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Review

Methods for assessment of trunk stabilization, a systematic review

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ABSTRACT

Trunk stabilization is achieved differently in patients with low back pain compared to healthy controls. Many methods exist to assess trunk stabilization but not all measure the contributions of intrinsic stiffness and reflexes simultaneously. This may pose a threat to the quality/validity of the study and might lead to misinterpretation of the results. The aim of this study was to provide a critical review of previously published methods for studying trunk stabilization in relation to low back pain (LBP). We primarily aimed to assess their construct validity to which end we defined a theoretical framework operationalized in a set of methodological criteria which would allow to identify the contributions of intrinsic stiffness and reflexes simultaneously. In addition, the clinimetric properties of the methods were evaluated. A total of 133 articles were included from which four main categories of methods were defined; upper limb (un)loading, moving platform, unloading and loading. Fifty of the 133 selected articles complied with all the criteria of the theoretical framework, but only four articles provided information about reliability and/or measurement error of methods to assess trunk stabilization with test–retest reliability ranging from poor (ICC 0) to moderate (ICC 0.72). When aiming to assess trunk stabilization with system identification, we propose a perturbation method where the trunk is studied in isolation, the perturbation is unpredictable, force controlled, directly applied to the upper body, completely known and results in small fluctuations around the working point.

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1. Introduction

Trunk stabilization can be defined as maintaining control over trunk posture and movement, in spite of the disturbing effects of gravity and external and internal perturbations. Trunk stabilization is dependent on the passive (osteoligamentous), active (muscular) and neural sub-systems that contribute mechanically and in terms of acquiring and processing information to guide mechanical responses (Cholewicki and McGill, 1996). Stabilization of the trunk is required to control trunk movement during daily activities like standing, sitting, walking (MacKinnon and Winter, 1993; van der Burg et al., 2005), and can be limiting in performing precise arm and hand functions (Kaminski et al., 1995; Pigeon et al., 2000). Importantly, it has been hypothesized that inadequate trunk stabilization could contribute to low-back pain (LBP) through high tissue strains and/or impingements (Panjabi, 1992a,b).

Trunk stabilization is achieved differently in patients with low back pain (LBP) compared to healthy controls. These differences in trunk control have been interpreted as cause of the persistence of LBP (Hodges et al., 2009; MacDonald et al., 2010), and were even shown to be prospectively associated to LBP incidence (Cholewicki et al., 2005). Specifically, several studies have indicated longer reflex delays after an external mechanical perturbation of trunk posture in LBP patients than in controls (Magnusson et al., 1996; Radebold et al., 2000, 2001; Reeves et al., 2005). In apparent contrast, higher trunk stiffness, i.e. a higher mechanical resistance to such perturbations has also been reported (Hodges et al., 2009; van Dieën et al., 2003a). The latter is probably explained by findings of increased co-contraction of trunk musculature in patients compared to controls (van Dieën et al., 2003b). This has been interpreted as an adaptive response to enhance control over trunk movement and therewith prevent pain (Lund et al., 1991; van Dieën et al., 2003a). In fact, increased trunk stiffness through co-contraction could explain the longer delays found. With increased stiffness, the same mechanical disturbance will cause a smaller and slower deviation of trunk posture. Consequently, the disturbance would be perceived later and cause a slower and smaller increase in excitatory drive of the trunk musculature, resulting in an apparent increase in reflex delays. So paradoxically, the finding of an increased delay could actually reflect a functional, adaptive response to enhance trunk stability.

The above indicates that the contributions of intrinsic stiffness and reflexes to trunk stabilization need to be assessed simultaneously. This is possible using system identification techniques, which apply some form of external (often mechanical) perturbation and measure responses such as the trunk kinematics and trunk muscle EMG, from which properties of the stabilizing system, such as the intrinsic stiffness and reflex delays are estimated (Schouten et al., 2008; van der Helm et al., 2002). Many different methods using such an approach have been reported (Goodworth and Peterka, 2009; van der Helm et al., 2002; van Drunen et al., 2013). However, not all methods appear equally suitable. For example, not all take into account the intrinsic and reflexive contributions simultaneously. Furthermore, setups in some studies allow movement corrections in multiple joints (e.g. ankle, knee and hip), due to which experimental effects or between-group differences cannot be ascribed solely to the trunk.

To support interpretation of previous literature and to optimize methods for studying trunk stabilization in relation to LBP, we

aimed to provide a critical review of previously published methods. We primarily aimed to assess their construct validity, to which end we defined a theoretical framework operationalized in a set of methodological criteria. This theoretical framework comprised the two criteria as introduced above as well as the criteria based on the requirement to allow for linear system identification, since a wide range of well-established techniques is available for this. The criteria are further detailed in the methods section. In addition, the clinimetric properties of the methods were evaluated, to assess their potential value in a clinical setting.

2. Methods

2.1. Theoretical framework

To evaluate the methods found in the literature, a theoretical framework was defined. In the introduction, two major criteria were already introduced: (1) the necessity of being able to simultaneously assess intrinsic and reflexive contributions to trunk stabilization and (2) the necessity to study the trunk in isolation.

To be able to assess the intrinsic and reflexive contributions to trunk control simultaneously through linear identification techniques, the method has to meet the following criteria:

Unpredictable	Disturbances must be unpredictable, since the presence of feed forward control to an expected perturbation renders it impossible to quantify reflexive and intrinsic components. System identification techniques assume a closed loop between the output forces and movements and the control input, e.g. the movement occurring upon perturbation of a static posture is assumed to be the basis for reflex inputs. When voluntary movements through feed forward control occur, this obviously would lead to a misinterpretation. To prevent feed forward control, an unpredictable perturbation should be used
Known Disturbance	To allow for system identification, the disturbance should be known (in terms of amplitude and timing). It is important to note that the disturbance is defined as the external input, which should be distinguished from the contact force between a device applying a perturbation and the subject, as this results from an interaction between device and subject
Perturbation Type	To permit the use of linear identification techniques, the disturbance should result in small fluctuations around a fixed working point, i.e. it should not entail large force differences and should not result

(continued on next page)

Force Control

in a large trunk displacements. To obtain sufficiently reliable information in spite of the limited trunk displacement and hence low signal to noise ratio, repeated perturbations are necessary. The perturbation should, therefore, not be a single impulse or step perturbation but preferably a multisine, repeated impulse or pseudo-random binary signal. When perturbations are applied directly to the trunk, a force controlled perturbation instead of a displacement controlled perturbation should be used. With a fixed trunk displacement relative to the pelvis, the subject is unable to exert any influence over the resulting perturbation. Therefore, the subject will not be motivated to perform and it has been observed that subjects reduce their efforts to counteract position controlled perturbations already after several seconds (de Vlugt et al., 2003a,b)

The following criteria should be met to study the trunk in isolation:

Pelvic restraint	The pelvis of the subject should be restrained, forcing motion at the level of the spine, i.e. this assures that motion does not occur solely at the level of the pelvis
Point of application	The application of the perturbation should occur at the trunk or at the pelvis

These criteria will be used to assess the construct validity of the methods found in the literature. For a method to be considered valid, it should comply with all criteria with the exception of the 'perturbation type' criterion (hereafter referred to as necessary criteria). Although there are drawbacks to use certain perturbation types (for more information, see discussion), using the recommended perturbation types described earlier is not a requirement to be considered valid.

2.2. Literature identification

To identify relevant literature, we conducted a comprehensive search in PubMed and Embase from the beginning of the database up to September 2014. To be inclusive, we used a broad search as outlined in Appendix A. Only articles written in Dutch, German or English were included. Animal and cadaveric studies were excluded. No restrictions were applied to study design. Additionally, a snowball technique was applied by scanning the reference sections of all selected articles for potentially relevant articles that were not retrieved in the original search.

2.3. Study selection

The publications were included according to the following criteria which should be discernable from either the title or abstract text: (1) trunk stabilization was studied; (2) external mechanical perturbations were applied; (3) measurements included trunk kinematics and/or trunk muscle EMG. Eligibility of studies was determined independently by two researchers. If based on title

Fig. 1. Flowchart of the search strategy.

and abstract uncertainty about eligibility of a study remained, the full text was reviewed. When discrepancies occurred between reviewers, the justifications for inclusion or exclusion of these articles was discussed until consensus was reached.

2.4. Data extraction

The following data were extracted from the included articles: author, year of publication, subject characteristics, muscle activity measurement and kinematic measurement techniques and perturbation technique. The construct validity of the methods was assessed independently by the two researchers with use of the theoretical framework as described above. When discrepancies occurred between reviewers, the justification for scoring on the set of methodological criteria was discussed until consensus was reached.

2.5. Assessment of methodological quality

If the objective of an included article comprised clinimetric assessment of reliability and/or measurement error of methods to assess trunk stabilization, the methodological quality of the study was assessed by the two reviewers using box B and C of an adapted version of the Consensus-based Standards for the selection of Health Measurement INstruments (COSMIN checklist (Terwee et al., 2012), see Appendix B).

3. Results

3.1. Results of the search

A total of 133 articles were included (see Fig. 1 for a flowchart of the search and selection procedure).

3.2. Categorization

Based on the articles retrieved from the search, four main categories of perturbation methods were distinguished; trunk loading, trunk unloading, moving platform and upper limb (un)loading (see Table 1). Loading perturbations involve pushes or pulls applied at the upper back, thorax or pelvis. Unloading perturbation methods use a horizontal force applied to the subject's thorax, upper back or pelvis by a cable from which a load is suspended and unexpectedly released. Alternatively, the subject applies a force, often controlled through visual feedback, on a cable that is unexpectedly released. During moving platform perturbations, subjects sit or stand on a platform, which is translated or tilted. Finally, in the upper limb (un)loading experiments the subjects stand while holding an

Table 1

Overview of studies included with assessment of validity based on the criteria listed in the methods section. The first columns contain information on subject and perturbation characteristics, EMG-measurements and kinematic measurements. The validity assessment scores can be found in the right thick outlined columns with 'X' = criterium is met, '-' = criterium is not met. ES = Erector Spinae, RA = Rectus Abdominis, EO = External Oblique, IO = Internal Oblique, MF = Multifidus, IC = Iliocostalis, LO = Longissimus, TrA = Transversus Abdominis, LD = Latisimus Dorsi.

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
<i>Trunk loading</i>										
Andersen et al. (2004)	10 Healthy males	52 N (upper back)	Surface: ES (L3)	Potentiometer (upper back)	X	X	Step	X	X	X
Bazrgari et al. (2011a)	12 healthy subjects (6m, 6f)	10 mm (upper back)	Surface: ES (L1, L3), RA, EO	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2011b)	3 healthy males	10 mm (upper back)	–	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2012)	6 healthy subjects (3m, 3f)	10 mm (upper back)	–	Displacement sensor and load cell at T8	X	X	Impulse	–	X	X
Bazrgari et al. (2009)	2 healthy males, 1 LBP patient	±100 N (upper back)	Surface: MF(L5), IC (lumbar), LO (L1), RA, EO	Potentiometer and load cell at T8	X	X	Step	X	X	X
Borghuis et al. (2011)	21 healthy subjects	±123 N and ±80 N (upper back)	Surface: ES (L3), RA, EO	Angular velocity of the balance seat with gyroscopes	X	X	Impulse	X	–	X
Carlson et al. (1981)	4 healthy males	5 kg from 3 cm (upper back)	LO, MF, RA, EO	Force plate, angle between C7-L3 and vertical line with opto-electronic motion analysis system	X	–	Step	X	–	X
Chiang and Potvin (2001)	13 healthy males	20% and 30% of maximum isometric lateral bend moment (upper back)	Surface: EO, IO, ES (lumbar and thoracic), RA	Force transducer and displacement transducer from chest	X	X	Step	X	X	X
Cresswell et al. (1994)	6 healthy males	5 kg from 25 cm (upper back)	Fine-wire: RA, EO, IO, TrA, Surface: ES (L3)	Displacement of hip and shoulder with video-based analysis system	X	X	Step	X	–	X
van Drunen et al. (2013)	15 healthy subjects	±35 N (upper back)	Surface: RA, IO, EO, LO (lumbar and thoracic), IC (lumbar and thoracic)	Trunk kinematics with optotrak motion tracking system, with markers at L1–L5, T1, clustermarkers at T6 and T12 Displacement and contact force at T10 with position sensor and force sensor	X	X	Multi-sine	X	X	X
Dupeyron et al. (2010)	10 healthy males	50% of body mass (upper back)	Surface: ES, EO	–	X	X	Impulse	X	X	X
Eriksson Crommert and Thorstensson (2009)	11 healthy males	10 kg from 40 cm (upper back)	Fine-wire: TrA, EO, RA, ES (L3)	–	X	–	Step	X	X	X
Essendrop et al. (2002)	9 healthy subjects (4m, 4f)	52 N (upper back)	Surface: RA, TrA, ES (L3), IC (lumbar), EO, IO	Potentiometer from shoulder	X	X	Step	X	X	X
Gardner-Morse and Stokes (2001)	14 healthy subjects (8m, 6f)	7.5% and 15% of maximum effort (upper back)	–	Load cell and displacement transducer from T12	X	X	Single sine wave	X	X	X
Gilles et al. (1999)	5 healthy subjects (3m, 2f)	4% of body weight (pelvis)	Surface: abdominal and spinal muscles	Force plate, load cell from pelvis. Position pelvis with linear motors	X	X	Step	X	–	X
Granata et al. (2005)	18 healthy subjects (9m, 9f)	75 N (upper back)	Surface: RA, IO, EO, ES	Infrared motion sensors on S1, L5, T10, C7	X	X	Multi-sine	X	X	X
Granata et al. (2004a)	10 healthy males	6.2 ± 1.6, 9.3 ± 1.4 and 12.0 ± 1.7 N (upper back)	Surface: IO, EO, RA	Load cell and motion sensors at lower back	X	X	Impulse	X	X	X
Granata et al. (2004b)	21 healthy subjects (11m, 10f)	2.27 kg from 0.5 and 1 m (upper back)	Surface: RA, EO, IO, ES (L3)	Force plate, load cell and goniometers at T10 and S1	X	–	Step	X	–	X
Hendershot et al. (2013)	8 males with unilateral limb amputation and 8 healthy males	±5 mm anterior–posterior (upper back)	Surface: ES (L3), EO	Load cell, postural displacements with laser displacement sensor and servomotor encoder	X	X	Pseudorandom binary step	–	X	X

Table 1 (continued)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Hendershot et al. (2011)	12 healthy subjects (6m, 6f)	±5 mm anterior–posterior (upper back)	Surface: ES (L1, L3), RA, EO	Load cell, encoder on servomotor-shaft, displacement sensor on frame at T8	X	X	Pseudorandom binary step	–	X	X
Herrmann et al. (2006)	10 healthy males	170 N (upper back)	Paraspinal muscles at L4	Load cell	X	–	Impulse	X	–	X
Hjortskov et al. (2005)	9 healthy males	52 N (upper back)	ES (L3/L4)	Potentiometer on wire attached to shoulder	X	X	Step	X	X	X
Hodges et al. (2009)	17 healthy subjects (9m, 8f) and 14 LBP patients (7m, 7f)	12–15% of body mass (upper back)	–	Trunk acceleration with force transducer from shoulder	X	X	Step	X	X	X
Kim et al. (2013a)	15 healthy males	9 kg from 30 cm (upper back)	Muscle thickness of EO, IO and TrA with brightness mode ultrasonography machines	–	X	X	Step	X	X	X
Krajcarski et al. (1999)	8 healthy males	12% or 24% of maximum isometric extensor moment (upper back)	Surface: ES (L3, T9), LD, RA, EO, IO	Force- and displacement transducer from shoulder	X	X	Step	X	X	X
Lariviere et al. (2010)	30 LBP patients (15m, 15f) and 30 healthy subjects (15m, 15f)	50% of the L5/S1 extension moment (upper back)	Surface: MF (L5), IC (L3), LO (L1), RA, EO	Load cell and position trunk with potentiometer	X	X	Step	X	X	X
Lawrence et al. (2005)	6 healthy males	The subjects trunk weight at 20° (upper back)	Surface: LO (L3/L4), IC (L3/L4), LD (T9)	Dynamometer to measure trunk torque, trunk displacement with electromagnetic sensor at T9	X	X	Step	X	X	X
Lee et al. (2006)	17 healthy subjects	±70 N anterior (upper back)	Surface: RA, ES (lumbar), IO, EO	Electromagnetic position sensors at S1 and T10	X	X	Pseudorandom binary step	X	X	X
Magnusson et al. (1996)	11 LBP patients (7m, 4f) and 11 healthy subjects (7m, 4f)	2 kg from 45 cm (upper back)	Surface: ES (L3)	Force plate, load cell	X	X	Step	X	X	X
Masani et al. (2009)	12 healthy males	131–148 N in 8 different directions (upper back)	Surface: RA, EO, IO, ES (T9, L3)	–	X	–	“Impulse”, manually applied	X	–	X
McGill et al. (1989)	3 healthy males	Unspecified (upper back)	–	Force plate	X	–	“Impulse”, manually applied	X	–	X
McMulkin et al. (1998)	6 healthy males	9.35 N (lower back)	Surface: ES (L3), RA, EO, LD	–	X	X	Step	X	–	X
Miller et al. (2013)	8 male LBP patients and 9 healthy males	10 mm (upper back)	Surface: RA, ES	Load cell, displacement with encoder at servomotor	X	X	Pseudorandom binary step	–	X	X
Miller et al. (2010)	20 healthy subjects (10m, 10f)	3.97, 5.96, 7.67, 9, 10.21 N.s (upper back)	Surface: RA, ES	Trunk angle with inertial motion sensor at T6/T8	X	X	Impulse	X	X	X
Moorhouse and Granata (2005)	21 healthy subjects (10m, 11f)	±30 N (upper back)	–	Force transducer and trunk kinematics with optotrak sensors placed on S1 and T10	X	X	Multi-sine	X	X	X
Moorhouse and Granata (2007)	11 healthy males	±2 mm (upper back)	–	Force transducer and trunk displacement with optical encoder	X	X	Step	–	X	X
Navalgund et al. (2013)	13 LBP patients (7m, 6f) and 13 healthy subjects (7m, 6f)	±30 N (upper back)	Surface: ES (L3), MF (L5)	Torque transducer at motor shaft	X	X	Step	X	X	X
Omino and Hayashi (1992)	9 healthy males	10 or 5 kg (upper back)	Surface: ES (T12, L3)	Sway of T5 was measured	X	–	Step	X	–	X

Parcero (2000)	13 healthy males	12%, or 24% of maximal isometric extensor moment (upper back)	Surface: ES (L3, T9), EO, IO, RA	Force and displacement transducers at upper back	X	X	Step	X	X	X
Pedersen et al. (2004)	38 healthy subjects (8m, 30f)	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Pedersen et al. (2007)	37 healthy subjects	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Pedersen et al. (2009)	46 healthy females	58 N (upper back)	–	Movement of upper back with potentiometer	X	X	Step	X	X	X
Rietdyk et al. (1999)	10 healthy males	122 N (± 1.3) (pelvis) and 108.7 N (± 1.22) (upper back)	–	Force plate, segment positions with infrared emitting diodes	X	–	“Impulse”, manually applied	X	–	X
Rogers and Granata (2006)	25 healthy subjects (12m, 13f)	± 75 N (upper back)	Surface: RA, IO, EO, ES	Electromagnetic position sensors on SI, T10 and manubrium	X	X	Multi-sine	X	X	X
Santos et al. (2011)	15 healthy males	35% (upper back)	Surface: LO (L1), ICL (L3), MF(L5)	Potentiometer at T8	X	X	Step	X	X	X
Skotte et al. (2004)	19 healthy males	58 N (upper back)	Surface: ES (L3)	Movement of upper back with potentiometer	X	X	Step	X	X	X
Stokes et al. (2006)	21 LBP patients (11m, 10f) and 23 healthy subjects (15m, 8f)	5% or 10% of maximum effort in 80 ms in 5 different directions (upper back)	Surface: RA, IO, EO, LO, IC	Load cell for unset perturbation	X	X	Single sine wave	X	X	X
Stokes et al. (2000)	13 healthy subjects (7m, 6f)	7.5% or 15% of maximum effort in 80 ms in 5 different directions (upper back)	Surface: RA, IO, EO, LO, IC	Load cell for unset perturbation and displacement transducer at T12	X	X	Single sine wave	X	X	X
Thomas et al. (1998)	20 healthy subjects (10m, 10f)	5% of maximum isometric trunk extensor strength (upper back)	Surface: LO (thoracic), ES, EO, RA	Trunk kinematics with triaxial torso electro-goniometer	X	–	Step	X	X	X
Thomas et al. (1999)	20 healthy subjects (10m, 10f)	5% of maximum isometric trunk extensor strength (upper back)	Surface: LO (thoracic), ES, EO, RA	Trunk kinematics with triaxial torso electro-goniometer	X	–	Step	X	X	X
Thrasher et al. (2010)	13 healthy males	Varied between 92.2 N and 293 N (upper back)	–	Force transducer and trunk position with optotrak motion analysis system with markers at SIAS, SIPS, C6, T9, L3 and clustermarkers between C6 and T9 and T9 and L3	X	X	“Impulse”, manually applied	X	–	X
Vera-Garcia et al. (2006)	14 healthy males	6.8 kg and 9.07 kg from 20 cm (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Load cell and trunk kinematics with electromagnetic tracking instrument with transmitter at sacrum and receiver at T12	X	X	Step	X	X	X
Vera-Garcia et al. (2007)	12 healthy males	6.8 kg from 5 cm (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Load cell and trunk kinematics with electromagnetic tracking instrument with transmitter at sacrum and receiver at T12	X	X	Step	X	X	X
Vette et al. (2014)	15 healthy males	39.9 $\pm$ 2.4 N in 8 different directions (upper back)	–	Load cell, position of T10 with motion capture system with markers 6 cm above and below T10	X	X	Impulse	X	–	X
Wilder et al. (1996)	11 LBP patients (6m, 5f)	2 kg from 45 cm (upper back)	Surface: ES, RA	Load cell at T4 and force plate	X	X	Step	X	X	X
Trunk unloading Brown and McGill (2009)	9 healthy males	5%, 10% and 15% of maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3)	Angular displacements of lumbar spine with electromagnetic tracking instrument. Force on level L4/L5 and upper body cradle with force transducer	X	–	Step	X	X	X

(continued on next page)

Table 1 (continued)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Brown et al. (2006)	14 healthy males	8 or 10.3 kg (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3, L5)	Angular displacements of lumbar spine with electromagnetic tracking instrument	X	X	Step	X	X	X
Carlson et al. (1981)	4 healthy males	5 kg (upper back)	Surface: LO, MF, RA, EO	Force plate, angle between C7-L3 and vertical line with opto-electronic motion analysis system	X	–	Step	X	–	X
Cholewicki et al. (2002)	17 subjects (10m, 7f) with symptom free low back injury, and 17 healthy subjects (10m, 7f)	20% and 30% maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	–	X	X	Step	X	X	X
Cholewicki et al. (1999)	10 healthy subjects	35% maximal isometric activation (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Displacement T9 with inductive sensor	X	X	Step	X	X	X
Cholewicki et al. (2010a)	20 subjects (14m, 6f)	100 N for men, 70 N for women (upper back)	–	Trunk acceleration at T5 with accelerometer	X	X	Step	X	X	X
Cholewicki et al. (2010b)	14 healthy subjects (11m, 3f)	115 N for men, 80 N for women (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Trunk displacement at T5 with three-dimensional electromagnetic motion device	X	X	Step	X	X	X
Cholewicki et al. (2005)	292 subjects (144m, 148f)	108 N for men, 72 N for women (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	–	X	X	Step	X	X	X
Cholewicki et al. (2000)	12 healthy subjects (6m, 6f)	35% maximal isometric activation (172 N $\pm$ 54 N) (upper back)	Surface: RA, EO, IO, LD, ES (lumbar and thoracic)	Displacement T9 with inductive sensor	X	X	Step	X	X	X
Eriksson Crommert and Thorstensson (2008)	11 healthy males	30, 50 and 70% of Maximal Voluntary Contraction (upper back)	Fine-wire: RA, EO, TrA, ES (L3)	–	X	X	Step	X	X	X
Kim et al. (2013b)	16 healthy females	8 kg (upper back)	Surface: MF (L4/ L5)	Angular displacement with motion analysis system, markers at bilateral acromion, T1, SIPS, S2	X	X	Step	X	X	X
Magnusson et al. (1996)	11 LBP patients (7m, 4f), 11 healthy subjects (7m, 4f)	Unspecified (upper back)	Surface: ES	Load cell, Force plate	X	–	Step	X	X	X
Marshall et al. (2009)	12 subjects with ankle instability (5m, 7f) and 12 healthy subjects (5m, 7f)	65 N for men and 40 N for females (upper back)	Surface: ES (L4), RA	Angular displacement, force output and movement velocity with dynamometer	X	X	Step	X	X	X
Radebold et al. (2000)	17 LBP patients (12m, 5f) and 17 healthy subjects (12m, 5f)	65 N and 108 N for men and 40 N and 72 N for women (upper back)	Surface: RA, EO, IO, LD, ES (T9, L3)	Undefined how trunk angle was measured	X	X	Step	X	X	X
Radebold et al. (2001)	16 LBP patients (1f, 15m) and 14 healthy subjects (1f, 13m)	Undefined (upper back)	Surface: 12 major trunk muscles	Undefined how trunk angle was measured	X	X	Step	X	X	X
Reeves et al. (2005)	35 LBP patients (27m, 8f) and 32 healthy subjects (22m, 10f)	65 N for males, 40 N for females (upper back)	Surface: RA, EO, ES (T9, L5)	–	X	X	Step	X	X	X

Reeves et al. (2009)	6 healthy subjects (4m, 3f)	20 N (upper back)	–	Motion capture system with markers at T9 and L4/L5	X	–	Step	X	X	X
<i>Moving platform</i> Blomqvist et al. (2014)	43 healthy subjects and 56 subjects with intellectual disability	3,5 cm, 55 cm/s, 200 cm/s ² posterior	Surface: ES (L4)	Accelerometer on platform	X	X	Step	X	–	–
Boudreau et al. (2011)	10 healthy subjects	8 cm, 270 cm/ms anterior and posterior and 10°, 120°/ms anterior and posterior tilt	Surface: ES (T12, L2, L4), EO	–	X	X	Impulse	X	–	–
Carpenter et al. (1999)	17 healthy subjects (8m, 9f)	7.5°, 50°/s tilts in 12 directions	Surface: paraspinals	Force plate, angular velocity sternum with transducers	X	X	Step	X	–	–
Carpenter et al. (2005)	12 healthy males	8 cm, 0.25 m/s, 1.7 m/s ² and 60 cm, 0.25 m/s, 1.3 m/s ² anterior and posterior	Surface ES (L4), Fine-wire: RA	Accelerometer on platform, rotations of trunk with opto-electronic motion-analysis system	X	X	Impulse	X	–	–
Chen et al. (2014)	19 healthy subjects (12m, 7f)	70 mm, 500 mm/s anterior and posterior and 7°, 50°/s anterior and posterior tilt	Surface: paraspinals (cervical, lumbar (L2/L3) and thoracic), RA	Kinematics with motion analysis system with 42 markers at bony landmarks	X	X	Step	X	–	–
Cort et al. (2013)	7 healthy males	4 cm, 4 m/s ² left and right	Surface: RA, EO, IO, ES (lumbar and thoracic), MF, LD	Accelerometer on platform, kinematics with active marker system with clustermarkers at sacrum and T9	X	X	Step	X	X	X
Cote et al. (2009)	10 patients with whiplash-associated disorder (5m, 5f) and 10 healthy subjects (5m, 5f)	15 cm in 500 ms anterior and posterior	Surface: paraspinals (cervical, thoracic and lumbar), trapezius, RA, EO	Kinematics with motion analysis system with markers on right scapula, C7, T6, T1, T8, T12, L1, S1, SIPS, sacrum, sternum, acromia	X	X	Impulse	X	X	X
Diener et al. (1988)	10 healthy subjects (5m, 5f)	1.2, 3.6, 6, 9 and 12 cm, 15 cm/s and 6 cm, 10, 15, 25 and 35 cm/s posterior	Surface: RA, ES	Force plate, Potentiometer on platform, hip angle with computerized movement analysis system	X	X	Impulse	X	–	–
Dobosiewicz (1997)	394 patients with adolescent scoliosis (83m, 311f) and 70 healthy children (10m, 60f)	8° left and right tilt	Surface: ES (T8, L1, L3)	–	X	X	Step	X	–	–
Farahpour et al. (2014)	10 patients with adolescent idiopathic scoliosis and 10 healthy subjects	10% of body mass from 70 cm was dropped to pull the platform	Surface: ES (L3, T10)	–	X	X	Step	X	–	–
Forssberg and Hirschfeld (1994)	8 healthy subjects (4m, 4f)	8 cm, 36 cm/s in 4 directions and 8°, 50°/s anterior and posterior tilt	Surface: ES (L3–L4 and T8–T9)	Platform and trunk displacement at C7, T10, L5, SIAS, TM with three-dimensional electromagnetic motion device	X	X	Step	X	–	X
Goodworth and Peterka (2009)	14 healthy subjects (7m, 7f)	±4° left and right tilt	–	Hip angular position, rotations between C6 and T3 and knees with potentiometer	X	X	Pseudorandom ternary step	X	X	X
Goodworth and Peterka (2010)	3 subjects with bilateral vestibular loss (2m, 1f) and 8 healthy subjects (3m, 5f)	±4° left and right tilt	–	Hip angular position, rotations between C6 and T3 and knees with potentiometer	X	X	Pseudorandom ternary step	X	X	X

Table 1 (continued)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Gruneberg et al. (2004)	5 healthy subjects (3m, 2f)	7.5°, 60°/s tilt in 6 directions	Surface: paraspinals (L1–L2)	Force plate, potentiometer on platform, angular velocity sternum with transducers	X	X	Step	X	–	–
Henry et al. (1998)	7 healthy subjects (3m, 4f)	9 cm, 35 m/s in 12 directions	Surface: RA, ES	Force plate	X	X	Impulse	X	–	–
Henry et al. (2006)	24 healthy subjects (12m, 12f) and 26 LBP patients (12m, 14f)	9 cm, 43 cm/s, 127 cm/s ² in 12 directions	–	Force plate, trunk positions with infrared camera system and reflexive markers	X	X	Impulse	X	–	–
Horak et al. (1989)	20 healthy subjects	1.2, 3.6, 6, 9, 12 cm, 10, 15, 35 cm/s posterior	Surface: RA, lumbar paraspinals	Force plate, potentiometer attached to hips	X	X	Impulse	X	–	–
Horak and Nashner (1986)	10 healthy subjects (4m, 6f)	13 cm/s in 250 ms anterior and posterior	ES (L4–L5), RA	Force plate (strain gauges) and hip angle with single-frame analysis of videotaped recordings with white markers	X	X	Impulse	X	–	–
Horak et al. (1990)	6 healthy subjects and 4 subjects with vestibular loss	6 cm, 15 cm/s and 1.2 cm, 6 cm/s and 12 cm, 35 cm/s anterior and posterior	Surface: RA, lumbar paraspinals	Force plate, potentiometer attached to hips	X	X	Impulse	X	–	–
Huang et al. (2001)	8 healthy males	10 cm, 0.5 m/s, 10 m/s ² left and right	–	Force plate, optoelectronic movement analysis system with cluster markers on L1 and left thigh	X	X	Impulse	X	–	–
Inglis et al. (1994)	9 patients with lower extremity neuropathy (6m, 3f) and 8 healthy subjects	6 cm, 10 cm/s, 15 cm/s, 25 cm/s, 35 cm/s and 1.2 cm, 3.6 cm, 6 cm, 9 cm, 12 cm at 15 cm/s posterior	Surface: lumbar paraspinals	Force plate	X	X	Impulse	X	–	–
Jacobs et al. (2011)	24 LBP patients (13m, 11f) and 21 healthy subjects (8m, 13f)	9 cm, 43 cm/s, 127 cm/s ² in 12 directions	Surface: ES (L1, L3), EO, IO, RA	–	X	X	Impulse	X	–	–
Jones et al. (2012)	20 LBP patients (9m, 11f) and 21 healthy subjects (8m, 13f)	43 cm/s, 127 cm/s ² in 12 directions	Surface: RA, IO, EO, ES (L1 and L3)	Force plate, 3D kinematic data of hip and trunk angle with passive marker system	X	X	Impulse	X	–	–
Kamper et al. (1999)	4 male tetraplegics, 4 male paraplegics and 5 healthy males	12° and 23° left tilt	–	Load cells for measuring axial forces between platform and wheelchair	X	X	Step	X	–	X
Keshner et al. (2004)	10 healthy subjects	10 cm, 15 cm/s and 3 m, 3.7 m/s anterior posterior	Surface: paraspinals (L2–L3 and T4–T5), RA	Strain gauge sensors under platform, potentiometer attached to hip	X	X	Impulse	X	–	–
Keshner et al. (1988)	11 healthy subjects	3 cm in 125 ms or 250 ms anterior posterior	–	Trunk angular position with video motion analysis system with markers on C7 and great trochanter	X	X	Impulse	X	–	–
Mok and Hodges (2013)	20 healthy subjects (11m, 9f)	0.7° in 250 ms, 1.8° in 300 ms and 3.2° in 400 ms anterior posterior	–	Force plate	X	X	Step	X	–	–
Newcomer et al. (2002)	20 LBP patients (9m, 11f) and 20 healthy subjects (9m, 11f)	1.25*patients height/72 in 300 ms and 2.25*patients height/72 in 400 ms and 8° in 80 ms anterior posterior	Surface: ES (L4/L5), RA	–	X	X	Impulse	X	–	–

Notzel et al. (2011)	8 female LBP patients and 12 healthy females	Undefined left and right and anterior posterior	Surface: ES, RA, IO, EO, MF	–	X	X	Impulse	X	–	–
Oddsson et al. (1999)	8 healthy males	0.11 m in 300 ms anterior posterior	Surface: ES (L3), RA	Accelerometer at L3 and hip and shoulder kinematics in sagittal plane with video-based motion analysis	X	X	Impulse	X	–	–
Parnianpour et al. (2001)	18 healthy males	2.5 cm with 3 cm/s and 4°, 2.4°/s tilt in 3 directions	–	Force plate, potentiometers on hips and shoulders	X	X	Impulse	X	–	–
Perret and Robert (2004)	13 scoliotic children and 3 healthy children	8° left and right tilting	Surface: paraspinals (T7–10 and L2–3)	Accelerometer at cervicothoracic junction level	X	X	Step	X	–	–
Preuss and Fung (2008)	13 healthy males	150 mm, 0.45 m/s in 8 directions	Surface: RA, IO, EO, thoracic paraspinals, ES (thoracic and lumbar), MF	Force plate, position-data of trunk with Vicon motion analysis system with markers at T1–T6, T7–T12, L1–L5 and pelvis	X	X	Impulse	X	X	X
Sayenko et al. (2012)	21 healthy subjects (14m, 7f)	10°, 50°/s, 200°/s backward tilt	Surface: ES	Displacement of C7 and great trochanter with laser displacement sensors	X	X	Step	X	–	–
Zedka et al. (1998)	5 healthy subjects (3m, 2f)	10°, 20°, 8°/s and 26°/s in four directions	Surface: ES (T10, L3), EO, IO, RA, LD	Angular displacement of platform with potentiometer	X	–	Step	X	X	X
Upper limb (un)loading Arui and Latash (1995)	7 healthy males	2.2 kg unloading	Surface: RA, ES	Force plate, goniometers for hip angles	X	X	Step	X	–	–
Brown et al. (2003)	11 healthy males	6.8 kg unloading	Surface: ES (lumbar and thoracic), EO, RA	Force plate	X	–	Step	X	–	–
Dupeyron et al. (2013)	30 LBP patients (19m, 11f)	2 kg from 40 cm	Surface: ES (L3), EO, RA	Accelerometer on box to determine perturbation onset	X	–	Step	X	–	–
Gregory et al. (2008)	13 healthy subjects (6m, 7f)	6.78 kg from 2 cm	Surface: ES (thoracic and lumbar), RA, EO	Force plate	X	–	Step	X	–	–
Grondin and Potvin (2009)	15 healthy females	5 kg from 2.5 cm	ES (thoracic and lumbar), EO, IO	Goniometers at L5 and L3	X	–	Step	X	–	–
Hodges et al. (2001)	5 healthy males	2 kg with a wire attached to hands	Fine-wire: TrA, IO, EO. Surface: RA, ES (L4)	Angle between T12 and S1 and iliac crest and S1 with opto-electronic system and infrared markers	X	–	Step	X	–	–
Hwang et al. (2008)	38 healthy subjects (21m, 17f)	1 kg from minimum of 0.5 m	Surface: ES (T12–L1), MF L5–S1)	Force plate, Electromagnetic tracking system with sensors at T1 at L1 and S1	X	–	Step	X	–	–
Lavender and Marras (1995)	4 healthy males	5.4 kg from 110 cm	Surface: ES (L3/L4), LD, RA, EO	Force plate	X	–	Step	X	–	–
Lavender et al. (1993)	4 healthy males	53.4 N	Surface: LD, ES, RA, EO, IO	Force plate, lumbar motion (L5–S1) with a lumbar motion monitor	X	–	Step	X	–	–
Lavender et al. (1989)	11 healthy males	6 kg from 78.4 cm	Surface: LD, ES (L3), RA, EO	–	X	–	Step	X	–	–
Lavender et al. (2000)	18 healthy subjects (8m, 10f)	7.5% maximal trunk extension force from 1m	Surface: LD (T7 and T10), ES (L3/L4), EO, RA	Force plate, trunk positions with magnetic motion measurement system with sensors on T1, L1 and S1.	X	X	Step	X	–	–
Lee et al. (2011)	10 healthy subjects (5m, 5f)	1 kg from 30 cm	Fine-wire: MF, LO (T5, T8, T11)	Force plate	X	–	Step	X	–	–
Leinonen et al. (2002)	20 LBP patients (15m, 5f) and 15 healthy subjects (10m, 5f)	0.68 kg from eye height	Surface: ES (L12–L1), MF (L5–S1)	Force plate and marker switch on load	X	–	Step	X	–	–

(continued on next page)

Table 1 (continued)

Author (year)	Subjects	Perturbation magnitude	Trunk-EMG measurement	Trunk kinematics measurement	Unpredictable	Known disturbance	Perturbation Type	Force control	Pelvic restraint	Point of application
Leinonen et al. (2003)	20 healthy subjects (10m, 10f)	0.69 kg from minimum of 0.5 m	Surface: ES (L12–L1), MF (L5–S1)	Marker switch on load	X	–	Step	X	–	–
MacDonald et al. (2010)	13 LBP patients (6m, 7f) and 14 healthy subjects (8m, 6f)	1 kg from eye height	Fine-wire: MF (L5, deep and superficial)	Load contact with box started EMG recording	X	–	Step	X	–	–
Mannion et al. (2000)	12 healthy subjects (6m, 6f)	2, 4 and 6 kg from 10 cm for men, 40% less for women	Surface: ES (T10 and L3), RA, EO	Force plate, Load cell, angle between L1 and S1 with motion analysis device	X	–	Step	X	–	–
Marras et al. (1987)	12 healthy males	2.27, 4.54, 6.8 and 9.07 kg from 83.8 cm	Surface: LD, ES, RA	–	X	X	Step	X	–	–
Mawston et al. (2007)	30 healthy males	100 N	ES (L4/5 and T9), RA, IO, EO	Hip joint angle with digital video camera with markers on lateral femoral condyle, great trochanter and sacrum and for lumbosacral angle on L1 and sacrum	X	–	Step	X	–	–
McGill et al. (1989)	3 healthy males	Undefined	–	Force plate	X	–	Impulse, manually applied Step	X	–	–
McMulkin et al. (1998)	6 healthy males	18.8 N	Surface: ES (L3), RA, EO, LD	–	X	X	Step	X	–	–
Mok et al. (2011)	11 LBP patients and 11 healthy subjects	1 kg from 30 cm	–	Force plate, Position of lumbar spine with electromagnetic analysis system with markers at L1, S1 and IC	X	–	Step	X	–	–
Moseley et al. (2003)	7 healthy subjects (5m, 2f)	1% body mass from eye height	Fine-wire: MF, TrA. Surface: ES (T7)	–	X	X	Step	X	–	–
Mullington et al. (2009)	19 healthy subjects (12m, 7f)	1.25 kg from undefined height	Surface: ES (T12, L4), RA (L4)	Accelerometers at shoulder and T12	X	X	Step	X	–	–
Ramprasad et al. (2011)	25 LBP patients (18m, 7f)	3 kg from 8 cm	Surface: RA, ES (L3–4)	Force plate	X	–	Step	X	–	–
Ramprasad et al. (2010)	25 LBP patients (18m, 7f) and 25 healthy subjects (15m, 10f)	3 kg from 8 cm	Surface: RA, ES (L3–4)	Force plate	X	–	Step	X	–	–
Shu et al. (2007)	10 healthy males	30% of maximal voluntary contraction	Surface: MF, LO (L2)	–	X	–	Step	X	–	–
Sung and Park (2009)	36 LBP patients (18m, 18f)	0.7 kg from 1.8 m	–	Force plate and impact force with load cell	X	X	Impulse	X	–	–
Sung et al. (2004)	46 LBP patients (22m, 24f)	6.4 N	Surface: ES (L3) MF	Onset perturbation with load cell	X	X	Impulse	X	–	–
Voglar and Sarabon (2014)	24 healthy subjects (15m, 9f)	8% of body weight loading or 25% of maximal voluntary force unloading	Surface: RA, EO, IO, ES, MF	Force sensor at hand-handle	X	X	Step	X	–	–
Wagner et al. (2005)	10 healthy males	Unspecified	–	Load cell, trunk kinematics with high-speed video system with markers at shoulders, hip, between L5 and C7	X	X	Step	X	–	–
Wilder et al. (1996)	6 LBP patients (4m, 2f) and 16 healthy subjects (6m, 10f)	6.4 N	Surface: ES (L3)	Onset perturbation with load cell	X	–	Step	X	–	–

empty receptacle in which a load is dropped. In some studies, the arms of the subjects are attached to a wire with a load on the other end which is suddenly dropped, resulting in a sudden force. In one setup, subjects hold a weighted box, which is suddenly pulled upward by a cable. In another setup, subjects hold a balloon attached to a load; popping the balloon results in sudden unloading.

LBP patients were included in 26 out of 133 articles distributed over the four different categories of perturbation methods (7 loading, 5 unloading, 5 moving platform, 9 upper limb (un)loading). None of these studies reported adverse events. A wide variety of perturbation magnitudes has been used across the four categories. Also, a wide variety in measurement methods of muscle activity and kinematics has been used. EMG measurements varied from no measurements in 25 articles to fine-wire and surface EMG measurements in several trunk muscles. Kinematic measurements varied from no measurements in 20 articles, to force plate and loading cell measurements to full 3 dimensional motion analyses. Detailed information on subject characteristics, perturbation magnitudes, EMG and kinematic measurements can be found in [Table 1](#).

Fifty of the 133 included articles described a method that complied with all necessary methodological criteria (see [Table 1](#)). All methods complied with the “unpredictable” criterion. In all but seven studies, force control was used. None of the upper limb (un)loading articles met with the “pelvic restraint” and “point of application” criteria.

3.3. Trunk loading perturbations

Among the 55 articles describing trunk loading perturbations, 32 complied with all necessary criteria (see [Table 1](#)). Ten articles did not comply with the “known disturbance” criterion, predominantly due to unknown onset of perturbation (i.e. timing). All but seven articles complied with the “force control” criterion. In 13 articles, the pelvis was not restrained. And all articles complied with the “point of application” criterion. Four types of perturbations were applied: in 14 studies, an impulse was applied, in 30 a step, in four a pseudorandom binary step, in three a single sine wave and in four a multi-sine.

3.4. Trunk unloading perturbations

Of the 17 articles describing trunk unloading perturbations, 13 complied with all necessary criteria (see [Table 1](#)). Four articles failed to comply with the “known disturbance” criterion while one did not restrain the pelvis. All studies applied step perturbations.

3.5. Moving platform perturbations

Five out of 35 articles describing moving platform perturbations complied with all necessary criteria (see [Table 1](#)). In one study, the timing of the disturbance was not known due to manual application of the perturbation. In only six articles, the pelvis was restrained. In 27 articles subjects stood on the platform and therefore these did not comply with the “point of application” criterion. Two types of perturbations were applied: in 15 articles a platform translation was applied, which equals a force impulse on the subject, while in the remaining 20, platform rotations/tilts were performed, which equals a step perturbation.

3.6. Upper limb (un)loading

Because all perturbations in this category were applied to the upper limbs, none of the 31 articles complied with the “point of application” criterion (see [Table 1](#)). Furthermore, none of the methods described used a pelvic restraint. For 21 articles, the perturba-

tion was unknown due to an unknown timing. Three studies applied impulse perturbations while the others applied step perturbations.

3.7. Clinimetric assessment

Reliability was tested in three of the included studies ([Hodges et al., 2009](#); [Santos et al., 2011](#); [Voglar and Sarabon, 2014](#)) and one study which used data from two previously published studies ([Hendershot et al., 2012](#)). Measurement error was tested in three studies ([Hendershot et al., 2012](#); [Santos et al., 2011](#); [Voglar and Sarabon, 2014](#)). [Hendershot et al. \(2012\)](#) described a sudden-loading task with standing subjects, who wore a wooden or plastic harness attached to a servo-motor, which applied pseudorandom binary anterior–posterior position perturbations. Within-day reliability, between-day reliability and measurement error were calculated for both harnesses. For both the wooden and plastic harness, the within-day reliability of trunk stiffness (0.84 and 0.90 respectively) and effective mass (0.91 and 0.95 respectively) were good ([Portney and Watkins, 2000](#)). Reflex gain (0.55 and 0.85), maximum reflex force (0.65 and 0.85) and timing of maximum reflex force (0.84 and 0.86) were found less reliable and within-day reliability was found superior to between-day reliability (mean ICC 0.42, range [0.19–0.72]). The plastic harness also seemed consistently more reliable than the wooden version.

In the study by [Santos et al. \(2011\)](#), subjects were seated with their pelvis restrained. A sudden load was applied via a cable connected to a load cell and attached to a harness worn by the subjects. Three different ways of analyzing the reflex latencies and amplitudes were used. Reliability of the method was poor to moderate (ICC 0–0.62).

[Hodges et al. \(2009\)](#) applied sudden loading in a semi-seated position via a cable attached to a thorax harness. Reliability was assessed in 10 subjects. For forward perturbations, the ICC's for stiffness, damping and mass were moderate at 0.67 (range [0.12–0.91]), 0.72 (range [0.20–0.92]) and 0.67 (range [0.12–0.91]) respectively. For backward perturbations, the ICC's for stiffness, damping and mass were poor to moderate at 0.60 (range [0.00–0.88]), 0.57 (range [–0.43 to 0.87]) and 0.31 (range [–0.36 to 0.77]) respectively.

In [Voglar and Sarabon \(2014\)](#), postural reflex delays to unexpected loading and unloading of the arms were assessed in a standing unrestrained position. The response of five trunk muscles was evaluated, for which a good intra-session (ICC = 0.79, range [0.56–0.96]) and moderate (ICC = 0.64, range [0.43–0.84]) inter-session reliability were reached.

The methodological quality of these four articles was assessed with use of Box B and C of the COSMIN checklist ([Appendix B](#)). [Hendershot et al. \(2011\)](#) scored ‘good’, [Santos et al. \(2011\)](#) fair and [Voglar and Sarabon \(2014\)](#) “poor” on both methodological qualities (see [Table 2](#) for the results). [Hodges et al. \(2009\)](#) scored “poor” on reliability.

4. Discussion

None of the articles from the upper limb (un)loading category complied with all the necessary criteria. One of the major problems with upper limb (un)loading is the point of application. When the perturbation is delivered through the hands/arms, the true extent of the perturbation to the trunk (i.e. timing and amplitude) is unknown. Therefore, studying trunk stabilization through upper limb (un)loading is not the most appropriate method.

Applying the perturbation by a moving/tilting platform is only suitable if the pelvis of the subject is restrained in either a seated or a standing position. However, applying the perturbation in a

Table 2
Scores of the COSMIN-criteria. E = Excellent, G = Good, F = Fair, P = Poor. For a further explanation of the different criteria of the Cosminlist, see [Appendix B](#).

Reliability criteria	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	Total
Hendershot et al. (2012)	G	G	G	E	E	E	G	E	E	E	G	–	–	–	G
Santos et al. (2011)	G	G	F	E	E	E	G	E	E	E	G	–	–	–	F
Hodges et al. (2009)	G	G	P	E	E	E	G	E	E	E	G	–	–	–	P
Voglar and Sarabon (2014)	G	G	P	E	E	E	G	E	E	E	G	–	–	–	P
Measurement error criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11				Total
Hendershot et al. (2012)	G	G	G	E	E	E	G	E	E	E	E				G
Santos et al. (2011)	G	G	F	E	E	E	G	E	E	E	E				F
Voglar and Sarabon (2014)	G	G	P	E	E	E	G	E	E	E	E				P

standing position has some drawbacks. For example, [Goodworth and Peterka \(2009\)](#) applied perturbations to standing subjects through a sideways tilting platform, but had to discard a large part of their measurements, due to the inability of many subjects to keep their knees locked. Bending of the knee(s) made the extent of the perturbation to the trunk due to the moving platform unknown.

Many of the methods applying trunk unloading perturbations complied with all the necessary methodological criteria. However, the use of a step perturbation is inherent to unloading and has two potential drawbacks. First, to reach the desired level of reliability, either many trials or high levels of pre-load (% MVC) are required. The combination of many trials and high pre-loads might not be feasible, especially not in LBP patients, who might not be able to produce many repetitions with high force levels without pain. The second potential drawback of step perturbations is the difficulty in making the perturbations truly unpredictable. Unloading often occurs within a certain time period after reaching a desired level of pre-load. However, if this time period is short, subjects are still able to anticipate on the perturbation by, for example, co-contracting. Therefore, to negate this possibility, long periods of uncertainty must be included. These long periods of uncertainty coupled with high levels of pre-load can be exhaustive and might not be feasible when studying certain patient populations.

Of the methods applying trunk loading perturbations, many complied with all the necessary methodological criteria. However, when applying loading perturbations, the perturbation should not be delivered manually by the experimenter (by e.g. dropping a weight). This makes the timing of the perturbation (i.e. the onset) uncertain, in turn, making estimates of reflex delays impossible and/or inaccurate. Putting a force sensor between the dropped load and the subject may not be sufficient as this is a measurement of the interaction between the subject and the load, where the force sensor introduces noise into the estimation of the onset of the perturbation. Among the methods using loading perturbations, different perturbation types were applied: single sine waves, step, impulse and pseudorandom binary perturbations and multi-sines. Single sine waves are only appropriate when the period of the sine wave is shorter than the shortest muscle reflex delay and when the onset of the sine wave is unpredictable. Otherwise, subjects are able to respond voluntarily and the reflexive and voluntary activation are no longer distinguishable. Both step and impulse perturbations are suitable but require sufficient power (i.e. large perturbation forces) and/or many repetitions for sufficient reliability. These potential drawbacks can be circumvented with either a pseudorandom binary signal or with multi-sines, where trials can last as long as needed, without becoming predictable. A drawback of multi-sines and pseudorandom sequences is the “unnatural” nature of the task, as the perturbation is continuous and never occurs from an unperturbed initial condition. An added benefit of multi-sines is that power can be selectively included (at selected frequencies).

Only four of the included articles performed a clinimetric assessment by determining the reliability of the method and only two of those complied with all the methodological criteria ([Santos et al., 2011](#); [Hodges et al., 2009](#)). The ICC was used as a measure of reliability and ranged from poor (ICC 0) to moderate (ICC 0.72). Besides these studies on reliability, nothing is known about the other clinimetric properties. Also, only limited studies have been performed on LBP patients and the ability of most methods to differentiate between healthy subjects and LBP patients is still unknown. Furthermore, specific information on included LBP patients are sometimes lacking (e.g. acute or chronic, resubmission during testing, referral pain), which hampers the interpretation of results and the assessment of the clinical value of the method.

Considering the methodological criteria and the arguments outlined above, a limited selection of articles describe methods that can be recommended when aiming to simultaneously assess the intrinsic stiffness and reflexive components of trunk stability with use of system identification, both in the trunk loading ([Granata et al., 2005](#); [Lee et al., 2006](#); [Moorhouse and Granata, 2005](#); [Rogers and Granata, 2006](#); [van Drunen et al., 2013](#)) and in the moving platform category ([Cort et al., 2013](#); [Cote et al., 2009](#); [Preuss and Fung, 2008](#)). None of these articles include a clinimetric evaluation and it is therefore recommended that future research focusses on determining the reliability and other clinimetric assessments of these methods.

Several limitations of this review have to be discussed. Beside the ever present publication bias, a certain amount of selection bias may be present as well. However, a snowball procedure was applied to minimize this effect. Furthermore, there is a wide variety of clinimetric assessments that are important when evaluating the quality of an instrument (e.g. internal consistency, content validity, structural validity, responsiveness) that we have not addressed. We have mainly focused on the construct validity for it is the overarching concern of validity research, subsuming all other types of validity evidence. Finally, one of the included studies ([van Drunen et al., 2013](#)) was performed by researchers from the same research group as the authors of the current review. Therefore, a certain amount of bias cannot be excluded.

In conclusion, because of the wide variety in methods and the lack of validation and reliability studies, it is difficult to compare studies and the interpretation in terms of the underlying mechanisms of trunk stabilization is limited. Therefore there is a need for standardization and clinimetric evaluation. When considering construct validity, in line with the methodological criteria as outlined in the methods section, we propose a method where the trunk is studied in isolation, i.e. the pelvis is restrained and the perturbation is applied directly to the upper body, either through the trunk or pelvis. Furthermore, the perturbation should be unpredictable, force controlled and completely known (in terms of amplitude and timing). Finally, the perturbation should result in small fluctuations around a fixed working point. To obtain sufficient reliability, a multi-sine, repeated impulse or pseudorandom

binary signal is preferred. A higher standardization of methods to study trunk control will contribute to a higher quality of research and enable better comparisons to be made between studies.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Appendix A. Search strategy

Search conducted in PubMed and Embase on September 1st, 2014: ((perturbat*[tiab] OR “sudden load*”[tiab] OR “quick release”[tiab] OR “external load*”[tiab] OR “Unload*”[tiab] OR “moving platform” [tiab] OR “moving surface” [tiab]) AND (Human OR Adult OR adults OR Patient OR patients OR Healthy control* OR Healthy subject* OR “Humans”[Mesh]) AND (“Back”[Mesh] OR spine[tiab] OR spines[tiab] OR spinal[tiab] OR paraspinal[tiab] OR “low back”[tiab] OR “posture”[tiab] OR “postural”[tiab] OR “motor control”[tiab] OR “Spine”[Mesh:noexp] OR “Intervertebral Disc”[Mesh] OR “Lumbar Vertebrae”[Mesh] OR “Sacrum”[Mesh] OR “Thoracic Vertebrae”[Mesh])).

Appendix B. COSMIN-list (Box B and C)

Box B. Reliability: relative measures (including test–retest reliability, intrarater reliability and intra-rater reliability)				
Design requirements	Excellent	Good	Fair	Poor
1. Was the percentage of missing items given?	Percentage of missing items described	Percentage of missing items NOT described		
2. Was there a description of how missing items were handled?	Described how missing items were handled	Not described but it can be deduced how missing items were handled	Not clear how missing items were handled	
3. Was the sample size included in the analysis adequate?	Adequate sample size (≥ 50)	Good sample size (25–49)	Moderate sample size (15–24)	Small sample size (< 15)
4. Were at least two measurements available?	At least two measurements			Only one measurement
5. Were the administrations independent?	Independent measurements	Assumable that the measurements were independent	Doubtful whether the measurements were independent	Measurements were NOT independent
6. Was the time interval stated?	Time interval stated		Time interval NOT stated	
7. Were patients stable in the interim period on the construct to be measured?	Patients were stable (evidence provided)	Assumable that patients were stable	Unclear if patients were stable	Patients were NOT stable
8. Was the time interval appropriate?	Time interval appropriate		Doubtful whether time interval was appropriate	Time interval NOT appropriate
9. Were the test conditions similar for both measurements?	Test conditions were similar (evidence provided)	Assumable that test conditions were similar	Unclear if test conditions were similar	Test conditions were NOT similar
10. Were there any important flaws in the design or methods of the study?	No other important methodological flaws in the design or execution of the study		Other minor methodological flaws in the design or execution of the study	Other important methodological flaws in the design or execution of the study

(continued on next page)

Appendix B (continued)

Box B. Reliability: relative measures (including test–retest reliability, intrarater reliability and intra-rater reliability)				
Design requirements	Excellent	Good	Fair	Poor
<i>Statistical methods</i>				
11. for continuous scores: Was an intraclass correlation coefficient (ICC) calculated?	ICC calculated and model or formula of the ICC described	ICC calculated but model or formula of the ICC not described or not optimal. Pearson or Spearman correlation coefficient calculated with evidence provided that no systematic change has occurred	Pearson or Spearman correlation coefficient calculated WITHOUT evidence provided that no systematic change has occurred or WITH evidence that systematic change has occurred.	No ICC or Pearson or Spearman correlations calculated
12. for dichotomous/nominal/ordinal scores: Was kappa calculated?	Kappa calculated			Only percentage agreement calculated
13. for ordinal scores: Was weighted kappa calculated?	Weighted Kappa calculated		Unweighted Kappa calculated	Only percentage agreement calculated
14. for ordinal scores: Was the weighting scheme described?	Weighting scheme described	Weighting scheme NOT described		

Box C. Measurement error: absolute measures				
Design requirements	Excellent	Good	Fair	Poor
1. Was the percentage of missing items given?	Percentage of missing items described	Percentage of missing items NOT described		
2. Was there a description of how missing items were handled?	Described how missing items were handled	Not described but it can be deduced how missing items were handled	Not clear how missing items were handled	
3. Was the sample size included in the analysis adequate?	Adequate sample size (≥ 50)	Good sample size (25–49)	Moderate sample size (15–24)	Small sample size (<15)
4. Were at least two measurements available?	At least two measurements			Only one measurement
5. Were the administrations independent?	Independent measurements	Assumable that the measurements were independent	Doubtful whether the measurements were independent	Measurements were NOT independent
6. Was the time interval stated?	Time interval stated		Time interval NOT stated	
7. Were patients stable in the interim period on the construct to be measured?	Patients were stable (evidence provided)	Assumable that patients were stable	Unclear if patients were stable	Patients were NOT stable
8. Was the time interval appropriate?	Time interval appropriate		Doubtful whether time interval was appropriate	Time interval NOT appropriate
9. Were the test conditions similar for both measurements?	Test conditions were similar (evidence provided)	Assumable that test conditions were similar	Unclear if test conditions were similar	Test conditions were NOT similar
10. Were there any important flaws in the design or methods of the study?	No other important methodological flaws in the design or execution of the study		Other minor methodological flaws in the design or execution of the study	Other important methodological flaws in the design or execution of the study
<i>Statistical methods</i>				
11. for CTT: Was the Standard Error of Measurement (SEM) of Limits of Agreement (LoA) calculated?	SEM, SDC, or LoA calculated	Possible to calculate LoA from the data presented		SEM calculated based on Cronbach's alpha, or on SD from another population

Box B (Reliability) and Box C (Measurement error) of the COSMIN-list. In question B3 and C3 the needed sample size was adjusted for this study.

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