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A systematic review of postural control during single-leg stance in patients with untreated anterior cruciate ligament injury

Hossein Negahban · Masood Mazaheri · Idsart Kingma · Jaap H. van Dieën

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Abstract

Purpose The aim of this review was to determine whether postural control is impaired in patients with anterior cruciate ligament (ACL) injury as compared to healthy controls.

Methods The relevant papers were retrieved through electronic databases including PubMed, EMBASE, Web of Science, and Sport Discus followed by hand search and contact with the authors. Studies that evaluated static postural control during single-leg stance without applying external perturbations were included. Also, the patients should not have undergone ACL reconstruction or any surgical repair on the injured knee.

Results In total, 12 studies were selected for full review. The included studies showed larger postural sway amplitudes or velocities during single-leg stance on the injured leg and the uninjured leg when compared to healthy controls with medium to large effect size. Also, no significant difference was found between the injured and uninjured legs of ACL-injured patients during eyes open condition in all studies supported by small effect size. However, the within-group difference was found to be significant during eyes closed condition, with injured leg displaying larger sway.

Conclusions The present review indicates that postural control is impaired in both legs, especially injured leg. The result of within-group difference in eyes open condition confirms bilateral deficit of postural control. However, the within-group difference during eyes closed condition indicates again that ACL injury affects the injured leg more than the uninjured leg. In designing rehabilitation protocols, clinicians should consider training postural control of not just the injured but also the uninjured leg.

Level of evidence Systematic review of Level III for prognostic studies.

Keywords Anterior cruciate ligament · Injury · Postural control · Single-leg stance

H. Negahban
Musculoskeletal Rehabilitation Research Center, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

M. Mazaheri (✉)
Musculoskeletal Research Center, Isfahan University of Medical Sciences, Hezarjarib Blvd, Isfahan, Iran
e-mail: mazaheri_masood@yahoo.com

I. Kingma · J. H. van Dieën
MOVE Research Institute Amsterdam, Faculty of Human Movement Sciences, VU University Amsterdam, Amsterdam, The Netherlands

Introduction

Anterior cruciate ligament (ACL) is one of the most commonly involved knee structures [41]. ACL injury may affect postural control as the ACL has a mechanical contribution in stabilizing the knee joint [6] and contributes to postural control through its proprioceptive function [25]. The proprioceptive deficit in ACL-injured patients as registered through tests of position sense and threshold of detection of active/passive motions [5, 14, 34, 37] has been proposed as the main determinant of impaired postural control [4, 9, 47]. The loss of sensory information following ACL injury can contribute to the loss of protective muscle responses [31, 32, 40], thereby enhancing the risk of secondary injury. Indeed, injuries such as meniscus lesions are frequently seen following ACL injury, and such complications (further) increase the risk of early knee osteoarthritis [1, 17, 28, 31].

Impaired postural control after ACL injury or even reconstruction surgery [22, 29], as measured by postural sway measurements in single-leg stance, has been reported in several studies [1, 3, 15, 17, 26, 28, 32, 40, 45]. This impairment was demonstrated not only during single-leg stance on the injured leg, but also on the uninjured leg of ACL-injured patients in some studies [1, 3, 7, 15, 17, 45]. It has been postulated that a deficit in afferent information from the torn ACL could also affect neuromuscular function of the contralateral knee [26]. However, results of different studies appear to be inconsistent. For example, Oconnell et al. [31] assessed balance performance in standing on the injured and uninjured legs with eyes open and closed in ACL-injured patients and healthy controls. In contrast to the findings described above, no significant difference was found when comparing standing on the injured leg to the matched leg of healthy controls, nor was there a difference between injured and uninjured legs. These findings support the need for a systematic review in order to provide a synthesis of the evidence on postural control in standing on the injured leg and the uninjured leg in ACL-injured patients. Such a review may reveal methodological differences that explain inconsistencies between studies, such as experimental conditions, sample size, and dependent variables used in these studies.

To the best of our knowledge, no systematic review has yet evaluated postural control during single-leg stance in patients with ACL injury without surgery. Therefore, the aim of this review was to compare standing balance between: (1) the injured leg and the matched leg of healthy controls (injured leg vs. control leg), (2) the uninjured leg and the matched leg of healthy controls (uninjured leg vs. control leg), and (3) the injured leg and the uninjured one in patients (injured leg vs. uninjured leg).

Materials and methods

Search strategy

The relevant papers were extracted through a search of electronic databases including PubMed, EMBASE, Web of Science, and Sport Discus from inception to July 2011. While limiting the search to English language, the key terms "anterior cruciate ligament", "posture", "balance", "sway", "stability", "force plate", "force platform", and "center of pressure" (COP) were used. The specific search string used in PubMed was as follows: (anterior cruciate ligament [MeSH] OR ACL [Title/Abstract]) AND (posture [MeSH] OR balance [Title/Abstract] OR sway [Title/Abstract] OR stabil* [Title/Abstract] OR "force plate" [Title/Abstract] OR "force platform" [Title/Abstract] OR "center of pressure" [Title/Abstract]). The search was complemented by reviewing the reference lists of papers selected from the original database search and also by e-mail contact with the corresponding authors, to identify additional papers that were not included in the list of articles but might be eligible for inclusion.

Study selection

After completion of the initial electronic search, two authors (HN and MM) independently reviewed the titles and abstracts and selected the eligible papers based on inclusion/exclusion criteria. Studies were eligible for inclusion when they compared static postural control during single-leg stance on the injured leg to the uninjured leg of ACL-deficient patients and/or to the matched leg of healthy controls. To be included in the review, studies had to assess patients with ACL injury who had not undergone reconstruction surgery. Studies which applied external perturbations (i.e. platform translations and rotations) were excluded as these were deemed too heterogeneous. Final decision on the selection of papers was obtained by agreement of both authors. Disagreement was resolved by consulting a third reviewer (IK). Papers that did not report new data such as review papers and papers with similar contents were excluded. In the latter case, the version that appeared first was included in the review. All comparative studies irrespective of the level of evidence were included. The level of evidence of each study was assessed using hierarchy of evidences proposed by Sackett et al. [38].

Data extraction

In this stage, two authors (HN and MM) independently extracted the relevant data from the included studies. For this purpose, the authors used a data extraction form designed to record information about subject characteristics (i.e. sample size, age, gender, injury duration, activity and disability levels, pretesting intervention, and associated injuries) and methods (i.e. instrumentation, procedure, and matching technique) (Table 1). Extracted data were agreed upon by the two authors.

Methodological quality

Different instruments have been used in the literature for quantifying methodological quality of observational studies [27, 39]. However, each of these instruments has its own limitations regarding weighting of items, empirical basis for item inclusion, reliability, validity, etc. More importantly, none of these instruments adequately covered all known important methodological issues and possible confounders with regard to the present review topic. Hence, we developed our own quality rating scale considering factors

Table 1 Subjects' characteristics of the included studies

Authors (year)	Number of subjects	Age (year) [a]	Gender (M/F)	Time since injury (month)[a]	Disability level[a]	Activity level (Tegner)[a,b]	Intervention before testing	% of subjects with additional cartilage or meniscus injury	Instrument and procedure	Matching technique
Friden et al. [15]	P:19 H:55	P:24 (15–41) H:26 (19–38)	P:12/7 H:22/33	29 (8–96)	Lysholm: $n = 6$:>83 $n = 6$:65–83 $n = 7$:<65	P:3 (1–6)[c]	No	0 ($n = 3$ had meniscus surgery after their injury)	Strain gauge FP 3 trials	Not reported
Gauffin et al. [17]	P:15 H:Not reported	P:27 (3) H:24 (5)	Not reported	16 (9)	Lysholm: 87 (12)	P:7.0[c]	Yes	0	FP WBL:straight and 30° flexed knee	Average of right/left legs of the control group
Mizuta et al. [28]	P (stable[d]):11 P (unstable[e]):15 H:20	P (stable): men 18.3 (1.9) women 18.4 (2.6) P (unstable): men 20.7 (4.7) women 17.4 (2.0) H:20.7 (18–26)	P (stable):6/5 P (unstable):7/8 H:10/10	P (stable): men 21.0 (8.6) women 15.0 (6.2) P (unstable): men 24.3 (15.4) women 10.4 (6.6)	Not reported	Not reported	No	0 ($n = 5$ in stable group and $n = 8$ in unstable group had meniscectomy after injury)	Gravicorder WBL: straight and 20° flexed knee Arms crossed Instruction: to look at a fixed point 3 × 60s trials	Average of right/left legs of the control group
Zatterstrom et al. [45]	P:26 H:55	P:24.8 (15–43) H:26 (19–38)	P:14/12 H:22/33	22 (1–96)	Lysholm: 73.4 (12.4)	Not reported	No	0	Strain gauge FP NWBL: 90° flex at hip and knee Arms hanged Instruction: to look at a fixed point 3 × 25.6s trials Sample freq: 20 Hz	Not reported
Shiraishi et al. [40]	P:30 H:30	P:23.7 (5.3) H:22.7 (2.9)	P:15/15 H:15/15	>4	Not reported	Not reported	Not reported	Not reported	Gravicorder WBL: 20° flex at knee NWBL: 90° flex at knee and hip Arms crossed Instruction: to look at a fixed point 3 × 20s trials	Average of right/left legs of the control group

Table 1 continued

Authors (year)	Number of subjects	Age (year) [a]	Gender (M/F)	Time since injury (month)[a]	Disability level[a]	Activity level (Tegner)[a,b]	Intervention before testing	% of subjects with additional cartilage or meniscus injury	Instrument and procedure	Matching technique
Lysholm et al. [26]	P:22 H:20	P:29 (19–41) [c] H:25 (17–42)[c]	P:12/10 H:10/10	Median (range) 60 (36-84)	Lysholm: 100 (90–100)[c]	P:5 (3–7)[c]	Yes	0 ($n = 10$ had meniscus surgery after injury)	Dynamic posturography WBL: 10° flex at knee NWBL: 90° flex at knee, 45° flex at hip Arms hanged 3 × 20s trials Sample freq: 50 Hz	Average of right/left legs of the control group
Oconnell et al. [31]	P:15 H:15	P:25 (3) H:25 (3)	P:8/7 Not reported	25 (17)	Not reported	Not reported	No	Not reported	Postural sway meter NWBL: neutral at hip and slight flex at knee Hands on hips 3 × 30s trials	Corresponding right/left legs of the control group
Ageberg et al. [3]	P:27 H:27	P:Not reported H:26 (22-32)[c]	P:13/14 H:13/14	12	Not reported	Not reported	Yes	$n = 14$ had an isolated ACL injury or an injury combined with 1 associated lesion $n = 13$ had more than 1 associated lesion	Strain gauge FP NWBL: 90° flex at hip and knee Arms hanged Instruction: to look at a fixed point and stand as still as possible 3 × 25s trials Sample freq: 20 Hz	Not reported
Ageberg et al. [1]	P:36 H:24	P:26 (5) H:24 (3)	P:18/18 H:11/13	45.6 (36)	VAS 68 (12–95)	P:4 (1–9)[c]	Yes	Not reported	Strain gauge FP NWBL: 90° flex at knee and hip Arms hanged Instruction: To stand as still as possible 3 × 25s trials (median value) Sample freq: 20 Hz	Average of right/left legs of the control group
Okuda et al. [32]	P:32 H:57	P: 22.0 (3.2) H: 23.6 (2.1)	P:17/15 H:Not reported	4.2 (1.8)	Not reported	Not reported	Not reported	Not reported	Gravicorder Arms hanged Instruction: to look at a visual target 3 × 10s trials	Average of right/left legs of the control group

Table 1 continued

Authors (year)	Number of subjects	Age (year) [a]	Gender (M/F)	Time since injury (month)[a]	Disability level[a]	Activity level (Tegner)[a,b]	Intervention before testing	% of subjects with additional cartilage or meniscus injury	Instrument and procedure	Matching technique
Bonfim et al. [7]	P:28 H:28	P:23.6 (4.23) H:22.1	P:26/2 H:26/2	20.2 (9.9)	Lysholm: 68 (37–95)	Not reported	Not reported	50 % associated with meniscus injury ($n = 10$ with medial and $n = 4$ with medial and lateral meniscus injury)	FP NWBL: 90° flex at knee and neutral at hip arms hanged 3 × 30s trials Sample freq: 100 Hz	Injured and uninjured legs with, respectively, right and left legs of the control group
Negahban et al. [30]	P:27 H:27	P:26.7 (5.8) H:26.3 (5.1)	P:27/0 H:27/0	21.6 (26.8)	KOOS: pain 67.1 (21.9) symptom 56.8 (11.8) daily livings 71.9 (22.4) sport 33.0 (27.6) quality of life 32.5 (24.2)	Not reported	Not reported	Not reported	Strain gauge FP NWBL: 30° flex at knee arms abducted 3 × 20s trials sample freq: 200 Hz	Corresponding dominant/non-dominant legs of the control group

M male, *F* female, *P* patient, *H* healthy, *ACL* anterior cruciate ligament, *VAS* visual analogue scale, *KOOS* knee osteoarthritis outcome score

[a] All values are mean with standard deviation or range in parenthesis, unless stated

[b] Activity level after injury has been reported

[c] Values are median with range in parenthesis

[d] Those who had returned to their full preinjury level of sports participation without giving way

[e] Those who were able to participate in sports activity at the same level but with recurring giving way, or had curtailed their participation, or had given up that sports activity because of instability

that may affect the relationship between ACL injury and postural sway (internal validity), the appropriateness of statistical procedures (statistical validity), and the generalizability of results (external validity) (Table 2). This tool was not used to weigh studies according to their methodological rigour or to exclude low-quality studies. However, differences between studies in methodological quality may explain the heterogeneity in results. Again, two authors (HN and MM) independently assessed the methodological quality of included studies, and disparities were resolved by consulting a third reviewer (IK).

Statistical analysis

Standardized mean difference (SMD) and 95 % confidence interval (CI) for each COP parameter of all included studies were calculated and presented in forest plots by Review Manager Software version 5.2. To determine the SMD and 95 % CI, it is necessary to have sample size, mean, and SD of COP parameters. Information related to mean and SD was not provided in four studies [3, 7, 15, 30] and was supplemented from our own records [30], kindly provided by the authors [3, 7] and estimated from range and median values [15] according to Hozo et al. [23]. In the current review, the effect size (ES) was defined as the SMD between the two limbs of the same group or different groups, and the strength of ES was interpreted according to Cohen's suggestion [10], that is, small = <0.40, medium = 0.41–0.70, and large = >0.70.

Table 2 Methodological quality checklist

	Scoring
Internal validity	
Reliability of the dependent variables	A positive point was assigned if a minimum sampling duration of 90s and/or 3–5 repetitions was used
Clear presentation of balance assessment	A positive point was assigned if replication of the experiment is possible based on the information in the article
Correction for confounding effect on dependent variables	A positive point was assigned if confounders (i.e. age, gender, body height, body mass, physical activity, and leg dominance) were taken into account, or appropriate matching on these variables was performed
Statistical validity	
The use of appropriate statistical tests	A positive point was assigned if appropriate tests were used to assess differences in balance
Adequacy of the number of subjects included in the study	A positive point was assigned if a minimum of 20 subjects per group were included
External validity	
Sufficient information about the subjects' characteristics	A positive point was assigned if information about age, gender, body length, body mass, physical activity, disability, prior intervention, and additional injury was provided
Sufficient information about instrumentation	A positive point was assigned if the measurement equipment was described clearly
Sufficient information about data analysis	A positive point was assigned if information about the sampling frequency, filtering, and balance parameter calculations was provided

Results

Literature search

The original database search identified 4,881 studies after removal of duplicates. Reviewing the title and abstract of the retrieved articles yielded a total of 22 papers that seemed to be eligible for inclusion [1–4, 7, 8, 11, 16, 17, 19, 21, 26, 28, 30–32, 36, 40, 42, 43, 45, 47]. Eleven studies were excluded after review of full texts. The information provided by the new version of 3 studies [8, 11, 43] was the same as the information provided by their old versions [7, 31, 42]. Thus, only the oldest papers on these studies were retained [7, 31, 42]. Also, in one study [4], the injured/uninjured legs were not distinguished in the "Results" section, and in another one [42] the standing position (single-leg or double-leg stance) of participants was not clear. The authors of these studies did not respond to our requests for more detailed information. These two articles were therefore excluded from the present review. In addition, in four studies [2, 19, 36, 47] postural sway was only reported for the injured leg, without comparing these results with the uninjured leg or with control subjects. Furthermore, in one study [21] a population of patients with various lower limb injuries was included, and in another study [16] postural sway was not assessed as an outcome measure. One additional article [15] was identified after hand search of reference lists of included studies. Contact with authors did not change the final result. In total, 12 studies [1, 3, 7, 15, 17, 26, 28, 30–32, 40, 45] were selected for full review.

Outcome measures

Outcome measures used in most of the included studies were those derived from COP data including mean (SD) amplitude/velocity, DEV 5/10, path length, sway area, and phase plane. DEV 5 and DEV 10 represent the number of

COP movements exceeding the amplitude levels of 5 and 10 mm, respectively. Sway area is defined as the surface enclosing all or a significant proportion (90 or 95 %) of data points of the COP trajectory. The phase plane portrait, a dimensionless COP measure, is the square root of the sum of variances of two-dimensional velocities and displacements [33]. COP velocity and DEV 10 in the frontal plane were the most common parameters, each used in 4 studies. One study [26] used equilibrium score which may not be comparable with other parameters extracted from COP data. Equilibrium score represents the angular difference between the subject's calculated anteroposterior (AP) centre of mass displacement and the theoretical maximum displacement of 12.5°. Due to heterogeneity of outcome measures, it was not possible to conduct a meta-analysis.

We categorized COP parameters into sway amplitude (i.e. area, mean amplitude, SD amplitude, sway range, DEV 5, and DEV 10) and sway velocity (i.e. mean velocity, SD velocity, maximum velocity, and path length) measures. We did not include body sway, equilibrium score, and phase plane in either amplitude or velocity categories.

Quality rating

Table 3 shows the quality rating of all included studies. A small proportion of studies reported comparability of experimental and control groups with respect to age (5 of 12) [1, 7, 30, 31, 40], gender (5 of 12) [7, 30, 31, 40], height (4 of 12) [1, 7, 30, 31], weight (4 of 12) [1, 7, 30, 31], and leg dominance (1 of 12) [30]. Most studies (9 of 12) [1, 15, 17, 26, 28, 30, 31, 40, 45] matched groups for physical activity level. Sample size was smaller than 20 in 4 studies [15, 17, 28, 31], which may adversely affect statistical power. Adequate information was reported for age and gender in all studies with only one exception for each variable [3, 17]. Insufficient data were provided on height and weight in 7 studies [3, 7, 15, 26, 28, 40, 45], on physical activity in 8 studies [3, 7, 28, 30–32, 40, 45], on disability in 5 studies [3, 28, 31, 32, 40], on additional injuries in 5 studies [1, 30–32, 40], and on prior interventions in 4 studies [7, 30, 32, 40]. Disagreements between the two reviewers were found in 6.7 % of the items, mostly related to correction for confounding effects of physical activity and leg dominance.

Main findings

The details of relevant findings of included studies are presented in forest plots 1–6. Four studies [7, 26, 31, 32] included a condition with occlusion of vision (i.e. eyes closed) to assess the effect of vision on regulation of posture during single-leg stance. Therefore, we categorized the results of included studies according to the visual condition (i.e. eyes open and eyes closed) in which postural sway was measured. The results for amplitude and velocity sway measures are reported in the following sections. One study, using a distinctly different measure, equilibrium score [26], is described separately and is not included in forest plots.

Comparison of the injured leg and the matched leg of healthy controls

Ten studies evaluated postural control in terms of an amplitude or velocity measure during single-leg stance with eyes open. Figure 1 shows that in seven of these 10 studies there was larger postural sway in the injured legs compared to healthy controls with medium to large ES (ES = 0.56–4.32) in at least one amplitude or velocity measure [3, 15, 17, 28, 32, 40, 45]. The studies with the largest ES (i.e. above 1) [28, 40] are relatively small; these ESs show large confidence intervals.

For the studies of Oconnell et al. [31] and Ageberg et al. [1], the plot demonstrates conflicting findings of smaller postural sway with large effect size (ES = 0.70–2.92) for the injured leg compared to the control leg of the healthy group. However, for Ageberg et al. [1], this only concerns one specific variable, mean AP velocity. The forest plot results for the study of Oconnell et al. [31] are in contrast to the reporting in the original study. While the forest plot based on reported means and standard deviations displays smaller mean velocity, maximum velocity, and path length for the injured leg, Oconnell et al. [31] reported no difference between the injured leg and the matched control leg in their study. In-depth evaluation reveals some other inconsistencies between the findings of the forest plot and those reported in the original studies. In the Okuda et al.'s study [32], no difference was reported between the injured leg and the matched control leg, while in the forest plot there was larger value of mean velocity in the injured leg. While Review Manager Software uses alpha level of 0.05 by default for all comparisons, Okuda et al. adopted a more conservative alpha level ($\leq$0.01), which may account for this disparity. Furthermore, the finding of larger body sway of the injured leg reported by Friden et al. [15] for average speed and DEV 5 in mediolateral (ML) direction does not match with non-significant results in the forest plot, which may be due to our estimation of average and standard deviation values for this study.

The forest plot in Fig. 2 shows that in all 3 studies that evaluated postural control during single-leg stance with eyes closed, there was larger postural sway in the injured legs compared to healthy controls with large ES

Table 3 Assessment of quality of the included studies

Authors	Internal validity								Score	Statistical validity		Score	External validity										Score	Total score
	1	2	3A	3B	3C	3D	3E	3F		4	5		6A	6B	6C	6D	6E	6F	6G	6H	7	8		
Friden et al. [15]	+	–	–	–	–	–	+	–	2	+	–	1	+	+	–	–	+	+	+	+	+	+	8	11
Gauffin et al. [17]	–	–	–	–	–	–	–	–	1	+	–	1	+	–	+	+	+	+	+	+	+	+	9	11
Mizuta et al. [28]	+	+	–	–	–	–	+	–	3	+	–	1	+	+	–	–	–	–	+	+	+	+	6	10
Zatterstrom et al. [45]	+	+	–	–	–	–	+	–	3	+	+	2	+	+	–	–	–	+	+	+	+	+	7	12
Shiraishi et al. [40]	+	+	+	+	–	–	+	–	5	+	+	2	+	+	–	–	–	–	–	–	+	+	4	11
Lysholm et al. [26]	+	+	–	–	–	–	+	–	3	+	+	2	+	+	–	–	+	+	+	+	+	+	8	13
Oconnell et al. [31]	+	+	+	+	+	+	+	–	7	+	–	1	+	+	+	+	–	–	–	+	+	+	7	15
Ageberg et al. [3]	+	+	–	+	–	–	–	–	3	+	+	2	–	+	–	–	–	–	+	+	+	+	5	10
Ageberg et al. [1]	+	+	+	–	+	+	+	–	6	+	+	2	+	+	+	+	+	+	–	+	+	+	9	17
Okuda et al. [32]	+	+	–	–	–	–	–	–	2	+	+	2	+	+	+	+	–	–	–	–	+	+	6	10
Bonfim et al. [7]	+	+	+	+	+	+	–	–	6	+	+	2	+	+	–	–	–	+	+	–	+	+	6	14
Negahban et al. [30]	+	+	+	+	+	+	+	+	8	+	+	2	+	+	+	+	–	+	–	–	+	+	7	17

1, Reliability of outcome measures; 2, clear presentation of balance assessment; 3A, study controls for age; 3B, study controls for gender; 3C, study controls for height; 3D, study controls for body mass; 3E, study controls for physical activity; 3F, study controls for leg dominance in matched limb; 4, use of appropriate statistical tests; 5, adequate sample size; 6A, adequate information regarding age; 6B, adequate information regarding gender; 6C, adequate information regarding height; 6D, adequate information regarding body mass; 6E, adequate information regarding physical activity; 6F, adequate information regarding disability; 6G, adequate information regarding additional injuries; 6H, adequate information regarding prior interventions; 7, adequate description of measurement equipment; 8, adequate description of data processing

Study or Subgroup	IL Mean	IL SD	IL Total	CL Mean	CL SD	CL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Ageberg [1] DEV10 AP	6	3	36	6.5	2.5	24		-0.18 [-0.69, 0.34]
Ageberg [1] DEV10 ML	3.5	2.6	36	3.5	1.8	24		0.00 [-0.52, 0.52]
Ageberg [1] VEL AP	20.3	5.4	36	24	5	24		-0.70 [-1.23, -0.16]
Ageberg [1], VEL ML	20.8	5.3	36	23.2	5.2	24		-0.45 [-0.97, 0.07]
Ageberg [3] AMP ML	4.85	0.66	27	4.19	0.74	27		0.93 [0.36, 1.49]
Ageberg [3] DEV10 ML	3.85	2.35	27	2.15	2.03	27		0.76 [0.21, 1.32]
Ageberg [3] DEV5 ML	19.78	4.91	27	18.63	6.06	27		0.21 [-0.33, 0.74]
Ageberg [3] VEL ML	22.85	4.54	27	22.33	5.52	27		0.10 [-0.43, 0.64]
Friden [15] AMP ML	13.1	5.5	19	12.7	4.75	55		0.08 [-0.44, 0.60]
Friden [15] DEV10 ML	2.1	2.75	19	0.6	1	55		0.91 [0.37, 1.46]
Friden [15] DEV5 ML	14.4	6.25	19	11.3	5.75	55		0.52 [-0.01, 1.05]
Friden [15], SD AMP ML	4	1	19	3.4	0.75	55		0.72 [0.19, 1.26]
Friden [15], VEL ML	18.6	5	19	16.2	5	55		0.47 [-0.05, 1.00]
Gauffin [17] AR FK	266	199	15	267	74	12		-0.01 [-0.77, 0.75]
Gauffin [17] AR SK	384	240	15	247	56	18		0.80 [0.09, 1.52]
Mizuta [28] AR FK Men*	2.4	0.7	7	1.5	0.5	10		1.45 [0.34, 2.57]
Mizuta [28] AR FK Women	1.9	0.2	8	1.2	0.2	10		3.33 [1.79, 4.88]
Mizuta [28] AR SK Men	3.5	1.1	7	1.7	0.2	10		2.40 [1.06, 3.73]
Mizuta [28] AR SK Women	2.3	0.8	8	1.4	0.4	10		1.41 [0.34, 2.47]
Mizuta [28] PL FK Men	98.7	8.4	7	81.9	13.1	10		1.39 [0.29, 2.50]
Mizuta [28] PL FK Women	93.6	11.7	8	65.2	4.9	10		3.16 [1.67, 4.65]
Mizuta [28] PL SK Men	115.9	11.2	7	80.2	9.1	10		3.39 [1.77, 5.01]
Mizuta [28], PL SK Women	87.7	9.4	8	63.7	11.2	10		2.19 [0.96, 3.42]
Negahban [30] SD VEL AP	2.47	0.51	27	2.32	0.55	27		0.28 [-0.26, 0.81]
Negahban [30] SD VEL ML	2.66	0.5	27	2.48	0.56	27		0.33 [-0.20, 0.87]
Negahban [30] VEL	2.87	0.49	27	2.69	0.58	27		0.33 [-0.21, 0.87]
Oconnell [31] MAX VEL	0.24	0.01	15	0.32	0.07	15		-1.56 [-2.39, -0.73]
Oconnell [31] PL	1.36	0.33	15	1.77	0.4	15		-1.09 [-1.86, -0.31]
Oconnell [31] RNG AP	39	21	15	46	12	15		-0.40 [-1.12, 0.33]
Oconnell [31] RNG ML	36	14	15	40	6	15		-0.36 [-1.08, 0.36]
Oconnell [31] VEL	0.04	0.01	15	0.07	0.01	15		-2.92 [-3.99, -1.85]
Okuda [32] AR	1.66	0.52	32	1.82	0.62	57		-0.27 [-0.71, 0.16]
Okuda [32] VEL	3.79	0.88	32	3.1	0.75	57		0.86 [0.40, 1.31]
Shiraishi [40] PL Men	98.7	5.7	15	79.6	9	15		2.47 [1.49, 3.45]
Shiraishi [40] PL Women	92.1	6.3	15	67.4	4.7	15		4.32 [2.95, 5.70]
Zatterstrom [45] DEV10 ML	1.9	2.6	26	0.6	0.9	55		0.78 [0.30, 1.27]
Zatterstrom [45] DEV5 ML	14.2	6.1	26	11.3	4.6	55		0.56 [0.09, 1.04]
Zatterstrom [45] VEL ML	18.4	5.3	26	16.2	3.8	55		0.50 [0.03, 0.98]

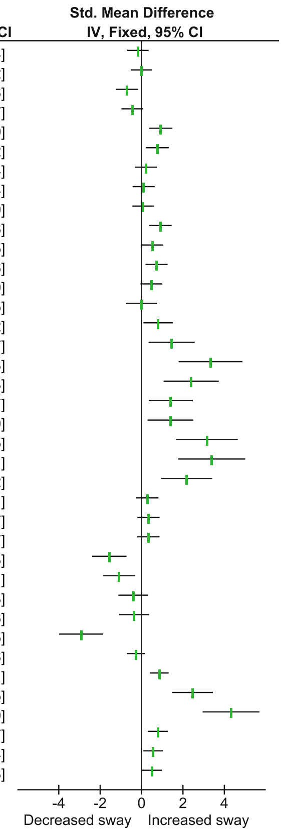

Fig. 1 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing IL versus CL during eyes open condition. The standardized mean difference denotes the value of the effect size. *To keep the plot more compact, the data related to stable group have not been presented. Although the stable patients had lower values of postural sway measures in injured leg when compared to healthy participants, the difference was not significant for all conditions. *IL* injured leg, *CL* control leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *DEV* deviation, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum, *RNG* range, *FK* flexed knee, *SK* straight knee

Study or Subgroup	IL Mean	IL SD	IL Total	CL Mean	CL SD	CL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Bonfim [7] SD AMP AP	1.5	0.43	28	1.01	0.14	28		1.51 [0.91, 2.11]
Bonfim [7] SD AMP ML	1.28	0.34	28	1.02	0.13	28		1.00 [0.44, 1.55]
Oconnell [31] MAX VEL	1.24	0.2	15	0.75	0.04	15		3.31 [2.16, 4.45]
Oconnell [31] PL	2.91	0.96	15	3.02	1.22	15		-0.10 [-0.81, 0.62]
Oconnell [31] RNG AP	85	37	15	73	22	15		0.38 [-0.34, 1.11]
Oconnell [31] RNG ML	83	34	15	65	18	15		0.64 [-0.09, 1.38]
Oconnell [31] VEL	0.08	0.03	15	0.11	0.04	15		-0.83 [-1.58, -0.08]
Okuda [32] AR	6.5	2.2	32	2.58	1.82	57		1.98 [1.45, 2.50]
Okuda [32] VEL	7.92	1.66	32	4.26	1.5	57		2.33 [1.77, 2.88]

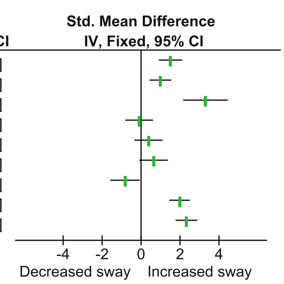

Fig. 2 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing IL versus CL during eyes closed condition. The standardized mean difference denotes the value of the effect size. *IL* injured leg, *CL* control leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum, *RNG* range

(ES = 1.51–3.31) in at least one amplitude or velocity measure [7, 31, 32]. Two of these studies had a large sample size (>27 in each group). The study of Oconnell et al. with both positive and negative effects of ACL injury on postural sway was a relatively small study (15 subjects in each group). For this study, both the forest plot results of significantly increased maximum velocity and the opposite result of a significantly reduced mean velocity in the injured leg do not correspond with the reporting of no difference in the original study.

Comparison of the uninjured leg and the matched leg of healthy controls

Eight studies compared postural control in terms of an amplitude or velocity measure during single-leg stance with eyes open between the uninjured legs and the matched legs of healthy controls. Figure 3 shows that in six of these 8 studies there was larger postural sway in the uninjured legs compared to control legs with medium to large ES (ES = 0.51–0.90) in at least one amplitude

Study or Subgroup	UL Mean	UL SD	UL Total	CL Mean	CL SD	CL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Ageberg [1] DEV10 AP	5.4	2.1	36	6.5	2.5	24		-0.48 [-1.00, 0.05]
Ageberg [1] DEV10 ML	3.4	2.1	36	3.5	1.8	24		-0.05 [-0.57, 0.47]
Ageberg [1] VEL AP	20.1	4.4	36	24	5	24		-0.83 [-1.37, -0.29]
Ageberg [1] VEL ML	3.4	2.1	36	3.5	1.8	24		-0.05 [-0.57, 0.47]
Ageberg [3] AMP ML	4.85	0.82	27	4.19	0.74	27		0.83 [0.27, 1.39]
Ageberg [3] DEV10 ML	4	2.24	27	2.15	2.03	27		0.85 [0.29, 1.41]
Ageberg [3] DEV5 ML	19.3	4.64	27	18.63	6.06	27		0.12 [-0.41, 0.66]
Ageberg [3] VEL ML	22.67	4.42	27	22.33	5.52	27		0.07 [-0.47, 0.60]
Friden [15] AMP ML	11.9	3	19	12.7	4.75	55		-0.18 [-0.70, 0.34]
Friden [15] DEV10 ML	1.4	2	19	0.6	1	55		0.60 [0.07, 1.13]
Friden [15] DEV5 ML	13.3	5.5	19	11.3	5.75	55		0.35 [-0.18, 0.87]
Friden [15] SD AMP ML	3.8	0.5	19	3.4	0.75	55		0.57 [0.04, 1.10]
Friden [15] VEL ML	17.7	5	19	16.2	5	55		0.30 [-0.23, 0.82]
Gauffin [17] AR FK	249	131	15	267	74	12		-0.16 [-0.92, 0.60]
Gauffin [17] AR SK	382	227	15	247	56	18		0.83 [0.12, 1.55]
Negahban [30] SD VEL AP	2.62	0.44	27	2.32	0.55	27		0.59 [0.05, 1.14]
Negahban [30] SD VEL ML	2.65	0.47	27	2.48	0.56	27		0.32 [-0.21, 0.86]
Negahban [30] VEL	2.86	0.51	27	2.69	0.58	27		0.31 [-0.23, 0.84]
Oconnell [31] MAX VEL	0.3	0.19	15	0.32	0.07	15		-0.14 [-0.85, 0.58]
Oconnell [31] PL	1.47	0.53	15	1.77	0.4	15		-0.62 [-1.36, 0.11]
Oconnell [31] RNG AP	43	17	15	46	12	15		-0.20 [-0.92, 0.52]
Oconnell [31] RNG ML	43	27	15	40	6	15		0.15 [-0.57, 0.87]
Oconnell [31] VEL	0.05	0.02	15	0.07	0.01	15		-1.23 [-2.02, -0.44]
Okuda [32] AR	2	0.85	32	1.82	0.62	57		0.25 [-0.18, 0.69]
Okuda [32] VEL	3.75	0.66	32	3.1	0.75	57		0.90 [0.44, 1.35]
Zatterstrom [45] DEV10 ML	1.2	1.6	26	0.6	0.9	55		0.51 [0.04, 0.98]
Zatterstrom [45] DEV5 ML	13.3	5.5	26	11.3	4.6	55		0.40 [-0.07, 0.87]
Zatterstrom [45] VEL ML	17.6	4.4	26	16.2	3.8	55		0.35 [-0.12, 0.82]

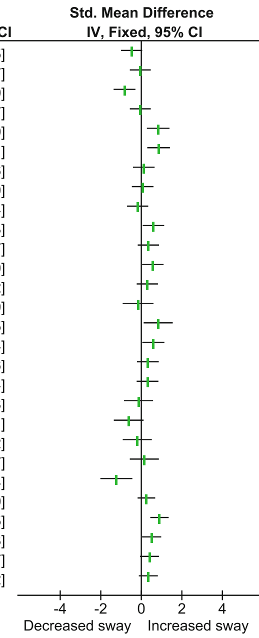

Fig. 3 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing UL versus CL during eyes open condition. The standardized mean difference denotes the value of the effect size. *UL* uninjured leg, *CL* control leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *DEV* deviation, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum, *RNG* range, *FK* flexed knee, *SK* straight knee

Study or Subgroup	UL Mean	UL SD	UL Total	CL Mean	CL SD	CL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Bonfim [7] SD AMP AP	1.24	0.31	28	1	0.16	28		0.96 [0.40, 1.51]
Bonfim [7] SD AMP ML	1.13	0.31	28	0.99	0.13	28		0.58 [0.05, 1.12]
Oconnell [31] MAX VEL	0.77	0.59	15	0.97	0.31	15		-0.41 [-1.14, 0.31]
Oconnell [31] PL	2.77	0.79	15	3.04	0.75	15		-0.34 [-1.06, 0.38]
Oconnell [31] RNG AP	77	40	15	70	17	15		0.22 [-0.50, 0.94]
Oconnell [31] RNG ML	71	34	15	69	17	15		0.07 [-0.64, 0.79]
Oconnell [31] VEL	0.09	0.02	15	0.1	0.03	15		-0.38 [-1.10, 0.34]
Okuda [32] AR	3.38	1.22	32	2.58	1.82	57		0.49 [0.05, 0.93]
Okuda [32] VEL	4.32	1.27	32	4.26	1.5	57		0.04 [-0.39, 0.47]

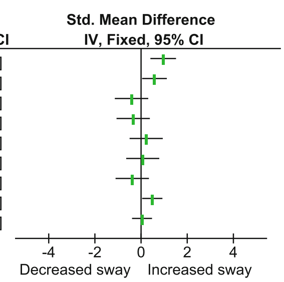

Fig. 4 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing UL versus CL during eyes closed condition. The standardized mean difference denotes the value of the effect size. *UL* uninjured leg, *CL* control leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum

or velocity measure [3, 15, 17, 30, 32, 45]. However, the ES for the difference in the uninjured leg versus control leg (3 large and 3 medium; all below 1) was smaller compared with those of the injured leg versus control leg. The sample size was over 20 per group in 4 of these 6 studies.

The larger values of mean velocity of the uninjured leg for the study of Okuda et al. [32] and SD of velocity in AP direction for the study of Negahban et al. [30] were reported to be not significant in the original papers. Furthermore, while the plot shows larger postural sway of the uninjured leg for one of three sway measures in the study of Zatterstrom et al. [45], they reported significant results for all sway variables in their original study.

In two studies [1, 31], conflicting findings of smaller postural sway for the uninjured leg with large ES (ES = 0.83 and 1.23) were found for a single (mean) velocity measure. Among these two studies, Oconnell et al. [31] in their original study reported this finding to be non-significant, which is not consistent with the data of the forest plot. For the study of Ageberg et al. [1], remarkably, Fig. 1 shows a conflicting finding between the injured leg and the control leg for the same (mean AP velocity) measure.

The forest plot in Fig. 4 shows that in 2 of 3 studies that evaluated postural control during single-leg stance with eyes closed, there was larger postural sway with medium to large ES (ES = 0.49–0.96) in the uninjured legs compared to healthy control leg [7, 32]. Both studies were quite large, that is, with more than 25 participants in each group. The larger sway displayed in the forest plot for the study of Okuda et al. [32] does not correspond with the original study, in which, due to a more conservative alpha level, no significant result was reported for any sway measure.

Study or Subgroup	IL Mean	IL SD	IL Total	UL Mean	UL SD	UL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Ageberg [1] DEV10 AP	6	3	36	5.4	2.1	36		0.23 [-0.23, 0.69]
Ageberg [1] DEV10 ML	3.5	2.6	36	3.4	2.1	36		0.04 [-0.42, 0.50]
Ageberg [1] VEL AP	20.3	5.4	36	20.1	4.4	36		0.04 [-0.42, 0.50]
Ageberg [1] VEL ML	20.8	5.3	36	21.4	5.8	36		-0.11 [-0.57, 0.36]
Ageberg [3] AMP ML	4.85	0.66	27	4.85	0.82	27		0.00 [-0.53, 0.53]
Ageberg [3] DEV10 ML	3.85	2.35	27	4	2.24	27		-0.06 [-0.60, 0.47]
Ageberg [3] DEV5 ML	19.78	4.91	27	19.3	4.64	27		0.10 [-0.43, 0.63]
Ageberg [3] VEL ML	22.85	4.54	27	22.67	4.42	27		0.04 [-0.49, 0.57]
Friden [15] AMP ML	13.1	5.5	19	11.9	3	19		0.27 [-0.37, 0.90]
Friden [15] DEV10 ML	2.1	2.75	19	1.4	2	19		0.29 [-0.35, 0.92]
Friden [15] DEV5 ML	14.4	5.25	19	13.3	5.5	19		0.20 [-0.44, 0.84]
Friden [15] SD AMP ML	4	1	19	3.8	0.5	19		0.25 [-0.39, 0.89]
Friden [15] VEL ML	18.6	5	19	17.7	5	19		0.18 [-0.46, 0.81]
Gauffin [17] AR FK	266	199	15	249	131	15		0.10 [-0.62, 0.81]
Gauffin [17] AR SK	384	240	15	382	227	15		0.01 [-0.71, 0.72]
Negahban [30] SD VEL AP	2.47	0.51	27	2.62	0.44	27		-0.31 [-0.85, 0.23]
Negahban [30] SD VEL ML	2.66	0.5	27	2.65	0.47	27		0.02 [-0.51, 0.55]
Negahban [30] VEL	2.87	0.49	27	2.86	0.51	27		0.02 [-0.51, 0.55]
Oconnell [31] MAX VEL	0.24	0.01	15	0.3	0.19	15		-0.43 [-1.16, 0.29]
Oconnell [31] PL	1.36	0.33	15	1.47	0.53	15		-0.24 [-0.96, 0.48]
Oconnell [31] RNG AP	39	21	15	43	17	15		-0.20 [-0.92, 0.51]
Oconnell [31] RNG ML	36	14	15	43	27	15		-0.32 [-1.04, 0.40]
Oconnell [31] VEL	0.04	0.01	15	0.05	0.02	15		-0.62 [-1.35, 0.12]
Okuda [32] AR	1.66	0.52	32	2	0.85	32		-0.48 [-0.97, 0.02]
Okuda [32] VEL	3.79	0.88	32	3.75	0.66	32		0.05 [-0.44, 0.54]
Zatterstrom [45] DEV10 ML	1.9	2.6	26	1.2	1.6	26		0.32 [-0.23, 0.87]
Zatterstrom [45] DEV5 ML	14.2	6.1	26	13.3	5.5	26		0.15 [-0.39, 0.70]
Zatterstrom [45] VEL ML	18.4	5.3	26	17.6	4.4	26		0.16 [-0.38, 0.71]

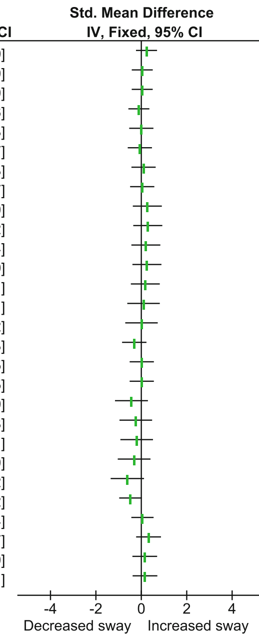

Fig. 5 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing IL versus UL during eyes open condition. The standardized mean difference denotes the value of the effect size. *IL* injured leg, *UL* uninjured leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *DEV* deviation, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum, *RNG* range, *FK*, flexed knee, *SK* straight knee

Study or Subgroup	IL Mean	IL SD	IL Total	UL Mean	UL SD	UL Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Bonfim [7] SD AMP AP	1.5	0.43	28	1.24	0.31	28		0.68 [0.14, 1.22]
Bonfim [7] SD AMP ML	1.28	0.34	28	1.13	0.31	28		0.45 [-0.08, 0.99]
Oconnell [31] MAX VEL	1.24	0.2	15	0.77	0.59	15		1.04 [0.27, 1.81]
Oconnell [31] PL	2.91	0.96	15	2.77	0.79	15		0.15 [-0.56, 0.87]
Oconnell [31] RNG AP	85	37	15	77	40	15		0.20 [-0.52, 0.92]
Oconnell [31] RNG ML	83	34	15	71	34	15		0.34 [-0.38, 1.07]
Oconnell [31] VEL	0.08	0.03	15	0.09	0.02	15		-0.38 [-1.10, 0.34]
Okuda [32] AR	6.5	2.2	32	3.38	1.22	32		1.73 [1.15, 2.31]
Okuda [32] VEL	7.92	1.66	32	4.32	1.27	32		2.41 [1.75, 3.06]

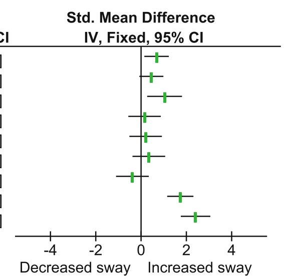

Fig. 6 Forest plot representing standardized mean difference and 95 % confidence interval (CI) for various sway measures in studies comparing IL versus UL during eyes closed condition. The standardized mean difference denotes the value of the effect size. *IL* injured leg, *UL* uninjured leg, *CI* confidence interval, *SD* standard deviation, *AP* anteroposterior, *ML* mediolateral, *AMP* amplitude, *VEL* velocity, *AR* area, *PL* path length, *MAX* maximum, *RNG* range

Comparison of the injured leg and the uninjured leg

Eight studies compared postural control in terms of an amplitude or velocity measure during single-leg stance with eyes open between the injured and uninjured legs of ACL-injured patients. Figure 5 shows that none of these studies demonstrated significant differences between the two legs [3, 15, 17, 30–32, 45]. The absence of a difference was further supported by small positive ESs in all studies (<0.40) and also the presence of 4 studies with at least 25 participants.

In contrast, as demonstrated in Fig. 6, all 3 studies evaluating postural control during single-leg stance with eyes closed display larger postural sway in the injured leg compared to uninjured leg of ACL-injured patients in at least one sway amplitude or velocity measure [7, 31, 32], with ES ranging from medium to large (0.45–2.41). Two of these 3 studies were large with more than 25 participants. However, in two of these three studies the differences found in the forest plots, that is, maximum velocity in Oconnell et al. [31] and SD of amplitude in AP direction reported by Bonfim et al. [7], were reported to be non-significant in the original study.

Additional variables

For phase plane variables, there were no significant differences between the injured or uninjured leg and the matched healthy controls, or between the injured and uninjured legs of patients in the only study reporting these variables [30]. For the equilibrium score, larger sway was demonstrated in the injured leg compared to the matched leg of the control group, both with eyes open and eyes closed. Greater body sway was found with the eyes closed but not with the eyes open when the patients were standing on the uninjured leg compared to the matched leg of control group. Larger body sway was also found when standing on the injured leg compared to the uninjured leg with the eyes open, but no difference was found with the eyes closed [26].

Discussion

The most important finding of the present study was that injury to the ACL is related to impaired postural control in both legs, especially the injured one. More specifically, a substantial proportion of the included studies showed larger postural sway amplitudes or velocities during single-leg stance on the injured leg (7/10 studies with eyes open; 3/3 studies with eyes closed) and the uninjured leg (6/8 studies with eyes open; 2/3 with eyes closed) when compared to healthy controls with medium to large ES. In contrast to between-group differences, all studies found no difference between the injured and uninjured leg in patients during eyes open condition (8/8 studies) supported by small ES. However, the within-group difference was found to be significant during eyes closed condition (3/3 studies).

The large ES of differences between the injured leg and control leg during eyes open single-leg stance indicates a pronounced effect of ACL injury on postural control of the injured leg. This is further supported by the eyes closed condition in which all studies with a positive finding show an ES equal to or larger than 1.0. The substantial number of studies showing significantly larger sway in the uninjured leg than in the legs of control subjects reveals impaired control of posture not just for the injured leg but also for the uninjured leg. However, the smaller ES of differences suggests that the uninjured leg may be less affected than the injured leg. For between-group differences, the most remarkable conflicting results were related to the studies of Oconnell et al. [31] and Ageberg et al. [1]. The results of forest plots show decreased rather than increased postural sway of the injured and uninjured legs for these two studies when compared with the control leg. This is in contrast to the results of the majority of studies that report the positive effect of ACL injury on body sway. For the study of Oconnell et al. [31], the forest plot results do not match the reporting of non-significant results in the original study. This might be due to erroneous descriptive data in the tables of the paper, as some of the numbers (i.e. path length and mean velocity, see Fig. 1) were over an order of magnitude smaller than in other studies. However, for the study of Ageberg et al. [1], the finding of the forest plots matches the results of the original study. According to the authors, the decreased sway of both the injured and uninjured legs relative to the control group may be related to the fact that patients in this study had undergone an intensive neuromuscular training before they participated in the study, leading to improved control of posture.

Regarding within-group differences, none of the eight studies that evaluated sway amplitude or velocity during eyes open condition found significant differences between the injured and uninjured legs of ACL-injured patients. When realizing that between-subject SDs are usually larger than within-subject SDs, this finding, which was further supported by small ES and sufficiently large numbers of subjects in most studies, is unlikely to be a coincidence. This finding supports the presence of a bilateral deficit of postural control in ACL-injured patients. The within-group difference, however, appeared to be significant in the eyes closed condition. This finding indicates again that ACL injury affects the injured leg more than the uninjured leg. The additional deficit of the injured leg can be attributed to the detrimental effect of disrupted ACL sensory inputs on postural control of the ipsilateral side. However, the difference disappears during the eyes open condition, probably due to compensation of the decreased proprioceptive function by visual input. Therefore, the eyes closed condition of postural control testing is likely more challenging and may be more sensitive to proprioceptive deficits than the eyes open condition.

In line with a bilateral deficit in postural control over the legs in patients with a unilateral ACL injury, a bilateral deficit in knee proprioception has been documented in these patients [35]. What is not clear from the present findings is whether the ACL injury caused a bilateral deficit of postural control or that pre-existent poor postural control predisposed the patients to the ACL injury they sustained. Findings from prospective studies showing that less adequate neuromuscular control over both the knee in a drop jump [20] and the trunk in a sudden-release experiment [46] predicted ACL injuries in females support the notion that impaired postural control predisposes patients to injury. Also, a systematic review by Hart et al. [18] reported that kinetic differences in the sagittal plane knee moments between the injured leg of ACL-injured patients and the matched leg of healthy controls are greater than those between the injured and uninjured legs of the ACL-injured group. These authors attributed these findings to bilateral kinetic responses to a unilateral injury of the ACL. Moreover, Yamazaki et al. [44] found a kinematic difference in single-leg squat between the uninjured leg and the matched leg of healthy control subjects. These authors reported that the uninjured legs of ACL-injured patients have less knee external rotation and hip flexion and more knee flexion and hip external rotation than those of the dominant leg of healthy control subjects. The likelihood of a bilateral deficit of postural control preceding or following ACL injury addresses an important limitation to the findings of some studies that used the uninjured leg as healthy control leg in their study [12, 13]. Based on the results obtained in this systematic review, contralateral uninjured leg cannot be considered as a completely healthy control leg and using the uninjured knee instead of a healthy control group may lead to misinterpretation of the results obtained in these studies.

Several mechanisms have been suggested to account for a bilateral deficit in postural control as a consequence ACL injury. First, loss of afferent information due to unilateral ACL injury could affect not only the neuromuscular function and joint stabilization of the ipsilateral leg but of the contralateral leg as well [1, 3]. Moreover, in animal studies, stimulation of the ACL not only affects the reflex and static gamma motor activity of the ipsilateral leg but also the contralateral leg [24], and this may be the case for humans as well. Another speculative mechanism is related to the central motor control mechanisms, that is, when the sensory information of one leg diminishes, the motor control system would have difficulty in the control of two legs with two different sensory properties [7]. Therefore, to avoid this asymmetric control, the system might prefer to reduce the performance of the uninjured leg in addition to the injured leg and this modification has been suggested to be attributable to the adjustments of the central motor programmes for motor coordination, by several authors [3, 7, 31]. Finally, some researchers [40, 45] believe that reduced physical activity after injury could contribute to the impaired postural control during single-leg stance on the uninjured leg of the ACL-injured patients. Therefore, this possibility must be evaluated in a longitudinal study to discover whether reduced physical activity after injury could account for bilateral deficit in postural control in unilateral ACL-injured patients.

This systematic review is not without limitations. First, due to heterogeneity of outcome measures, it was not possible to conduct a meta-analysis. Second, the type of the included studies (case–control studies) results in rating of the present review as level III-a evidence. Another limitation of the present study relates to the lack of evidence supporting the reliability and validity of the self-developed quality rating instrument used in the present review. Future studies should assess the psychometric properties of this instrument. Finally, like in other reviews, the relative number of positive findings may be overestimated in the present study due to publication bias.

Based on the results of the present review, clinicians should be careful in their assessment when making within-group comparisons between injured and non-injured legs. They should focus their neuromuscular training in ACL-injured patients on restoration of postural control, not just for the injured leg but also for the uninjured leg.

Conclusion

The present review indicates that postural control over the ACL-injured leg is substantially worse than in control subjects. The absence of a within-group difference in the eyes open condition suggests that postural control deficits in ACL-injured patients are bilateral. The positive within-group difference in the eyes closed condition, however, reveals an additional deficit of the injured leg that is compensated by visual input.

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