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Title page

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The association between pain-related psychological variables and postural control in low back pain: a systematic review and meta-analysis

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1 ABSTRACT

Background: Alterations in postural control have been found in individuals with low back pain (LBP), particularly during challenging postural tasks. Moreover, higher levels of negative pain-related psychological variables are associated with increased trunk muscle activity, reduced spinal movement, and worse maximal physical performance in individuals with LBP.

Research question: Are pain-related psychological variables associated with postural control during static bipedal standing tasks in individuals with LBP?

Methods: A systematic review and meta-analysis were conducted. Pubmed, Web of Science, and PsycINFO were searched until March 2023. Studies were included if they evaluated postural control during static bipedal standing in individuals with LBP by measuring center of pressure (CoP) variables and reported at least one pain-related psychological variable. Correlation coefficients between pain-related psychological variables and CoP variables were extracted. Study quality was assessed with the "Quality In Prognosis Studies" tool (QUIPS). Random-effect models were used to calculate pooled correlation coefficients for different postural tasks. Sub-analyses were performed for positional or dynamic CoP variables. Certainty of evidence was assessed with an adjusted "Grading of Recommendations, Assessment, Development, and Evaluations" tool (GRADE). The protocol was registered on PROSPERO (CRD42021241739).

Results: Sixteen studies (n= 723 participants) were included. Pain-related fear (16 studies) and pain catastrophizing (three studies) were the only reported pain-related psychological variables. Both pain-related fear ($-0.04 < \text{pooled } r < 0.14$) and pain catastrophizing ($0.28 < \text{pooled } r < 0.29$) were weakly associated with CoP variables during different postural tasks. For all associations, the certainty of evidence was very low.

Significance: Pain-related fear and pain catastrophizing are only weakly associated with postural control during static bipedal standing in individuals with LBP, regardless of postural task difficulty. Certainty of evidence is very low thus it is conceivable that future studies accounting for current study limitations might reveal different findings.

Keywords: low back pain, postural control, center of pressure, pain-related fear, pain catastrophizing

2 INTRODUCTION

Low back pain (LBP) is the leading cause of disability worldwide [1]. It is a complex condition with multiple contributors, such as biological, psychological, and social factors [2]. One of the biological factors associated with LBP is an altered postural control [3]. Postural control is the ability to achieve, maintain, or restore a state of balance during any activity or posture [4]. To maintain this state of balance (i.e., postural stability), the central nervous system needs to accurately process sensory inputs from visual, vestibular, and proprioceptive systems in order to produce adequate motor output [5].

A common method to evaluate postural control is by measuring the motion of the body's center of pressure (CoP) in upright standing [6]. In general, it is stated that an increase in the amplitude and velocity of CoP motion reflects impaired postural control [7]. Numerous studies examined CoP motion in patients with LBP. However, the findings were inconsistent. Although the majority of the studies concluded that patients with LBP exhibited greater CoP motion compared to healthy controls [3], other studies reported no differences [8], inconsistent results [9], or less CoP motion [10]. Differences in postural task difficulty between studies and the potential influence of psychological variables may explain the heterogeneity of the results [3, 11].

Increasing postural task difficulty by manipulating visual or proprioceptive input may affect CoP motion, as it forces individuals to reweight sensory inputs [12]. For example, during standing with eyes closed, individuals must upweight proprioceptive and vestibular inputs to maintain postural stability [13]. Compared to pain-free individuals, patients with LBP are less able to compensate for increased postural task difficulty by sensory reweighting [14], leading to decreased postural variability [15]. Consequently, they exhibit greater CoP motion when standing on an unstable support surface [15], when standing with vision occluded [16], or while being exposed to vibrational stimuli on the calf muscles [14] compared to healthy controls. Accordingly, recent systematic reviews reported a tendency of more notable differences in CoP motion between individuals with and without LBP when postural task difficulty increased [3, 11].

In addition to task difficulty, pain-related psychological variables may also account for some of the heterogeneity observed in the CoP motion of patients with LBP. Pain-related psychological variables describe the individual's emotions and cognitions regarding their pain. They can be classified into either positive (e.g., pain-related self-efficacy) or negative (e.g., pain-related fear, pain catastrophizing) variables according to the implications of the pain-related emotions and cognitions [17]. Research shows that negative pain-related psychological variables are related to alterations in motor behavior, more specifically to the use of protective postural strategies, in individuals with LBP [18]. The fear-avoidance model offers a plausible framework for these findings. It states that the presence of maladaptive pain-related cognitions (e.g. pain catastrophizing) may induce pain-related fear resulting in avoidance and protective behaviors (e.g., tight control strategies) [19]. This framework is supported by recent meta-analyses indicating that higher levels of negative pain-related psychological variables in individuals with LBP are (weakly) associated with increased trunk muscle activity, reduced spinal movement, and worse maximal physical performance [20-22]. As such, it is likely that negative pain-related psychological variables could also be related to reduced CoP motion.

One recent systematic review and meta-analysis of Shanbehzadeh et al. (2022) on the association between pain-related psychological variables and CoP motion in individuals with LBP revealed non-significant correlations for the majority of the studies (75%) [22]. However, they reported a large methodological heterogeneity between studies in terms of testing conditions and CoP variables. To elaborate on these findings, the current review aimed to elucidate the association between pain-related psychological variables and postural control by focusing on CoP variables during static bipedal tasks only. To further reduce the potential impact of methodological heterogeneity between studies, subgroup-analyses based on task conditions were performed. This is particularly relevant considering the influence of postural task difficulty on CoP motion [23].

We performed a systematic review and meta-analysis of the current evidence on associations between pain-related psychological variables and CoP motion in patients with LBP in different task conditions

during static bipedal standing. We hypothesized that higher levels of negative pain-related psychological variables in patients with LBP correlate with less CoP motion, as they might result in the use of protective, “stiffening” postural strategies. The opposite was hypothesized for higher levels of positive pain-related psychological variables, as the absence of the protective aspect is postulated to result in less stiffening behaviors. Moreover, we hypothesized that correlations would be particularly apparent during more demanding postural tasks, given the decreased postural variability in individuals with LBP.

3 METHODS

This review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [24]. The study protocol was registered on the International Prospective Register of Systematic Reviews (PROSPERO: CRD42021241739).

3.1 Search strategy

Pubmed, Web of Science, and PsycInfo were searched from inception to March 2023. Eligible literature was obtained by combining two clusters of keywords. The first cluster contained terms related to LBP, the second comprised terms related to postural control. Specific search strategies for each database are reported in Appendix 1.

1. *Cluster 1:* 'low back pain', 'spinal pain', 'back pain', 'lumbago', 'LBP', 'CLBP', 'back aches', 'lumbar pain', 'lumbopelvic pain'

   AND

2. *Cluster 2:* 'postural balance', 'postural control', 'postural sway', 'sway', 'postural stability', 'center of pressure', 'stabilometry'

Although studies often measure both CoP variables and pain-related psychological variables, correlations between these variables are not always reported. Therefore, the search strategy did not contain terms regarding pain-related psychological variables. As such, unreported useful data could still be obtained by contacting the authors, and loss of potentially relevant data could be avoided. In addition to searching the electronic databases, registers and the reference lists of relevant and included studies were screened as well.

3.2 Study selection

Studies were considered eligible if they met the criteria reported in Table 1.

***** INSERT TABLE 1*****

The studies were uploaded in Rayyan (Cambridge, MA, USA) and duplicates were removed [25]. Primarily, studies were screened by evaluating title and abstract against the eligibility criteria. Then, a second screening based on the full texts of the potentially eligible studies was conducted. Studies were screened by three independent reviewers (C.A., S.V.W., and S.S.) and discrepancies between them were resolved by a fourth reviewer (L.J.).

3.3 Quality assessment

The risk of bias assessment of the included studies was conducted by three independent reviewers (S.V.W., C.A., and S.S.) by using an adapted version of the 'Quality in Prognosis Studies' tool (QUIPS) [26], as recommended by the Cochrane Handbook for Systematic Reviews for prognostic studies. The adaptations were used because the QUIPS tool was originally developed for prognostic instead of cross-sectional studies. Hence, some items (e.g. about drop-outs) were not applicable and could therefore not be scored. The QUIPS-tool assesses risk of bias in six domains: study participation, study attrition, prognostic factor measurement, outcome measurement, confounding factors, and statistical analysis and reporting. All domains were rated as low, moderate, or high risk of bias based on predetermined scoring criteria. The scoring criteria for each domain were specified based on recent systematic reviews assessing the association between pain-related psychological variables and protective movement behavior in individuals with LBP [20, 21]. The studies' QUIPS assessment should be interpreted as the risk of bias in context of inclusion in this review, rather than the risk of bias within the study itself [20]. For example, correlation coefficients obtained through author contact were rated with high risk of bias because these data were not peer-reviewed [27]. The adapted QUIPS assessment form and predetermined scoring criteria are available in Appendix 2.

3.4 Data extraction

Different clusters were made regarding CoP variables (i.e., linear, non-linear), and postural task difficulty (i.e., number of postural manipulations) to reduce heterogeneity between studies. CoP variables were categorized as linear variables if they represented the magnitude or variability of CoP motion, and as non-linear variables if they reflected the dynamic time-dependent structure of CoP motion. Linear CoP variables were further divided into positional, dynamic, and frequency variables [28]. Considering the influence of postural task difficulty on CoP variables and the extensive number of combinations of postural manipulations in the included studies, postural task difficulty was quantified as the number of postural manipulations applied during the postural task (e.g., exclusion of vision, standing on an unstable surface, applying muscle vibration), with standing on a stable support surface with eyes open as the reference condition (i.e., score= 0). For example, when CoP motion was assessed during standing on an unstable support surface with eyes open, a score of 1 was given. After data extraction, pain-related psychological variables could be subdivided into pain-related fear and pain catastrophizing. Pain-related fear reflects the individual's fear, anxiety, and avoidance regarding pain or movement [29]. Pain catastrophizing is conceptualized as a negative cognitive–affective response to anticipated or actual pain and is characterized by rumination, magnification, and helplessness [30].

One author (S.V.W.) extracted data from the included studies by using a data extraction table. This was verified by a second author (S.S.). Data were extracted with regards to (1) study details: first author and publication year; (2) sample characteristics: LBP characteristics (chronic, recurrent, non-specific), age, sex (% female), body mass index, pain intensity levels, disability levels, pain-related psychological levels; (3) postural task characteristics: task description, number of postural manipulations, stance width of feet on force plate; (4) pain-related psychological variables: pain-related psychological variable (pain-related fear, pain catastrophizing), questionnaire for measuring pain-related psychological variable, whether the pain-related psychological variable was measured before or after the CoP measurement (temporal precedence); (5) CoP variables: category (linear with subcategories positional, dynamic, frequency, or non-linear), specific CoP variable; (6) results: significant correlation

coefficients between pain-related psychological variables and CoP variables (if reported), and (8) whether correlation coefficients were extracted from the study, received through author contact, or calculated from raw data received through author contact.

3.5 Data syntheses and meta-analyses

We performed separate meta-analyses for each postural task (e.g., standing on a stable support surface with eyes open) within each psychological variable (pain-related fear, pain catastrophizing). For the linear CoP variables, further sub-analyses were performed for the positional and dynamic linear CoP variables. At least three studies had to be available to proceed with a meta-analysis.

The meta-analyses were performed based on correlation coefficients, without making a distinction between Spearman or Pearson correlation coefficients [31]. In line with recent reviews, if a study reported multiple correlation coefficients for a particular meta-analysis, these correlation coefficients were averaged [20, 31]. Prior to performing the meta-analyses, correlation coefficients were transformed using a Fisher's z-transformation. Then, meta-analyses were executed based on the z-score, and an inverse Fisher's z-transformation was used to obtain the pooled correlation coefficient and 95% confidence interval (95% CI) [32, 33]. The effect size of the pooled correlation coefficients was interpreted as weak ($r < 0.30$), moderate ($0.30 \leq r < 0.50$), or strong ($r \geq 0.50$) [34]. All meta-analyses were conducted using a random-effects model [32, 35]. The I^2 statistics were calculated to assess statistical heterogeneity [35]. Furthermore, potential outliers and influential cases were assessed according to Viechtbauer et al. (2012) [36], and publication bias was assessed with funnel plots and Egger's regression if more than ten studies were included in the meta-analysis [32, 37]. All statistical analyses were performed using calculations based on R within the 'Jamovi 2.3.18' software.

If heterogeneity was moderate or high ($I^2 \geq 30\%$), moderation and sensitivity analyses were performed to determine whether study characteristics explained this heterogeneity [38]. Moderation analyses were conducted with respect to characteristics that may affect the strength and direction of the relationship between pain-related psychological variables and CoP variables: demographic

characteristics (age [39], sex [40], body mass index [41]), pain characteristics (pain duration [42], pain intensity [43]), and stance width on the force plate [44]. Furthermore, the influence of the following factors was determined by performing moderation analyses: result of risk of bias assessment, whether the correlation coefficient was reported in the study or obtained by contacting the author, and whether the pain-related psychological variables were assessed before or after the CoP measurement. When influential cases were present, sensitivity analyses were performed by excluding these cases. To conduct moderation and/or sensitivity analyses, at least four studies had to be available [45].

3.6 Certainty of evidence

The Grading of Recommendations, Assessment, Development, and Evaluation criteria (GRADE) were used to assess the certainty of evidence of the conducted meta-analyses [46]. Based on these criteria, the certainty of evidence was classified as high (4+), moderate (3+), low (2+), or very low (1+). Similar to previous reviews, some modifications were made to optimize the use of the GRADE criteria for the current review [21]. Evidence of non-randomized controlled trial designs was not downgraded, as this review did not aim to investigate the effect of interventions. Therefore, all certainty of evidence started as 'high' (+4), and could be downgraded for (1) study limitations when >25% (-1 level) or >50% (-2 levels) of the participants came from studies with high risk of bias; (2) inconsistency when I^2 was >30% (-1 level); (3) imprecision when the meta-analysis contained <400 participants (-1 level) or <100 participants (-2 levels); or (4) publication bias if present on funnel plots and Egger's regression for meta-analyses including ≥10 studies. Certainty of evidence was not downgraded for indirectness, since the eligibility criteria resulted in satisfaction of this criterion. The certainty of evidence was upgraded if the effect size was moderate or large (i.e., absolute value of pooled correlation coefficient ≥0.30) (+1 level).

3.7 Deviations from protocol

The study protocol on PROSPERO was updated once due to the involvement of additional authors. Moreover, to reduce methodological heterogeneity, small adjustments were made regarding the postural task requirements, and sub-analyses were performed in terms of linear CoP variables.

4 RESULTS

4.1 Study selection

Figure 1 shows the PRISMA flowchart. The search strategy resulted in 8161 unique records. After removing the duplicates and screening the titles, abstracts, and full texts, 16 studies with a total of 723 participants were included. Three additional studies also fulfilled the eligibility criteria, but were excluded [47-49] because they reported results of the same dataset [15, 50].

***** INSERT FIGURE 1*****

4.2 Study characteristics

The extracted study characteristics are presented in Table 2. Additionally, an overview of data clusters based on pain-related psychological variables, postural task difficulty, CoP variables, and the conducted meta-analyses is reported in Figure 2.

***** INSERT TABLE 2*****

***** INSERT FIGURE 2*****

Across the 16 included studies, the average age of the participants was 34.4 (±7.7) years [8, 15, 23, 50-62], the average body mass index was 25.5 (±3.0) kg/m² [15, 23, 53-57, 60, 61], and 60.3% (±12.6%) of the participants were female [8, 15, 23, 50, 51, 53-61]. The average intensity of LBP was 3.4 (±1.5) measured by the numeric rating scale (NRS) and visual analogue scale (VAS) (converted to a score on 10) [8, 15, 23, 50-62]. The average disability score was 18.4% (±4.5%) for the Oswestry Disability Index (ODI) [8, 15, 50-52, 54-56, 58, 61, 62] and 6.9 (±2.9) for the Roland Morris Disability Questionnaire (RMDQ) [23, 53, 57, 60]. Individuals with chronic, recurrent, and subacute LBP were included in respectively six [23, 50-52, 60, 62], three [54, 56, 61], and one [58] study. Six studies did not specify the patient population based on the duration of the LBP complaints [8, 15, 53, 55, 57, 59].

Regarding the pain-related psychological variables, all 16 studies measured pain-related fear [8, 15, 23, 50-62], and three studies additionally assessed pain catastrophizing [52, 58, 61]. No other pain-related psychological variables were measured. The pain-related fear variables contained data measured by the Tampa Scale for Kinesiophobia (TSK-17 and TSK-11), Fear-Avoidance and Beliefs Questionnaire (FABQ), and Pain Anxiety Symptom Scale (PASS-20). The pain catastrophizing variables contained data measured by the Pain Catastrophizing Scale (PCS). The average scores were; 36.3 (±6.1) on TSK-17 [15, 50-52, 54-56, 58, 60-62], 20.0 (±5.6) on TSK-11 [59], 10.6 (±2.6) on FABQ-PA [8, 23, 52-54, 56, 57, 61, 62], 9.9 (±3.1) on FABQ-W [8, 23, 52-54, 56, 61], 11.6 (±7.7) on PCS [52, 58, 61], and 31.6 (±9.3) on PASS-20 [62].

Regarding CoP motion, all 16 studies measured linear variables [8, 15, 23, 50-62]. Within the linear variables, positional CoP variables were assessed in 15 studies [8, 15, 23, 50-60, 62]. Dynamic CoP variables and frequency CoP variables were reported in respectively 12 [8, 23, 50-53, 57-62], and two studies [8, 58]. Four studies measured non-linear CoP variables [8, 50, 51, 58].

Regarding postural task difficulty, nine studies assessed CoP motion during standing on a stable support surface with eyes open, labelled as the reference condition [8, 23, 50-52, 58, 60-62]. Twelve studies used one postural manipulation; i.e., standing on a stable support surface with eyes closed [8, 15, 23, 50, 51, 53, 55, 57, 59, 60, 62], unstable support surface with eyes open [60], stable support surface with eyes open and muscle vibration [62], and stable support surface with eyes open while performing a dual task [58, 62]. Ten studies measured CoP motion during tasks involving two postural manipulations; i.e., standing on an unstable support surface with eyes closed [8, 15, 50, 51, 53, 55, 60], stable support surface with eyes closed and muscle vibration [8, 15, 54-56, 62], stable support surface with eyes closed while performing a dual task [62], and stable support surface with eyes open and muscle vibration while performing a dual task [62]. Finally, six studies used three postural manipulations; i.e., standing on an unstable support surface with eyes closed and vibration [8, 15, 54-56], and stable support surface with eyes closed and vibration while performing a dual task [62].

4.3 Risk of bias and publication bias

The risk of bias regarding study participation was rated low in four studies [23, 50, 54, 60], moderate in five studies [51, 56, 58, 61, 62], and high in seven studies [8, 15, 52, 53, 55, 57, 59]. The most prevalent reasons for risk of participation bias were limited reporting of the eligibility criteria, and the recruitment time and location. There was a low risk of bias due to study attrition, prognostic factor measurement, and outcome measurement in the majority of the studies. Regarding study confounding, 12 studies were rated as high risk of bias [8, 15, 50-56, 58, 61, 62], three studies as moderate risk of bias [23, 57, 59], and only one study was rated as low risk of bias [60]. This was mostly because correlations of interest were not reported by the study itself. Due to a similar reason, risk of bias in statistical analysis and reporting was high for 11 studies [8, 15, 50-53, 55, 56, 58, 61, 62], moderate for one study [54], and low for four studies [23, 57, 59, 60]. Table 3 shows the QUIPS risk of bias assessment in detail. Publication bias was not present in the two meta-analyses containing ≥10 studies (Appendix 3).

***** INSERT TABLE 3 *****

4.4 Correlations between pain-related psychological variables and CoP variables

The results and forest plots of the conducted meta-analyses are reported in respectively Table 4 and Figure 3. The forest plots of the sub-analyses and the GRADE certainty of evidence assessment can be found in Appendices 4 and 5, respectively.

***** INSERT FIGURE 3 *****

4.4.1 Pain-related fear

4.4.1.1 Pain-related fear and linear CoP without postural manipulations

A non-significant pooled correlation coefficient of 0.07 (95% CI= -0.04, 0.18) (nine studies, n= 303) [8, 23, 50-52, 58, 60-62] was found between pain-related fear and CoP variables during standing on a stable support surface with eyes open (see Figure 3a). Sub-analyses for positional CoP variables yielded

a significant pooled correlation coefficient of 0.14 (95% CI= 0.03, 0.26) (eight studies, n= 284) [8, 23, 50-52, 58, 60, 62]. No significant pooled correlation coefficient was found for dynamic CoP variables (nine studies, n= 303; pooled r= 0.05, 95% CI= -0.07, 0.16) [8, 23, 50-52, 58, 60-62]. The certainty of evidence for all pooled correlation coefficients was very low.

4.4.1.2 Pain-related fear and linear CoP with one postural manipulation

A non-significant pooled correlation coefficient of 0.05 (95% CI= -0.03, 0.13) (11 studies, n= 590) [8, 15, 23, 50, 51, 53, 55, 57, 59, 60, 62] was found between pain-related fear and CoP variables during standing on a stable support surface with eyes closed (see Figure 3b). Sub-analyses for dynamic CoP variables yielded a significant pooled correlation coefficient of 0.10 (95% CI= 0.01, 0.18) (nine studies, n= 551) [8, 23, 50, 51, 53, 57, 59, 60, 62]. No significant pooled correlation coefficient was found for positional CoP variables (11 studies, n= 590; pooled r= 0.04, 95% CI= -0.04, 0.12) [8, 15, 23, 50, 51, 53, 55, 57, 59, 60, 62]. The certainty of evidence for all pooled correlation coefficients was very low.

4.4.1.3 Pain-related fear and linear CoP with two postural manipulations

A non-significant pooled correlation coefficient of 0.04 (95% CI= -0.06, 0.13) (seven studies, n= 424) [8, 15, 50, 51, 53, 55, 60] was found between pain-related fear and CoP variables during standing on an unstable support surface with eyes closed (see Figure 3c). Sub-analyses yielded non-significant pooled correlation coefficients of 0.05 (95% CI= -0.05, 0.14) and 0.07 (95% CI= -0.03, 0.17) for respectively positional (seven studies, n= 424) [8, 15, 50, 51, 53, 55, 60], and dynamic (five studies, n= 388) [8, 50, 51, 53, 60] CoP variables. The certainty of evidence for all pooled correlation coefficients was very low.

A non-significant pooled correlation coefficient of 0.06 (95% CI= -0.10, 0.22) (six studies, n= 153) [8, 15, 54-56, 62] was found between pain-related fear and CoP variables during standing on a stable support surface with eyes closed and muscle vibration (see Figure 3d). Sub-analyses yielded a non-significant pooled correlation coefficient of 0.06 (95% CI= -0.10, 0.22) for positional CoP variables (six studies, n= 153) [8, 15, 54-56, 62]. The certainty of evidence for all pooled correlation coefficients was very low.

4.4.1.4 Pain-related fear and linear CoP with three postural manipulations

A non-significant pooled correlation coefficient of -0.04 (95% CI= -0.22, 0.14) (five studies, n= 115) [8, 15, 54-56] was found between pain-related fear and CoP variables during standing on an unstable support surface with eyes closed and muscle vibration (see Figure 3e). No sub-analyses were executed because all included CoP variables were positional. The certainty of evidence for the pooled correlation coefficient was very low.

4.4.2 Pain catastrophizing

4.4.2.1 Pain catastrophizing and linear CoP without postural manipulations

A non-significant pooled correlation coefficient of 0.28 (95% CI= -0.10, 0.67) (three studies, n= 87) [52, 58, 61] was found between pain catastrophizing and CoP variables during standing on a stable support surface with eyes open (see Figure 3f). Sub-analyses yielded a non-significant pooled correlation coefficient of 0.29 for dynamic CoP variables (95% CI= -0.15, 0.74) (three studies, n= 87) [52, 58, 61]. The certainty of evidence for all pooled correlation coefficients was very low.

***** INSERT TABLE 4 *****

Due to heterogeneity in the non-linear CoP variables [8, 50, 51, 58], and a lack of studies using particular postural tasks [58, 60, 62], meta-analyses for these variables were not performed. All correlations of individual studies are reported in Appendix 6.

4.5 Moderation and sensitivity analyses

Two meta-analyses showed statistical heterogeneity greater than 30%, for which we planned to perform moderation and sensitivity analyses. However, because these meta-analyses contained only three studies, moderation and sensitivity analyses could not be conducted.

5 DISCUSSION

5.1 Study findings

This systematic review investigated the associations between pain-related psychological variables and CoP variables during static bipedal standing in individuals with LBP. The findings of the meta-analyses indicated weak, overall non-significant, associations of very low certainty of evidence. This was not in line with our hypothesis, as we assumed to find negative correlations implying that increased levels of negative pain-related psychological variables would result in decreased CoP motion. Moreover, and contrary to our hypotheses, pooled correlation coefficients were not stronger during more difficult postural tasks.

Although pain-related psychological variables were subdivided into pain-related fear and pain-catastrophizing based on distinctive underlying mechanisms, results of both meta-analyses could not be compared due to the high statistical heterogeneity in the meta-analyses regarding pain catastrophizing. More research is needed to determine whether the discrepancies in findings between pain-related fear and pain catastrophizing are due to distinctive underlying mechanisms.

Potentially, the use of generic (non-task-specific) questionnaires to measure pain-related psychological variables could explain the weak and mainly non-significant findings. Matheve et al. (2019) highlighted the importance of using task-specific measures when assessing the association between pain-related fear and movement patterns in individuals with LBP. They show that individuals with LBP might be fearful of particular activities, without achieving a high score on generic questionnaires, such as the TSK or FABQ [63]. Therefore, instead of solely relying on total scores of generic questionnaires, it had been recommended to use a person-centered approach that evaluates an individual's pain-related cognitions and emotions regarding particular tasks, taking into account motivational and contextual factors [64]. In accordance with these findings, Meinke et al. (2022) found weak to strong positive associations between directional fear questions (e.g., 'I could harm my back if I bend forward') and postural sway [59]. Moreover, although some studies reported scores exceeding the cut-off scores of

the pain-related psychological questionnaires, the majority of the studies found scores below the cut-off scores, indicating the absence of highly present negative pain-related psychological variables [65-67]. As a result, the averaged questionnaire scores of the included studies were below the cut-off scores, and the results of the meta-analyses should be interpreted in this context.

Furthermore, the static bipedal standing tasks investigated in our meta-analyses might have not been sufficiently challenging or threatening to alter CoP motion and consequently its association with pain-related psychological variables. Da Silva et al. (2018) investigated CoP motion in people with chronic LBP during different tasks and concluded that the most difficult postural tasks (e.g., semi-tandem stance and unipedal stance) were the most sensitive to alterations in CoP motion [23]. Similarly, Van Daele et al. (2010) only found a difference in the effect of a cognitive dual tasks on CoP motion between patients with and without LBP in the most difficult postural task [68]. The assumption that task difficulty also affects the correlation between pain-related psychological variables and CoP variables is substantiated by Kahraman et al. (2018), who only observed moderate to strong negative correlations between fear of movement and postural sway during a dynamic task (i.e., testing limits of stability), but not during static bipedal nor unipedal standing [69]. Moreover, static bipedal standing of short duration may not typically provoke fear of pain or be perceived as a threatening postural task in individuals with LBP. Therefore, it may be less influenced by pain-related fear compared to more pain- or fear-provoking postures or movements. For example, a recent meta-analysis from Ippersiel et al. (2022) demonstrated associations between pain-related threat and guarded motor behavior during flexion-based tasks, but not consistently during for example gait and extension-based tasks [18].

In addition, postural threats and emotions are known to affect postural control, even in healthy individuals [70, 71]. For example, CoP motion decreases when healthy individuals are standing on an elevated platform in comparison with standing on a ground-level platform, although the biomechanical requirements for maintaining balance remain the same [72]. This might be explained by the ‘integrated model of anxiety and postural control‘, which states that threat assessment is

critically linked to every aspect of postural control at multiple levels in the brain (e.g., amygdala, sensory cortex, motor cortex) [73]. It might be likely that the postural tasks included in this review were not threat-inducing nor demanding enough to evoke alterations in CoP motion, particularly in the relatively young [74] and minimally disabled [75] cohorts that are included in the meta-analyses. This is in line with a recent meta-analysis of Nzamba et al. (2023) who found negative associations between disability and spinal movement in individuals with LBP [76], and more specifically, Shanbehzadeh et al. (2022) who showed that higher levels of disability may also be related to poorer postural control [22].

Another possible explanation for the weak and mainly non-significant correlations might be the divergence in presentation of motor control alterations (including postural strategies) in patients with LBP [77]. As the divergence in motor control strategies (ranging from 'tight' to 'loose' motor control) is often overlooked in research, results may be conflicting. Subgrouping patients with LBP based on their motor control strategy might yield stronger associations between pain-related psychological and CoP variables in individuals with LBP.

5.2 Considerations

Some considerations should be taken into account. Overall, the number of included studies in the meta-analyses was limited. The certainty of evidence of the meta-analyses was very low, and planned moderation analyses could not be performed. Thus, future studies accounting for the limitations of the current literature could reveal different findings. Moreover, we used unpublished data obtained through author contact. As these data have not been peer-reviewed, their quality is not guaranteed. We compensated for this by scoring high risk of bias for statistical analyses and reporting. Nevertheless, we believe that the data obtained through author contact added considerable value by enlarging the body of evidence. Furthermore, even though methodological heterogeneity in terms of postural tasks (i.e., only static bipedal standing tasks) and outcomes (i.e., only measures of CoP) was limited, the included studies still varied regarding stance width, verbal instructions, the number of trial

repetitions, data acquisition duration, and sampling frequency, possibly impacting postural control measurement [44]. In addition, different outcome measurements regarding CoP variables (e.g. sway, area) and pain-related psychological questionnaires were used, which increased the methodological heterogeneity. Finally, the type and duration of LBP complaints has not been accounted for. Although recent evidence indicated no differences in terms of postural control between acute, subacute and chronic low back pain [42], research suggests that the duration or intensity of complaints might affect the interaction between postural control and pain-related psychological variables as fear and avoidance behaviors were identified as predisposing factors for long-term consequences on motor behaviors [78].

5.3 Future directions

The evidence provided in this study is too preliminary to transfer directly into clinical practice. However, based on our findings, we recommend future studies to explore more challenging (in terms of sensorimotor demands) and/or threat-inducing (in terms of perceived danger or damage) postural tasks, as they may have stronger effects on the association between pain-related psychological variables and CoP variables. Furthermore, adding task-specific measures of pain-related psychological variables might increase our insight. In line with this, tailoring the postural task to each patient by taking into account their individually feared tasks, might add useful knowledge. Also, adding kinematic and electromyographic measures to evaluate postural control might help us to gain more insight into the specific postural strategies (e.g., loose versus tight) and the associations between pain-related psychological variables and motor control. Given the heterogeneity of LBP, we recommend to distinguish subgroups based on the clinical presentation of LBP (e.g., specific versus non-specific LBP, acute versus chronic LBP) to examine whether this affects the correlation between pain-related psychological variables and CoP variables. Finally, longitudinal studies are needed to gain more knowledge about the causality between pain-related psychological variables and postural control in patients with LBP.

6 CONCLUSION

In summary, this systematic review and meta-analysis assessed whether pain-related psychological variables are associated with postural control during static bipedal standing in individuals with LBP, during different postural tasks.

Meta-analyses regarding pain-related fear and CoP variables resulted in weak associations during static bipedal standing regardless of the task conditions. Additionally, weak (close to moderate) associations were found between pain catastrophizing and CoP variables during standing on a stable support surface with eyes open.

These findings do not support the idea of a strong relationship between pain-related psychological variables and postural control strategies in individuals with LBP. However, given the very low certainty of evidence and methodological limitations, it is difficult to draw conclusions and it is conceivable that further research, accounting for current study limitations, may lead to different conclusions.

7 REFERENCES

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Captions to illustrations

Figure 1. PRISMA flow-chart of search results

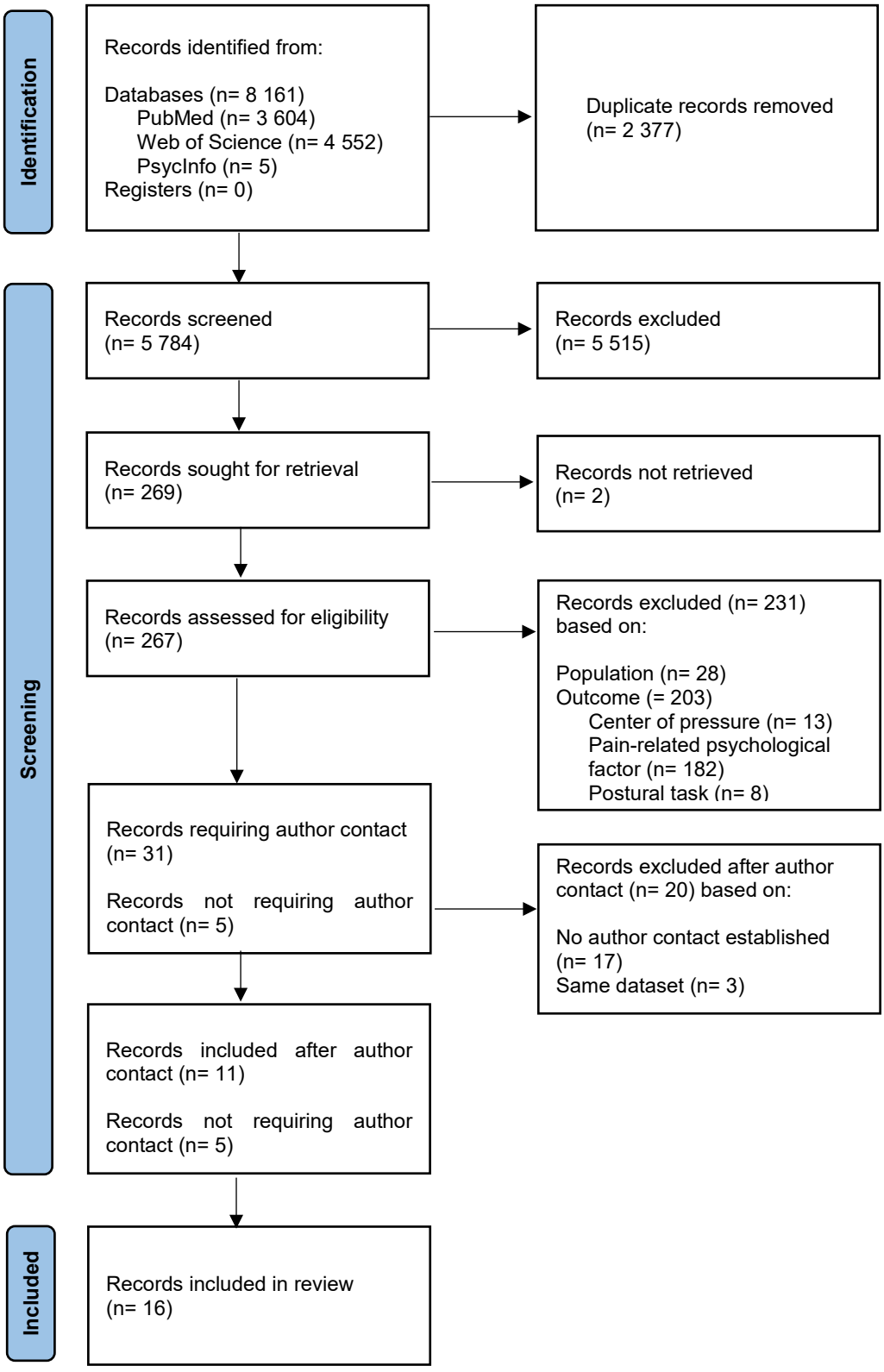
Figure 1 displays the results of the conducted search strategy and the study selection process.

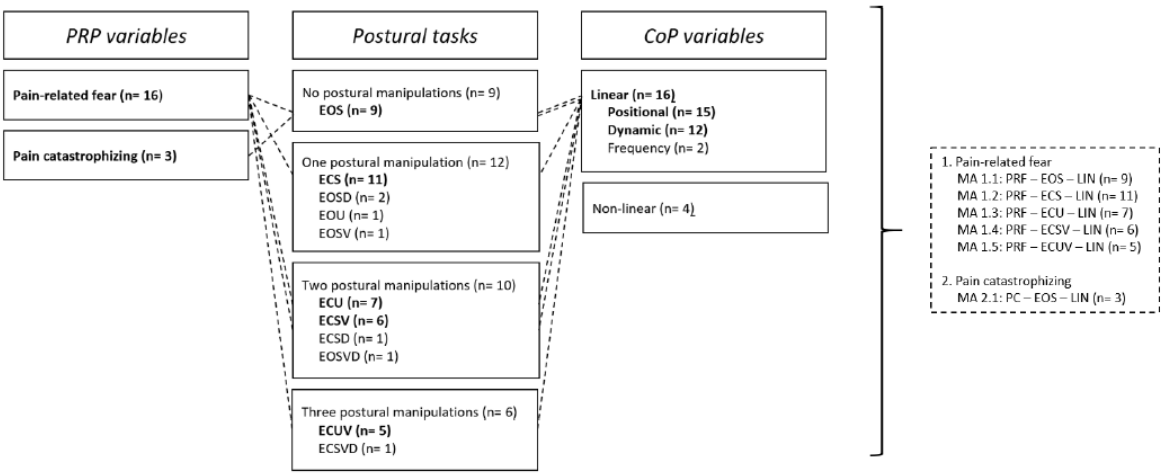
Figure 2. Data clustering and performed meta-analyses

Figure 2 displays the different data clusters with their subgroups, the number of studies reporting these data, and the conducted meta-analyses. Abbreviations: PRP= pain-related psychological, CoP= center of pressure, EOS= standing on stable surface with eyes open, ECS= standing on stable surface with eyes closed, EOSD= standing on stable surface with eyes open while performing a dual task, EOU= standing on unstable surface with eyes open, EOSV= standing on stable surface with eyes open and muscle vibration, ECU= standing on unstable surface with eyes closed, ECSV= standing on stable surface with eyes closed and muscle vibration, ECSD= standing on stable surface with eyes closed while performing a dual task, EOSVD= standing on stable surface with eyes open and muscle vibration while performing a dual task, ECUV= standing on unstable surface with eyes closed and muscle vibration, ECSVD= standing on stable surface with eyes closed and muscle vibration while performing a dual task, MA= meta-analysis, PRF= pain-related fear, LIN= linear, PC= pain catastrophizing, dotted lines indicate conducted meta-analyses, n= number of articles reporting the variable

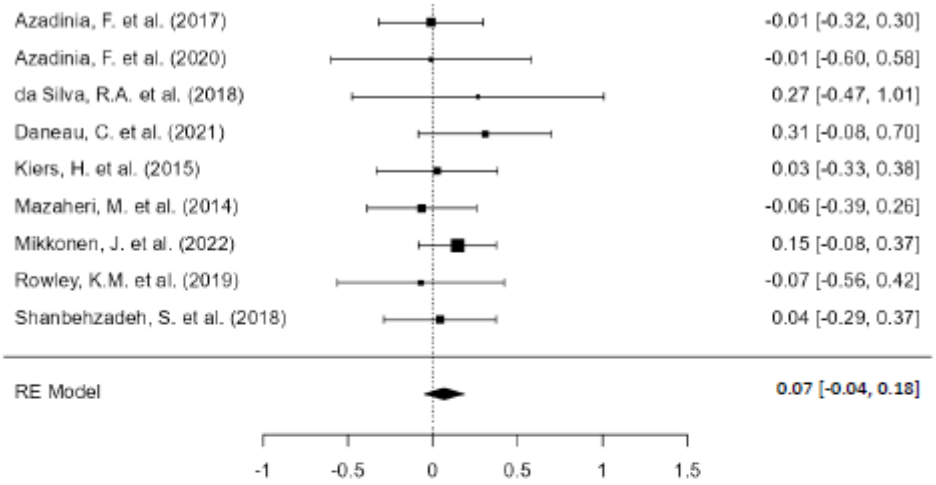
Figure 3. Forest plots of main meta-analyses

Figure 3 displays the forest plots of the main meta-analyses. Forest plots of the sub-analyses are added in the Appendices.

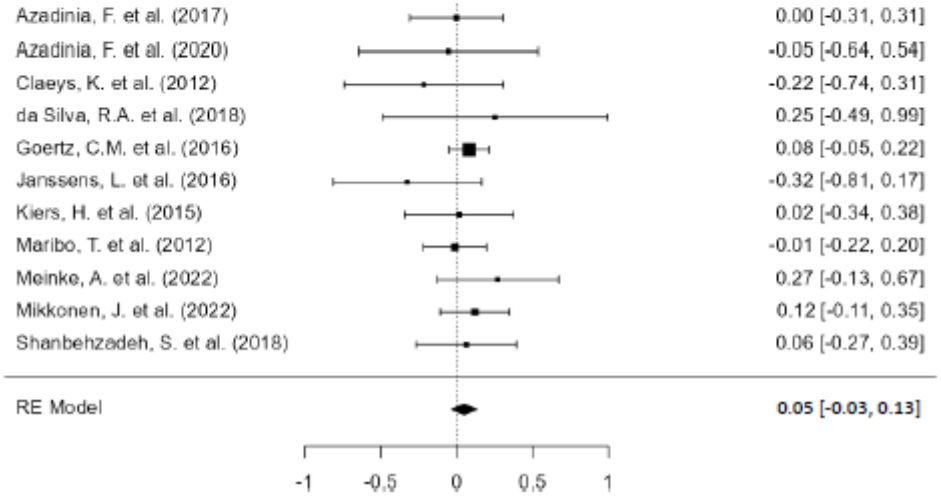

Identification
Screening
Included
Records identified from:
Databases (n= 8 161)
PubMed (n= 3 604)
Web of Science (n= 4 552)
PsycInfo (n= 5)
Registers (n= 0)
Duplicate records removed (n= 2 377)
Records screened (n= 5 784)
Records excluded (n= 5 515)
Records sought for retrieval (n= 269)
Records not retrieved (n= 2)
Records assessed for eligibility (n= 267)
Records excluded (n= 231) based on:
Population (n= 28)
Outcome (= 203)
Center of pressure (n= 13)
Pain-related psychological factor (n= 182)
Postural task (n= 8)
Records requiring author contact (n= 31)
Records not requiring author contact (n= 5)
Records excluded after author contact (n= 20) based on:
No author contact established (n= 17)
Same dataset (n= 3)
Records included after author contact (n= 11)
Records not requiring author contact (n= 5)
Records included in review (n= 16)


PRP variables
Pain-related fear (n= 16)
Pain catastrophizing (n= 3)
Postural tasks
No postural manipulations (n= 9)
EOS (n= 9)
One postural manipulation (n= 12)
ECS (n= 11)
EOSD (n= 2)
EOU (n= 1)
EOSV (n= 1)
Two postural manipulations (n= 10)
ECU (n= 7)
ECSV (n= 6)
ECSD (n= 1)
EOSVD (n= 1)
Three postural manipulations (n= 6)
ECUV (n= 5)
ECSVD (n= 1)
CoP variables
Linear (n= 16)
Positional (n= 15)
Dynamic (n= 12)
Frequency (n= 2)
Non-linear (n= 4)
1. Pain-related fear
MA 1.1: PRF – EOS – LIN (n= 9)
MA 1.2: PRF – ECS – LIN (n= 11)
MA 1.3: PRF – ECU – LIN (n= 7)
MA 1.4: PRF – ECSV – LIN (n= 6)
MA 1.5: PRF – ECUV – LIN (n= 5)
2. Pain catastrophizing
MA 2.1: PC – EOS – LIN (n= 3)

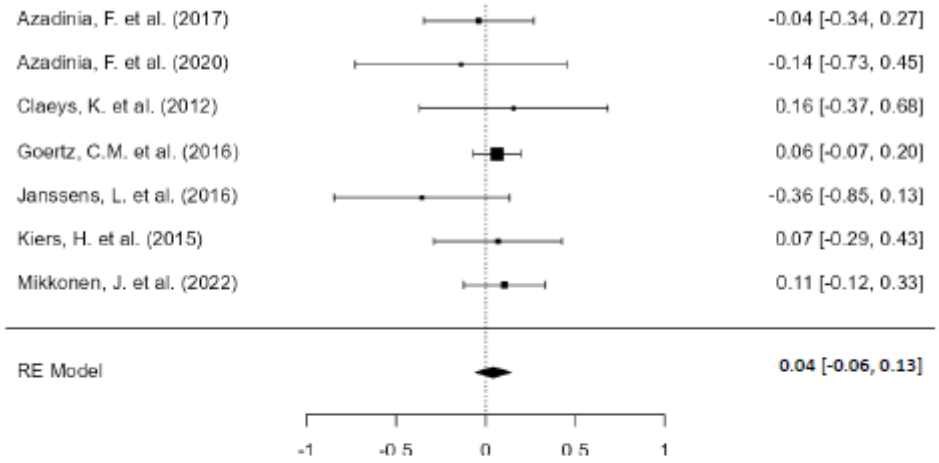
βa - Pain-related fear and linear center of pressure during standing on a stable support surface with eyes open (MA 1.1)



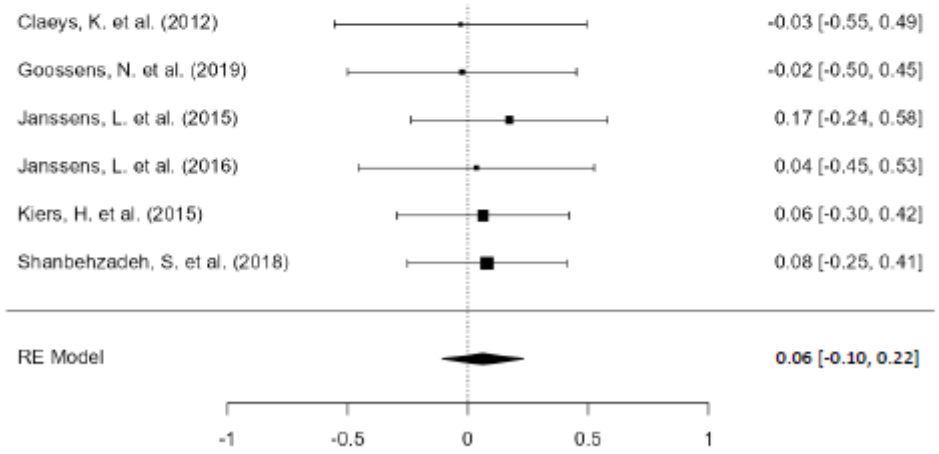
3b - Pain-related fear and linear center of pressure during standing on a stable support surface with eyes closed (MA 1.2)



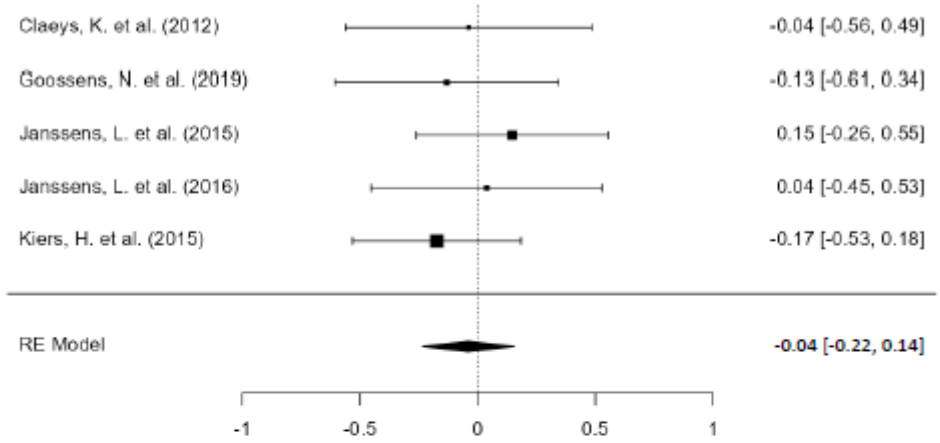
3c - Pain-related fear and linear center of pressure during standing on an unstable support surface with eyes closed (MA 1.3)



3d - Pain-related fear and linear center of pressure during standing on a stable support surface with eyes closed and muscle vibration (MA 1.4)



3e - Pain-related fear and linear center of pressure during standing on an unstable support surface with eyes closed and muscle vibration (MA 1.5)



3f - Pain catastrophizing and linear center of pressure during standing on a stable support surface with eyes open (MA 2.1)

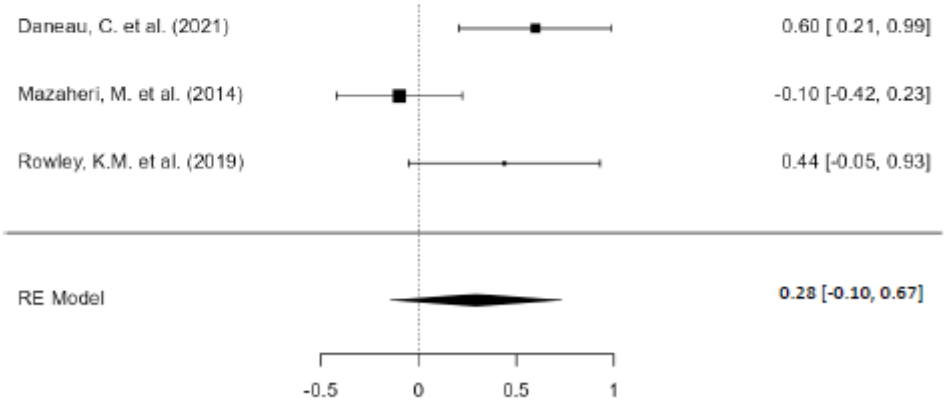


Table 1. Eligibility criteria

Population	Studies were included if they recruited adults (≥18y) with low back pain, defined as pain between the lower edge of the ribs and the buttock. Both specific and non-specific low back pain were included and no restrictions on pain duration were applied. Studies were excluded if low back pain was experimentally induced or if participants were pregnant.
Pain-related psychological variables	Studies were included if they reported at least one pain-related psychological variable (e.g., fear of movement, pain catastrophizing) that was measured by a validated instrument. Studies were excluded if they measured psychological variables not specifically related to pain (e.g., depression, anxiety), or if a non-validated measurement instrument was used.
CoP variables	Studies were included if postural control was reported in terms of CoP variables (e.g., CoP displacement, CoP velocity). Studies that solely used other measures of postural control, such as clinical measures (e.g., Berg Balance Scale, Timed Up & Go Test), kinetics, kinematics (e.g., 2D/3D motion capture, center of mass), or muscle activity (by electromyography) were excluded.
Postural task	Studies were included if CoP was measured during static bipedal upright standing with parallel foot positioning in the frontal plane. Studies were excluded if CoP was measured during any other postural task (e.g., unipedal standing, tandem stance, sitting, supine lying), during dynamic tasks, or if external force plate perturbations were applied. This decision was made to reduce methodological heterogeneity between the included studies.
Reporting of data	Studies were included if they reported at least one correlation coefficient between a pain-related psychological variable and a CoP variable, or if they reported at least one pain-related psychological variable and one CoP variable without reporting the correlation coefficient between these variables. In the latter case, the corresponding author was contacted at least three times to obtain raw data or unpublished correlation coefficients between CoP and pain-related psychological variables. When raw data or correlation coefficients between CoP and pain-related psychological variables were obtained through author contact, studies were included.

Study design	Cross-sectional studies and longitudinal studies were considered eligible. In the latter case, only baseline data were used. Case reports, study protocols, and reviews were considered non-eligible.
Language	Studies were considered eligible if they were written in English or Dutch.

Abbreviations: CoP= center of pressure

Table 2: Study characteristics

First author (publication year)	Sample characteristics	Postural task description (number of postural manipulations) and stand width	Pain-related psychological variable (questionnaire) and temporal precedence with center of pressure measurement	Center of pressure subcategory (specific variable)	Significant correlation coefficient (significance level)	Meta-analysis
Azadinia, F. et al. (2017 & 2019)	CLBP (n= 44) Age= 27.2 (±5.3) Sex= 63% female BMI= not reported VAS= 3.1 (±3.4) ODI= 21.5 (±5.8) TSK-17= 38.6 (± 5.8)	EOS (0) ECS (1) ECU (2) Stance width= 'feet close together'	Pain-related fear (TSK) Temporal precedence= not reported	Positional (CoP area (95%)) Dynamic (CoP velocity (TOT), SD of CoP velocity (AP & ML, Phase plan portrait (TOT, AP & ML)) Non-linear (Sample entropy (AP & ML), Correlation dimension (AP & ML), %Determinism (AP & ML))	/	# MA 1.1 MA 1.2 MA 1.3
Azadinia, F. et al. (2020)	CLBP (n= 14) Age= 26.7 (±3.9) Sex= 85% female BMI= not reported VAS= 3.2 (±1.7) ODI= 21.0 (±7.5) TSK-17= 36.6 (±8.6)	EOS (0) ECS (1) ECU (2) Stance width= 'feet close together'	Pain-related fear (TSK) Temporal precedence= not reported	Positional (CoP area (95%), SD of CoP displacement (AP & ML)) Dynamic (CoP velocity (TOT), SD of CoP velocity (AP & ML, Phase plan portrait (TOT, AP & ML)) Non-linear (Sample entropy (AP & ML), Correlation dimension (AP & ML), Lyapunov exponent (AP & ML))	/	# MA 1.1 MA 1.2 MA 1.3
Claeys, K. et al. (2011, 2012, 2015)	NSLBP (n= 17) Age= 27 (±5.3) Sex= 76% female BMI= 22.3 (±2.2) NRS= 3.9 (±2.0) ODI= 9.2 (±4.5) TSK-17= 35.3 (± 4.9)	ECS (1) ECU, ECSV (2) ECUV (3) Stance width= 10cm	Pain-related fear (TSK, FABQ) Temporal precedence= not reported	Positional (CoP displacement (AP), SD CoP displacement (AP))	/	# MA 1.2 MA 1.3 MA 1.4 MA 1.5
da Silva, R.A. et al. (2018)	CLBP (n= 10) Age= 34.4 (±2.9) Sex= 50% female BMI= 27.2 (±3.9) VAS= 4.5 (±2.2) RMDQ= 7.6 (±5.2) FABQ-PA= 9.3 (± 9.8) FABQ-W= 9.4 (± 7.5)	EOS (0) ECS (1) Stance width= not reported	Pain-related fear (FABQ) Temporal precedence= before CoP measurement	Positional (CoP area (95%)) Dynamic (CoP velocity (AP & ML), CoP frequency (AP & ML))	None	* MA 1.1 MA 1.2
Daneau, C. et al. (2021)	CLBP (n= 28) Age= 36.5 (±16.0) Sex= not reported BMI= not reported	EOS (0) Stance width= not reported	Pain-related fear (TSK, FABQ) Pain catastrophizing (PCS) Temporal precedence= before CoP measurement	Positional (CoP displacement (AP)) Dynamic (CoP velocity (TOT))	/	#, § MA 1.1 MA 2.1

	VAS= 1.9 (±2.2) ODI= 10.9 (±6.9) TSK-17= 33.1 (± 6.6) FABQ-PA= 7.1 (± 5.0) FABQ-W= 7.5 (± 9.9) PCS= 9.7 (± 6.9)					
Goertz, C.M. et al. (2016)	LBP (n= 220) Age= 44.3 (±10.4) Sex= 46% female BMI= 29.4 (±6.0) NRS= 5.5 (±1.7) RMDQ= 5.6 (±3.8) FABQ-PA= 12.2 (±5.6) FABQ-W= 11.5 (±9.3)	ECS (1) ECU (2) Stance width= not reported	Pain-related fear (FABQ) Temporal precedence= before CoP measurement	Positional (CoP displacement (AP & ML)) Dynamic (CoP velocity (TOT))	/	# MA 1.2 MA 1.3
Goossens, N., et al. (2019)	RNSLBP (n= 20) Age= 25.0 (23.4–28.0) Sex= 70% female BMI= 21.7 (20.4–24.1) NRS= 2.4 (± 1.9) ODI= 18.0 (18–20) TSK-17= 33.0 (± 8.0) FABQ-PA= 10.6 (± 5.9) FABQ-W= 15.5 (± 9.5)	ECSV (2) ECUV (3) Stance width= 10 cm	Pain-related fear (TSK, FABQ) Temporal precedence= after CoP measurement	Positional (CoP displacement (AP))	None	* MA 1.4 MA 1.5
Janssens, L. et al. (2015)	RNSLBP (n= 26) Age= 32.1 (±7.6) Sex= 63% female BMI= 23.8 (±3.6) NRS= 5.3 (±1.7) ODI= 19.1 (±8.0) TSK-17= 36.8 (± 5.8) FABQ-PA= 13.8 (± 4.0) FABQ-W= 14.3 (± 7.3)	ECSV (2) ECUV (3) Stance width= 10 cm	Pain-related fear (TSK, FABQ) Temporal precedence= after CoP measurement	Positional (CoP displacement (AP))	/	# MA 1.4 MA 1.5
Janssens, L. et al. (2016)	LBP (disc herniation) (n= 19) Age= 46.2 (± 9.2) Sex= 52% female BMI= 25.8 (±3.8) NRS= 2.6 (±2.1) ODI= 25.6 (±13.3) TSK-17= 43.0 (±6.1)	ECS (1) ECU, ECSV (2) ECUV (3) Stance width= 10 cm	Pain-related fear (TSK) Temporal precedence= not reported	Positional (CoP displacement (AP))	/	#, § MA 1.2 MA 1.3 MA 1.4 MA 1.5

Kiers, H. et al. (2015)	LBP (n= 33) Age= 41.3 (±11) Sex= 36% female BMI= not reported NRS= 4.5 (±1.4) ODI= 21.6 (±20.0) FABQ-PA= 7.4 (± 6.3) FABQ-W= 7.3 (± 6.9)	EOS (0) ECS (1) ECU, ECSV (2) ECUV (3) Stance width= 'shoulder width'	Pain-related fear (FABQ) Temporal precedence= before CoP measurement	Positional (CoP displacement (AP & ML), SD CoP displacement (AP & ML)) Dynamic (CoP velocity (TOT, AP & ML)) Frequency (Mean power frequency (AP & ML)) Non-linear (Recurrence entropy, Determinism, Recurrence rate, Mean diagonal length, Lyapunov exponent)	/	# MA 1.1 MA 1.2 MA 1.3 MA 1.4 MA 1.5
Maribo, T. et al. (2012)	LBP (n= 91) Age= 44,9 (±10,0) Sex= 51% female BMI= 30.1 (±6.2) NRS= 5.9 (±2.5) RMDQ= 10.5 (±5.3) FABQ-PA= 10.9 (± 5.3)	ECS (1) Stance width= 2 cm	Pain-related fear (FABQ) Temporal precedence= not reported	Positional (CoP displacement (AP)) Dynamic (CoP velocity (TOT))	None	* MA 1.2
Mazaheri, M. et al. (2014)	NSLBP (n= 40) Age= 34.4 (± 9.7) Sex= 60% female BMI= not reported VAS= 31.2 (±25.7) ODI= 25.5 (±6.7) TSK-17= 42.3 (±7.3) PCS= 20.1 (±11.9)	EOS (0) EOSD (1) Stance width= 'shoulder width'	Pain-related fear (TSK) Pain catastrophizing (PCS) Temporal precedence= before CoP measurement	Positional (SD of CoP displacement (AP & ML)) Dynamic (CoP velocity (TOT)) Frequency (Mean power frequency (AP & ML)) Non-linear (Sample entropy (TOT))	/	# MA 1.1 MA 2.1
Meinke, A. et al. (2022)	NSLBP (n= 27) Age= 35.0 (±25.5) Sex= 63% female BMI= not reported NRS= 2.6 (±1.3) ODI= not reported TSK-11= 20.0 (± 5.6)	ECS (1) Stance width= NS	Pain-related fear (TSK) Temporal precedence= not reported	Positional (CoP displacement (AP & ML)) Dynamic (CoP velocity (AP & ML))	TSK-11 x CoP velocity ML (ECS): r= 0.43 (p= 0.049)	* MA 1.2
Mikkonen, J. et al. (2022)	CLBP (n= 77) Age= 43.8 (41.1-46.5) Sex= 66% female BMI= 25.5 (24.6-26.5) NRS= 4.4 (4.0-4.9) RMDQ= 3.7 (2.9-4.5) TSK-17= 31.4 (29.5 - 33.2)	EOS (0) ECS, EOU (1) ECU (2) Stance width= 'as close together as possible without discomfort'	Pain-related fear (TSK) Temporal precedence= after CoP measurement	Positional (CoP area (95%)) Dynamic (CoP velocity (TOT))	TSK x CoP area (EOS): r= 0.22 (p< 0.05) TSK x CoP area (ECS): r= 0.18 (p< 0.05) TSK x CoP area (EOU): r= 0.22 (p< 0.05)	* MA 1.1 MA 1.2 MA 1.3

Rowley, K.M. et al. (2019)	RLBP (n= 19) Age= 23.5 (± 2.8) Sex= 63% female BMI= 23.6 (± 2.4) VAS= 0.4 (± 0.4) ODI= 12.0 (6.0-16.0) TSK-17= 31.3 (±6.5) FABQ-PA= 12.2 (±7.7) FABQ-W= 8.1 (±6.7) PCS= 5.0 (3.0-11.0)	EOS (0) Stance width= 'preferred stance width'	Pain-related fear (TSK, FABQ) Pain catastrophizing (PCS) Temporal precedence= not reported	Dynamic (CoP velocity (TOT))	/	#, § MA 1.1 MA 2.1
Shanbehzadeh, S. et al. (2018)	NSCLBP (n= 38) Age= 28.6 (±4.85) Sex= not reported BMI= not reported VAS= 1.6 (±1.0) ODI= 18.0 (±9.3) PASS-20= 31.6 (±15.8) TSK-17= 38.2 (±6.9) FABQ-PA= 15.0 (±5.8)	EOS (0) ECS, EOSD, EOSV (1) ECSV, ECSD, EOSVD (2) ECSVD (3) Stance width= 'toes and heels touching'	Pain-related fear (TSK, FABQ, PASS-20) Temporal precedence= not reported	Positional (CoP area (95%), CoP displacement (AP & ML)) Dynamic (CoP velocity (TOT))	/	#, § MA 1.1 MA 1.2 MA 1.4
Mean scores	Age= 34.4 (±7.7), Sex= 60.3% (±12.6%) female, BMI= 25.5 (±3.0), VAS/NRS= 3.1 (±1.5), ODI= 18.4 (±4.5), RMDQ= 6.9 (±2.9), TSK= 35.0 (±6.1), FABQ-PA= 10.6 (±2.6), FABQ-W= 9.9 (±3.1), PASS-20= 31.6 (±0.0), PCS= 11.6 (±7.7)					

Abbreviations: LBP= low back pain, CLBP= chronic low back pain, NSLBP: non-specific low back pain, RNSLBP= recurrent non-specific low back pain, RLBP= recurrent low back pain, NSCLBP= non-specific chronic low back pain, BMI= body mass index, VAS= visual analogue scale, NRS= numeric rating scale, ODI= oswestry disability index, RMDQ= roland morris disability questionnaire, TSK= tampa scale for kinesiophobia, FABQ= fear avoidance beliefs questionnaire, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PCS= pain catastrophizing scale, PASS-20= pain anxiety symptoms scale, EOS= standing on stable support surface with eyes open, ECS= standing on stable support surface with eyes closed, EOU= standing on unstable support with eyes open, EOSV= standing on stable support surface with eyes open and muscle vibration, EOSD= standing on stable support surface with eyes open while performing a dual task, ECU= standing on unstable support with eyes closed, ECSV= standing on stable support surface with eyes closed and muscle vibration, ECSD= standing on stable support surface with eyes closed while performing a dual task, EOSVD= standing on stable support surface with eyes open and muscle vibration while performing a dual task, ECUV= standing on unstable support surface with eyes closed and muscle vibration, ECSVD= standing on stable support surface with eyes closed and muscle vibration while performing a dual task, CoP= center of pressure, AP= anteroposterior, ML= mediolateral, TOT= total, SD= standard deviations, MA= meta-analysis, *= reported correlation coefficients in article, #= non-published correlation coefficients obtained through author contact, §= additional non-published data obtained through author contact

Table 3: QUIPS risk of bias assessment

First author (publication year)	Study participation	Study attrition	Prognostic factor measurement	Outcome measurement	Study confounding	Statistical analysis and reporting	Overall
Azadinia, F. et al. (2017)	Low	Low	Low	Low	High	High	High
Azadinia, F. et al. (2020)	Moderate	High	Low	Low	High	High	High
Claeys, K. et al. (2012)	High	Low	Low	Low	High	High	High
da Silva, R.A. et al. (2018)	Low	High	Low	Low	Moderate	Low	High
Daneau, C. et al. (2021)	High	Low	Low	Low	High	High	High
Goertz, C.M. et al. (2016)	High	Low	High	Low	High	High	High
Goossens, N. et al. (2019)	Low	Low	Moderate	Low	High	Moderate	High
Janssens, L. et al. (2015)	Moderate	Low	Moderate	Low	High	High	High
Janssens, L. et al. (2016)	High	Low	Low	Low	High	High	High
Kiers, H. et al. (2015)	High	Low	Low	Moderate	High	High	High
Maribo, T. et al. (2012)	High	High	Low	Moderate	Moderate	Low	High
Mazaheri, M. et al. (2014)	Moderate	Low	Low	Low	High	High	High
Meinke, A. et al. (2022)	High	Low	Low	Low	Moderate	Low	High
Mikkonen, J. et al. (2022)	Low	Low	Low	Low	Low	Low	Low
Rowley, K.M. et al. (2019)	Moderate	Low	Low	Low	High	High	High
Shanbehzadeh, S. et al. (2018)	Moderate	Low	Low	Low	High	High	High

Table 4: Results of performed meta-analyses

Performed meta-analyses	Number of studies	Number of participants	Pooled r	95% CI	I^2	GRADE
1. Pain-related fear						
		No postural manipulation				
MA 1.1: Standing on a stable support surface with eyes open	9	303	0.07	[-0.04, 0.18]	0%	Very low
MA 1.1.1: Positional CoP	8	284	0.14	[0.03, 0.26]	0%	Very low
MA 1.1.2: Dynamic CoP	9	303	0.05	[-0.07, 0.16]	0%	Very low
		One postural manipulation				
MA 1.2: Standing on a stable support surface with eyes closed	11	590	0.05	[-0.03, 0.13]	0%	Very low
MA 1.2.1: Positional CoP	11	590	0.04	[-0.04, 0.12]	0%	Very low
MA 1.2.2: Dynamic CoP	9	551	0.10	[0.01, 0.18]	0%	Very low
		Two postural manipulations				
MA 1.3: Standing on an unstable support surface with eyes closed	7	424	0.04	[-0.06, 0.13]	0%	Very low
MA 1.3.1: Positional CoP	7	424	0.05	[-0.05, 0.14]	0%	Very low
MA 1.3.2: Dynamic CoP	5	388	0.07	[-0.03, 0.17]	0%	Very low
MA 1.4: Standing on a stable support surface with eyes closed during muscle vibration	6	153	0.06	[-0.10, 0.22]	0%	Very low
MA 1.4.1: Positional CoP	5	153	0.06	[-0.10, 0.22]	0%	Very low

		Three postural manipulations				
MA 1.5: Standing on an unstable support surface with eyes closed during muscle vibration	5	115	-0.04	[-0.22, 0.14]	0%	Very low
2. Pain catastrophizing						
		No postural manipulations				
MA 2.1: Standing on a stable support surface with eyes open	3	87	0.28	[-0.10, 0.67]	72.67%	Very low
MA 2.1.1: Dynamic CoP	3	87	0.29	[-0.15, 0.74]	79.5%	Very low

Abbreviations: CI= confidence interval, MA= meta-analysis, CoP, center of pressure, I^2= statistical heterogeneity, GRADE= Grading of Recommendations, Assessment, Development, and Evaluations

Author statement

CRediT author statement is as follows:

Sofie Van Wesemael: conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft, visualization. **Katleen Bogaerts:** conceptualization, methodology, resources, writing – review & editing, supervision. **Liesbet de Baets:** conceptualization, methodology, resources, writing – review & editing, supervision. **Nina Goossens:** conceptualization, methodology, resources, writing – review & editing, supervision. **Elke Vlemincx:** conceptualization, methodology, writing – review & editing, supervision. **Charlotte Amerijckx:** conceptualization, methodology, investigation, data curation, writing – review & editing. **Suniya Sohail:** validation, investigation, writing – review & editing. **Thomas Matheve:** conceptualization, methodology, resources, writing – review & editing, supervision. **Lotte Janssens:** conceptualization, methodology, resources, writing – review & editing, supervision, project administration.

Due to the extensive amount of work regarding the methodology (quality control and meta-analyses), nine authors collaborated on this review. Thereby, there is a shared first and shared last author contribution.

Each author meets the authorship criteria.

Appendix 1: Search strategy for each database

	Pubmed	Web of Science	PsycINFO
Low back pain	(((((((low back pain) OR (spinal pain)) OR (back pain)) OR (lumbago)) OR (LBP)) OR (CLBP)) OR (back aches)) OR (lumbar pain)) OR (lumbopelvic pain)	(((((((ALL=(low back pain)) OR ALL=(spinal pain)) OR ALL=(back pain)) OR ALL=(lumbago)) OR ALL=(LBP)) OR ALL=(CLBP)) OR ALL=(back aches)) OR ALL=(lumbar pain)) OR ALL=(lumbopelvic pain)	Any Field: low back pain OR Any Field: spinal pain OR Any Field: back pain OR Any Field: lumbago OR Any Field: LBP OR Any Field: CLBP OR Any Field: back aches OR Any Field: lumbar pain OR Any Field: lumbopelvic pain
Postural control	(((((((postural balance) OR (postural control)) OR (postural sway)) OR (sway)) OR (postural stability)) OR (center of pressure)) OR (centre of pressure)) OR (stabilometr*)	(((((((ALL=(postural balance)) OR ALL=(postural control)) OR ALL=(postural sway)) OR ALL=(sway)) OR ALL=(postural stability)) OR ALL=(center of pressure)) OR ALL=(centre of pressure)) OR ALL=(stabilometr*)	Any Field: postural balance OR Any Field: postural control OR Any Field: postural sway OR Any Field: sway OR Any Field: postural stability OR Any Field: center of pressure OR Any Field: centre of pressure OR Any Field: stabilometry

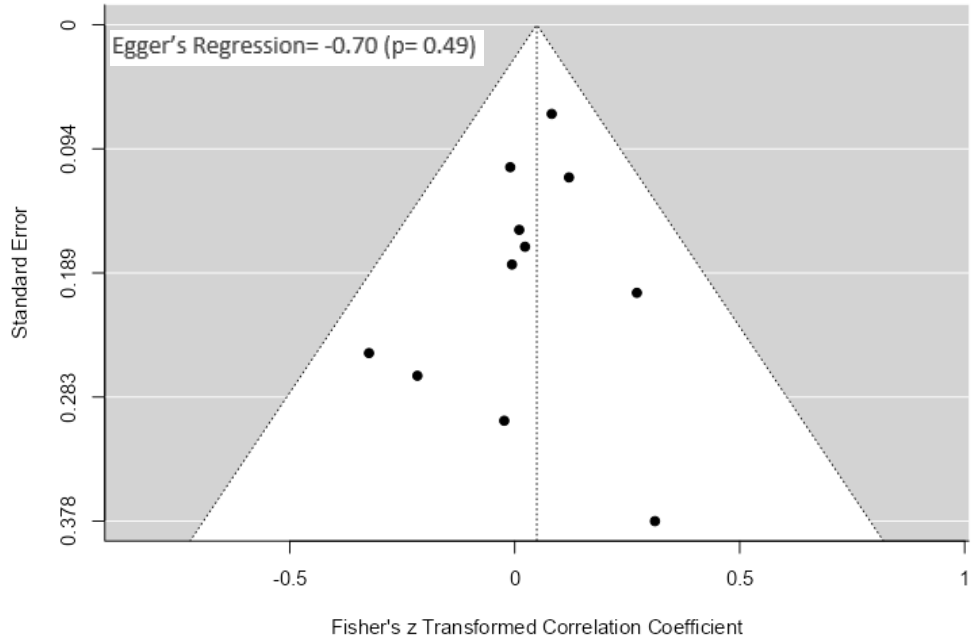
Appendix 2: Adapted QUIPS assessment form and predetermined scoring criteria

Domain	*Assessed for review?*	*Risk assessment*
1. Study Participation		
The source population or population of interest is adequately described for key characteristics.	Yes	**Low bias**: no items poorly reported **Moderate bias**: 1 or 2 items poorly reported, and baseline characteristics had to be adequately reported **High bias**: >2 items poorly reported, or poor reporting of baseline characteristics Adequate reporting of baseline characteristics: age, sex, body weight, low back pain type, pain intensity and disability
The sampling frame and recruitment are adequately described, including methods to identify the sample sufficient to limit potential bias	Yes	
Period of recruitment is adequately described	Yes	
Place of recruitment (setting and geographic location) is adequately described	Yes	
Inclusion and exclusion criteria are adequately described	Yes	
There is adequate participation in the study by eligible individuals	Yes	
The baseline study sample is adequately described for key characteristics.	Yes	
2. Study Attrition		
Response rate is adequate.	Yes	**Low bias**: data of >80% of participants available for analysis **High bias**: data of <80% of participants available for analysis Some items were not assessed because we only included cross-sectional data (including baseline data of longitudinal studies and RCTs)
Attempts to collect information on participants who dropped out	No	
Reasons for loss to follow-up are provided.	No	
Participants lost to follow-up are adequately described for key characteristics.	No	
There are no important differences between key characteristics and outcomes in participants who completed the study and those who did not.	No	
3. **Psychological Factor Measurement**		
Definition of the psychological factor	Yes	**Low bias**: no items poorly reported **Moderate bias**: 1 or 2 items poorly reported, but adequate definition of the psychological factor **High bias**: >2 items poorly reported, or poor definition of the psychological factor For adequate definition of the psychological factor, a reference to an available questionnaire should be provided, or the measurement should be adequately described in the report itself.
Valid and Reliable Measurement of the psychological factor	Yes	
Continuous variables are reported or appropriate cut-points are used.	Yes	
The method and setting of measurement of PF is the same for all study participants.	Yes	
Adequate proportion of the study sample has complete data for PF variable.	Yes	

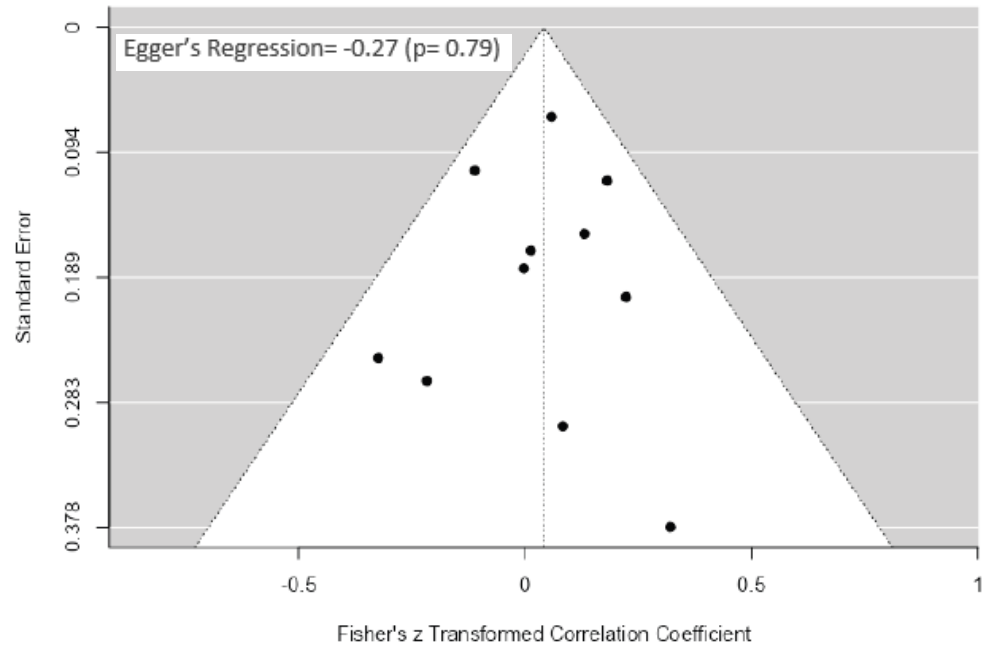
Appropriate methods of imputation are used for missing data.	No	
4. Outcome measurement		
A clear definition of outcome is provided	Yes	**Low bias**: no items poorly reported **Moderate bias**: 1 item poorly reported, but adequate definition of the outcome measurement **High bias**: >1 item poorly reported, or poor definition of the outcome measurement For adequate definition of the outcome measurement, a reference to the outcome measurement should be provided, or the outcome measurement should be adequately described in the report itself.
Valid and Reliable Measurement of Outcome	Yes	
The method and setting of measurement of the outcome is the same for all study participants.	Yes	
5. Study Confounding		
Important Confounders Measured	Yes	**Low bias**: no items poorly reported **Moderate bias**: 1 or 2 items poorly reported, or moderate accounting for confounding factors **High bias**: >2 items poorly reported or poor accounting for confounding factors Accounting for confounding factors: age, sex and body weight, type low back pain, pain intensity, disability Adequate: ≥ 3 factors taken into account Moderate: 1-3 factors taken into account Poor: no factor taken into account or correlations obtained through author contact Taking these factors into account may have been done by setting specific inclusion criteria (e.g., only inclusion of male participants) or in the statistical analyses (e.g., moderation analyses, subgroup analyses).
Clear definition of the confounding factors	Yes	
Valid and Reliable Measurement of confounders	Yes	
Method and Setting of Confounding Measurement the same for all participants	Yes	
Appropriate methods used for missing data imputation	No	
Important confounders are accounted for in the study design	Yes	
Important potential confounders are accounted for in the analysis	yes	
6. Statistical Analysis and Reporting		
There is sufficient presentation of data to assess the adequacy of the analysis.	Yes	**Low bias**: no items poorly reported **Moderate bias**: 1 or 2 items poorly reported **High bias**: >2 items poorly reported or correlation obtained through author contact because this data was not peer-reviewed thus the quality was not guaranteed
The strategy for model building is appropriate	Yes	
The selected statistical model is adequate for the design of the study.	Yes	
There is no selective reporting of results.	Yes	
Overall rating of the study		Low risk of bias: At least 4/6 domains with low risk, including the domains 'study confounding' and 'statistical analysis and reporting'. High risk of bias: When studies did not fulfill the criteria for low risk of bias.

Appendix 3: Publication bias (Funnel plots)

MA 1.2: Pain-related fear and linear center of pressure variables during standing on a stable support surface with eyes closed

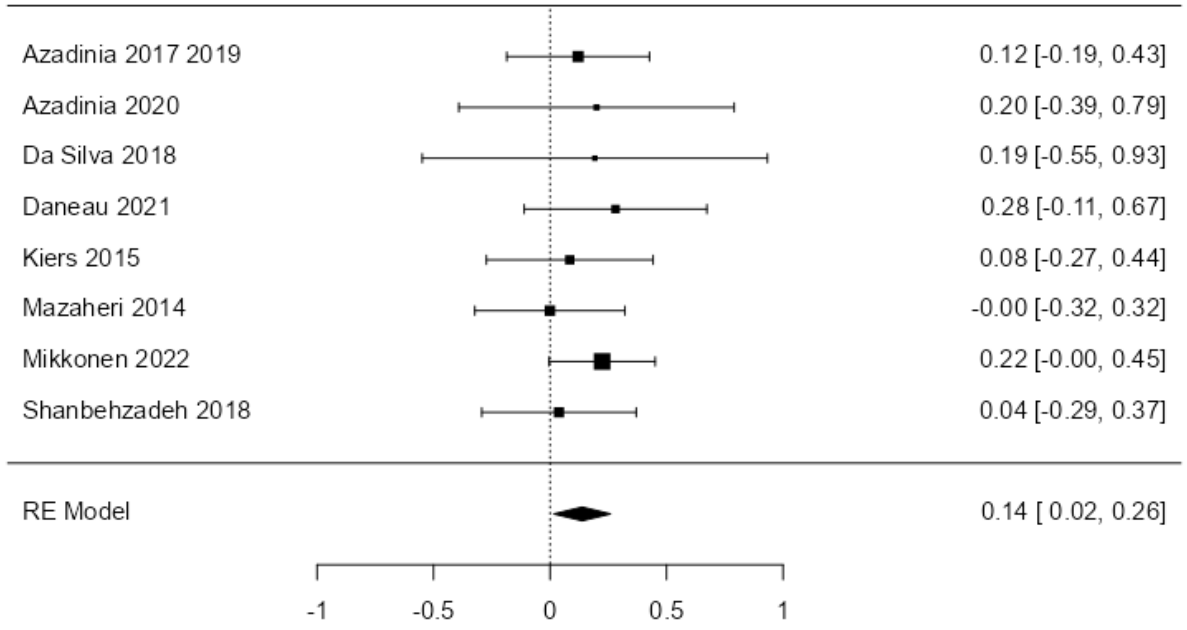


MA 1.2.1: Pain-related fear and positional center of pressure variables during standing on a stable support surface with eyes closed

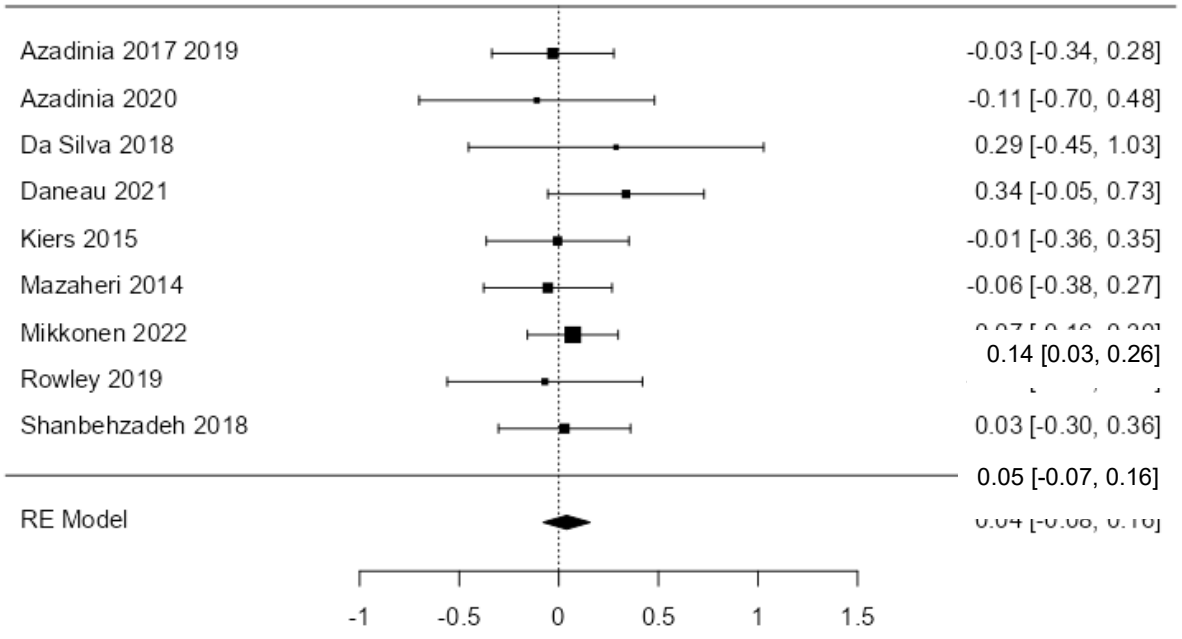


Appendix 4: Forest plots of sub-analyses

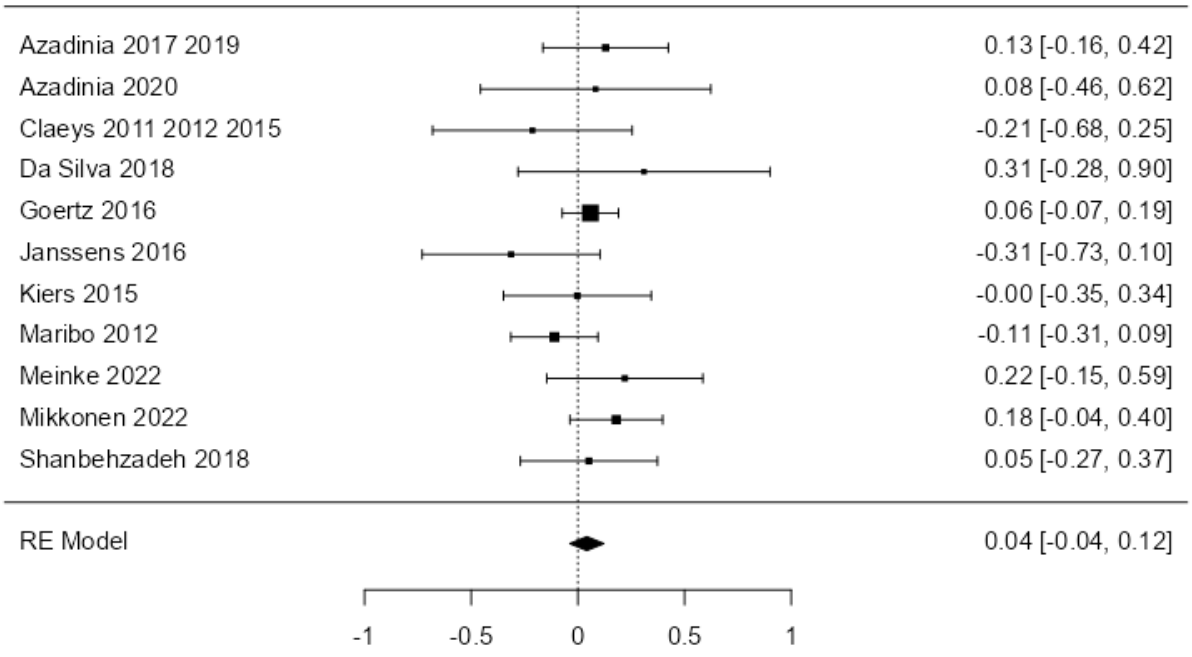
MA 1.1.1: Pain-related fear and positional center of pressure variables during standing on a stable support surface with eyes open



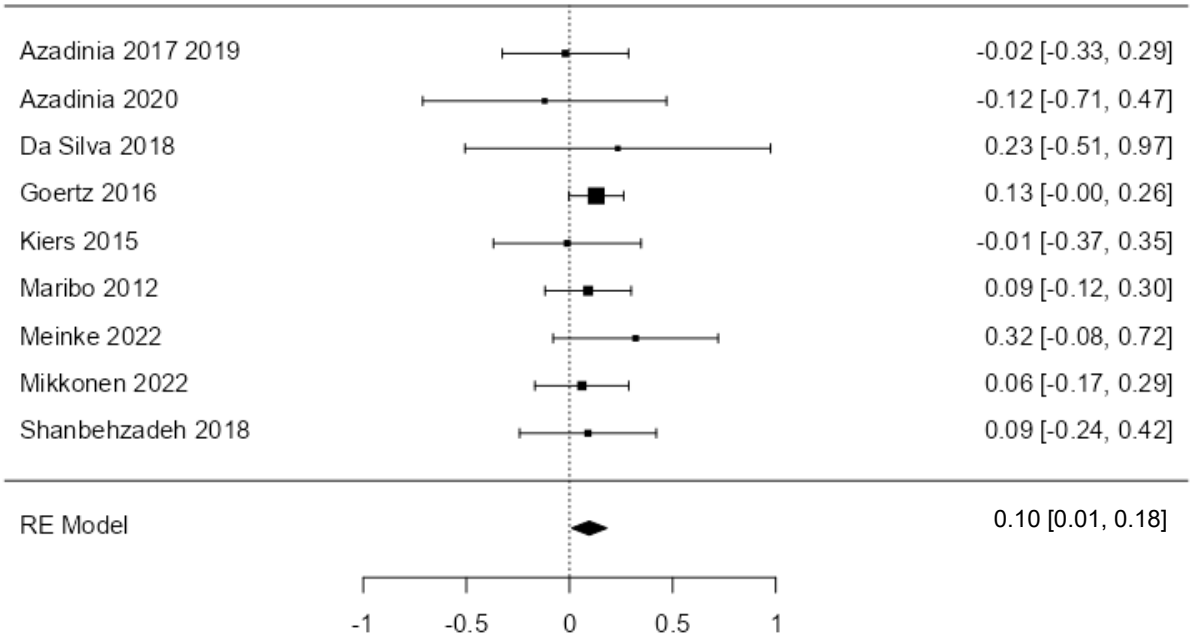
MA 1.1.2: Pain-related fear and dynamic center of pressure variables during standing on a stable support surface with eyes open



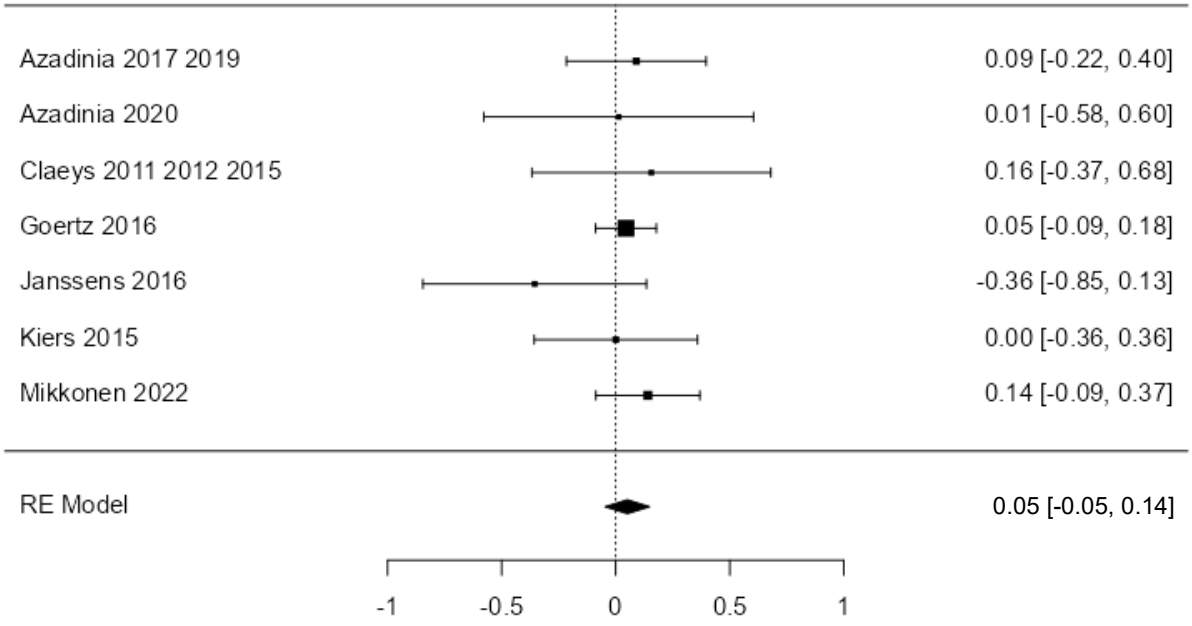
MA 1.2.1: Pain-related fear and positional center of pressure variables during standing on a stable support surface with eyes closed



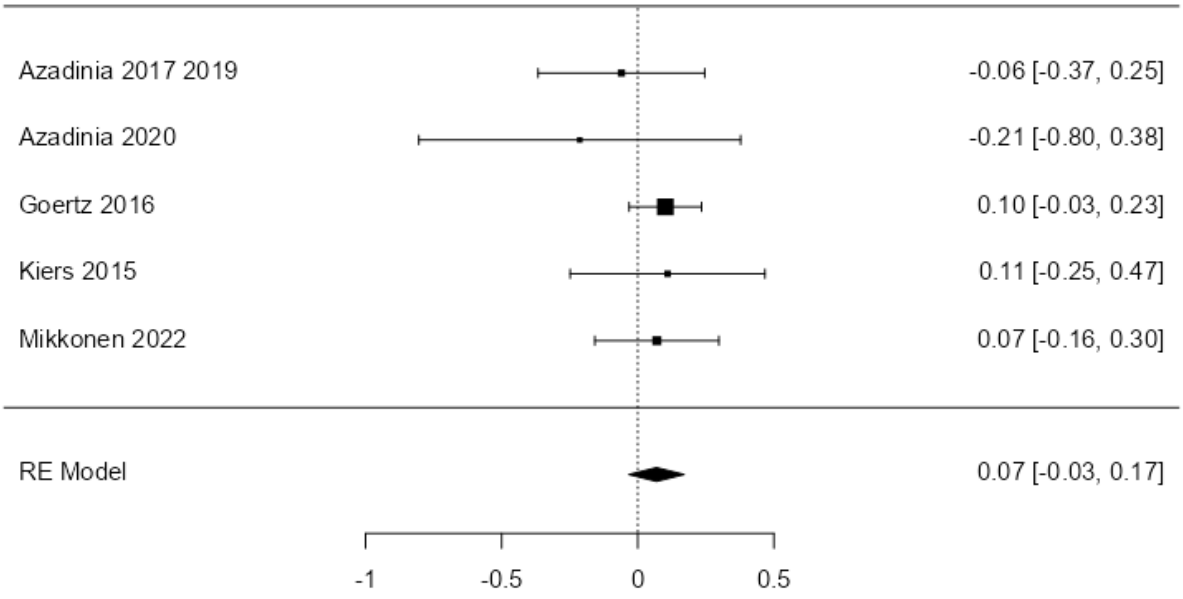
MA 1.2.2: Pain-related fear and dynamic center of pressure variables during standing on a stable support surface with eyes closed



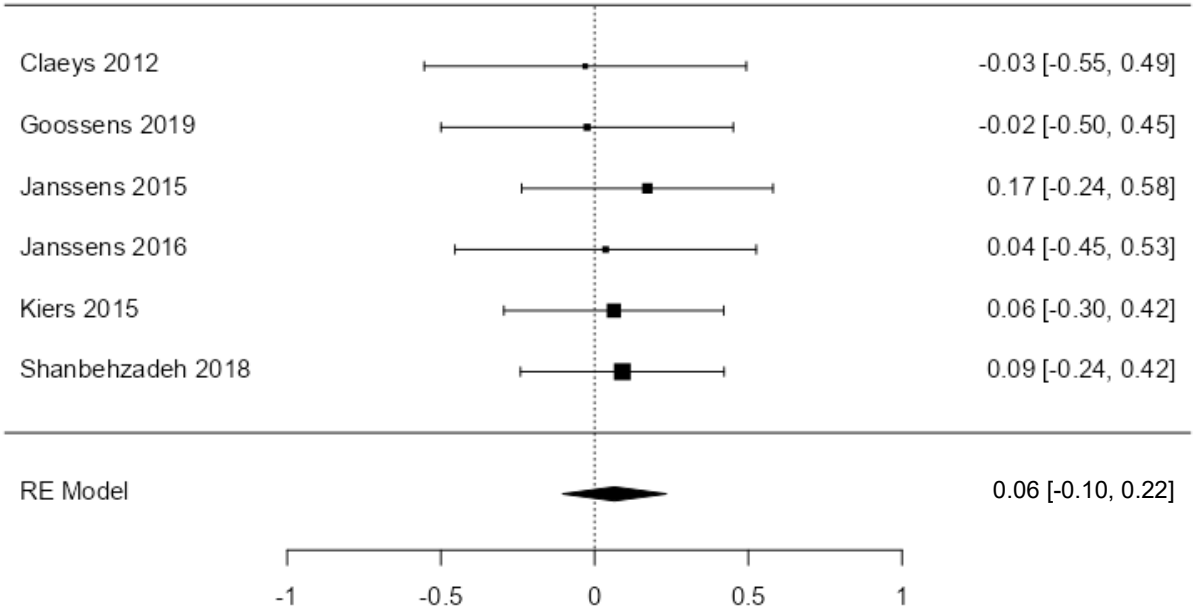
MA 1.3.1: Pain-related fear and positional center of pressure variables during standing on an unstable support surface with eyes closed



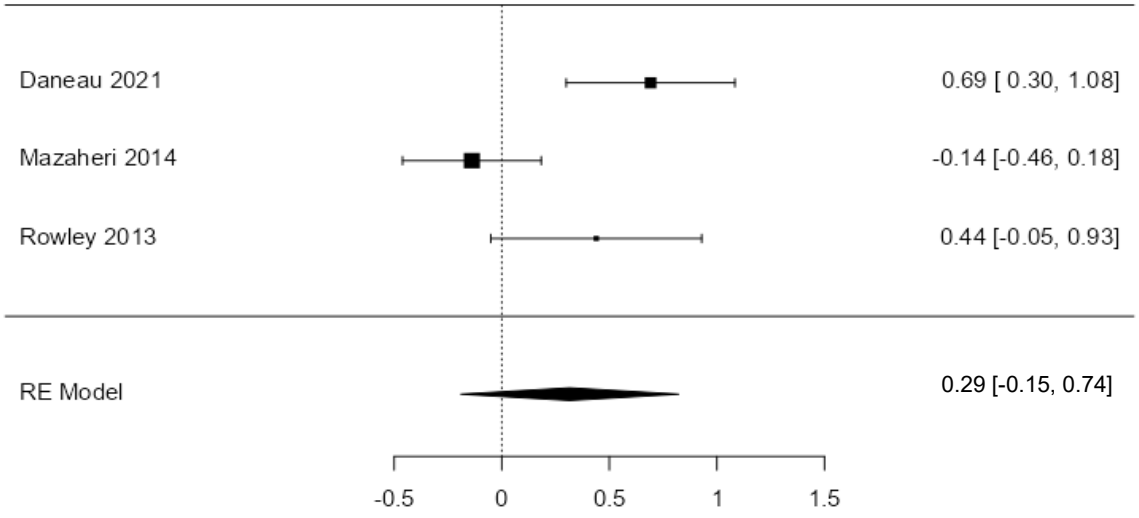
MA 1.3.2: Pain-related fear and dynamic center of pressure variables during standing on an unstable support surface with eyes closed



MA 1.4.1: Pain-related fear and positional center of pressure variables during standing on a stable support surface with eyes closed and muscle vibration



MA 2.1.1: Pain catastrophizing and dynamic center of pressure variables during standing on a stable support surface with eyes open



Appendix 5: GRADE certainty of evidence assessment

	Risk of bias	Inconsistencies	Imprecision	Publication bias	Effect size	Certainty of evidence
1. Pain-related fear						
MA 1.1: EOS	Very serious	Not serious	Serious	NA	Not serious	Very low
x Positional (MA 1.1.1)	Very serious	Not serious	Serious	NA	Not serious	Very low
x Dynamic (MA 1.1.2)	Very serious	Not serious	Serious	NA	Not serious	Very low
MA 1.2: ECS	Very serious	Not serious	Not serious	Not serious	Not serious	Very low
x Positional (MA 1.2.1)	Very serious	Not serious	Not serious	Not serious	Not serious	Very low
x Dynamic (MA 1.2.2)	Very serious	Not serious	Not serious	NA	Not serious	Very low
MA 1.3: ECU	Very serious	Not serious	Not serious	NA	Not serious	Very low
x Positional (MA 1.3.1)	Very serious	Not serious	Not serious	NA	Not serious	Very low
x Dynamic (MA 1.3.2)	Very serious	Not serious	Serious	NA	Not serious	Very low
MA 1.4: ECSV	Very serious	Not serious	Serious	NA	Not serious	Very low
x Positional (MA 1.4.1)	Very serious	Not serious	Serious	NA	Not serious	Very low
MA 1.5: ECUV	Very serious	Not serious	Serious	NA	Not serious	Very low
2. Pain catastrophizing						
MA 2.1: EOS	Very serious	Serious	Very serious	NA	Not serious	Very low
x Dynamic (MA 2.1.1)	Very serious	Serious	Very serious	NA	Not serious	Very low

Abbreviation: MA= meta-analysis, EOS= standing on stable support with eyes open, POS= positional, DYN= dynamic, FREQ= frequency, ECS= standing on stable support with eyes closed, ECU= standing on unstable support with eyes closed, ECSV= standing on stable support with eyes closed and muscle vibration, ECUV= standing on unstable support with eyes closed and muscle vibration, NA= non-applicable)

Appendix 6: Correlation coefficients

MA 1.1: Pain-related fear and linear center of pressure during standing on a stable support surface with eyes open

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Correlation coefficient*
Azadinia (2017 & 2019)	TSK	Positional	CoP area	0.12
		Dynamic	CoP mean velocity total	-0.02
			SD CoP mean velocity AP	-0.05
			SD CoP mean velocity ML	-0.02
			Phase plane parameter total	-0.01
			Phase plane parameter AP	0.03
			Phase plane parameter ML	-0.09
Azadinia (2020)	TSK	Positional	CoP area	0.21
			SD CoP displacement AP	0.37
			SD CoP displacement ML	0.01
		Dynamic	CoP mean velocity total	-0.14
			SD CoP mean velocity AP	-0.21
			SD CoP mean velocity ML	-0.06
			Phase plane parameter total	-0.09
			Phase plane parameter AP	-0.12
			Phase plane parameter ML	-0.06
Da Silva (2018)	FABQ-PA	Positional	CoP area	0.29
		Dynamic	CoP mean velocity AP	0.36
			CoP mean velocity ML	0.06
			CoP mean frequency AP	0.33
			CoP mean frequency ML	0.1
	FABQ-W	Positional	CoP area	0.09
		Dynamic	CoP mean velocity AP	0.42
			CoP mean velocity ML	0.27
			CoP mean frequency AP	0.06
			CoP mean frequency ML	0.6
Daneau (2021)	TSK	Positional	CoP displacement AP	0.18
			CoP displacement AP	0.30
		Dynamic	CoP mean velocity total	0.27
			CoP mean velocity total	0.37

	FABQ-PA	Positional	CoP displacement AP	0.07
			CoP displacement AP	0.24
		Dynamic	CoP mean velocity total	0.02
			CoP mean velocity total	0.25
	FABQ-W	Positional	CoP displacement AP	**0.40***
			CoP displacement AP	0.25
		Dynamic	CoP mean velocity total	**0.42***
			CoP mean velocity total	**0.38***
Kiers (2015)	FABQ-PA	Positional	CoP displacement AP	0.19
			CoP displacement ML	0.15
			SD CoP displacement AP	0.10
			SD CoP displacement ML	0.07
		Dynamic	CoP mean velocity total	-0.09
			CoP mean velocity AP	-0.05
			CoP mean velocity ML	-0.12
		Frequency	CoP mean power frequency AP	-0.16
			CoP mean power frequency ML	-0.08
	FABQ-W	Positional	CoP displacement AP	0.06
			CoP displacement ML	0.01
			SD CoP displacement AP	-0.01
			SD CoP displacement ML	0.12
		Dynamic	CoP mean velocity total	0.17
			CoP mean velocity AP	-0.17
			CoP mean velocity ML	0.22
			CoP mean power frequency AP	-0.13
			CoP mean power frequency ML	0.20
Mazaheri (2014)	TSK	Positional	SD CoP displacement AP	0.09
			SD CoP displacement ML	-0.09
		Dynamic	CoP mean velocity total	-0.06
		Frequency	CoP mean power frequency AP	-0.12
			CoP mean power frequency ML	-0.14
Mikkonen (2022)	TSK	Positional	CoP area	**0.22***
		Dynamic	CoP mean velocity total	0.07
Rowley (2019)	TSK	Dynamic	CoP mean velocity total	-0.03
	FABQ-PA		CoP mean velocity total	0.16
	FABQ-W		CoP mean velocity total	-0.27

Shanbehzadeh (2018)	TSK	Positional	CoP area	0.21
			CoP displacement AP	0.30
			CoP displacement ML	0.09
		Dynamic	CoP mean velocity total	0.10
	FABQ-PA	Positional	CoP area	-0.19
			CoP displacement AP	0.16
			CoP displacement ML	-0.06
		Dynamic	CoP mean velocity total	0.03
	PASS-20	Positional	CoP area	**-0.40***
			CoP displacement AP	0.19
			CoP displacement ML	-0.00
		Dynamic	CoP mean velocity total	-0.05

Abbreviations: CoP= center of pressure, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety scale, AP= antero-posterior, ML= medio-lateral, SD= standard deviation, *= significant

MA 1.2: Pain-related fear and linear center of pressure during standing on a stable support surface with eyes closed

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Correlation coefficient*
Azadinia (2017 & 2019)	TSK	Positional	CoP area	0.13
		Dynamic	CoP mean velocity total	0.12
			SD CoP mean velocity AP	-0.05
			SD CoP mean velocity ML	-0.16
			Phase plane parameter total	-0.10
			Phase plane parameter AP	-0.02
			Phase plane parameter ML	0.08
Azadinia (2020)	TSK	Positional	CoP area	0.09
			SD CoP displacement AP	0.17
			SD CoP displacement ML	-0.01
		Dynamic	CoP mean velocity total	-0.13
			SD CoP mean velocity AP	-0.13
			SD CoP mean velocity ML	-0.13
			Phase plane parameter total	-0.12
			Phase plane parameter AP	-0.09
			Phase plane parameter ML	-0.13
Claeys (2011, 2012 & 2015)	TSK	Positional	SD CoP displacement AP	-0.37
	FABQ-PA		SD CoP displacement AP	0.17
	FABQ-W		SD CoP displacement AP	-0.44
Da Silva (2018)	FABQ-PA	Positional	CoP area	0.11
		Dynamic	CoP mean velocity AP	0.01
			CoP mean velocity ML	0.16
			CoP mean frequency AP	0.04
			CoP mean frequency ML	0.29
	FABQ-W	Positional	CoP area	0.51
		Dynamic	CoP mean velocity AP	0.44
			CoP mean velocity ML	0.58
			CoP mean frequency AP	0.07
			CoP mean frequency ML	0.27
Goertz (2016)	FABQ-PA	Positional	CoP displacement AP	0.06
			CoP displacement ML	0.07
		Dynamic	CoP mean velocity total	0.12

	FABQ-W	Positional	CoP displacement AP	0.11
			CoP displacement ML	-0.01
		Dynamic	CoP mean velocity total	**0.14***
Janssens (2016)	TSK	Positional	CoP displacement AP	-0.31
Kiers (2015)	FABQ-PA	Positional	CoP displacement AP	-0.10
			CoP displacement ML	-0.06
			sdCoP displacement AP	-0.14
			sdCoP displacement ML	-0.15
		Dynamic	CoP mean velocity total	-0.18
			CoP mean velocity AP	-0.22
		Frequency	CoP mean power frequency AP	0.18
			CoP mean power frequency ML	-0.03
	FABQ-W	Positional	CoP displacement AP	0.05
			CoP displacement ML	0.14
			SD CoP displacement AP	0.11
			SD CoP displacement ML	0.12
		Dynamic	CoP mean velocity total	0.10
			CoP mean velocity AP	0.09
			CoP mean velocity ML	0.20
		Frequency	CoP mean power frequency AP	0.13
			CoP mean power frequency ML	0.13
Maribo (2012)	FABQ-PA	Positional	CoP displacement AP	-0.11
		Dynamic	CoP mean velocity total	0.09
Meinke (2022)	TSK	Positional	CoP displacement AP	0.13
			CoP displacement ML	0.31
		Dynamic	CoP mean velocity AP	0.19
			CoP mean velocity ML	**0.43***
Mikkonen (2022)	TSK	Positional	CoP area	**0.18***
		Dynamic	CoP mean velocity total	0.06
Shanbehzadeh (2018)	TSK	Positional	CoP area	0.22
			CoP displacement AP	0.07
			CoP displacement ML	0.19
		Dynamic	CoP mean velocity total	0.19
	FABQ-PA	Positional	CoP area	-0.30
			CoP displacement AP	-0.05
			CoP displacement ML	-0.06

		Dynamic	CoP mean velocity total	-0.09
	PASS-20	Positional	CoP area	-0.16
			CoP displacement AP	0.21
			CoP displacement ML	0.11
		Dynamic	CoP mean velocity total	0.02

Abbreviations: CoP= center of pressure variable, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety scale, AP= antero-posterior, ML= medio-lateral, SD= standard deviation, *= significant

MA 1.3: Pain-related fear and linear center of pressure during standing on an unstable support surface with eyes closed

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Correlation coefficient*
Azadinia (2017 & 2019)	TSK	Positional	CoP area	0.09
		Dynamic	CoP mean velocity total	-0.17
			SD CoP mean velocity AP	-0.02
			SD CoP mean velocity ML	-0.25
			Phase plane portrait total	-0.15
			Phase plane portrait AP	-0.01
			Phase plane portrait ML	0.24
Azadinia (2020)	TSK	Positional	CoP area	-0.05
			SD CoP displacement AP	0.05
			SD CoP displacement ML	0.04
		Dynamic	CoP mean velocity total	-0.20
			SD CoP mean velocity AP	-0.30
			SD CoP mean velocity ML	-0.15
			Phase plane portrait total	-0.20
			Phase plane portrait AP	-0.27
			Phase plane portrait ML	-0.14
Claeys (2011, 2012 & 2015)	FABQ-PA	Positional	SD CoP displacement AP	0.27
	FABQ-W		SD CoP displacement AP	0.05
Goertz (2016)	FABQ-PA	Positional	CoP displacement AP	0.03
			CoP displacement ML	0.01
		Dynamic	CoP mean velocity total	0.06
	FABQ-W	Positional	CoP displacement AP	0.11
			CoP displacement ML	0.04
		Dynamic	CoP mean velocity total	**0.14***
Janssens (2016)	TSK	Positional	CoP displacement AP	-0.34
Kiers (2015)	FABQ-PA	Positional	CoP displacement AP	-0.17
			CoP displacement ML	-0.05
			SD CoP displacement AP	-0.25
			SD CoP displacement ML	-0.11
		Dynamic	CoP mean velocity total	-0.09
			CoP mean velocity AP	-0.15

			CoP mean velocity ML	-0.06
		Frequency	CoP mean power frequency AP	0.16
			CoP mean power frequency ML	-0.05
	FABQ-W	Positional	CoP displacement AP	0.15
			CoP displacement ML	0.17
			sdCoP displacement AP	0.19
			sdCoP displacement ML	0.15
		Dynamic	CoP mean velocity total	0.33
			CoP mean velocity AP	0.26
			CoP mean velocity ML	**0.36***
		Frequency	CoP mean power frequency AP	**0.37***
			CoP mean power frequency ML	0.07
Mikkonen (2022)	TSK	Positional	CoP area	0.14
		Dynamic	CoP mean velocity total	0.07

Abbreviations: CoP variable= center of pressure variable, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety symptom scale, AP= antero-posterior, ML= medio-lateral, SD= standard deviation, *= significant

MA 1.4: Pain-related fear and linear center of pressure during standing on a stable support surface with eyes closed and muscle vibration

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Location vibration*	*Correlation coefficient*
Claeys (2011, 2012 & 2015)	TSK	Positional	CoP displacement AP	Ankle	-0.38
			CoP displacement AP	Back	0.39
	FABQ-PA		CoP displacement AP	Ankle	0.16
			CoP displacement AP	Back	-0.16
	FABQ-W		CoP displacement AP	Ankle	-0.19
			CoP displacement AP	Back	0.00
Goossens (2019)	TSK	Positional	CoP displacement AP	Ankle	0.01
			CoP displacement AP	Back	0.19
			CoP displacement AP	Ankle and back	0.06
	FABQ-PA		CoP displacement AP	Ankle	0.05
			CoP displacement AP	Back	0.03
			CoP displacement AP	Ankle and back	0.17
	FABQ-W		CoP displacement AP	Ankle	-0.35
			CoP displacement AP	Back	-0.05
			CoP displacement AP	Ankle and back	-0.33
Janssens (2015)	TSK	Positional	CoP displacement AP	Ankle	0.32
			CoP displacement AP	Back	0.21
			CoP displacement AP	Ankle and back	0.14
	FABQ-PA		CoP displacement AP	Ankle	0.09
			CoP displacement AP	Back	-0.03
			CoP displacement AP	Ankle and back	0.05
	FABQ-W		CoP displacement AP	Ankle	-0.10
			CoP displacement AP	Back	0.04
			CoP displacement AP	Ankle and back	0.29
Janssens (2016)	TSK	Positional	CoP displacement AP	Ankle	0.24
			CoP displacement AP	Back	-0.17
Kiers (2015)	FABQ-PA	Positional	CoP displacement AP	Ankle	0.10
			CoP displacement AP	Back	0.01
	FABQ-W		CoP displacement AP	Ankle	-0.10
			CoP displacement AP	Back	0.24
Shanbehzadeh (2018)	TSK	Positional	CoP displacement AP	Ankle	**0.36***
			CoP displacement ML	Ankle	0.17

			CoP area	Ankle	0.30
		Dynamic	CoP total velocity	Ankle	0.32
	FABQ-PA		CoP displacement AP	Ankle	0.18
			CoP displacement ML	Ankle	-0.15
			CoP area	Ankle	-0.08
		Dynamic	CoP total velocity	Ankle	0.06
	PASS-20		CoP displacement AP	Ankle	0.20
			CoP displacement ML	Ankle	-0.18
			CoP area	Ankle	-0.03
		Dynamic	CoP total velocity	Ankle	-0.14

*Abbreviations: COP variable= center of pressure variable, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety symptom scale, AP= antero-posterior, *= significant correlation*

MA 1.5: Pain-related fear and linear center of pressure during standing on an unstable support surface with eyes closed and muscle vibration

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Vibration location*	*Correlation coefficient*
Claeys (2011, 2012 & 2015)	TSK	Positional	CoP displacement AP	Ankle	-0.08
			CoP displacement AP	Back	-0.01
	FABQ-PA		CoP displacement AP	Ankle	-0.33
			CoP displacement AP	Back	0.17
	FABQ-W		CoP displacement AP	Ankle	-0.09
			CoP displacement AP	Back	0.04
Goossens (2019)	TSK	Positional	CoP displacement AP	Ankle	-0.06
			CoP displacement AP	Back	0.25
			CoP displacement AP	Ankle and back	-0.30
	FABQ-PA		CoP displacement AP	Ankle	-0.11
			CoP displacement AP	Back	-0.14
			CoP displacement AP	Ankle and back	-0.31
	FABQ-W		CoP displacement AP	Ankle	-0.41
			CoP displacement AP	Back	0.36
			CoP displacement AP	Ankle and back	**-0.47***
Janssens (2015)	TSK	Positional	CoP displacement AP	Ankle	0.08
			CoP displacement AP	Back	-0.02
			CoP displacement AP	Ankle and back	0.07
	FABQ-PA		CoP displacement AP	Ankle	0.15
			CoP displacement AP	Back	-0.13
			CoP displacement AP	Ankle and back	-0.09
	FABQ-W		CoP displacement AP	Ankle	0.11
			CoP displacement AP	Back	0.16
			CoP displacement AP	Ankle and back	0.01
Janssens (2016)	TSK	Positional	CoP displacement AP	Ankle	0.25
			CoP displacement AP	Back	-0.18
Kiers (2015)	FABQ-PA	Positional	CoP displacement AP	Ankle	-0.25
			CoP displacement AP	Back	-0.15
	FABQ-W		CoP displacement AP	Ankle	-0.17
			CoP displacement AP	Back	-0.12
			Mean power frequency ML	Back	

Abbreviations*: COP variable= center of pressure variable, POS= positional COP,* TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, AP= anteroposterior*= significant correlation

MA 2.1: Pain catastrophizing and linear center of pressure during standing on a stable support surface with eyes open

First author (publication year)	*Pain-related psychological variable questionnaire*	*Linear CoP category*	*Specific CoP variable*	*Correlation coefficient*
Daneau (2021)	PCS	Positional	CoP displacement AP	**0.45***
			CoP displacement AP	**0.49***
		Dynamic	CoP mean velocity total	**0.59***
			CoP mean velocity total	**0.61***
Mazaheri (2014)	PCS	Positional	SD CoP displacement AP	-0.05
			SD CoP displacement ML	**-0.28***
		Dynamic	CoP mean velocity total	-0.14
		Frequency	CoP mean power frequency AP	0.05
			CoP mean power frequency ML	-0.06
Rowley (2019)	PCS	Dynamic	CoP mean velocity total	0.41

COP variable= center of pressure, PCS= pain catastrophizing scale, AP= antero-posterior, ML= mediolateral, *= significant correlation

Not included in meta-analyses: pain-related psychological variables and non-linear CoP variables

First author (publication year)	*Pain-related psychological variable questionnaire*	*Specific CoP variable*	*Correlation coefficient*
	Standing on a stable support surface with eyes open		
Azadinia (2017 & 2019)	TSK	Sample entrophy AP	0.05
		Sample entrophy ML	0.23
		Correlation dimension AP	0.14
		Correlation dimension ML	0.07
		Percentage of determinism AP	-0.04
		Percentage of determinism ML	-0.16
Azadinia (2020)	TSK	Sample entrophy AP	-0.39
		Sample entrophy ML	0.04
		Correlation dimension AP	-0.44
		Correlation dimension ML	0.03
		Lyapunov exponent AP	0.3
		Lyapunov exponent ML	0.18
Kiers (2015)	FABQ-PA	Mean diagonal length	0.23
		Recurrence entrophy	0.23
		Determinism	0.2
		Recurrence rate	0.18
		Lyapunov exponent	-0.3
		Sample entrophy total	**-0.39**
	FABQ-W	Mean diagonal length	-0.34
		Recurrence entrophy	-0.34
		Determinism	**-0.38**
		Recurrence rate	-0.29
		Lyapunov exponent	0.24
		Sample entrophy total	0.31
Mazaheri (2014)	PCS	Sample entrophy total	0.13

	TSK	Sample entrophy total	-0.09
	Standing on a stable support surface with eyes closed		
Azadinia (2017 & 2019)	TSK	Sample entrophy AP	-0.01
		Sample entrophy ML	0.02
		Correlation dimension AP	-0.01
		Correlation dimension ML	0.01
		Percentage of determinism AP	-0.03
		Percentage of determinism ML	-0.03
Azadinia (2020)	TSK	Sample entrophy AP	-0.39
		Sample entrophy ML	-0.03
		Correlation dimension AP	-0.42
		Correlation dimension ML	-0.01
		Lyapunov exponent AP	0.35
		Lyapunov exponent ML	-0.1
Kiers (2015)	FABQ-PA	Mean diagonal length	0.06
		Recurrence entrophy	0.08
		Determinism	0.07
		Recurrence rate	0.03
		Lyapunov exponent	-0.17
		Sample entrophy total	-0.07
	FABQ-W	Mean diagonal length	-0.12
		Recurrence entrophy	-0.17
		Determinism	-0.16
		Recurrence rate	-0.07
		Lyapunov exponent	0.12
		Sample entrophy total	0.2
	Standing on an unstable support surface with eyes closed		
Azadinia (2017 & 2019)	TSK	Sample entrophy AP	0.12
		Sample entrophy ML	0.15
		Correlation dimension AP	-0.06
		Correlation dimension ML	0.13

		Percentage of determinism ML	-0.14
		Percentage of determinism AP	-0.13
Azadinia (2020)	TSK	Sample entrophy AP	-0.27
		Sample entrophy ML	-0.07
		Correlation dimension AP	-0.18
		Correlation dimension ML	**-0.59**
		Lyapunov exponent AP	0.05
		Lyapunov exponent ML	0.48
Kiers (2015)	FABQ-PA	Mean diagonal length	-0.01
		Recurrence entrophy	-0.08
		Determinism	-0.1
		Recurrence rate	-0.26
		Lyapunov exponent	0.01
		Sample entrophy total	-0.01
	FABQ-W	Mean diagonal length	-0.29
		Recurrence entrophy	-0.34
		Determinism	-0.33
		Recurrence rate	-0.25
		Lyapunov exponent	0.32
		Sample entrophy total	0.3
	Standing on a stable support surface with eyes open while performing a dual task		
Mazaheri (2014)	PCS	Sample entrophy total	-0.08
	TSK	Sample entrophy total	-0.05

Abbreviations: CoP= center of pressure variable, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety scale, AP= antero-posterior, ML= medio-lateral, SD= standard deviation, *= significant

Not including in meta-analyses: Pain-related psychological variables and CoP variables during remaining tasks

First author (publication year)	*Pain-related psychological variable questionnaire*	*CoP category*	*Specific CoP variable*	*Correlation coefficient*
	Standing on a stable support surface with eyes open while performing a dual task			
Mazaheri (2014)	PCS	Frequency	CoP mean power frequency AP	-0.03
			CoP mean power frequency ML	0.09
		Dynamic	CoP mean velocity total	0.06
		Positional	SD CoP displacement AP	0.02
			SD CoP displacement ML	0.02
		Non-linear	Sample entrophy	-0.08
	TSK	Dynamic	CoP mean velocity total	0.02
		Frequency	CoP mean power frequency AP	0.05
			CoP mean power frequency ML	0.02
		Positional	SD CoP displacement AP	0.01
			SD CoP displacement ML	0.05
		Non-linear	Sample entrophy	-0.05
Shanbehzadeh (2018)	FABQ-PA	Dynamic	CoP mean velocity total	-0.07
		Positional	CoP area	-0.29
			CoP displacement ML	0.01
			CoP displacement AP	0.05
	TSK	Dynamic	CoP mean velocity total	0.07
		Positional	CoP displacement ML	-0.14
			CoP displacement AP	0.02
			CoP area	0.17
	PASS-20	Dynamic	CoP mean velocity total	-0.15
		Positional	CoP displacement ML	-0.01
			CoP displacement AP	-0.04
			CoP area	-0.24
	Standing on an unstable support surface with eyes open			
Mikkonen (2022)	TSK	Dynamic	CoP mean velocity total	0.12
		Positional	CoP area	**0.22***
	Standing on a stable support surface with eyes closed while performing a dual task			
Shanbehzadeh (2018)	FABQ-PA	Dynamic	CoP mean velocity total	-0.14
		Positional	CoP area	-0.24

			CoP displacement ML	-0.21
			CoP displacement AP	-0.03
	TSK	Dynamic	CoP mean velocity total	0.09
		Positional	CoP displacement ML	0.02
			CoP displacement AP	0.06
			CoP area	0.25
	PASS-20	Dynamic	CoP mean velocity total	-0.03
		Positional	CoP displacement ML	-0.03
			CoP displacement AP	0.14
			CoP area	-0.27
	Standing on a stable support surface with eyes closed with muscle vibration while performing a dual task			
Shanbehzadeh (2018)	FABQ-PA	Dynamic	CoP mean velocity total	0.03
		Positional	CoP area	-0.12
			CoP displacement AP	-0.10
			CoP displacement ML	-0.11
	TSK	Dynamic	CoP mean velocity total	0.24
		Positional	CoP area	0.13
			CoP displacement AP	0.05
			CoP displacement ML	0.09
	PASS-20	Dynamic	CoP mean velocity total	-0.04
		Positional	CoP area	-0.09
			CoP displacement AP	-0.17
			CoP displacement ML	-0.05
	Standing on a stable support surface with eyes open and muscle vibration			
Shanbehzadeh (2018)	FABQ-PA	Dynamic	CoP mean velocity total	-0.11
		Positional	CoP area	-0.17
			CoP displacement ML	-0.12
			CoP displacement AP	-0.02
	TSK	Dynamic	CoP mean velocity total	0.13
		Positional	CoP displacement ML	0.04
			CoP area	0.29
			CoP displacement AP	0.32
	PASS-20	Dynamic	CoP mean velocity total	-0.11
		Positional	CoP displacement ML	-0.09

			CoP area	-0.09
			CoP displacement AP	0.19
	Standing on a stable support surface with eyes open and muscle vibration while performing a dual task			
Shanbehzadeh (2018)	FABQ-PA	Dynamic	CoP mean velocity total	0.04
		Positional	CoP displacement ML	-0.18
			CoP area	-0.07
			CoP displacement AP	0.07
	TSK	Dynamic	CoP mean velocity total	0.07
		Positional	CoP displacement AP	0.02
			CoP displacement ML	0.11
			CoP area	0.16
	PASS-20	Dynamic	CoP mean velocity total	-0.15
		Positional	CoP displacement AP	-0.16
			CoP displacement ML	-0.21
			CoP area	-0.24

Abbreviations: CoP= center of pressure variable, TSK= tampa scale for kinesiophobia, FABQ-PA= fear avoidance beliefs questionnaire physical activity subscale, FABQ-W= fear avoidance beliefs questionnaire work subscale, PASS-20= pain anxiety scale, AP= antero-posterior, ML= medio-lateral, SD= standard deviation, *= significant