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Review

Failed single-leg assessment of postural stability after anterior cruciate ligament injuries and reconstruction: An updated systematic review and meta-analysis

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ABSTRACT

Background: Postural control deficits and persistent joint stability issues are prevalent in population with anterior cruciate ligament (ACL) injuries or reconstructions. Postural control is typically assessed using the center of pressure (CoP) parameters during the static single-leg stance with a force plate. However, previous studies have reported unclear definitions and descriptions of the CoP parameters, causing inconsistent results of postural control deficits in a specific population.

Objective: To 1) summarize CoP parameters commonly used to evaluate postural control deficits in ACL injured or reconstructed population, and 2) identify the differences in CoP parameters with opened and closed eyes during the single-leg stance between ACL injured or reconstructed and control groups.

Methods: PubMed, Embase, Cochrane Library, CINAHL, Scopus, Web of Science, and SPORTDiscus databases were searched up to July 2023. Data were obtained from the selected articles and underwent quality and risk of bias assessment and meta-analysis using random-effect models. Subgroup analysis within ACL injured or reconstructed group were also performed.

Results: A total of 14 articles were included in the analysis after screening. The injured knee of the ACL injured or reconstructed group differed insignificantly in sway amplitude, sway area, and sway velocity during static single-leg stance under opened and closed eyes when compared with the control group. In the subgroup analysis, we found that there was only significant difference in sway velocity with open eyes ($SMD = 0.47$, $p = 0.001$) between ACL reconstructed group and control group.

Conclusion: This study summarized the common CoP parameters used to evaluate postural control in ACL injured or reconstructed population. The results only showed weak difference in sway velocity between ACL reconstructed population and healthy individuals with opened eyes during the static single-leg stance.

1. Introduction

Anterior cruciate ligament (ACL) rupture is a common knee injury in daily life and sports, and is a risk factor for the development of knee osteoarthritis. It has an estimated occurrence of 200 000 cases annually in the United States, with an average lifetime cost of $38 121 per injury in medical care.[1,2] Individuals with ACL injuries (ACLI) generally undergo anterior cruciate ligament reconstruction (ACLR)[3] and rehabilitation programs afterward to restore the mechanical stability of the knee joint and re-establish knee function.[4] However, functional deficits that may cause persistent knee joint instability and even re-rupture during joint movement still exist in patients with ACL injuries after surgeries or rehabilitation.[4] Therefore, it is beneficial for clinical diagnosis and treatment through the in-depth exploration of the underlying mechanisms of the above functional deficits.

Postural control is defined as the ability to monitor and control the position of the body in space for the dual purposes of stability and

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Abbreviations

ACL	anterior cruciate ligament
ACLR	anterior cruciate ligament reconstruction
ACLI	anterior cruciate ligament injuries
AP	anterior-posterior
ML	medial-lateral
CoP	center of pressure
SMD	standardized mean difference
CI	confidence interval
SD	standard deviation
EAI	epidemiological appraisal instrument

orientation.[5] The postural control system involves complex interactions between the musculoskeletal and neural systems, including components of sensory inputs (e.g., visual, vestibular, and somatosensory inputs), neural processing, nerve conduction, muscle reflex, and joint range of motion.[5] Impaired postural control, resulting from reduced or altered sensory information at the knee, is an ACL injury characteristic that has gotten much research attention.[6,7] Most updated theories proposed that a reduced sensory relay from the knee to the central nervous system results in a reduced ability to control the lower limbs, thereby causing a repetitive cycle of sensory impairment and postural control deficits in the knee.[8–11] Therefore, it is important to assess and treat the postural control deficits of the population of ACL injuries or reconstruction. However, although there are many methods to measure postural control,[12] there is no consensus on a standardized measure of ACL-specific postural control deficits.

The center of pressure (CoP) trajectory during static single-leg stance is measured using a force plate and is significantly the most frequently used method to assess the postural control in the ACL injured or reconstructed population.[6,7] The CoP, which was described using many variables (e.g., sway amplitude, sway area, and sway velocity), is the center of the weighted average of all pressures created from the feet in contact with the force plate, and these variables describing the CoP trajectory indicated postural deficits (e.g., larger CoP sway, worse postural control).[5,13] However, many previous studies have used force plates to measure postural control deficits with inconsistent results in the ACL injured or reconstructed population because of their small sample sizes or inconsistent selection of COP parameters.[14–17] Therefore, systematic reviews and meta-analyses are needed to address the above problems. Meanwhile, there was a recent review of CoP parameters for evaluating postural control deficits in the ACL injured or reconstructed population, but the definition and description of the CoP parameters were unclear.[6] Furthermore, the review was performed more than five years ago, and, therefore, an updated review on this topic with detailed CoP outcomes definition and subgroup analyses were required.

This study aimed to (1) summarize CoP parameters commonly used to evaluate postural control deficits in the ACL injured or reconstructed population, and (2) determine the differences in CoP parameters with opened and closed eyes during the single-leg stance between ACL injured or reconstructed and control groups. It was hypothesized that compared with healthy controls, the ACL injured or reconstructed population would exhibit greater postural control deficits (e.g., larger CoP sway) based on the results of the previous study.[6]

2. Material and methods

2.1. Study design

The system review and meta-analysis were performed following the reporting guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses.[18] The study protocol has been registered at the International Prospective Register of Systematic Reviews (CRD42022307093).

2.2. Search strategy

A systematic literature search was conducted independently by two of the authors using seven databases: PubMed, Embase, Cochrane Library, CINAHL, Scopus, Web of Science, and SPORTDiscus from their earliest available date to July 2023 to obtain all related articles investigating postural stability in patients with ACL injury or reconstruction. The search strategy comprised of keywords and synonyms that combined the following strings with “AND”: (1) ACL-related, (2) injury-related, and (3) posture-related. Search terms within each string were combined with “OR.” The full search strategies are presented in Supplementary Appendix 1. Reference lists of articles found were also checked manually. Additionally, search returns were checked for duplicates before screening for eligibility criteria.

2.3. Inclusion criteria

Inclusion criteria were as follows: (1) comparisons between knees of patients with ACL injury or reconstruction and of healthy participants without a history of ACLI or ACLR, (2) investigations of postural control through measurements of CoP trajectory during static single-leg stance using a stable force plate, (3) peer-reviewed, full text, and English-language publications, and (4) investigations reporting at least one primary outcome measure of static postural stability based on the CoP. Studies between limb comparisons among patients were excluded because of bilateral sensorimotor impairments in unilateral ACLI or ACLR.[19]

2.4. Outcome measures

The outcome measures considered in this review were parameters of CoP trajectory in terms of sway amplitude, area, and velocity when eyes were opened and closed with three sway directions (anterior-posterior [AP], medial-lateral [ML], and total direction). The 95th percentile ellipse was the preferred definition of sway area where > 1 measurement was reported and sway velocity was preferred over sway length because sway velocity represents the sway length traveled by the CoP over time.[5] Table 1 summarized detailed information on these CoP parameters.

2.5. Articles selection and data extraction

The articles were reviewed and extracted by two authors independently for pertinent data. Articles were searched, selected, and screened for eligibility by two authors (L.Y. and S.Z.) and then verified by the third senior author (Y.H.) at each stage of identification, screening, and eligibility, based on the search strategy (Fig. 1). In the case of

Table 1
Detailed information on the included CoP parameters.

CoP parameters	Definitions
Sway area	**Area covered by the CoP trajectory, generally defined by the 95% confidence ellipse of the CoP trajectory**
Sway velocity	**Averaged CoP velocity (mean velocity), equal to the length of the CoP path divided by the duration of recording**
Sway amplitude	**Distance between points of CoP trajectory**
range of sway amplitude	Maximal distance over any two points of CoP trajectory
mean sway amplitude	Average distance over all data points of CoP trajectory
SD of sway amplitude	*SD* of distance of the CoP from the center or axis of trajectory

CoP, center of pressure; *SD*, standard deviation.

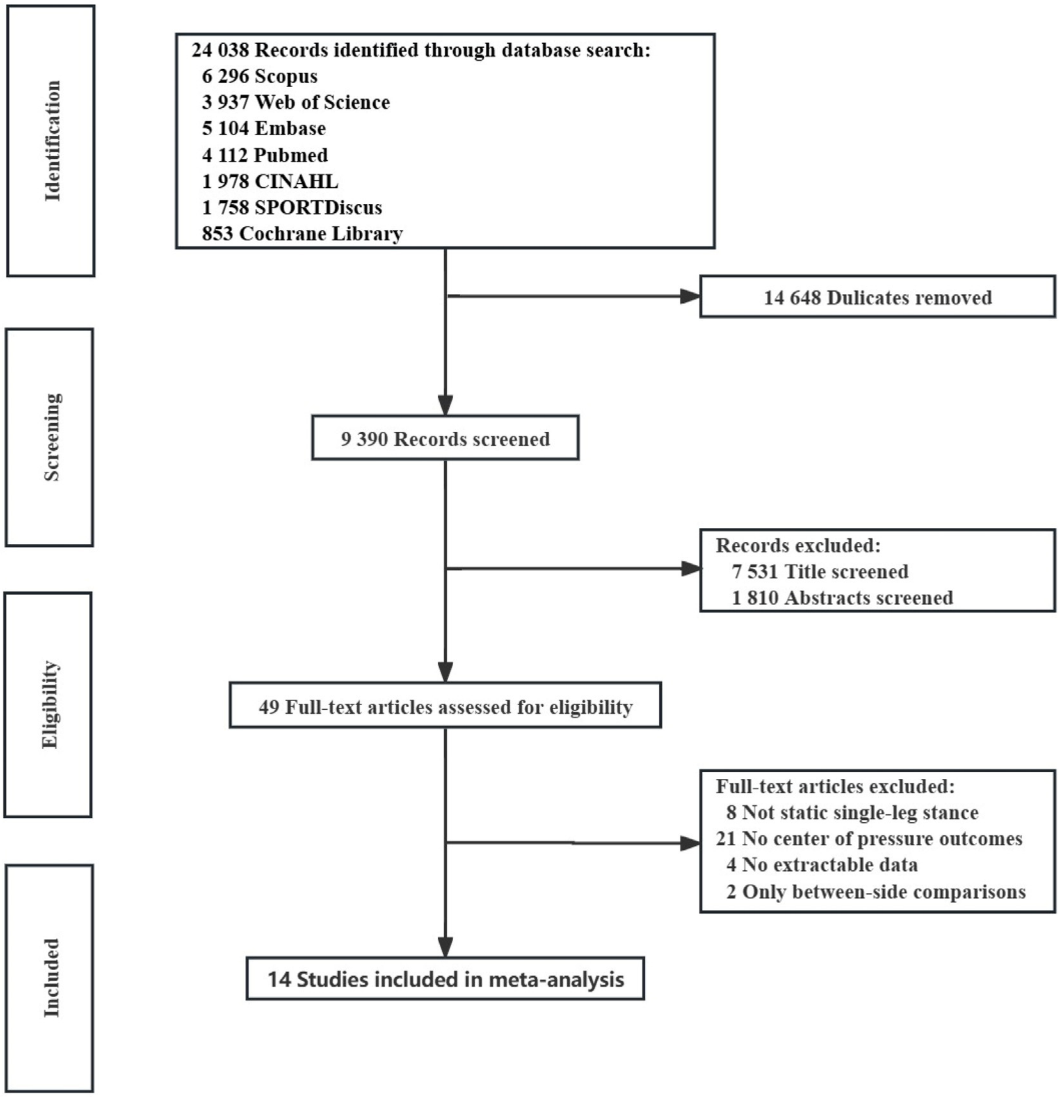


Fig. 1. Flow chart of the systematic review selection process.

disagreement, a consensus was achieved through a discussion between the two authors The full text of all eligible studies was retrieved and the following data were extracted for each study: demographic characteristics (age, sex, etc), sample size, time from injury/surgery to test, associated injuries, test information (test device, duration of each trial and times of repetitions, visual condition, and CoP parameters with sway directions), and means and standard deviations of CoP parameters.

2.6. *Quality and risk of bias assessment*

The quality and risk of bias assessment of included studies were independently conducted by two separate authors (L.Y. and S.Z.) and any discrepancies were discussed with the third author until consensus was reached. The quality of each eligible article was evaluated using the valid and reliable epidemiological appraisal instrument (EAI); it has 43 items in the original instrument.[20] Ten items from the EAI were "not applicable" across all studies because of the case-control and cross-sectional design of studies included in this systematic review. The risk of bias in included studies was assessed using a tool for non-randomized cross-sectional and case-control studies.[21] The risk of bias comprises of the following five dimensions: selection, performance, detection, attrition, and reporting biases. Reporting bias was removed because of the difficulty of quantifying.[21]

2.7. *Statistical analysis*

The studies were analyzed qualitatively if the number of studies on the same CoP parameters was too small ($n < 3$). Meta-analyses were performed using Stata Version 16 (Stata Corp LP) for studies with similar CoP parameters and visual conditions (opened and closed eyes), and subgroups were divided by sway directions (AP, ML, total). Comparability of results across units was illustrated using the standardized mean difference (*SMD*) of Cohen's *d* effect sizes between the injured knee and control with 95% CIs accounting for between-group differences between the injured ACL and controls. *SMD*, a measure of effect size, is calculated by dividing the mean difference between the study groups (e.g., ACL injured or reconstructed and control groups) by the pooled SD.[22] A larger SMD was associated with higher patient outcomes, with 0.2 – 0.5 being small, 0.5 – 0.8 being moderate, and > 0.8 being a large effect size.[6,23] The results were pooled using a random-effects model, considering the heterogeneity of testing methods and population across studies. We also conducted the subgroup analysis within ACL injured and reconstructed patients. The presence of heterogeneity was assessed using the I^2 statistics, with $I^2 \geq 75\%$ indicating high heterogeneity and requiring cautious interpretation.[24] Sensitivity analysis was performed by removing 1 study at a time to estimate the impact on the pooled result from > 2 studies. If a significant result turned out to be an insignificant one, the pooled result would be considered unstable, requiring cautious interpretation. The statistical significance level was set at 5%.

3. Results

3.1. Articles selection and characteristics

Twenty-four thousand and thirty-eight studies were identified in the initial search, and 14 studies were included after titles and abstracts of the initial search results were screened, duplicates were removed, and articles were excluded following a full-text review (Fig. 1). Further details among the included studies, including age, sex, sample size, time from injury/surgery to test, associated injuries, test information (test device, duration of each trial and times of repetitions, visual condition, and CoP parameters), are presented in Supplementary Appendix 2.

3.2. Quality and risk of bias assessment

The quality rating scores on EAI ranged from 0.58 to 0.7 (median score is 0.62; Supplementary Appendix 3). Most studies have clearly reported the objectives or hypotheses, study design, and description of outcomes clearly. However, almost all studies lacked a sample size calculation, important covariates, and confounders described and blinded assessors during testing. The risk of bias assessment showed a high risk of detection (blindness). All studies described the statistical tests, reported the required characteristics of ACLI or ACLR and control, and used a force plate to measure the CoP trajectory during static single-leg stance when the eyes were opened and closed. Rating scales of quality and risk of bias assessment are shown in Supplementary Appendix 3.

3.3. Quantitative data synthesis of outcome measures

3.3.1. Sway amplitude

Because of the small amount of literature comprising the parameter of sway amplitude, data from articles that included this parameter were not pooled. Many parameters of sway amplitude were used during the single-leg stance when the eyes were opened and closed. One study (7% of 14) calculated the range of sway amplitude in the AP and ML directions during the single-leg stance when the eyes were opened and closed.[16] Two studies (14% of 14) quantified the mean sway amplitude in the AP and ML directions during single-leg stance with the eyes closed.[14,25] Finally, one study (7% of 14) used the parameter of *SD* of sway amplitude in AP and ML directions during the single-leg stance with the eyes open.[15]

3.3.2. Sway area

Five studies assessed sway area on the single-leg stance with the eyes open,[15,26–29] and it differed insignificantly between the ACLI or ACLR and control groups when the eyes were opened ($SMD = 0.218, p = 0.498$) and this was not affected by removal of the included single study. Under conditions of closed eyes, three studies reported indifference between the two groups during the single-leg stance ($SMD = 0.745$, $p = 0.275$).[27–29] However, definitions of areas were extremely varied and unclear. Two studies defined the area through the 95th percentile ellipse,[28,29] one study calculated the sway area through the two-dimensional confidence ellipse,[26] and the remaining two studies defined the area calculation unclearly.[15,27]

3.3.3. Sway velocity

Nine studies calculated mean sway velocity (or length).[15,16,27,28,30–34] There were no significant differences between the ACLI or ACLR and control groups in the AP ($SMD = 0.847, p = 0.09$), ML ($SMD = 0.404, p = 0.13$), and total ($SMD = 0.441, p = 0.129$) directions when the eyes were opened, but the pooled results of mean sway velocity in total direction were significant ($SMD = 0.738$, $p = 0.001$) when the study of O'Connell et al.[16] was removed during sensitivity analysis. Under conditions of closed eyes, three studies reported insignificant differences in total ($SMD = 0.437$, $p = 0.658$) directions between the ACLI or ACLR and control groups,[16,27,28] and one study (7% of 14) used the parameter of mean sway velocity in the AP and ML directions, which was not pooled, because it's the only one literature that reported the parameters.[28] Fig. 2 shows the forest plot results.

3.4. Subgroup analysis

Due to the limits of studies number, we only included sway area with eyes open in patients with ACLR, sway velocity with open eyes in patients with ACLR and sway velocity with open eyes in patients with ACL injury to conduct the subgroup analysis. We found that there was only significant difference in sway velocity with open eyes ($SMD = 0.47, p = 0.001$) between ACLR group and control group. However, there were no significant difference in sway area with eyes open ($SMD = 0.15, p = 0.882$) in patients with ACLR and sway velocity with open eyes ($SMD = 0.17$, $p = 0.864$) in patients with ACL injury. The forest plot results of subgroup analysis were presented in Supplementary Appendix 4.

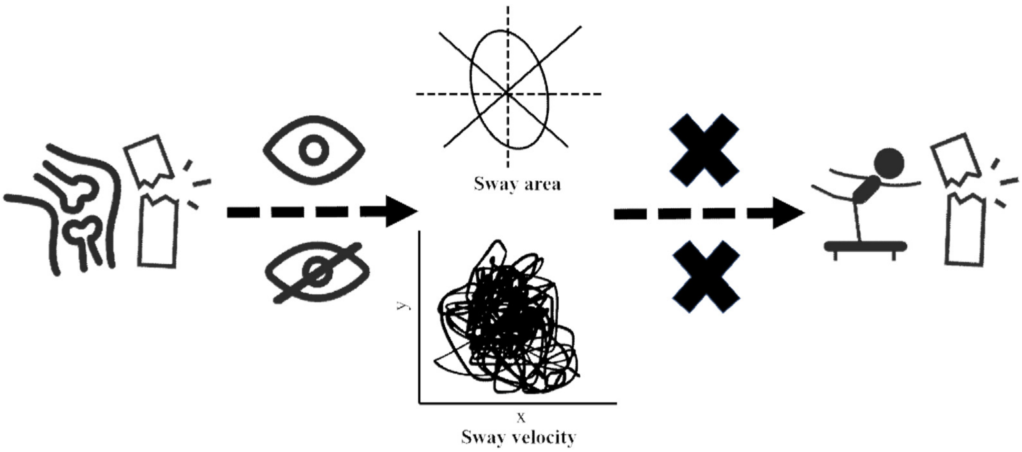
4. Discussion

This study summarized the CoP parameters (sway amplitude, sway area, sway velocity) commonly used to evaluate postural control deficits in patients with ACLI and ACLR. It also compared the differences in these parameters between the ACL and control groups. However, where meta-analyses could be performed, no differences were found in most of CoP parameters between the two groups in the single-leg stance with opened and closed eyes situation. In the subgroup analysis, we found that the results had between-group difference in sway velocity with eyes open in patients with ACLR. However, it only had a small effect size and was occurred in ACLR population.

Because of the inherently unstable human body, the musculoskeletal and neural systems must be regulated precisely to maintain the stability of postural control, which receives information from peripheral sensory inputs (e.g., visual, vestibular, and somatosensory), integrates them through spinal/cortical processing (e.g., sensory integration, motor planning), and corrects motor outputs (e.g., muscle reflex, voluntary movement).[13] The importance of postural control assessment was based on the reduced control of the operated joint in modified Romberg's test in patients with ACLR.[35] Meanwhile, impaired proprioception, weakened muscle strength, delayed neural reflex, reduced knee joint range of motion, and maladaptive neuroplasticity in the corticospinal tract are all possible sources of the impairment of the postural control system in individuals with ACLI and ACLR.[5,36–39] Therefore, it was suggested that establishing a reliable and valid assessment method of impaired postural control may be beneficial to further investigate the diagnosis, rehabilitation, and return to play decision-making.

4.1. CoP parameters

The range of sway amplitude was estimated to assess the ability to sustain an upright stance but its accuracy to reflect balance has been questioned due to the high variability.[5] The maximum and minimum amplitude of the CoP trajectory were used to calculate the range of sway amplitude, but it is susceptible to environmental disturbances (sudden noises) that can cause inconsistent results and incorrect interpretations.[5,13] Mean sway amplitude was used to solve this problem but its credibility was still questioned because of the parameter's unclear calculation method.[5,13] *SD* of sway amplitude was used to evaluate the distribution of CoP displacement over time, which is sensitive to altered postural control.[5,13] Sway area was used to evaluate the overall spatial qualities of postural control.[5,13] These pooled results revealed



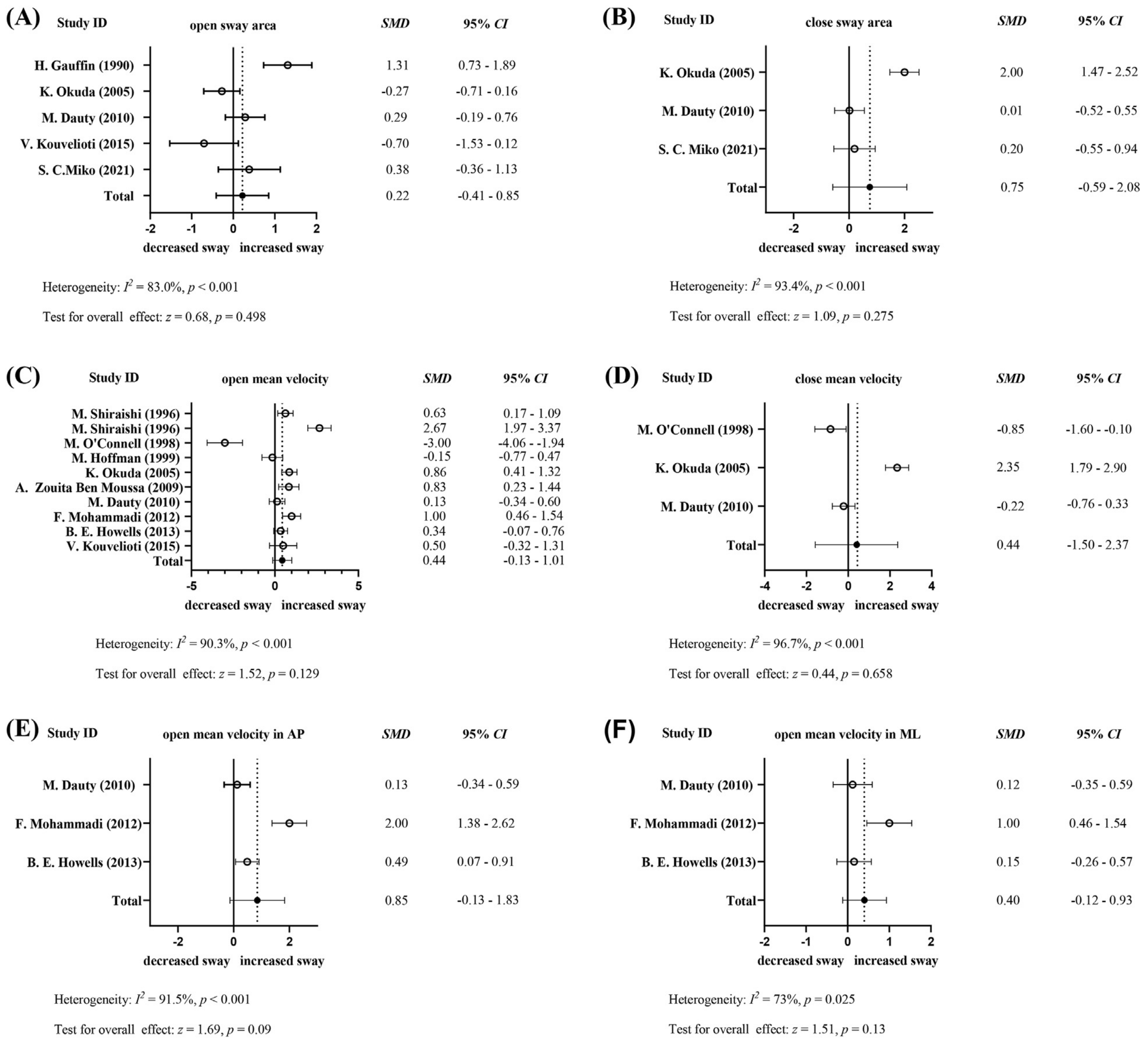


Fig. 2. Forest plots comparisons of sway area under open (A) and closed (B) eyes, mean velocity under open (C) and closed (D) eyes, mean velocity in AP (E) and ML (F) direction under open eyes during static single-leg stance between ACL injured or reconstructed population and healthy controls. *SMD*, standardized mean difference; *CI*, confidence interval; AP, anterior-posterior; ML, medial-lateral.

insignificant differences between ACL injured or reconstructed and control groups because of the aforementioned various definitions of sway area. The parameter of mean sway velocity was used to evaluate the temporal qualities of postural control and was considered as one of the most widely used and reliable CoP parameters,[5,13] but its usefulness remained questionable because a previous study reported that mean sway velocity in a group of control subjects with an intact anterior cruciate ligament (ACL) was greater than that in subjects with ACL rupture.[40] Although the pooled results of mean sway velocity in total direction were significant when the study of O'Connell et al.[16] was removed during sensitivity analysis, the study of O'Connell et al. met our inclusion criteria and mentioned that the two groups were matched for demographic information and activity/sporting background. The authors suggested that patients with ACL injuries had a smaller sway velocity due to compensations from other structures of knee. However, we suggested that this explanation was still debatable.

Lehmann et al. reported significantly increased sway magnitudes (sway amplitude, sway area, and path length) and velocities in the ACL group compared with the controls. However, these CoP parameters differed insignificantly between the ACL injured or reconstructed and control groups in our study. Four variables may account for this discrepancy in results: (1) Lehmann et al. had problems with CoP parameters classification, with sway amplitude, sway area, and path length being equal to sway magnitudes, which led to an excessively larger sample size in their study; (2) the results of between-group significant difference in CoP parameters had high heterogeneity in their study; (3) More than half of the ACL injured or reconstructed population in this study underwent post-injury or post-operative rehabilitation, which improved the ability of postural control, and (4) the included articles of this study assessed the static balance ability using CoP parameters above four months after ACL injury or reconstruction, which may indicate that at this point their static balance related to CoP parameters has been restored.

Meanwhile, we have concluded the clear description and definition of the CoP parameters have been concluded, solving the problem of CoP parameter classifications. It was suggested that the CoP parameters using a force plate may be not used to reflect the postural control deficits comprehensively in ACL injured or reconstructed population based on our negative results and previous studies.[17] Simultaneously, using single-leg stance with opened or closed eyes to test the CoP may respectively exhibit ceiling effects and floor effects (meaning the test is either too easy or too difficult for the control and the ACL injured or reconstructed groups), limiting the ability of such tests to differentiate between the ACL injured/reconstructed population and the control group.

However, this study's results are only based on cross-sectional studies, and further prospective studies are required to investigate this test's usefulness in ACL injured or reconstructed population and to discover better methods to explore postural control deficits in ACL injured or reconstructed population.

4.2. *Implication*

This study's results can advance studies on the assessment of postural control deficits following ACLI and ACLR. The current study provides reference material favorable for the selection of CoP parameters and test conditions commonly used to evaluate the postural deficits with visual conditions (opened and closed eyes) in patients with ACLI and ACLR during the single-leg stance. However, it is worth noting that the CoP parameters differed insignificantly between the ACL injured or reconstructed and control groups. The factors contributing to the results may be that the sensitivity and reliability of CoP parameters during static single-leg stance need to be improved and the static task is not challenging enough to fully assess the postural control deficits in patients with ACLI and ACLR. Therefore, future research may need to choose other test strategies, such as dynamic tasks, and dual tasks, which aid in identifying postural control deficits.

Simultaneously, it should be clarified that the recovery of static balance abilities is a focus of exercise during the mid-phase of systematic rehabilitation post-injury and post-surgery, and it is among the bodily functions that recover earlier. This may be the reason for the negative results observed in this study. Therefore, in clinical work/relevant scientific research, when to conduct tests related to CoP in anticipation of providing scientific references for clinical decision-making should be determined. The assessment of static balance related to CoP parameters should be brought forward and used at an earlier stage post-operatively/post-injury, as an important factor for the treatment and rehabilitation of static balance ability.

4.3. *Limitations*

There are some limitations to be considered in this systematic review. First, the major limitation was the heterogeneity of the pooled data in this review, which requires caution during result interpretation. The source of high heterogeneity may be related to the sex distribution and age in the ACL injured or reconstructed and control groups.

Second, the cross-sectional design makes it difficult to investigate the causal relationship between postural control deficits and ACL injuries. Therefore, longitudinal studies are needed to account for changes in postural control deficits from pre-injury to ACL injury.

Third, the study numbers and methodological quality among some subgroups were low, which may have influenced the reliability of the results and the power of publication bias estimation.[41] Future studies need to follow a consistent methodological checklist, making the future review have high-quality evidence to pool.

Fourth, whether the ACL injured or reconstructed population in the included studies is rehabilitated or not, as well as post-injury or post-operative duration may all affect postural control performance, which may be the primary reason for the indifferences in CoP parameters between ACLI or ACLR patients and healthy individuals.

Fifth, the methodological components of the research protocols among the included studies differed in terms of test device, duration of single-leg stances, and times of repetitions. These methodological factors may have also contributed to conflicting findings among the included studies. Future research should adopt a reliable and verified uniform protocol to assess postural control deficits in ACLI or ACLR.

Finally, the descriptions and definitions of CoP parameters differ widely and are vague in different studies. There was still a risk to consider, although we did our best to categorize them.

5. Conclusion

This study summarized the common CoP parameters used to assess postural control in ACL injured or reconstructed population. The results of this study indicated weak difference in sway velocity between ACL reconstructed population and healthy individuals with opened eyes during the static single-leg stance, suggesting that the CoP parameters under static single-leg stance may be unable to sensitively reveal postural control deficits in ACLI or ACLR population. Therefore, further research is required in the future to enhance the sensitivity and reliability of postural deficit assessments using force plates and investigate postural control deficits using other methods in ACL injured or reconstructed population.

Conflict of interest

The authors declare that they have no competing interests.

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CRediT authorship contribution statement

Le Yu: Writing – original draft, Software, Methodology, Investigation. **Xiao'ao Xue:** Writing – original draft, Visualization, Data curation. **Shanshan Zheng:** Writing – original draft, Conceptualization. **Weichu Tao:** Writing – review & editing, Formal analysis. **Qianru Li:** Writing – review & editing, Formal analysis. **Yiran Wang:** Investigation, Data curation. **Xicheng Gu:** Software, Formal analysis. **Yang Sun:** Writing – review & editing, Supervision, Methodology, Data curation. **Ru Wang:** Writing – review & editing, Validation, Supervision. **Yinghui Hua:** Writing – review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

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