

# Title Page

## Trunk postural control during unstable sitting among individuals with and without low back pain: A systematic review with an individual participant data meta-analysis

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## Abstract

**Introduction:** Sitting on an unstable surface is a common paradigm to investigate trunk postural control among individuals with low back pain (LBP), by minimizing the influence lower extremities on balance control. Outcomes of many small studies are inconsistent (e.g., some find differences between groups while others do not), potentially due to confounding factors such as age, sex, body mass index [BMI], or clinical presentations. We conducted a systematic review with an individual participant data (IPD) meta-analysis to investigate whether trunk postural control differs between those with and without LBP, and whether the difference between groups is impacted by vision and potential confounding factors.

**Methods:** We completed this review according to PRISMA-IPD guidelines. The literature was screened from five electronic databases: MEDLINE, CINAHL, Embase, Scopus, and Web of Science Core Collection. Outcome measures were extracted that describe unstable seat movements, specifically centre of pressure or seat angle. Our main analyses included: 1) a two-stage IPD meta-analysis to assess the difference between groups and their interaction with age, sex, BMI, and vision on trunk postural control; 2) and a two-stage IPD meta-regression to determine the effects of LBP clinical features (pain intensity, disability, pain catastrophizing, and fear-avoidance beliefs) on trunk postural control.

**Results:** Forty studies (1,821 participants) were included for the descriptive analysis and 24 studies (1,050 participants) were included for the IPD analysis. IPD meta-analyses revealed three main findings: (a) trunk postural control was worse (higher root mean square displacement [ $RMS_{displ}$ ], range, and long-term diffusion; lower mean power frequency) among individuals with than without LBP; (b) trunk postural control deteriorated more (higher  $RMS_{displ}$ , short- and long-term diffusion) among individuals with than without LBP when vision was removed; and (c) older age and higher BMI had greater adverse impacts on trunk postural control (higher short-term diffusion; longer time and distance coordinates of the

critical point) among individuals with than without LBP. IPD meta-regressions indicated no associations between the limited LBP clinical features that could be considered and trunk postural control.

**Conclusion:** Trunk postural control appears to be inferior among individuals with LBP, which was indicated by increased seat movements and some evidence of trunk stiffening. These findings are likely explained by delayed or less accurate corrective responses.

**Systematic review registration:** This review has been registered in PROSPERO (registration number: CRD42021124658).

## 1. Introduction

Low back pain (LBP) is a multifactorial condition [1] and the leading cause of disability globally [2-4]. Recurrence of LBP episodes is common [1, 5, 6], and in some cases LBP becomes chronic [7, 8]. The quality of trunk postural control has been suggested as a risk factor for LBP development, recurrence, and/or perpetuation, mediated by effects of suboptimal loading on spine tissue health [9-11]. Although this proposal is plausible, LBP is heterogeneous and findings from many (small samples) studies are inconsistent and inconclusive.

Trunk postural control is critical for executing human motion and completing everyday activities [12]. Such control can be reflected in the capacity to maintain both postural equilibrium (control of the centre of mass over the base of support) and postural orientation between segments (within spine regions and between the spine and other body regions) [13-15]. Trunk postural control requires motor skill [16], involving the integration of kinematic (position and movement) feedback from visual, vestibular, and proprioceptive systems [17, 18], and the generation of coordinated motor output using an array of muscles [12, 19, 20].

An unstable sitting paradigm has been developed to assess the contribution of the trunk to postural control [21], by limiting contributions from the legs and arms [22]. This paradigm (**Figure 1**) involves sitting on an unstable surface attached to a hemisphere [21] or on a chair (aka “wobble chair”) that moves about a central pivot and is supported by four adjustable springs [23]. Typically, the seat is placed over a force platform, and the seat movement is measured by calculating time series of the centre of pressure (CoP) – the location of the point of contact of the seat hemisphere [21, 22], or the barycentre of the forces under the wobble chair with springs [24]. To maintain balance in this paradigm, the global position of the upper body is maintained via dynamic movements at the base/seat [25]. Movements at the base/seat are attenuated by coordinated movements of the hip and spine [26, 27] to limit upper body movements, and maintain the overall centre of mass close to the CoP.

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Figure 1 here

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**Figure 1.** Illustration of the unstable sitting paradigm. A seat is attached to (A) a hemisphere or (B) a central pivot surrounded by four springs. Task difficulty depends on the seat apparatus and its build characteristics. For the hemisphere-based seat, task difficulty depends on the radius of a hemisphere and the seat height from the support surface. For the springs-based seat, task difficulty depends on the stiffness of springs and the distance of springs ( $R_{spring}$ ) from the pivot in percentage. The percentage of  $R_{spring}$  is relative to the gravitation gradient (e.g., 100% = the location of springs that would fully balance the mass of the participant as if sitting on a stable chair). Both seats are commonly positioned on a force platform. A foot plate is usually attached to the seat that maintains the knees at 90° flexion and reduces the contribution of the lower limbs to balance control. In most applications, participants are asked to keep their arms crossed at their chest, to minimize the contribution of the upper limbs.

Many outcome measures from this paradigm have been reported to have acceptable to excellent test-retest reliability for assessing trunk postural control among individuals with or without LBP [21, 24, 28, 29]. These outcome measures are usually related to the amplitude of CoP/seat motion, and include root mean square (RMS) displacement, mean velocity, range, mean frequency, and other measures related to CoP/seat dispersion dynamics (stabilogram diffusion analysis). In most cases, greater CoP/seat motion is interpreted as inferior or impaired trunk postural control [19, 22, 30].

Many individuals with and without LBP have been studied using the unstable sitting paradigm. Results from some studies suggest that trunk postural control is inferior among those with LBP [19, 22, 30-32], whereas other results indicate no difference from those without LBP [29, 33, 34]. These conflicting findings might be explained by differences in LBP presentation (e.g., LBP clinical features), experimental setup (e.g., seat apparatus and its build characteristics) and protocol (e.g., visual condition), or statistical approaches. Regarding the latter, there is variability in whether covariates/confounders were included, such as age, sex, and body mass index (BMI) [21, 34, 35]. Progress in understanding trunk postural control in LBP would be aided by a systematic review of available studies and an individual participant data (IPD) meta-analysis.

An IPD meta-analysis enables calculating more precise estimates of effects (due to increased statistical power) [36-40], inclusion of explanatory covariates [36-38], adjustment for confounding factors [38-40], more powerful investigation of interactions [36-38, 40], and exploring between-study heterogeneity [37, 38, 40]. Although prior systematic reviews have considered postural control among individuals with and/or without LBP during static/perturbed sitting [41-44], semi-sitting [41-43], standing [41-54], or walking [55], trunk postural control has not been evaluated in unstable sitting, and no reviews have used an IPD meta-analysis.

In the current study, we performed a systematic review with an IPD meta-analysis (when data were available) and a narrative review (when IPD were not available) of studies that used an unstable sitting paradigm to investigate trunk postural control among individuals with LBP and/or those without LBP (pain-free controls/individuals). Our aims were to:

- (1) Identify characteristics and summarize the main findings of studies that investigated trunk postural control among individuals with and/or without LBP when seated on an unstable surface.
- (2) Summarise the experimental methods used.
- (3) Assess the comprehensiveness of reporting and methodological quality.
- (4) Use IPD meta-analysis to determine whether trunk postural control (primary outcome measures included root mean square displacement [ $RMS_{displ}$ ] and mean velocity [ $M_{vel}$ ]) differs between individuals with and without LBP, by using studies that included both individuals with and without LBP.
- (5) Use IPD meta-analysis to determine whether similar conclusions are derived from alternative (secondary) outcome measures (e.g., stabilogram diffusion analysis) that are available for fewer studies, by using studies that included both individuals with and without LBP.
- (6) Use IPD meta-analysis to investigate the interaction between participant-level variables (age, sex, and BMI) and the difference between groups on trunk postural control, by using studies that included both individuals with and without LBP.
- (7) Use IPD meta-analysis to determine whether trunk postural control differs between individuals with and without LBP when vision is removed, by using studies that included both individuals with and without LBP in conditions with eyes open and closed.

- (8) Use IPD meta-regression to identify whether trunk postural control among individuals with LBP depends on pain intensity, pain duration, disability, and psychological features, by using all studies that included individuals with LBP.
- (9) Use visual inspection of mean plots to compare the outcomes of studies that tested both individuals with and without LBP (IPD meta-analysis) with: (a) the outcomes of studies that tested only LBP or pain-free individuals using IPD analysis (standardised statistical methods); and (b) a narrative review of studies with outcomes for which IPD could not be obtained.

## **2. Methods**

### **2.1. Design, registration, and ethics**

This systematic review with IPD meta-analyses was planned according to the Preferred Reporting Items for Systematic Review and Meta-Analyses of Individual Participant Data (PRISMA-IPD) guidelines [56]. The study was registered in PROSPERO (registration number: CRD42021124658), and the study protocol has been published [57]. Ethics exemption for this systematic review with IPD analysis was obtained from the Institutional Human Research Ethics Committee (The University of Queensland: 2019003026). Other ethical considerations (e.g., ownership and confidentiality of the IPD set of included studies) have been described previously [57].

### **2.2. Eligibility criteria**

#### **2.2.1. Inclusion criteria**

Studies were included if they investigated trunk postural control using an unstable sitting paradigm among participants aged  $\geq 18$  years. Cross-sectional studies, clinical trials, and cohort studies with baseline data were considered. Studies had to include any of the following: (1) individuals with and without LBP (LBP versus pain-free control); (2) individuals with only LBP; or (3) only pain-free individuals. Participants with LBP of any duration were

considered (e.g., acute, subacute, or chronic). Participants had to perform trunk postural control tasks using an unstable sitting paradigm that required individuals to control balance in the sagittal and frontal plane. Trunk postural control must have been measured by quantifying seat motion, either from CoP (force platform) or seat angle (from motion capture systems/sensors).

### **2.2.2. Exclusion criteria**

Studies with insufficient details to determine eligibility were excluded if the authors did not respond to requests (at least two attempts via email) to provide the required information. Non-English reports were excluded. For individuals with only LBP, studies were excluded if they included participants with: neurological disorders (e.g., stroke) except for sciatica (pain due to sciatic nerve compression); spinal structure deformities (e.g., scoliosis); cancer or infection; spine surgery; or a major injury/pain in any other body region within the preceding 12 months. For pain-free controls/individuals, studies were excluded if they included participants with: a history of LBP in the previous year; neurological disorders; structure deformities; cancer or infection; spine surgery; a major injury/pain in any body region within the preceding 12 months. In addition, studies were excluded if they: investigated disorders or diseases other than LBP; involved different seated balance tasks, such as provision of visual feedback or moving the seat to specific target locations; involved sitting on a hemisphere/springs but with feet supported on the floor; involved sitting tasks with perturbations; involved sitting on soft surfaces (e.g., a ball, foam, or air cushion); or studies that referred to an already identified dataset (e.g., studies that referred to secondary use of the same data presented in another study), these studies were excluded from the quantitative analysis but included in the descriptive analysis.

### **2.2.3. Outcome measures**

**Table 1** presents additional information about the outcome measures. The primary outcome measures were  $RMS_{displ}$  and  $M_{vel}$  of the CoP/seat angle during trials in which

participants balanced with eyes open or closed in the forward-to-backward (anteroposterior) and side-to-side (mediolateral) directions. Greater  $RMS_{displ}$  and  $M_{vel}$  are generally considered to reflect impaired postural control of the trunk [22, 30]. These measures are those most often used to quantify postural control.  $RMS_{displ}$  [21, 24] and  $M_{vel}$  [21, 24, 28] measures have high test-retest reliability during unstable sitting tasks. These measures of postural control have also successfully differentiated individuals with and without pathologies [58]. Secondary outcome measures included those less commonly reported/extracted, including range, mean power frequency (MPF), and measures related to stabilogram diffusion analysis [21, 24].

**Table 1.** Primary and secondary outcome measures

Outcome		Unit		Description
		CoP	Angle*	
<b>Primary</b>	$RMS_{displ}$	mm	degree (°)	Root mean square (RMS) of CoP (or seat angle) displacement time series after subtracting the mean position
	$M_{vel}$	mm/s	°/s	Total path length travelled by CoP (or seat angle) divided by total trial duration
<b>Secondary</b>	Range	mm	°	Distance between minimum and maximum CoP (or seat angle) positions
	MPF	Hz	Hz	Mean power frequency (MPF) of CoP (or seat angle)
	D	mm <sup>2</sup> /s	° <sup>2</sup> /s	Diffusion coefficient (D) that reflects how fast (slope) CoP (or seat angle) is diffusing (spreading). Sometimes referred to as the energy/stochastic activity of CoP (or seat angle)
	$D_{short}$	mm <sup>2</sup> /s	° <sup>2</sup> /s	Linear slope fitted to the early part of the diffusion-time profile (short-term diffusion coefficient)
	$D_{long}$	mm <sup>2</sup> /s	° <sup>2</sup> /s	Linear slope fitted to the later part of the diffusion-time profile (long-term diffusion coefficient)
	CP			Critical point (CP) reflecting the intersection coordinates (time and distance) of the short and long-term slopes
	$CP_{time}$	s	s	Mean time coordinate of the critical point
	$CP_{dist}$	mm <sup>2</sup>	° <sup>2</sup>	Mean squared distance coordinate of the critical point

**Abbreviations:** CoP, centre of pressure;  $M_{vel}$ , mean velocity.

\*Some studies calculated seat angle (as a surrogate of CoP) from motion capture systems/sensors to assess trunk postural control.

### 2.3. Identifying studies

The following electronic databases were searched from their date of establishment to 25 March 2022: MEDLINE and CINAHL via EBSCO, Embase and Scopus via Elsevier, and Web of Science Core Collection via Clarivate. Reference lists of included studies were screened for other relevant studies. Corresponding authors of included studies were contacted and asked if they had other studies on the same topic. Search terms were determined based on the inclusion criteria (see **Supplementary Tables S1-4** for details on our search strategies).

### 2.4. Study selection

EndNote software (version X9) was used to collect the search results, and to remove duplicates automatically and manually. Titles and abstracts of articles were screened for potential inclusion by two independent reviewers (MAA and HA) familiar with systematic reviews and meta-analyses. For articles that potentially met eligibility criteria, full texts were reviewed for final decisions. Disagreement between reviewers was resolved by consensus or a third reviewer (PWH). Cohen's kappa (inter-rater reliability) analysis [59] was performed to assess the degree of agreement between reviewers. The number of included and excluded articles, and reasons for exclusion, were recorded.

### 2.5. IPD collection

The corresponding authors of included studies were asked to share their IPD using author information reported in the article, or profiles on their university websites. If no response was received, co-authors were contacted. Authors were informed about the proposal IPD meta-analysis study/methods, and were asked if they were willing to provide their IPD sets. Any eligible studies for which IPD could not be obtained (e.g., authors did not respond or did not have access/authorization to provide IPD set) were retained for narrative analysis.

## 2.6. Data items

Study- and individual-level data were extracted using a standardised form. Extracted data were [57]: study characteristics, participant characteristics, LBP clinical features, inclusion and exclusion criteria, experimental setup, experimental protocol, any reported adverse effects, outcome measures, and main findings. Collected IPD sets were stored in a master spreadsheet and were screened in terms of presentation of overall data and available variables. The unit of measurement for each outcome measure was unified. For instance, some outcome measures from CoP data, such as  $RMS_{displ}$ , were reported in two different units (cm or mm) and the unit of  $RMS_{displ}$  was unified as “mm” before applying the IPD meta-analysis.

## 2.7. Comprehensiveness of reporting and methodological quality

Comprehensiveness of reporting and quality of methods were assessed with an adapted checklist [57], which includes components from a quality checklist developed by Mazaheri et al. [46] and Ruhe et al. [45] for systematic reviews of balance measures. This checklist has 25 items with three options to assess the comprehensiveness of reporting and quality of methods across five main domains: participant characteristics, LBP characteristics, experimental setup/protocol, confounding effects control, and statistical information (**Supplementary Table S5** presents the checklist content and item descriptions). Items were scored as ‘1’ (yes), ‘0.5’ (partially; some information was provided) or ‘0’ (no) by two independent reviewers (MAA and HA). The overall reporting/quality score was obtained from the sum of all scores converted to a percentage. Separate reporting/quality scores were calculated for each domain. Reporting/Quality scores ranged from 0 to 100%, with higher scores indicating higher reporting/quality. Discrepancies between reviewers were settled by consensus and a third reviewer (PWH) when necessary.

## **2.8. Synthesis methods**

### **2.8.1. Descriptive analysis**

A descriptive analysis (see **Supplementary Table S6** for a detailed listing of items included for the descriptive analysis) was used to identify characteristics and to summarize main findings of studies that investigated trunk postural control among individuals with and/or without LBP when seated on an unstable surface (**Aim 1**), and to assess the comprehensiveness of reporting and quality of methods (**Aim 3**). All studies were included in the descriptive analysis, including those that reported data from only LBP or pain-free individuals, and studies for which IPD data were unavailable. Outcomes of each specific study were summarised in tabular format (**Aim 1**) and were discussed narratively only for studies that did not provide IPD (**Aim 9**). A detailed descriptive analysis was also undertaken to describe the experimental setup and protocol (**Aim 2**). Comprehensiveness of reporting and quality of methods before and after obtaining the IPD were summarised in tabular format (**Aim 3**).

### **2.8.2. IPD meta-analysis**

Stata/IC 16.1 software (Release 16, StataCorp LLC, College Station, Texas, USA) was used for statistical analyses and generating forest plots. Results were regarded as statistically significant if  $P < 0.05$ .

A quantitative analysis was conducted using a two-stage IPD meta-analysis to investigate trunk postural control among individuals with and without LBP when sitting on an unstable surface, while considering the characteristics of each individual participant (**Aims 4-5**). The two-stage IPD meta-analysis was obtained by (1) analysing IPD from each study separately to calculate aggregate data of interest using multilevel mixed-effects models, then (2) combining the results using conventional meta-analysis methods. The advantage of this approach is that it applies a standardised statistical method [38-40] and enables to control for covariates and confounding factors in the analysis [36-40]. Potential confounding variables of

age and BMI (as covariates) and sex (as a fixed factor) [21, 34, 35] were included in the models. This analysis was limited to studies that included both individuals with and without LBP to identify between-group differences and was performed for each identified outcome ( $RMS_{displ}$ ,  $M_{vel}$ , range, MPF,  $D_{short}$ ,  $D_{long}$ ,  $CP_{time}$  and  $CP_{dist}$ ; for definitions see **Table 1**), visual condition (eyes open and closed), and direction (anteroposterior and mediolateral directions).

A random effects model, fitted using the restricted maximum likelihood (REML) method, was used [60] to avoid misleading effect estimates and potentially inappropriate conclusions [61]. Overall and individual study (observed) effect sizes were estimated using standardised mean differences (SMDs), since different studies used different units to measure the same outcome [62]. SMD effect sizes can be classified as small (0.2–0.5), medium (0.5–0.8) and large ( $>0.8$ ) [63]. The  $I^2$  index [64] was calculated to assess the percentage of total variability due to between-study heterogeneity rather than sampling error (within-study variability) [65, 66]. Prediction interval (PI) can provide a predicted range for the true effect (without sampling error) in a new (similar) study [67–69]. This was calculated (when having a sufficient number of studies) to estimate how much the effect size varies across studies included in the IPD meta-analysis [70, 71].

A two-stage IPD analysis was performed to investigate the interaction between participant-level variables (age, sex, and BMI) and the difference between groups (**Aim 6**). In the first stage, group and participant-level variables and their interactions were entered using multilevel mixed-effects models. An interaction of one variable (age) with group was entered and the remaining variables (sex and BMI) were included without interaction terms in the models. This method was applied for each of the participant-level variables, and was performed for each study separately. In the second stage, a conventional meta-analysis was performed to pool interaction effect (adjusted) coefficients using a random-effects model with the REML method. Both  $I^2$  index and PI were calculated. This analysis was limited to studies that included

both individuals with and without LBP, and was performed for each identified outcome, visual condition, and direction.

A two-stage IPD analysis was performed to investigate the interaction between vision (eyes open and closed) and the difference between groups (**Aim 7**). In the first stage, group and visual condition and their interaction were entered using multilevel mixed-effects models (for each study separately), including age and BMI as covariates, and sex as a fixed factor in the models. In the second stage, a conventional meta-analysis was performed to pool interaction effect (adjusted) coefficients using a random-effects model with the REML method. Both  $I^2$  index and PI were calculated. This analysis was limited to studies that included both individuals with and without LBP and that investigated the effect of vision on trunk postural control, and was performed for each identified outcome and direction.

A two-stage IPD meta-regression was performed on data from studies that included individuals with LBP to identify the relationship between LBP clinical features and trunk postural control (**Aim 8**). In the first stage, each LBP clinical feature (pain intensity, disability, pain catastrophizing, and fear-avoidance beliefs) was entered using multilevel mixed-effects models (for each study separately), including participant-level variables (age, sex, and BMI). In the second stage, a standard meta-regression was performed to pool regression (adjusted) coefficients using a random-effects model with the REML method. This analysis was performed for each identified outcome, visual condition, and direction.

### **2.8.3. Other analysis**

Descriptive statistics (e.g., means and standard errors) of the outcomes from studies with data from only LBP or pain-free individuals were plotted with the outcomes from other studies with both groups (individuals with and without LBP) using IPD (if available) or aggregate data (**Aim 9**). We did this by applying standardised statistical methods (multilevel mixed-effects models), including confounding variables (age, sex, and BMI). This analysis was

performed for each identified outcome, visual condition, and direction. We compared between groups using the visual inspection of mean plots. Outcomes from studies for which IPD could not be obtained were summarised briefly in a narrative manner and were contrasted with the findings of the IPD meta-analysis.

### **3. Results**

#### **3.1. Study selection**

From among 18,595 identified articles, a total of 40 articles [19, 21-35, 72-95] met the eligibility criteria and was included for the descriptive analysis. After removal of studies that referred to secondary use of data presented in another study ( $n=10$ ), and studies for which individual-level data could not be provided ( $n=6$ ), IPD sets were obtained from 24 articles for the IPD analysis [19, 22, 23, 25, 28-35, 73, 77, 78, 80, 83-85, 87, 88, 90-92]. **Figure 2** shows the PRISMA-IPD flow diagram. There was a moderate agreement ( $\kappa=0.45$ ) between both reviewers on study inclusion and exclusion decisions, and all disagreements were resolved by consensus.

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Figure 2 here

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**Figure 2.** PRISMA-IPD flow diagram of the study selection process. LBP = low back pain; IPD =

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individual participant data; BMI = body mass index.

## 3.2. Descriptive analysis

### 3.2.1. Characteristics of participants

Forty studies with a total of 1,821 participants were included in this systematic review. Fourteen studies (1,236 participants) involved comparisons between individuals with (636 participants) and without (600 participants) LBP [19, 22, 24, 29-35, 72, 74-76], one study (18 participants) included individuals with only LBP [73] and the remaining 25 studies (567 participants) included pain-free individuals [21, 23, 25-28, 77-95] either alone or with comparison to individuals with conditions other than LBP. Sex, age, and BMI characteristics are described in **Tables 2** and **3**. **Supplementary Tables S7-8** show the inclusion and exclusion criteria used in the included studies.

All studies with data from individuals with LBP (studies including both individuals with and without LBP or individuals with only LBP;  $n=15/40$ ) included participants considered to have non-specific LBP. Six studies included participants with chronic LBP [22, 24, 30, 34, 73, 75], one studied acute LBP [35] and another studied subacute LBP [72]. Five studies included participants with mixed LBP presentation/stages [19, 29, 31, 32, 76], such as acute to sub-acute [19], sub-acute to chronic [31], or acute to chronic [29, 32, 76]. Two studies provided insufficient detail [33, 74].

Of the 24 studies included in the IPD analysis, nine provided IPD sets [19, 22, 29-35] for both individuals with (361 participants) and without LBP (369 participants) for 378 female (individuals with LBP = 189; individuals without LBP = 189) and 352 male (individuals with LBP = 172; individuals without LBP = 180) participants. Those with LBP were younger (individuals with LBP =  $36.1 \pm 11.9$  years; individuals without LBP =  $37.5 \pm 10$  years;  $P < 0.05$ ) and had higher BMI (individuals with LBP =  $24.9 \pm 3.8$  kg/m<sup>2</sup>; individuals without LBP =  $24.0 \pm 3.6$  kg/m<sup>2</sup>;  $P < 0.05$ ) than those without LBP (**Table 2**). Other studies ( $n=14/24$ ) included in the IPD analysis [23, 25, 28, 77, 78, 80, 83-85, 87, 88, 90-92] had data for only pain-free

individuals (302 participants: 77 female and 225 male participants). For those individuals, mean age and BMI were  $24.5 \pm 6.0$  years and  $23.6 \pm 2.7$  kg/m<sup>2</sup> (**Table 3**), respectively.

Most studies with LBP data provided information about LBP intensity ( $n=12/15$ ) [19, 22, 24, 29-32, 34, 35, 72, 73, 76] and disability ( $n=10/15$ ) [19, 22, 24, 29, 30, 32, 34, 35, 73, 76] either as IPD or aggregate data, but less than half ( $n=7/15$ ) [19, 24, 29, 30, 32, 34, 35] provided information about psychological features. For the IPD, the mean scores of pain intensity (visual analogue or numeric pain rating scale), disability (Roland-Morris questionnaire) and pain catastrophizing were  $4.3 \pm 2$ ,  $7.1 \pm 4.8$  and  $16.1 \pm 11.2$ , respectively. The mean scores of physical activity subscale, work subscale and total scale of fear-avoidance beliefs questionnaire were  $14.5 \pm 6$ ,  $13.1 \pm 10.8$  and  $27.3 \pm 13.3$ , respectively. LBP clinical features are described in **Table 4**.

**Table 2.** Participant characteristics for studies with data from individuals with LBP

Study	Group <i>LBP stage (pain duration)</i> <i>Control</i>	Sample Size [IPD analysis]*			Mean ± Standard Deviation			
		Total	Male	Female	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m <sup>2</sup> )
Radebold et al. [22]	<i>Chronic LBP (&gt; 6 months)</i>	16 [16]	15 [15]	1 [1]	38.8±10.1	175.8±8.6	81.9±15.3	26.3±3.1
	<i>Control</i>	14 [14]	13 [13]	1 [1]	38.1±9.6	176.6±8.9	80.4±17.5	25.6±4.2
Reeves et al. [73]	<i>Chronic LBP (&gt; 6 months)</i>	18 [18]	10 [10]	8 [8]	38.6±12.6	174.2±10	75.7±12.4	24.9±3
Navalgund [72]†	<i>Subacute LBP (≤ 8 weeks)</i>	10	5	5	32.6±11.1	174±13	84.2±19.9	27.3±4.5
	<i>Control</i>	10	5	5	35±8.3	175±9	79±22.3	26.1±7.1
van Dieen et al. [33]	<i>Current LBP (not available)</i>	58 [58]	21 [21]	37 [37]	42.1±0.7	176.3±8.5	77.7±14.2	24.9±3.8
	<i>Recent LBP (not available)§</i>	79	36	43	42.2±0.7	177.2±9	75.9±12.1	24.1±3.1
	<i>Control</i>	164 [160]	83 [82]	81 [78]	42±0.7	176.8±8.7	78.1±14.7	24.9±3.8
van Dieen et al. [74]‡	<i>Current LBP (not available)</i>	58	21	37	42.1±0.7	176.3±8.5	77.7±14.2	24.9±3.8
	<i>Recent LBP (not available)§</i>	79	36	43	42.2±0.7	177.2±9	75.9±12.1	24.1±3.1
	<i>Control</i>	164	82	78	42±0.7	176.8±8.7	78.1±14.7	24.9±3.8
Willigenburg et al. [31]	<i>Subacute to chronic LBP (≥ 6 weeks)</i>	20 [20]	11 [11]	9 [9]	33.4±15.6	178.7±11.2	76±15.5	23.6±3
	<i>Control</i>	11 [11]	7 [7]	4 [4]	32.6±10.4	178±12.2	71.3±9	22.5±2.5
Larivière et al. [24]‡	<i>Chronic LBP (≥ 3 months)</i>	17	9	8	38±13	169.6±10.5	70±12.7	24.2±2.5
	<i>Control</i>	19	9	10	38.7±14	170±7.1	67.4±12.8	23.1±2.7
Larivière et al. [34]	<i>Chronic LBP (≥ 3 months)</i>	17 [17]	9 [9]	8 [8]	38±13	169.6±10.5	70±12.7	24.2±2.5
	<i>Control</i>	19 [19]	9 [9]	10 [10]	38.7±14	170±7.1	67.4±12.8	23.1±2.7
Sung et al. [19]	<i>Acute to subacute LBP (&lt; 3 months)</i>	33 [34]	13 [13]	20 [21]	33.6±14.9	170±8.5	75.5±16.4	26±4.9
	<i>Control</i>	33 [34]	13 [13]	20 [21]	35.4±13.8	169.4±9.4	68.4±11.9	23.8±3.3
Shahvarpour et al. [75]‡	<i>Chronic LBP (≥ 3 months)</i>	6	6	NA	-	179±7	82.8±18.9	-
	<i>Control</i>	6	6	NA	-	178±9	81.2±29	-
Shahvarpour et al. [29]	<i>Acute to chronic LBP (≥ 4 weeks)</i>	34 [35]	15 [16]	19 [19]	46.1±12.6	167.2±7.4	73.5±11.4	26.3±3.4
	<i>Control</i>	30 [30]	15 [15]	15 [15]	39.6±14	171.1±10	70±12.7	23.8±3.4
Shahvarpour et al. [32]	<i>Acute to chronic LBP (≥ 4 weeks)</i>	40 [40]	20 [20]	20 [20]	42.9±11.2	169.1±9.3	70.6±11.7	24.6±2.9
	<i>Control</i>	20 [19]	10 [9]	10 [10]	39.8±13.4	169.5±7.8	69±11.8	23.9±2.7
Cyr et al. [30]	<i>Chronic LBP (&gt; 3 months)</i>	10 [10]	2 [2]	8 [8]	40.6±5.3	-	-	25.1±3.1
	<i>Control</i>	10 [10]	2 [2]	8 [8]	41.4±6.1	-	-	24.6±3.3
Larivière et al. [76]‡	<i>Acute to chronic LBP (≥ 4 weeks)</i>	30	15	15	♂43±14 ♀48±11	♂173±6 ♀164±6	♂76±13 ♀72±10	♂25±4 ♀27±3
	<i>Control</i>	28	14	14	♂38±14 ♀41±14	♂178±9 ♀164±6	♂77±11 ♀62±10	♂24±3 ♀23±4
van den Hoorn et al. [35]	<i>Acute LBP (&lt; 2 weeks)</i>	129 [131]	62 [63]	67 [68]	28.7±8.1	172.6±9	72.7±14.8	24.3±4
	<i>Control</i>	72 [72]	29 [29]	43 [43]	26.6±6.6	169.6±10.5	64.6±13.7	22.3±3.1
[Overall]**	<i>LBP</i>	636 [361]	298 [172]	342 [189]	<b>[36.05±11.86]</b>	[172.36±9.43]	[74.13±14.37]	<b>[24.86±3.78]</b>
	<i>Control</i>	600 [369]	295 [180]	297 [189]	<b>[37.48±10.04]</b>	[173.45±9.87]	[72.61±14.87]	<b>[23.99±3.58]</b>

**Abbreviations/Symbols:** LBP, low back pain; IPD, individual participant data; BMI, body mass index; NA, not available; ♂, male; ♀, female.

**Statistics for IPD analysis:** Overall summary measures for studies that provided IPD sets. Fisher's exact test was used for categorical data (e.g., sex). Independent t-test was used for normally continuous data (e.g., height, weight, and BMI) and Wilcoxon Rank-Sum test was used for not normally distributed continuous data (e.g., age). Values of statistically significant differences ( $P<0.05$ ) are printed bold.

\*Number of participants included in the IPD analysis.

†IPD were not available as authors did not have access/authorisation to provide the IPD set.

‡Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

§No current pain, but pain within last 12 months.

\*\*Overall summary measures for only studies with IPD and included both individuals with and without LBP.

**Table 3.** Participant characteristics for studies with data from only pain-free individuals

Study	Sample Size [IPD analysis]*			Mean $\pm$ Standard Deviation			
	Total	Male	Female	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m <sup>2</sup> )
Cholewicki et al. [21]†	11	9	2	36.9 $\pm$ 10.1	176.7 $\pm$ 7.7	84.9 $\pm$ 21	27 $\pm$ 5.8
Silfies et al. [77]	13 [13]	9 [9]	4 [4]	20.8 $\pm$ 0.9	175.5 $\pm$ 12.5	77.3 $\pm$ 12.8	25 $\pm$ 2.5
van der Burg et al. [79]‡	8	4	4	63.1 $\pm$ 10	177.1 $\pm$ 12.6	79 $\pm$ 12	-
Reeves et al. [78]	10 [10]	6 [6]	4 [4]	22.3 $\pm$ 4.6	173.8 $\pm$ 11.8	68.4 $\pm$ 11.8	22.6 $\pm$ 3.1
Cholewicki et al. [80]	23 [22]	12 [12]	11 [10]	25.3 $\pm$ 7.8	173.4 $\pm$ 9.8	67.6 $\pm$ 12.2	22.4 $\pm$ 2.8
Lee and Granata [81]§	12	9	3	♂28 $\pm$ 3.1 ♀25.7 $\pm$ 2.5	♂178.8 $\pm$ 9.5 ♀165.7 $\pm$ 4.2	♂80.4 $\pm$ 14.8 ♀60.4 $\pm$ 3.4	-
Lee et al. [82]‡	12	7	5	♂25.7 $\pm$ 6.9 ♀21.4 $\pm$ 1.7	♂178.7 $\pm$ 6.9 ♀161.3 $\pm$ 8.2	♂79.9 $\pm$ 9 ♀59.6 $\pm$ 8.3	-
Slota et al. [23]	21 [21]	13 [13]	8 [8]	23 $\pm$ 4	170.8 $\pm$ 12.2	73.9 $\pm$ 14	-
Hendershot & Nussbaum [83]	8 [8]	8 [8]	NA	36.9 $\pm$ 13.4	174.4 $\pm$ 3.9	80.3 $\pm$ 11.4	26.5 $\pm$ 4.6
Hendershot et al. [84]	12 [12]	6 [6]	6 [6]	23.9 $\pm$ 2.5	173.8 $\pm$ 12.9	69.3 $\pm$ 9.5	22.9 $\pm$ 1.4
Barbado et al. [86]†	25	25	NA	23.5 $\pm$ 7.2	174 $\pm$ 6.6	74.6 $\pm$ 11.2	24.5 $\pm$ 2.5
Barbado et al. [85]	78 [69]	78 [69]	NA	24.6 $\pm$ 5.5	175.1 $\pm$ 6.6	74.7 $\pm$ 10.4	24.3 $\pm$ 2.5
Beaudette et al. [87]	28 [28]	14 [14]	14 [14]	23.8 $\pm$ 2.6	175.8 $\pm$ 9.4	73.7 $\pm$ 14.7	23.6 $\pm$ 3
Ruggiero et al. [88]	24 [24]	NA	24 [24]	Range: 20-24	171 $\pm$ 6	64.9 $\pm$ 10.1	22.1 $\pm$ 2.4
Barbado et al. [28]	23 [23]	23 [23]	NA	25.3 $\pm$ 5.5	174.5 $\pm$ 5.6	73.2 $\pm$ 7.4	24 $\pm$ 2.3
Barbado et al. [89]†	22	22	NA	24.6 $\pm$ 4.6	174 $\pm$ 7	73.6 $\pm$ 7.5	-
Glofcheskie & Brown [90]	36 [29]	36 [29]	NA	20.6 $\pm$ 1.7	176.7 $\pm$ 6.3	70.3 $\pm$ 8.7	22.5 $\pm$ 2
Acasio et al. [91]	13 [13]	11 [11]	2 [2]	28.9 $\pm$ 7.9	177.5 $\pm$ 5.7	75.2 $\pm$ 11.8	23.8 $\pm$ 2.5
Williams et al. [92]	15 [15]	10 [10]	5 [5]	23.9 $\pm$ 2.3	172.5 $\pm$ 10	73.3 $\pm$ 13.8	24.4 $\pm$ 2.8
Barbado et al. [93]‡	19	12	7	27.9 $\pm$ 7.1	-	83.6 $\pm$ 11.6	-
Roberts & Vette [25]	15	15	NA	25.3 $\pm$ 5.2	179.6 $\pm$ 6.7	75.1 $\pm$ 13.1	23.1 $\pm$ 2.8
Roberts et al. [27]†	15 [15]	15 [15]	NA	25.3 $\pm$ 5.2	179.6 $\pm$ 6.7	75.1 $\pm$ 13.1	23.1 $\pm$ 2.8
Acasio et al. [94]†	13	11	2	28.9 $\pm$ 7.9	177.5 $\pm$ 5.7	75.2 $\pm$ 11.8	23.8 $\pm$ 2.5
Alshehri et al. [26]†	72	29	43	26.8 $\pm$ 6.5	169.2 $\pm$ 10.5	64.3 $\pm$ 13.9	22.3 $\pm$ 3.1
de Oliveira et al. [95]§	39	6	33	22 $\pm$ 3 / 22 $\pm$ 4 / 26 $\pm$ 5	164 $\pm$ 9 / 167 $\pm$ 5 / 164 $\pm$ 6	62 $\pm$ 13 / 65 $\pm$ 10 / 67 $\pm$ 6	22 $\pm$ 4 / 24 $\pm$ 3 / 25 $\pm$ 2
[Overall]**	567 [302]	390 [225]	177 [77]	[24.48 $\pm$ 5.99]	[175.04 $\pm$ 8.18]	[72.63 $\pm$ 11.54]	[23.61 $\pm$ 2.74]

**Abbreviations/Symbols:** IPD, individual participant data; BMI, body mass index; NA, not available; ♂, male; ♀, female.

**Statistics for IPD analysis:** Overall summary measures for studies that provided IPD sets.

\*Number of participants included in the IPD analysis.

†Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

‡IPD were not available as authors did not have access/authorisation to provide the IPD set.

§IPD were not available as authors did not respond to IPD request.

\*\*Overall summary measures for only studies with IPD.

**Table 4.** Clinical features of individuals with LBP

Study	Mean ± Standard Deviation							
	Pain Intensity		Disability		Pain Catastrophizing	Fear-Avoidance		
	VAS (/10)	NPRS (/10)	RMDQ (/10, /24, /28)	ODI (/100)	PCS (/52)	FABQ-PA (/30)	FABQ-W (/66)	FABQ (/96)
Radebold et al. [22]	2.7±2	-	/24: 5.1±4.2	-	-	-	-	-
Reeves et al. [73]	4.4±2.2	-	/10: 2.3±1.6§	-	-	-	-	-
Navalgund [72]*	-	4±1.2	-	-	-	-	-	-
van Dieen et al. [33]	-	-	-	-	-	-	-	-
van Dieen et al. [74]†	-	-	-	-	-	-	-	-
Willigenburg et al. [31]	2.7±1.7	-	-	-	-	-	-	-
Larivière et al. [24]†	2.5±1.9	-	/24: 4.2±3.2	-	17.2±10.2	-	-	-
Larivière et al. [34]	2.5±1.9	-	/24: 4.2±3.2	-	17.2±10.2	-	-	-
Sung et al. [19]	-	4±1.8	-	20.8±11.2	12.2±11.1	13.4±8.9	14.3±13.5	28.9±17.8
Shahvarpour et al. [75]†	-	-	-	-	-	-	-	-
Shahvarpour et al. [29]	-	4.9±1.3	/24: 12.1±3.9	29.3±9.7	23.9±12	16.5±5.8	-	-
Shahvarpour et al. [32]	-	2.6±1.6	/24: 5±3.4	-	20.1±9.9	13.9±5.1	16.6±12	30.5±14.6
Cyr et al. [30]	-	3.7±1.9	/24: 6±2.9	22.4±10.1	-	11.9±2.8	11.8±6.8	22.7±8.9
Larivière et al. [76]†	-	♂4.7±1.4 ♀4.6±1	-	♂28±9 ♀28±9	-	-	-	-
van den Hoorn et al. [35]	-	5±1.9	/28: 6.9±4.7	-	13.7±10.3	14.7±5.5	11.8±9.7	26.3±11.7
IPD Sample Size [Overall]‡	276 [4.34±2.01]		232 [7.13±4.77]	79 [24.77±11.08]	254 [16.13±11.22]	248 [14.53±6.04]	213 [13.10±10.78]	214 [27.33±13.34]

**Abbreviations/Symbols:** LBP, low back pain; VAS, Visual Analogue Scale; NPRS, Numeric Pain Rating Scale; RMDQ, Rolland-Morris Disability Questionnaire; ODI, Oswestry Disability Index; PCS, Pain Catastrophizing Scale; FABQ-PA, Fear-Avoidance Beliefs Questionnaire - Physical Activity; FABQ-W, Fear-Avoidance Beliefs Questionnaire - Work; FABQ, fear-avoidance beliefs questionnaire; IPD, individual participant data; ♂, male; ♀, female.

**Statistics for IPD analysis:** Overall summary measures for studies that provided IPD sets.

\*IPD were not available as authors did not have access/authorisation to provide the IPD set.

†Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

‡Overall summary measures for only studies with IPD.

§This was not included in the overall summary measure of RMDQ.

### 3.2.2. Experimental setup and protocol

**Supplementary Tables S9-10** provide detailed information about the experimental setup and protocol used in all included studies. Most studies ( $n=25/40$ ) used an unstable seat that attached to part of a hemisphere (LBP data:  $n=8$  [19, 22, 30, 31, 33, 35, 73, 74]; only pain-free data:  $n=17$  [21, 25-28, 77-80, 85-90, 92, 93]). Other studies ( $n=15/40$ ) used an unstable chair that attached to four springs moving about a pivot (LBP data:  $n=7$  [24, 29, 32, 34, 72, 75, 76]; only pain-free data:  $n=8$  [23, 81-84, 91, 94, 95]). Seat characteristics differed between studies. For the hemisphere-base seat, the radius range was 10-25 cm and the seat height from the support surface range was 6.25-19 cm. For the springs-base seat, the distance of springs from the pivot in percentage ranged from 43.5-100%. Some studies ( $n=11/40$ ) used multiple levels of seat instability [21, 22, 25, 27, 72, 73, 77, 81, 91, 92, 94]. Most studies ( $n=34/40$ ) attached a foot plate to the seat to maintain knee flexion at 90° [19, 21-24, 26, 28-35, 72-86, 89, 91, 93-95]. Outcome measures of trunk postural control were calculated from CoP data (force platform) in 27/40 studies [19, 21, 22, 28, 30, 31, 33, 35, 72-74, 77-80, 83-91, 93-95], seat angle data (motion capture systems/sensors) in 8/40 studies [25-27, 29, 32, 76, 82, 92], or both methods in 5/40 studies [23, 24, 34, 75, 81].

Trunk postural control was assessed with both eyes open and closed in 12/40 studies [19, 21, 22, 25-27, 30, 31, 35, 77, 78, 92], eyes closed only in 7/40 studies [24, 29, 32, 34, 73, 75, 76], and eyes open only in 21/40 studies [23, 28, 33, 72, 74, 79-91, 93-95]. Trial duration ranged between 7 and 70 s, but most used 60 s or more ( $n=23/40$ ) [19, 23, 24, 28, 29, 32, 34, 72, 75-77, 81-87, 89-91, 93, 94]. One to six repetitions were recorded. Though many studies ( $n=25/40$ ) included clear (specific) instruction to participants (e.g., ‘sit as quietly as possible’ or ‘maintain an upright posture’), not all did so [21, 24, 25, 29, 30, 32, 34, 73, 76-78, 80-82, 95].

### 3.2.3. Comprehensiveness of reporting and methodological quality

The comprehensiveness of reporting and quality of methods were assessed twice (see **Supplementary Tables S11-16** for details): first using the study-level data as reported in the published version of all included papers ( $n=40$ ), and second using the IPD obtained from authors ( $n=24/40$ ).

Using published versions ( $n=40$ ), the overall reporting/quality score of all domains was 66.3% for studies with LBP data ( $n=15/40$ ) and 63.4% for studies with only pain-free data ( $n=25/40$ ). The lowest and highest reporting/quality domain score for studies with LBP data were obtained for the confounding effects control domain (39.4%) and the experimental setup/protocol domain (76.7%), respectively. For studies with only pain-free data, the lowest and highest reporting/quality domain score were obtained for the confounding effects control domain (18.7%) and participant characteristics (80%), respectively.

When reporting/quality was assessed using the IPD set ( $n=24$ ), there was a marked improvement in reporting/quality scores. The overall reporting/quality score of all domains increased from 67.5% to 90% for studies with LBP data ( $n=10/24$ ) and from 63.3% to 88.2% for studies with only pain-free data ( $n=14/24$ ).

### 3.2.4. Outcome measures and main findings

Primary outcome measures were calculated in most studies:  $RMS_{displ}$  ( $n=26/40$ ) and  $M_{vel}$  ( $n=26/40$ ). Secondary outcome measures were less frequently calculated/reported: range ( $n=8/40$ ), MPF ( $n=10/40$ ),  $D_{short}$  ( $n=11/40$ ),  $D_{long}$  ( $n=7/40$ ),  $CP_{time}$  ( $n=8/40$ ), and  $CP_{dist}$  ( $n=6/40$ ). There was an increase in the number of calculated measures when IPD were obtained. Many outcome measures were calculated in both the anteroposterior and mediolateral directions, but some measures were only calculated in the resultant direction. Outcomes and main findings of each study are presented in **Tables 5-6**. The following sections describe the

449 outcomes and results of the IPD analysis and then compare them with the findings of studies  
450 that could not be included in the IPD analysis.

**Table 5.** Outcome measures and main findings for studies with data from individuals with LBP

Study	Primary measures		Secondary measures						Main findings	IPD
	RMS <sub>displ</sub>	M <sub>vel</sub>	Range	MPF	D <sub>short</sub>	D <sub>long</sub>	CP <sub>time</sub>	CP <sub>dist</sub>		
Radebold et al. [22]	AP, ML	R	AP, ML	-	R	R	R	R	RMS <sub>displ</sub> (AP-SIL 1-2; ML-SIL 2), M <sub>vel</sub> (R-SIL 1), range (AP-SIL 1-2; ML-SIL 2), D <sub>short</sub> (R-SIL 2), D <sub>long</sub> (R-SIL 2), & CP <sub>dist</sub> (R-SIL 2) were higher in LBP than control. RMS <sub>displ</sub> , M <sub>vel</sub> , range, D <sub>short</sub> , & D <sub>long</sub> increased with higher seat instability level (task difficulty) & EC.	✓
Reeves et al. [73]	-	AP, ML	-	-	-	-	-	-	M <sub>vel</sub> (ML) was lower in the 25-50% stochastic resonance stimulation of paraspinal muscles than the 0% stochastic resonance stimulation.	✓
Navalgund [72]*	R	-	-	-	R	R	-	-	RMS <sub>displ</sub> (R) & D <sub>short</sub> (R) were higher in LBP than control during the highest seat instability level. All measures were increased with higher seat instability level.	×
van Dieen et al. [33]	AP, ML	-	-	AP, ML	AP, ML	-	AP, ML	AP, ML	No differences between current-LBP & no-LBP groups in RMS <sub>displ</sub> (AP, ML), CP <sub>time</sub> (AP, ML), & CP <sub>dist</sub> (AP, ML). MPF (AP) & D <sub>short</sub> (AP) were lower in current-LBP than no-LBP. RMS <sub>displ</sub> (AP, ML), D <sub>short</sub> (AP), & CP <sub>dist</sub> (AP, ML) were lower in recent-LBP than no-LBP.	✓
van Dieen et al. [74]†	AP, ML	R	AP, ML	AP, ML R	R	R	R	-	CoP parameters had low-moderate test-retest reliability: RMS <sub>displ</sub> (0.49-0.51), M <sub>vel</sub> (0.68), range (0.46-0.49), MPF (0.41-0.49), D <sub>short</sub> (0.52), D <sub>long</sub> (0.03), & CP <sub>time</sub> (0.32).	✓
Willigenburg et al. [31]	AP, ML	R	-	AP, ML	AP, ML	-	-	-	D <sub>short</sub> (ML) was higher in LBP than control. LBP grabbed the safety rail more often than control. RMS <sub>displ</sub> , M <sub>vel</sub> , & D <sub>short</sub> increased with EC.	✓
Larivière et al. [24]†	AP, ML R	AP, ML R	-	AP, ML R	R	R	R	-	High correlations (0.86-0.97) between outcomes measured by inertial sensors & optoelectronic system, inertial sensors & CoP, optoelectronic system & CoP. Many CoP measures had high test-retest reliability: RMS <sub>displ</sub> (0.80-0.84), M <sub>vel</sub> (0.76-0.86), MPF (0.80-0.82), D <sub>short</sub> (0.81), D <sub>long</sub> (0.74), & CP <sub>time</sub> (0.64).	✓
Larivière et al. [34]	AP, ML R	AP, ML R	-	AP, ML R	-	-	-	-	No differences between LBP & control groups. RMS <sub>displ</sub> (AP) was higher & MPF (AP, R) was lower in females than males.	✓

**Abbreviations:** LBP, low back pain; RMS<sub>displ</sub>, root mean square displacement; M<sub>vel</sub>, mean velocity; MPF, mean power frequency; D<sub>short</sub>, short-term diffusion coefficient; D<sub>long</sub>, long-term diffusion coefficient; CP<sub>time</sub>, mean time coordinate of the critical point; CP<sub>dist</sub>, mean squared distance coordinate of the critical point; IPD, individual participant data; AP, anteroposterior; ML, mediolateral; R, resultant; SIL, seat instability level (higher level = higher difficulty); EC, eyes closed; CoP, center of pressure.

\*IPD were not available as authors did not have access/authorisation to provide the IPD set.

†Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

**Table 5.** Outcome measures and main findings for studies with data from individuals with LBP (cont.)

Study	Primary measures		Secondary measures						Main findings	IPD
	RMS <sub>displ</sub>	M <sub>vel</sub>	Range	MPF	D <sub>short</sub>	D <sub>long</sub>	CP <sub>time</sub>	CP <sub>dist</sub>		
Sung et al. [19]	-	-	-	-	-	-	-	-	CoP area was higher in LBP than control. CoP area increased with EC (both groups) & greatest CoP deviation was seen in LBP during EC. No correlations between CoP area & LBP intensity, number of previous LBP episodes, duration of pain, & fear of movement.	✓
Shahvarpour et al. [75]*	-	-	-	-	-	-	-	-	No differences between LBP & control groups in seat kinematics (e.g., angular velocity/acceleration).	✓
Shahvarpour et al. [29]	AP, ML R	AP, ML R	-	AP, ML R	-	-	-	-	No differences between LBP & control groups at baseline. Moderate-high test-retest reliability for RMS <sub>displ</sub> (0.77-0.84), M <sub>vel</sub> (0.68-0.73), & MPF (0.75-0.82).	✓
Shahvarpour et al. [32]	AP, ML R	AP, ML R	-	AP, ML R	-	-	-	-	No differences between LBP & control groups. Lumbar belts increased RMS <sub>displ</sub> (R) & decreased MPF (R).	✓
Cyr et al. [30]	AP, ML	R	-	-	-	-	-	-	M <sub>vel</sub> (R) was higher in LBP than control (in EO, FB, & EC). RMS <sub>displ</sub> (AP, ML) & M <sub>vel</sub> (R) were higher in EC than EO & FB. RMS <sub>displ</sub> (ML-FB) positively correlated with pain intensity.	✓
Larivière et al. [76]*	-	AP, ML	-	AP, ML	-	-	-	-	Postural control during unstable sitting can be used as a single proxy measure for determinants (mechanisms) associated with lumbar stability.	✓
van den Hoorn et al. [35]	AP, ML	AP, ML	-	AP, ML	AP, ML	AP, ML	AP, ML	AP, ML	RMS <sub>displ</sub> (main effect), D <sub>long</sub> (AP-EC), CP <sub>time</sub> (main effect), & CP <sub>dist</sub> (main effect) were higher in LBP than control. CoP velocity measures (RMS <sub>vel</sub> , D <sub>short</sub> ) were not different between groups. No linear relations between CoP measures & LBP intensity, disability, & psychological features. Higher pain catastrophizing was associated with more safety bar touches. Higher CoP values were seen in males (RMS <sub>displ</sub> , M <sub>vel</sub> , D <sub>short</sub> , D <sub>long</sub> , CP <sub>dist</sub> ), & associated with higher BMI (RMS <sub>displ</sub> , M <sub>vel</sub> , D <sub>short</sub> , CP <sub>dist</sub> ), & more bar touches (RMS <sub>displ</sub> , M <sub>vel</sub> , MPF, D <sub>short</sub> , CP <sub>time</sub> , CP <sub>dist</sub> ).	✓

**Abbreviations:** LBP, low back pain; RMS<sub>displ</sub>, root mean square displacement; M<sub>vel</sub>, mean velocity; MPF, mean power frequency; D<sub>short</sub>, short-term diffusion coefficient; D<sub>long</sub>, long-term diffusion coefficient; CP<sub>time</sub>, mean time coordinate of the critical point; CP<sub>dist</sub>, mean squared distance coordinate of the critical point; IPD, individual participant data; AP, anteroposterior; ML, mediolateral; R, resultant; CoP, center of pressure; EC, eyes closed; EO, eyes open; FB, feedback; BMI, body mass index.

\*Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

**Table 6.** Outcome measures and main findings for studies with data from only pain-free individuals

Study	Primary measures		Secondary measures						Main findings	IPD
	RMS <sub>displ</sub>	M <sub>vel</sub>	Range	MPF	D <sub>short</sub>	D <sub>long</sub>	CP <sub>time</sub>	CP <sub>dist</sub>		
Cholewicki et al. [21]*	AP, ML	R	AP, ML	-	AP, ML R	AP, ML R	R	AP, ML R	All measures (all directions) increased when seat instability (task difficulty) increased. All measures correlated positively with age & weight. Moderate-high test-retest repeatability for RMS <sub>displ</sub> (0.79-0.90), M <sub>vel</sub> (0.91), range (0.77-0.91), D <sub>short</sub> (0.91-0.96), D <sub>long</sub> (0.56-0.57), CP <sub>time</sub> (0.93), & CP <sub>dist</sub> (0.89-0.96).	✓
Silfies et al. [77]	AP, ML	R	AP, ML	-	AP, ML R	AP, ML R	R	AP, ML R	RMS <sub>displ</sub> (AP, ML), M <sub>vel</sub> (R), range (AP, ML), D <sub>short</sub> (AP, ML, R), D <sub>long</sub> (AP, ML, R), & CP <sub>dist</sub> (AP, ML, R) increased when seat instability increased & during EC (all except D <sub>long</sub> ).	✓
van der Burg et al. [79]†	AP, ML	R	AP, ML	AP, ML	-	-	-	-	Non-relevant findings (Parkinson's disease vs control).	×
Reeves et al. [78]	-	AP, ML	-	-	-	-	-	-	M <sub>vel</sub> (main effect) was higher with EC than EO. M <sub>vel</sub> (main effect) was higher in trunk co-activation condition than control & arm co-activation conditions. M <sub>vel</sub> (main effect) was lower in belt condition than trunk co-activation condition.	✓
Cholewicki et al. [80]	-	AP, ML R	-	-	-	-	-	-	No difference between groups with & without lumbosacral orthosis in M <sub>vel</sub> (AP, ML, R).	✓
Lee and Granata [81]‡	AP, ML R	-	-	-	-	-	-	-	RMS <sub>displ</sub> (AP, ML, R) had moderate-high (0.38-0.80) intra-session test-retest reliability. Intra-session test-retest reliability improved in more difficult seat instability conditions. Trial duration to achieve process stationarity was ≈30 seconds.	×
Lee et al. [82]†	R	-	-	-	-	-	-	-	RMS <sub>displ</sub> (R) increased as exertion force increased. Flexion exertions exhibited higher RMS <sub>displ</sub> than extension exertions.	×
Slota et al. [23]	AP, ML R	-	-	-	-	-	-	-	RMS <sub>displ</sub> (AP, ML, R) increased after whole-body vibration.	✓
Hendershot & Nussbaum [83]	AP, ML	AP, ML	-	-	-	-	AP, ML	AP, ML	Non-relevant findings (lower-limb amputation vs control).	✓
Hendershot et al. [84]	AP, ML	AP, ML	-	-	AP, ML	-	-	-	All measures (AP, ML) increased following flexion exposure & increased further with increasing flexion exposures (e.g., longer flexion duration & presence of external load).	✓

**Abbreviations:** RMS<sub>displ</sub>, root mean square displacement; M<sub>vel</sub>, mean velocity; MPF, mean power frequency; D<sub>short</sub>, short-term diffusion coefficient; D<sub>long</sub>, long-term diffusion coefficient; CP<sub>time</sub>, mean time coordinate of the critical point; CP<sub>dist</sub>, mean squared distance coordinate of the critical point; IPD, individual participant data; AP, anteroposterior; ML, mediolateral; R, resultant; EC, eyes closed; EO, eyes open.

\*Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

†IPD were not available as authors did not have access/authorisation to provide the IPD set.

‡IPD were not available as authors did not respond to IPD request.

**Table 6.** Outcome measures and main findings for studies with data from only pain-free individuals (cont.)

Study	Primary measures		Secondary measures						Main findings	IPD
	RMS <sub>displ</sub>	M <sub>vel</sub>	Range	MPF	D <sub>short</sub>	D <sub>long</sub>	CP <sub>time</sub>	CP <sub>dist</sub>		
Barbado et al. [86]*	-	-	-	-	-	-	-	-	Lack of significant correlations between trunk postural control & trunk strength/endurance.	✓
Barbado et al. [85]	-	-	-	-	-	-	-	-	Specialization in sports with large balance demands had a significant effect on trunk stability (e.g., competitive kayakers had better trunk postural control than recreational athletes).	✓
Beaudette et al. [87]	AP, ML	AP, ML	AP, ML	-	-	-	-	-	Non-relevant findings (treatment vs placebo).	✓
Ruggiero et al. [88]	AP, ML	AP, ML	-	-	-	-	-	-	RMS <sub>displ</sub> (ML) & M <sub>vel</sub> (AP) were lower when wearing the Kinesio tape compared to pre-tape time point. RMS <sub>displ</sub> (AP, ML) & M <sub>vel</sub> (ML, ML) were lower after the tape was removed compared to the pre-tape time point.	✓
Barbado et al. [28]	-	AP, ML	-	-	-	-	-	-	M <sub>vel</sub> (AP, ML) showed a high (0.72-0.85) test-retest reliability. CoP analysis alone cannot adequately discern different postural strategies, as changes in balance performance (e.g., standard deviation of CoP) may not be accompanied by similar spine kinematic changes.	✓
Barbado et al. [89]*	-	-	-	-	-	-	-	-	Primary & secondary outcome measures were not reported.	✓
Glofcheskie & Brown [90]	AP, ML	-	AP, ML	-	-	-	-	-	RMS <sub>displ</sub> (AP, ML) & range (AP, ML) were lower in golfers & runners than controls. Both athlete groups demonstrated greater trunk neuromuscular control (e.g., faster trunk muscle activation onsets) & better proprioceptive performance than control group.	✓
Acasio et al. [91]	AP, ML	R	-	-	-	-	-	-	RMS <sub>displ</sub> (AP, ML) & M <sub>vel</sub> (R) increased with higher seat instability level.	✓
Williams et al. [92]	AP, ML	AP, ML	-	-	AP, ML	-	-	-	Residuals between measurements of motion capture & inertial measurement unit were small (AP, ML). Higher RMS <sub>displ</sub> , M <sub>vel</sub> , & D <sub>short</sub> were correlated (AP, ML) with greater height & weight. RMS <sub>displ</sub> , M <sub>vel</sub> , & D <sub>short</sub> were higher with less stable seat (AP, ML) & EC (AP, ML). Vibrotactile feedback (EO) decreased RMS <sub>displ</sub> (AP), M <sub>vel</sub> (AP), & D <sub>short</sub> (ML).	✓

**Abbreviations:** RMS<sub>displ</sub>, root mean square displacement; M<sub>vel</sub>, mean velocity; MPF, mean power frequency; D<sub>short</sub>, short-term diffusion coefficient; D<sub>long</sub>, long-term diffusion coefficient; CP<sub>time</sub>, mean time coordinate of the critical point; CP<sub>dist</sub>, mean squared distance coordinate of the critical point; IPD, individual participant data; AP, anteroposterior; ML, mediolateral; R, resultant; CoP, center of pressure; EC, eyes closed; EO, eyes open.

\*Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

**Table 6.** Outcome measures and main findings for studies with data from only pain-free individuals (cont.)

Study	Primary measures		Secondary measures						Main findings	IPD
	RMS <sub>displ</sub>	M <sub>vel</sub>	Range	MPF	D <sub>short</sub>	D <sub>long</sub>	CP <sub>time</sub>	CP <sub>dist</sub>		
Barbado et al. [93]†	-	-	-	-	-	-	-	-	Primary & secondary outcome measures were not reported.	X
Roberts & Vette [25]	AP, ML	AP, ML	AP, ML	-	-	-	-	-	For all measures (AP, ML), seat movements were larger than pelvis & trunk movements. Trunk remained relatively stationary & stabilized by regulating seat (wobble board) movements.	✓
Roberts et al. [27]*	-	-	-	-	-	-	-	-	Wobble board-human system was stabilized through direction-specific activation of trunk & upper leg muscles that preceded seat (wobble board) displacement.	✓
Acasio et al. [94]*	AP, ML	R	-	-	-	-	-	-	Trunk-pelvic anti-phase movement increased (AP, ML) & trunk-pelvic in-phase movement decreased (AP, ML) when seat instability increased. Low (AP, ML) to moderate (AP) correlations between: CoP & trunk-pelvic anti-phase movement (+ correlation); CoP & trunk-pelvic in-phase movement (- correlation). Trunk coordination measures during unstable sitting directly quantified underlying movement strategies more than CoP measures.	✓
Alshehri et al. [26]*	-	-	-	-	-	-	-	-	Seat amplitude spectrum (movement) was higher (AP, ML) than hip/spine amplitude spectrums. In AP, amplitude spectrums of hip & lumbar segments were higher than other segments (lower lumbar, upper lumbar, thoracic), their coherence with the seat was high, & their motion was generally opposite in direction to the seat. In ML, amplitude spectrums of lower lumbar & lumbar segments, but not the hip, were higher than other segments (hip, upper lumbar, thoracic), their coherence with the seat was high, & their motion was generally opposite in direction to the seat. Although EC & higher BMI increased seat movements, this was associated with enhanced coordination (higher coherence) between hip/spine segments & the seat.	✓
de Oliveira et al. [95]‡	-	AP, ML	-	-	-	-	-	-	Non-relevant findings (exercise vs control).	X

**Abbreviations:** RMS<sub>displ</sub>, root mean square displacement; M<sub>vel</sub>, mean velocity; MPF, mean power frequency; D<sub>short</sub>, short-term diffusion coefficient; D<sub>long</sub>, long-term diffusion coefficient; CP<sub>time</sub>, mean time coordinate of the critical point; CP<sub>dist</sub>, mean squared distance coordinate of the critical point; IPD, individual participant data; AP, anteroposterior; ML, mediolateral; R, resultant; CoP, center of pressure; EC, eyes closed; BMI, body mass index.

\*Studies that were only included in the descriptive analysis but excluded from quantitative/IPD analysis as these studies referred to an already identified IPD set.

†IPD were not available as authors did not have access/authorisation to provide the IPD set.

‡IPD were not available as authors did not respond to IPD request.

### 3.3. Quantitative analysis

#### 3.3.1. Included studies and participants

Twenty-six studies (1,097 participants) were included for the quantitative analysis. Twenty-four studies (1,050 participants) provided IPD sets [19, 22, 23, 25, 28-35, 73, 77, 78, 80, 83-85, 87, 88, 90-92] and were included for the IPD analysis. Nine studies (730 participants) were used for the IPD meta-analysis [19, 22, 29-35] to compare between individuals with (361 participants) and without (369 participants) LBP, and to test the effects of participant characteristics and vision on trunk postural control in relation to the difference between groups. Ten studies (379 participants) were used for the IPD meta-regression [19, 22, 29-35, 73] to test the effects of LBP clinical features on trunk postural control. The results of 17 studies that tested either only LBP (one study with IPD; 18 participants) or pain-free data (14 studies with IPD [23, 25, 28, 77, 78, 80, 83-85, 87, 88, 90-92]; 302 participants – two studies with aggregate data [79, 95]; 47 participants) were compared (visually using the mean plots) with the results of the IPD meta-analysis (individuals with and without LBP).

IPD for some participants (102 participants) were excluded from the analysis because of missing demographic information (23 participants) [19, 33, 80, 85, 90], or because they included participants who had no current pain (79 participants) but had a LBP history within the last 12 months [33] (**Table S17** provides details of the excluded participants). For studies with multiple levels of seat difficulty, the level of seat difficulty was selected that matched closest with the seat build characteristics of other studies that included a single seat difficulty level (**Table S18** provides details of the excluded seat difficulty levels).

Studies ( $n=10/40$ ) that referred to an already identified IPD set were excluded [21, 24, 26, 27, 74-76, 86, 89, 94]. Data for four studies that were considered for the quantitative analysis (either as IPD or aggregate data) were excluded from quantitative analysis because they did not report the required values (e.g., means) of any of the identified primary and

secondary outcome measures [81, 93], or they only reported analysis of measures in the resultant direction [72, 82].

### 3.3.2. IPD meta-analysis: between-group differences

IPD meta-analyses revealed significant differences between groups (all  $P < 0.05$ ). For primary outcome measures (**Figure 3**), individuals with LBP exhibited a higher  $RMS_{displ}$  than those without LBP during eyes closed in both the anteroposterior (SMD = 0.39,  $P < 0.001$ ) and mediolateral (SMD = 0.37,  $P < 0.01$ ) directions, and also during eyes open in the mediolateral direction (SMD = 0.28,  $P < 0.05$ ).  $M_{vel}$  did not differ between individuals with and without LBP in any condition. For secondary outcome measures (see **Figures S1-3** for forest plots), individuals with LBP exhibited a higher range than those without LBP during both visual conditions and in both directions (SMD = 0.28-0.38, all  $P < 0.05$ ; **Figure S1**), lower MPF during eyes open in the anteroposterior direction (SMD = -0.23,  $P < 0.05$ ; **Figure S1**), and higher  $D_{long}$  during eyes closed in the anteroposterior direction (SMD = 0.44,  $P < 0.01$ ; **Figure S2**).

Figure 3 here

**Figure 3.** A two-stage individual participant data (IPD) meta-analysis, comparing individuals with and without low back pain (LBP) on primary outcome measures of trunk postural control. (A) root mean square displacement ( $RMS_{displ}$ ) and (B) mean velocity ( $M_{vel}$ ). The results are presented as standardised mean differences (SMDs) with 95% confidence intervals (95% CIs). Significant overall effect sizes with their respective P-values are highlighted in bold font. Sizing of squares reflects the weight (WT) of the contribution of a study on the pooled meta-analysis (weighted average) in percentage.  $I^2$  reflects the percentage of total variability due to heterogeneity between studies. 95% prediction interval (95% PI) reflects how much the effect size varies across studies.

### 3.3.3. Comparison between the outcomes of single-group studies with the outcome of two-group studies using IPD or aggregate data

Mean plots of the outcomes of studies with data from only LBP or pain-free individuals (using either IPD or aggregate data) are presented with mean plots of the outcomes of studies included in the IPD meta-analysis (individuals with and without LBP). For primary outcome measures, the visual inspection of mean plots of  $RMS_{displ}$  (**Figure 4**) and  $M_{vel}$  (**Figure 5**) revealed substantial variation in outcomes between studies renders comparisons between groups unclear for the eyes open condition in both directions. Few studies with data from only pain-free individuals were available for  $RMS_{displ}$  ( $n=3$ ) [25, 77, 92] and  $M_{vel}$  ( $n=4$ ) [25, 73, 78, 92] during eyes closed, and the results of outcomes differed considerably from studies with data including both individuals with and without LBP. One study with data from individual with only LBP [73] showed that  $M_{vel}$  was higher during eyes closed compared to most studies with data either from only pain-free individuals or individuals with versus without LBP in both directions (**Figure 5**). Similar observations can be made for secondary outcome measures (range, MPF,  $D_{short}$ ,  $D_{long}$ ,  $CP_{time}$ , and  $CP_{dist}$ ), for which there were differences in outcomes when comparing studies with data from only pain-free individuals and studies with data from individuals with versus without LBP (see **Figures S4-9** for mean plots).

There was only one study [72] that included individuals with and without LBP for which IPD could not be obtained. That study reported that  $RMS_{displ}$  and  $D_{short}$  were higher among individuals with than without LBP in the resultant direction during the most difficult level of seat instability (50%  $R_{spring}$ ), which is similar to the results of the IPD meta-analysis. There were five studies [79, 81, 82, 93, 95] that included data from only pain-free individuals where IPD could not be obtained, but aggregate data were obtained for  $RMS_{displ}$  [79],  $M_{vel}$  [95], and range [79] from two studies [79, 95] (**Figures 4-5** and **S4**). Neither IPD nor aggregate data could be obtained for the other studies [81, 82, 93], as two of these studies [81, 93] investigated

different outcome measures, and one study [82] reported outcome measures only in the resultant direction. As such, it was it challenging to compare the results of these studies with studies included in the IPD meta-analysis.

After standardising the statistical analysis and including covariates in the models for all studies with available IPD, there were significant between-group differences for some outcome measures ( $RMS_{displ}$ , range, and  $D_{long}$  were higher among individuals with than without LBP) in two studies [31, 34] that reported no differences between groups for the same outcome measures in the original published versions.

Figure 4 here

**Figure 4.** A quantitative (non-pooled) analysis of all studies on the root mean square displacement ( $RMS_{displ}$ ) of CoP/seat angle using IPD or aggregate data (if IPD were not available). Mean plots of the results from studies that were included in the individual participant data (IPD) meta-analysis (individuals with versus without low back pain [LBP]) are presented with mean plots of the results from studies that tested only pain-free individuals [CTRL]. The results are presented as means with standard errors. For studies with two groups, significant differences between individuals with and without LBP are shown with square bracket. No bars in some studies = no data available.

Figure 5 here

**Figure 5.** A quantitative (non-pooled) analysis of all studies on the mean velocity ( $M_{vel}$ ) of CoP/seat angle using IPD or aggregate data (if IPD were not available). Mean plots of the results from studies that were included in the individual participant data (IPD) meta-analysis (individuals with versus without low back pain [LBP]) are presented with mean plots of the results from studies that tested either only LBP or pain-free individuals [CTRL]. The results are presented as means with standard errors. For studies with two groups, significant differences between individuals with and without LBP are shown with square bracket. No bars in some studies = no data available.

### 3.3.4. IPD meta-analysis: effects of participant characteristics

IPD meta-analyses revealed significant interaction effects with participant characteristics on some outcome measures (see **Figures S10-17** for forest plots). For the effects of age, the difference between groups was greater (worse effect for LBP group versus control group) in those with older age than those with younger age for  $D_{\text{short}}$  (eyes open; both directions; all  $P < 0.05$ ; **Figure S14**) and  $CP_{\text{dist}}$  (eyes open; both directions; all  $P < 0.05$ ; **Figure S16**). For the effects of BMI, the difference between groups was greater in those with higher BMI than those with lower BMI for  $CP_{\text{dist}}$  (eyes closed; mediolateral direction;  $P < 0.01$ ; **Figure S16**) and  $CP_{\text{time}}$  (eyes open; mediolateral direction;  $P < 0.05$ ; **Figure S17**). In contrast, for  $M_{\text{vel}}$ , the difference between groups was greater in those with lower BMI than those with higher BMI (eyes closed; both directions; all  $P < 0.05$ ; **Figure S11**).

### 3.3.5. IPD meta-analysis: effects of vision

IPD meta-analyses also revealed significant interaction effects with vision on some outcome measures. For primary outcome measures (**Figure 6**), the difference between groups was greater with eyes closed than eyes open for  $RMS_{\text{displ}}$  in both the anteroposterior and mediolateral directions (all  $P < 0.05$ ). For secondary outcome measures (see **Figures S18-20** for forest plots), the difference between groups was also greater with eyes closed than eyes open for  $D_{\text{short}}$  and  $D_{\text{long}}$  in the anteroposterior direction (all  $P < 0.05$ ; **Figure S19**).

### 3.3.6. IPD meta-regression: effects of LBP clinical features

IPD meta-regressions revealed no significant associations (see **Tables S19-20**) between LBP clinical features (VAS/NPRS, RMDQ, PCS, FABQ-PA, FABQ-W and FABQ) and either primary ( $RMS_{\text{displ}}$  and  $M_{\text{vel}}$ ) or secondary (range and MPF) outcome measures. Results of individual analysis for each study using IPD are presented in **Supplementary Tables S21-30**.

Figure 6 here

**Figure 6.** A two-stage individual participant data (IPD) meta-analysis of interactions between visual condition and the difference between groups on primary outcome measures of trunk postural control. (A) root mean square displacement ( $RMS_{displ}$ ) and (B) mean velocity ( $M_{vel}$ ). The results are presented as interaction (interact.) effect coefficients with 95% confidence intervals (95% CIs). Significant overall interact. effects with their respective P-values are highlighted in bold font. Greater effect in either directions indicates worse effect on trunk postural control for individuals with versus without low back pain. Sizing of circles reflects the weight (WT) of the contribution of a study on the pooled meta-analysis (weighted average) in percentage.  $I^2$  reflects the percentage of total variability due to heterogeneity between studies. 95% prediction interval (95% PI) reflects how much the effect size varies across studies.

## 4. Discussion

This systematic review with IPD meta-analyses had several major findings. First, IPD meta-analyses indicate that trunk postural control differs between individuals with and without LBP. A pooling of results from multiple studies showed that  $RMS_{displ}$ , range and  $D_{long}$  were higher, and MPF was lower, among individuals with LBP, which can be concluded as indicating poorer postural control of the trunk. Second, IPD meta-analyses revealed that trunk postural control deteriorates more from removal of vision among individuals with than without LBP. Third, IPD meta-analyses revealed that older age and higher BMI have greater adverse impacts on trunk postural control among individuals with than without LBP. Fourth, IPD meta-regressions indicated that the limited clinical features that we could evaluate for the LBP group are not associated with poorer trunk postural control. Fifth, the visual inspection of mean plots indicated that the comparison between groups using the data from single-group studies (only LBP or pain-free data) with the data from two-group studies (LBP and pain-free data) was challenging, due to substantial variation in outcomes between studies, which suggests that the comparison between groups is only compelling when both groups are tested identically in the same study.

### 4.1. Experimental methods

Differences in experimental methods between studies comparing individuals with and without LBP that were included in the IPD meta-analysis can explain some of the inconsistency in study outcomes [19, 22, 29-35]. Important variation between studies includes differences in the seat apparatus – greater differences between groups were observed in studies that used the hemisphere-based seat [19, 22, 30, 31, 35] than the springs-based seat [29, 32, 34]. This is likely explained by differences in seat dynamics imposed by hemisphere-based seats (more challenging) versus springs-based seats (less challenging) when balancing. A lesser task difficulty might limit the potential to identify differences between groups [22, 72, 96]. The

research group using the unstable springs-based sitting paradigm chose to use a not too difficult task (60%  $R_{\text{spring}}$ ) to help participants maintain balance long enough (60 s) to obtain reliable summary measures of trunk postural control [24]. It might be possible to slightly increase the difficulty of the task (e.g., from 60% to 50%), without affecting reliability too much, to increase the discriminative power of this test. Another possibility is to find the threshold of stability by finding the maximum task difficulty (e.g., ... 50, 55, 60, 65, 70%  $R_{\text{spring}}$ , ...) in which stability can be maintained over a given time [97]. Removal of vision (eyes open versus eyes closed) also increases the challenge for trunk postural control, though this effect was not investigated in many studies [29, 32-34]. One study described the LBP group in limited detail (e.g., no information about pain intensity, disability, or other clinical features) [33]. These limitations reduced the total sample size that could be included in the IPD meta-analysis/meta-regression. As suggested by the analysis of covariates (see below), differences in participant characteristics might also explain some of the conflicting results between studies.

There are also several differences in experimental methods for studies with data from only LBP or pain-free individuals (single-group studies) that might explain the high differences in mean plots of the same outcome, including sample size, participant characteristics (e.g., sex, or anthropometrics), experimental setup (e.g., seat apparatus) and protocol (e.g., trial duration), and the data pre-processing (e.g., filters, data sampling for data reduction, etc.). These differences are greatly impacted on the comparison between groups, when we compared (visually using the mean plots) the outcomes of studies with data from only LBP or pain-free individuals with the outcomes of studies included in the IPD meta-analysis (individuals with and without LBP). This suggests that between-group comparison demands measurement within the same study with the same experimental parameters.

## 4.2. Differences in trunk postural control between individuals with and without LBP

IPD meta-analyses revealed that individuals with LBP had higher  $RMS_{displ}$ , range, and  $D_{long}$  than those without LBP, suggesting greater CoP/seat movements and less corrective long-term behaviour [98-100]. Further, IPD meta-analyses indicated that some individuals with LBP had lower MPF, which could be explained by greater trunk stiffness [33]. Taken together, these findings suggest the presence of compromised trunk postural control among individuals with LBP, and which might be explained by multiple plausible mechanisms. For instance, less proprioceptive sensitivity would likely reduce the ability to coordinate the muscle responses (e.g., delayed trunk muscle responses) required to maintain balance in the unstable sitting task [22, 101], affecting the accuracy and precision of trunk movement [102], and also affecting the detection of movement errors to execute required postural adjustments [19, 103]. Together, these features would tend to destabilize trunk postural control as reflected by higher  $RMS_{displ}$ , range, and  $D_{long}$ . Alternatively, some individuals with LBP might adopt a distinct muscle activation strategy to control balance, such as increased muscle co-activation [78, 104, 105], either to reduce reliance on proprioception or to protect the spine from threat. Trunk stiffening would result in moving the trunk more as a whole and increase the moments of inertia on an unstable seat [79], resulting in lower sway frequency, and thus greater movements and stochastic activity of the CoP/seat. Decreased sense of lumbar proprioception [106-109], increased trunk stiffness [105, 110-112], and delayed onset or offset of trunk muscles activity [22, 42, 105, 113-115] have been widely documented in the LBP population. Regardless of the origin, impaired trunk postural control could be problematic for individuals with LBP and might expose them to the risk of sustaining or aggravating a back injury if maintained. For instance, A delay in response time would increase the vulnerability of spine to injury under sudden loading conditions [116], such as increasing tissue strain (further displacement) and stress (greater muscle force) of the spine [101]. Accordingly, an altered muscle recruitment

pattern would be used as a compensation strategy [105]. However, adopting a co-contraction strategy also would increase spinal loads [117, 118].

#### **4.3. Effects of vision**

Corrective adjustments for postural control require contributions of the visual, vestibular, and proprioceptive (sense of positioning and movements) senses [119-121]. The demand for proprioceptive feedback (e.g., sensory receptors in spinal muscles, joints, and other tissues [73, 122]) is even greater in the absence of visual feedback. In line with this, IPD meta-analyses revealed that  $RMS_{displ}$ ,  $D_{short}$ , and  $D_{long}$  were each increased by removal of vision, but this effect was greater for individuals with than without LBP, indicating greater CoP/seat movements and less tightly regulated behaviour [98-100]. This implies that, without visual feedback, the quality of trunk postural control is reduced to a greater extent with LBP, as it potentially cannot be adequately compensated for by other alternative sensory sources. Control of CoP/seat diffusion rate relies on adequate and timely sensory information [123]. Moving the CoP/seat further away from a relative equilibrium point over shorter periods of time in the LBP group might be a strategy to overcome higher sensory thresholds caused by LBP injury, and thus would enhance feedback [22, 98], or a strategy to increase muscle stiffness to promote rapid postural corrections [77, 78, 124]. Further, fewer corrective adjustments for CoP/seat movements over long-term intervals of time observed in the LBP group may due to lower proprioceptive sensitivity [22, 35, 101] or deficits in sensory reweighting [35, 77]. This conjecture is consistent with previous data that show individuals with LBP could not modulate and reweight their sensory information to other alternative sources (most likely proprioceptive feedback) when visual feedback was unavailable [22, 35].

#### **4.4. Effects of participant characteristics**

IPD meta-analyses revealed that older age and higher BMI more negatively impacted trunk postural control for those with than without LBP. The findings of higher  $D_{short}$  and longer

CP<sub>dist</sub> and CP<sub>time</sub> indicate that the CoP/seat moved further within the short-term region, with a later critical point (the point at which corrective responses take place to slow CoP/seat diffusion rate and limit further displacement of CoP/seat [98, 99]) among individuals with LBP who were older or had higher BMI. These findings might be explained by age-related changes in muscle mass [125, 126], proprioception [127], muscle response [103], or sensory thresholds [103]. Higher body mass that is placed above the radius of a hemisphere creates a mechanically more challenging system to balance [21]. Higher body mass is also likely to impose biomechanical constraints that require greater muscular activity and torque [128] and interfere with the coordination of joints and muscles due to changes in anthropometrics [129]. The impacts of these factors might be accentuated for the LBP group, who already have impaired balance. Although anthropometric characteristics (height and weight) may influence measures of trunk postural control during unstable sitting [21, 24], IPD meta-analyses confirmed differences between groups while adjusting for these confounding variables.

#### **4.5. Effects of LBP clinical features**

Although we had limited data available, IPD meta-regressions indicated that LBP intensity, disability, pain catastrophizing, and fear of movement were not associated with poorer trunk postural control among individuals with LBP. It should be noted, though, that individuals with LBP in most studies had low scores on disability, catastrophizing, and fear avoidance. It is unlikely that our findings are explained by insufficient time for these features to develop [35, 130], since several studies included participants who suffered from LBP for long periods [22, 29-32, 34, 73]. Greater detail and consistent collection of clinical features would have made findings more robust.

#### **4.6. Limitations**

This review has several limitations that require consideration. First, IPD could not be obtained for six studies, although the impact of this will be limited as only one of those studies

included data from individuals with versus without LBP. Second, overall SMD effect sizes for between-group differences were small or close to medium (maybe due to the small number of included studies), and 95% PIs were wider in some IPD meta-analyses (likely due to lack of precision). Third, the effect of LBP duration (e.g., acute, sub-acute, chronic) on trunk postural control could not be evaluated in the IPD meta-analysis because of between-study variation in how these features were defined (or not at all), and an overall very few studies included individuals with acute LBP. Fourth, the effect of task difficulty (based on seat apparatus and its build characteristics) on trunk postural control between groups could not be examined because of the limited number of studies that used springs-base seats. Fifth, we limited our review to include only those studies that were published in English.

## **5. Conclusions**

This IPD analysis provides robust evidence that trunk postural control is compromised among individuals with LBP. The findings are likely explained by delayed or less accurate corrective responses, for which there are several plausible mechanisms – impaired proprioception, altered sensory processing/reweighting, or increased muscle co-activation. We cannot discriminate whether changes in trunk postural control are a cause or consequence of LBP. Our investigation highlights the value of IPD analysis to draw robust conclusions from biomechanical data, but also brings to light the affect variation in available (limited) data has on addressing important questions related to the association with LBP clinical and related features.

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730    **Competing Interests**

731           The authors have declared that no competing interests exist.

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