1998, 2007; Chen & Woollacott, 2007; Cherng et al., 1999; Liao et al., 1997) and manipulation of the seat surface (Cherng et al., 2009).

The studies manipulating the availability of visual information for postural control showed that children with CP exhibited greater COP displacement with eyes closed compared to typical developing children (Rose et al., 2002). Visual deprivation also increased hip and ankle balance strategies in this population (Ferdjallah et al., 2002). However, muscular activation of the ankle dorsiflexors is limited in these children. Thus, it seems that the use of visual information for postural control is appropriate in most children with CP, but they apparently use it to compensate for musculoskeletal and neuromotor dysfunction. With regard to visual manipulation, Barela et al. (2011) showed that children with CP can couple sensory information from visual inputs to motor action, but not with the same magnitude as typically-developing children, possibly due to difficulties in adaptation.

Reilly et al. (2008) explored dual-task effects on postural control. The children stood on the force plate while an attentionally challenging cognitive task was performed. They verified that children with CP have less ability to allocate intentional resources to the processing of tasks involving visual working memory and executive attention. This may be due to limitations in the executive component of attention. Thus, the interaction between executive attention and postural control in children with cerebral palsy seems to increase the deficits in standing postural control.

Perturbation of the support surface led to a greater instability in children with CP than in typical children (Burtner et al., 2007), especially under visual deprivation. Apparently, impaired sensory integration abilities (Cherng et al., 1999) increase agonist–antagonist co-contraction in order to provide stability for these children (Burtner et al., 1998). However, these motor adaptations were not always successful in maintaining both stability and alignment for different postures. Thus, it has been shown that these joint in coordination contributed to the delayed postural control responses in children with CP (Chen & Woollacott, 2007).

In summary, the survey shows that extrinsic factors play an important role in postural control adjustments in children with CP. Postural control is indeed constantly challenged in daily routine situations, and different sensory environments require different adjustments.

3.5. Characterization of the postural control in CP

Postural control was assessed in the reviewed studies under a variety of conditions, including sitting posture (Bigongiari et al., 2011; Cherng et al., 2009; Ju et al., 2012; Saavedra et al., 2010), standing posture (Barela et al., 2011; Burtner et al., 1998, 1999; Chen & Woollacott, 2007; Cherng et al., 1999; Corrêa et al., 2007; Donker et al., 2008; Ferdjallah et al., 2002; Girolami et al., 2011; Liu et al., 2007; Näslund et al., 2007; Reilly et al., 2008; Rha et al., 2010; Rose et al., 2002; Zaino & McCoy, 2008) and gait (Hsue et al., 2009; Liao et al., 1997). In addition, three experimental conditions have been assessed while in sitting and standing postures, including steady-state postural control (quiet sitting or standing), reactive postural control during recovery from an unexpected threat to balance (usually caused by a moveable platform) and anticipatory postural control, which requires that the children activate their postural muscles prior to the reaching movement.

The postural responses performed by children with CP in the conditions mentioned above are presented in the next section.

3.6. Sitting postural control

Previous studies have shown that primary direction-specific adjustments required for postural recovery while sitting are preserved in child with mild to moderate CP. However, secondary adjustments, which are related to the characteristics of the muscle response, are impaired (Carlberg & Hadders-Algra, 2005). When sitting posture is perturbed, these children exhibit proximal-distal patterns of activation and excessive co-activation of antagonist muscles, as well as poor modulation of the amplitude of muscle responses (Brogren et al., 1998; Carlberg & Hadders-Algra, 2005). During self-paced voluntary reaching while seated, postural anticipatory adjustments rarely show antagonist co-activation. Thus, co-activation of postural muscles appears to be task-specific in these children. During quiet sitting, children with CP also exhibit more head oscillation than typical children, even when trunk support is provided (Saavedra et al., 2010).

3.7. Standing posture

With regard to postural control while standing at rest, the studies demonstrated that children with CP who are able to stand and walk independently display increased sway during quiet stance. Apparently, the best predictor of gross motor function is the postural stability in the eyes-closed condition (Liao & Hwang, 2003) because children with CP use preferentially visual information to compensate for musculoskeletal and neuromotor dysfunctions. However, it has also been shown that not all the children with CP have abnormal postural sway during quiet stance. In a study of ambulatory children with spastic diplegia, the majority of children showed normal values for sway (Rose et al., 2002). Donker et al. (2008) reported that children with CP during quiet stance, while performing a visual feedback task (requiring an external focus of attention), show larger and more regular sway amplitude compared with typical children (Donker et al., 2008). COP regularity is viewed as inversely related to automaticity in postural control, which suggests that postural control is less automatic for children with CP (Donker et al., 2008; Roerdink et al., 2006). It was also shown that when provided visual feedback, which created an external focus of attention, both the amount and the regularity of sway decreased. This supports the concept that adopting an external focus of attention can improve motor skill performance as it increases the automaticity in postural control (Wulf, McNevin, & Shea, 2001).

3.8. Reactive posture control

Studies using a movable platform to perturb the balance of children with CP classified as GMFCS levels I, II and III (simulating standing on a bus or train that starts to move) have found that children with spastic hemiplegia and diplegia have to use a step strategy at lower platform displacement velocities than typical children. In addition, they take significantly longer to recover stability and move the COP significantly more when recovering balance (Chen & Woollacott, 2007). Although they showed direction-specific adjustments to the movement of the platform, the excursion of the COP was larger than in typical children (Woollacott & Shumway-Cook, 2005).

The difficulties with balance recovery may be due to impaired neuromuscular responses. Children with spastic diplegia typically show high levels of background muscle activity when quietly standing, with long-duration responses to balance threats as they attempt to recover stability (Burtner et al., 1998). The neuromuscular response time in these children seems to be disorganized (increased proximal-distal muscle activation and more co-contraction in response to platform movements) compared to healthy children (Burtner et al., 1998; Woollacott & Shumway-Cook, 2005). These patterns of neuromuscular responses may be related with the smaller muscle activation in the ankle joint verified in children with CP when in standing posture (Ferdjallah et al., 2002). Another constraint leading to reduced stability in children with spastic diplegia is their inability to increase the muscle contraction amplitudes when platform displacement is increased. Typical children increase muscle response amplitude as the level of perturbation also increases, whereas children with spastic diplegia do not (Roncesvalles, Woollacott, & Burtner, 2002).

With regard to biomechanical constraints affecting balance recovery in children with CP, Burtner et al. (1998) found that healthy children, when in a crouch position similar to that of children with CP, exhibited patterns of muscle recruitment and COP displacements similar to those exhibited by children with CP. These findings suggest that not only brain the injury but also biomechanical constraints may contribute to deficits in postural recovery in children with CP (Burtner et al., 1998).

3.8.1. Anticipatory postural control—Problems in activating postural muscle responses prior to voluntary muscle activity occur in children with spastic hemiplegic CP (Nashner, Shumway-Cook, & Marin, 1983). When children with CP are asked to push or pull on a handle while standing, there is a lack of preparatory postural activity on the affected side compared with unaffected side. On the affected side, muscle activity in the arm precedes activity in the postural muscles of the leg. On the unaffected side, postural activity was activated in an anticipatory manner before activation of the prime movers of the arm (Nashner et al., 1983).

In other studies that assessed postural control in children with spastic cerebral palsy classified as GMFCS II, it was shown that these children use anticipatory adjustments before the beginning of a reaching movement in standing posture, but they have a high variability of muscle activity (Liu et al., 2007). This can result from abnormal muscle recruitment patterns, high co-contraction levels, and altered muscle recruitment order (Zaino & McCoy, 2008).

To analyze the relationship between standing balance and walking performance, Liao et al. (1997) examined children with spastic diplegia. They found that dynamic balance was significantly correlated with walking function. Gait analysis also showed that the greater the COP displacement during gait, the poorer the body alignment and inter-limb coordination and the slower the gait (Liao et al., 1997).

Although these studies carefully describe postural control impairments in children with CP, very few studies have assessed postural control during functional activities and described functional constraints in these activities arising from postural control impairments. We suggest that this information would be relevant because of the role played by functionality in rehabilitation of postural control.

4. Conclusion

Research investigating the assessment of postural control in children with CP has been widely performed and described in the literature, with reliable methods. However, a lack of studies was observed assessing postural control in these children by means of scales and functional tests, as well as exploring postural control during daily functional activities. The assessment of postural control in these children by means of scales and functional tests may provide a better knowledge about functional constraints in CP. Moreover exploring postural control during functional activities allow to determine the mainly affected activities in this population and its repercussion in the level of activity and participations of thee children. Thus research addressing these issues can be a promising field for further research on postural control.

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Table 1

Sample description.

Author	Year	Experimental design	Population				
			Sample size	CP	Typical	Age	GMFCS
Nashner et al.	1983	Cross-sectional	20	10	10	7–9 years old	
Liao et al.	1997	Cross-sectional	24	8	16	5–12 years old	
Burtner et al.	1998	Cross-sectional	14	7	7	1–14 years old	
Burtner et al.	1999	Cross-sectional	8	4	4	3.5–15 years old	
Cherng et al.	1999	Cross-sectional	21	7	14		
Ferdjallah et al.	2002	Cross-sectional	19	11	8	5–18 years old	
Roncesvalles et al.	2002	Cross-sectional	48	8	40	9 month–10 years old	
Rose et al.	2002	Cross-sectional	115	23	92	5–18 years old	
Liao and Hwang	2003	Cross-sectional	15	15		5–12 years old	
Burtner et al.	2007	Cross-sectional	44	8	36	9 month–10 years old	I, II, III
Chen and Woollacott	2007	Cross-sectional	15	7	8	4–13 years old	I, II, III
Corrêa et al	2007	Cross-sectionall	20	10	10	5–10 years old	I and II
Liu et al.	2007	Cross-sectional	14	7	7	8–12 years old	II
Näslund et al.	2007	Cross-sectional	12	6	6	5–12 years old	III and IV
Zaino and McCoy	2008	Cross-sectionall	40	20	20	8–14 years old	I, II, III
Donker et al.	2008	Cross-sectional	19	10	9	5–11 years old	
Reilly et al.	2008	Cross-sectional	14	8	6	7–14 years old	I, II, III
Hsue et al.	2009	Cross-sectional	42	32	10	8–14 years old	
Cherng et al.	2009	Cross-sectional	26	10	16	6–10 years old	
Rha et al.	2010	Cross-sectional	43	21	22		I, II and III
Saavedra et al.	2010	Cross-sectional	52	15	26 and 11 adults	4–16 years old and adults of 22–30 years old	I, II and III
Barela et al.	2011	Cross-sectional	30	15	15	8–16 years old	
Bigongiari et al.	2011	Cross-sectional	24	12	12	7–11 years old	
Girolami et al.	2011	Cross-sectional	27	18	7	7–17 years old	I, II
Ju et al.	2012	Cross-sectional	28	12	16		II, III and IV

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Table 2

Posture, activity and measurements adopted during postural control evaluation.

Author	Posture	Activity	Extrinsic factors	Assessment tools	Dependent variables	Other analyses
Nashner et al. (1983)	Stand	Static stance	Manipulation of visual conditions (eyes open, eyes closed and stabilized vision), postural perturbations with displacement of the support surface and postural manipulation with voluntary arm movements	Force plate signal analysis and surface electromyography recordings	Torsional forces, total vertical force exerted by foot resting upon its surface, horizontal force exerted by the child during voluntary arm movements, muscle onset latency	
Liao et al. (1997)	Stand	Gait and static stance	Postural perturbations with movement of support basis associated to manipulation of visual conditions	Commercial device associated to force plate	Amplitude of CoP excursion in A-P and M-L directions and area of CoP excursion	Analysis of gait velocity and Physiological Cost Index
Burtner et al. (1998)	Stand	Static stance	Postural perturbations with movement of support basis in both groups associated to crouch position in the control group	Surface electromyographic recordings	Muscle onset latencies	
Burtner et al. (1999)	Stand	Static stance	Postural perturbations with movement of support basis	Surface electromyographic recordings	Muscles onset latencies and time difference between perturbations and muscle onset response	Kinematic analysis with optical electronic movement-analysis system
Cherng et al. (1999)	Stand	Static stance	Postural perturbations with movement of support basis associated to manipulation of visual conditions	Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions and area of CoP excursion	
Ferdjallah et al. (2002)	Stand	Static stance	Manipulation of visual conditions (eyes open/eyes closed)	Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions	
Roncesvalles et al. (2002)	Stand	Static stance	Postural perturbations with displacement of support surface	Surface electromyographic recordings	Muscle onset latencies, frequency of stretch reflex, co-contraction rate, baseline muscle activity	
Rose et al. (2002)	Stand	Static stance	Manipulation of visual conditions (eyes open/eyes closed)	Force plate signal analysis	CoP calculations of path length/s, average radial displacement, mean frequency of sway, and Brownian random motion measures of the short-term diffusion coefficient, and long-term scaling exponent	
Liao and Hwang (2003)	Stand	Static stance	Manipulation of visual conditions (eyes open, eyes closed, swaying vision) and postural perturbations with displacement of support surface	Force plate signal analysis	Amplitude of the CoP excursion in A-P and M-L directions and area of sway	Analysisofgross motor ability and clinical balance test
Burtner et al. (2007)	Stand	Static stance	Postural perturbations with movement of support basis	Force plate signal analysis	COP trajectory, directional changes in CoP trajectory and percentage of the total displacement of CoP after balance recover	
Chen and Woollacott (2007)	Stand	Static stance	Postural perturbations with movement of support basis	Force plate signal analysis	Joint torque onset latency, maximum joint torque and rate of joint torque	Kinematic collected data

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Author	Posture	Activity	Extrinsic factors	Assessment tools	Dependent variables	Other analyses
					generation	
Corrêa et al. (2007)	Stand	Static stance	Absence of perturbation in both groups associated to proprioceptive manipulation in control group	Pressure platform analysis	Amplitude of CoP excursion in A-P and M-L directions and mean velocity of CoP excursion	
Liu et al. (2007)	Stand	Manual reaching		Force plate signal analysis	CoP excursion, amplitude of CoP excursion in A-P (CoPx) and M-L (CoPy) directions, velocity of CoP excursion, onset time of the first CoP excursion	Temporal analysis of the movement with electronic switches
Näslund et al. (2007)	Stand	Manual reaching		Force plate signal analysis	Amplitudes of A-P ground reaction forces during the reaching	3D optoelectronic kinematic analysis and surface electromyography recording
Zaino and McCoy (2008)	Stand	Manual reaching		Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions and mean velocity of CoP excursion	Surface electromyography recording
Donker et al. (2008)	Stand	Static stance	Manipulation of visual conditions (eyes open/eyes closed)	Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions and CoP regularity	
Reilly et al. (2008)	Stand	Static stance	Interaction between executive attention (visual working memory) and postural control (wide and narrow stance)	Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions and the RMS of the velocity of CoP displacement in A-P and M-L directions	
Cherng et al. (2009)	Sitting	Manual reaching	Postural perturbation with different seat inclinations	Force plate signal analysis	Magnitude of the peak vertical ground reaction force and amplitude of CoP excursion in A-P and M-L directions	
Hsue et al. (2009)	Stand	Gait		Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions	3D optoelectronic kinematic analysis
Rha et al. (2010)	Stand	Static stance	Tactile proprioceptive manipulation (with and without hinged ankle–foot orthoses)	Force plate signal analysis	Amplitude of CoP excursion in A-P and M-L directions, CoP coordinates of path length per second, and sway contribution from ankle control, hip load/unload, and body transverse rotation.	
Saavedra et al. (2010)	Sitting	Static stance	Manipulation of visual conditions (eyes open/eyes closed) and external trunk support	Magnetic tracking	Displacement-related measure of the head, mean velocity of the head, speed variability of the head, frequency of head displacement	
Barela et al. (2011)	Stand	Static stance	Coupling between visual information and body sway (moving room)	Infrared emitter (OPTOTRAK–Digital Northern, Inc).	Mean amplitude (AP), gain values, phase values, position variability of body sway, and velocity variability of body sway.	
Bigongiari et al. (2011)	Sitting	Manual grasping	Manipulation of tactile-proprioceptive information (effect of mass of the object grasped)	Surface electromyographic recordings	Intensity of muscular activation, degree of reciprocal inhibition, amount of co-contraction.	

Author	Posture	Activity	Extrinsic factors	Assessment tools	Dependent variables	Other analyses
Girolami et al. (2011)	Stand	Upper limbs movement		Force plate signal analysis, surface electromyographic recordings and accelerometer measures	Baseline muscle activity, anticipatory muscle activity, COP displacements in the anterior/posterior direction and peak acceleration during the movement	
Ju et al. (2012)	Sitting	Functional raching	The direction of the reaching: (1) anterior, (2) deviated 40° laterally, and (3) deviated 40° medially	Force plate signal analysis,	Hand-reach movement units (hand_MUs), sway ratio (SR), and mean ground reaction force in the anterior and posterior direction (GRF-AP)	3D optoelectronic kinematic analysis