Knee Kinematics During Landing

Is It Really a Predictor of Acute Noncontact Knee Injuries in Athletes? A Systematic Review and Meta-analysis

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Background: Although knee kinematics during landing tasks has traditionally been considered to predict noncontact knee injuries, the predictive association between noncontact knee injuries and kinematic and kinetic variables remains unclear.

Purpose: To systematically review the association between kinematic and kinetic variables from biomechanical evaluation during landing tasks and subsequent acute noncontact knee injuries in athletes.

Study Design: Systematic review; Level of evidence, 2.

Methods: Databases used for searches were MEDLINE, LILACS, IBECS, CINAHL, SPORTDiscus, SCIELO, IME, ScienceDirect, and Cochrane from database inception to May 2020. Manual reference checks, articles published online ahead of print, and citation tracking were also considered. Eligibility criteria included prospective studies evaluating frontal and sagittal plane kinematics and kinetics of landing tasks and their association with subsequent acute noncontact knee injuries in athletes.

Results: A total of 13 studies met the eligibility criteria, capturing 333 acute noncontact knee injuries in 8689 participants. A meta-analysis revealed no significant effects for any kinematic and kinetic variable with regard to subsequent noncontact knee injuries.

Conclusion: No kinetic or kinematic variables from landing tasks had a significant association with acute noncontact knee injuries. Therefore, the role and application of the landing assessment for predicting acute noncontact knee injuries are limited and unclear, particularly given the heterogeneity and risk of bias of studies to date.

Keywords: motion analysis; knee; injury prevention; biomechanics

An important topic for health and sports professionals is the prevention of injuries, especially those that occur in the lower limbs due to a lack of motor control.[12] Before designing injury prevention programs, sports medicine practitioners often evaluate risk factors that can be addressed through biomechanical analysis during sports-related

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tasks such as side-cutting, landing, running, or specific sports movements.[42,43] The functional screening of these exercises may provide important information about the level of motor control that athletes have during certain movements, as well as return-to-play criteria after a knee injury.[44]

Biomechanical cadaveric models have shown increased levels of anterior cruciate ligament (ACL) strain as consequences of frontal plane knee loading during a simulated jump landing.[3] Thus, the high prevalence of knee joint injuries in athletes has resulted in the use of kinematic analysis, mainly in the frontal plane, as a tool to assess athletes' knee injury risk.[2,30,39] Increased dynamic knee valgus during drop-jump landing and the derived frontal plane kinetic and kinematic variables have traditionally been considered potential risk factors for noncontact knee injuries such as ACL tears.[1,2]

However, many of the studies that reported risk factors for knee injury based on biomechanical analysis did not subsequently evaluate actual noncontact knee injuries, and none of the studies performed appropriate follow-up to confirm a higher rate of knee injury.[20,28] Thus, when studies

register subsequent noncontact knee injuries after biomechanical evaluation, the frontal plane knee kinematic variables are not always related to a true increase in the rate of noncontact knee injuries. Ortiz et al[26] did not find differences in landing biomechanics after comparing healthy women with those who had ACL reconstruction. Therefore, the capacity of kinematic variables to predict noncontact knee injuries during drop-jump landing tasks is unclear. In addition, the high variability among studies in terms of follow-up period, type of athletes included, or kinematic variables may increase the controversy.[37]

Many practitioners continue to use knee kinematics during landing as a screening tool for injury risk[19,21] or to assess the effectiveness of prevention programs for knee injury prevention.[31] Because many of the training adaptations to reduce injury risk are based on variables derived from these evaluations, it is important to clarify which kinematic or kinetic variables are related to an increase in subsequent noncontact knee injuries. Therefore, the aim of this systematic review was to evaluate whether dynamic knee valgus and derived kinetic and kinematic variables really predict noncontact knee injuries in athletes. Additionally, we considered kinematic variables from the sagittal plane and kinetic variables.

METHODS

Search Strategy

This systematic review was registered on the PROSPERO database and conducted according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.[34] The following databases were used to search the existing literature (from database inception to May 2020): MEDLINE, LILACS, IBECS, CINAHL, SPORTDiscus, SCIELO, IME, ScienceDirect, and Cochrane. To conduct the database search, Boolean operators "AND" and "OR" were used, which, in some cases, were truncated to generate the maximum number of results: "knee injuries" AND "athletes" AND ("genu valgum" OR "knee valgus" OR "knee abduction" OR "dynamic valgus" OR "knee separation") AND ("biomechanical phenomena" OR "landing" OR "drop jump"). Appendix Table A1 provides the details of the search strategies in every database. To ensure the identification of all relevant issues, the reference lists of all studies included in this systematic review were screened, and the "similar articles" tool of the PubMed database was used. Endnote X7 (Thompson Reuters) was used to import references and to delete duplicated copies. Searches were rerun before the final analysis.

Study Selection

Two independent reviewers (N.R.F. and J.M.M.) applied predetermined eligibility criteria to screen titles and abstracts of the records. Once potentially eligible studies were selected, the same 2 reviewers screened full texts by independently reapplying the eligibility criteria.

Disagreement for definitive inclusion of studies was resolved by consensus between both reviewers.

Selection Criteria

Participants. Studies were included if they considered athletes with subsequent occurrence of an acute noncontact knee injury (primary injury or recurrence) during sports-related activity.

Biomechanical Evaluation. Studies were eligible if they examined kinematic and kinetic variables of the knee in the frontal plane during vertical jump landing tasks and their relationships with knee injuries. The specific kinematic and kinetic variables considered were knee abduction moment, maximum knee valgus angle or medial knee displacement during landing, knee valgus angle at initial contact, knee valgus during the stance phase, and other variables derived from the aforementioned variables (ie, the lower extremity stability score [LESS]). Additionally, kinematic and kinetic variables of the knee in the sagittal plane during vertical jump landing tasks were considered.

Study Type. Observational, retrospective, and prospective studies were considered if they examined the aforementioned kinematic or kinetic variables of landing before noncontact knee injuries or reinjuries and if the studies performed a subsequent follow-up to evaluate the relationship of these variables with knee injury occurrence. Studies were excluded if they only examined the relationship between kinematic or kinetic variables and risk factors of knee injury without registering the noncontact knee injuries. Full texts were required to ensure rigorous appraisal of all the studies included. Studies written in English or Spanish were considered.

Data Collection

Risk of Bias Assessment

Risk of bias was assessed using the Quality in Prognosis Studies (QUIPS) scale for all of the studies included. The QUIPS tool considers 6 domains as possible sources of bias: study participation, study attrition, prognostic factor measurement, outcome measurement, study confounding, and statistical analysis. Each of the 6 domains was appraised according to specific criteria that helped determine the degree of risk, and they were scored as "yes," "no," or "unclear" (not enough information). If a single domain contained $\geq 75\%$ of the "yes" replies, it was considered low risk. If it contained $<75\%$ of the "yes" replies, it was considered high risk. In addition, if a single domain contained ≥ 2 "unclear" replies, it was considered moderate risk. Subsequently, the overall qualification of risk for every study was calculated depending on the number of domains falling within the high, moderate, and low risk of bias classifications. If a single study contained at least 4 domains classified as low risk and none as high risk, the overall risk of bias was considered low. If a study contained at least 3 domains classified as low risk and only 1 classified as high risk, the overall risk of bias was considered to be moderate. If a single study contained ≥ 2 domains classified as high

risk, the overall risk of bias was considered to be high. This method has been used in previous reviews.[10] The same 2 reviewers independently verified the qualification of the 6 QUIPS domains and the overall qualification for every study. A consensus between both reviewers resolved possible discrepancies. The QUIPS tool has been described and used in similar systematic reviews.[8]

Data Extraction

One reviewer extracted the data (N.R.F.) while another reviewer independently verified the data (J.M.M.). The data focused on the study design (type and duration), participants (age, sex, sport type, and level of competition), definitions of injury and reinjury, risk of sustaining a future noncontact knee injury (or associated injury risk data such as odds ratio, risk ratio, incidence rate ratios, or similar), and kinematic or kinetic variables during vertical jump landing tasks.

Data Analysis and Synthesis

Qualitative Synthesis

Qualitative analysis was undertaken to determine the strength of the relationship analysis between all variables and the risk of noncontact knee injury and to help interpret data from the meta-analysis because the substantial heterogeneity or insufficient data prevented the inclusion of all studies in the meta-analysis. According to PRISMA guidelines, the results were grouped according to the type of kinematic or kinetic variable monitored as a risk parameter of knee injury.

To determine the strength of the associations between all kinetic and kinematic variables and the risk of knee injury and to help interpret data from the meta-analysis, as well as the studies that could not be included in the meta-analysis, the following criteria were used, which were adapted from similar studies[8,32,33,41]:

- Evidence was considered *strong* when ≥2 studies with low risk of bias reported consistent results.
- Evidence was considered *moderate* when 1 study with low risk of bias and ≥1 studies with moderate or high risk of bias reported consistent results, or when ≥2 studies with moderate or high risk of bias reported consistent results.
- Evidence was considered *limited* when only a study with low, moderate, or high risk of bias reported results.
- Evidence was considered *conflicting* when studies with low, moderate, or high risk of bias reported conflicting results, with ≥75% of these studies showing consistent results.
- Evidence was considered *very conflicting* when studies with low, moderate, or high risk of bias reported conflicting results, with <75% of these studies showing consistent results.

Quantitative Synthesis

To estimate the effect size indices, the sample size, mean, and standard deviation were extracted from the selected studies of each group: injured versus noninjured. When at least 2 studies examined double-leg drop-jump landing to prospectively associate it with subsequent injuries using an equivalent biomechanical statistic, meta-analysis was performed using the Meta-Essential tool for Excel 2013 and IBM SPSS 22.[38] For continuous data, standardized mean differences (SMDs) and 95% confidence intervals were calculated by dividing the means of the injured and uninjured groups by the pooled standard deviation. The SMDs in the means proposed by Cohen (ie, the Cohen d statistic) in each study were weighted by the inverse of their variance in order to obtain the pooled index of the magnitude of the effect. Because of the heterogeneous nature of the selected studies, a random-effects model was used. Finally, the heterogeneity was evaluated by using the inferential Cochran Q test and the I^2 heterogeneity index with its 95% confidence interval. Heterogeneity was considered high when I^2 was >50%.[13] The asymmetries of the effect size distribution due to publication bias or other types of bias were analyzed through 2 different strategies: the Begg strategy and the Egger test. A sensitivity analysis was performed to test the influence of possible outliers and to observe the trends in the results. The data not suitable for the meta-analyses were used to determine the association between the frontal plane and sagittal kinematic and kinetic variables and the risk of knee injury in the qualitative synthesis. The thresholds for the interpretation of the effect sizes were as follows: 0.1 = small; 0.3 = moderate; 0.5 = large; 0.7 = very large; and 0.9 = extremely large.[14] Statistical significance was set at $P < .05$.

RESULTS

Search Results

After removal of duplicates, 349 articles underwent title and abstract screening. When we applied eligibility criteria, 102 studies remained for further analysis. Full-text screening resulted in a final yield of 13 studies included in the systematic review and 6 included in the meta-analysis (Figure 1).

Description of the Included Studies

The present systematic review captured 333 noncontact knee injuries in 8689 participants (sex, 71.9% female and 28.1% male; age, 17.5 ± 2.2 years) who practiced basketball,[7,11,16,18,24,36,40] soccer,[§] handball,[6,15,24,35] volleyball,[6,7,11,16,35,36,40] korfball,[40] floorball,[18] hockey,[7,36] athletics,[29] gymnastics,[7] lacrosse,[7,36] rugby,[7,36] or frisbee.[7] Among noncontact knee injuries, 187 noncontact ACL injuries were registered. Additionally, 3 studies[6,25,40] monitored noncontact knee injuries without specifying the type of injury, registering 146 events (Appendix Table A2). Therefore, 3.8% of participants had a noncontact knee injury, with a mean ± SD age of 16.0 ± 1.5 years in the injured participants and 17.8 ± 2.4 years in the uninjured participants.

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§References 6, 7, 11, 15, 16, 25, 27, 35, 36.
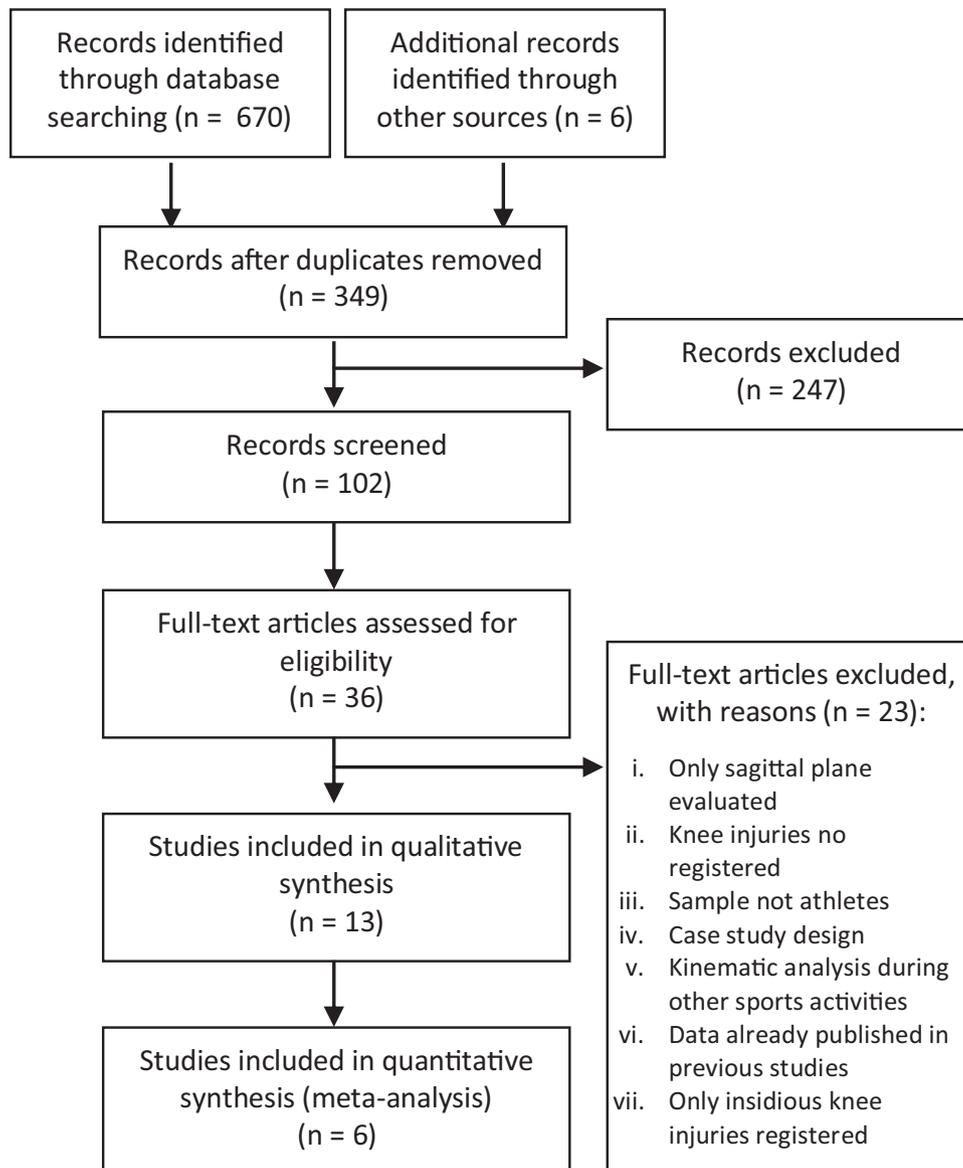
Figure 1. Flow diagram using the PRISMA (Preferred Reporting Items for Systematic Meta-Analyses) guidelines.

The mean follow-up duration per study was 104.4 ± 87.8 weeks. Of the selected cohort studies, only 12.5% (n = 2)[24,25] established randomization procedures, 53.8% (n = 7)[7,11,15,25,27,29,36] received funding, 46.2% (n = 6)[7,11,16,25,29,36] were carried out in the United States, 38.4% (n = 5)[6,15,18,35,40] were carried out in Western Europe (Norway, Belgium, the Netherlands, and Finland), and the remaining 6.3% (n = 1)[24] were carried out in Asia (Japan).

Knee Injury Risk

Qualitative Analysis

Results showed a total of 14 variables. Of these, 6 variables referred to frontal plane kinematics, with knee valgus during landing[15,16,18,29,35,40] and knee valgus at initial contact[11,15,18,24] the 2 variables most frequently evaluated in the studies. The other 4 variables referred to sagittal plane kinematics, with knee flexion during landing[16,35,40] and peak knee flexion[11,15,18,35] the 2 most frequently evaluated. Finally, the 4 remaining variables were about kinetics, with peak knee abduction moment[11,15,18,40] and vertical ground-reaction force (vGRF)[15,18,35] the most frequently evaluated.

Results identified that 3 of these 14 variables had no association with future noncontact knee injuries: 2 of these variables had moderate evidence for lack of such an association, and the remaining 1 variable had limited evidence for lack of such an association. Furthermore, 4 variables were identified as predictors of knee injury risk: 3 of these variables had limited evidence and only 1 study reported moderate evidence; the remaining 1 variable had moderate
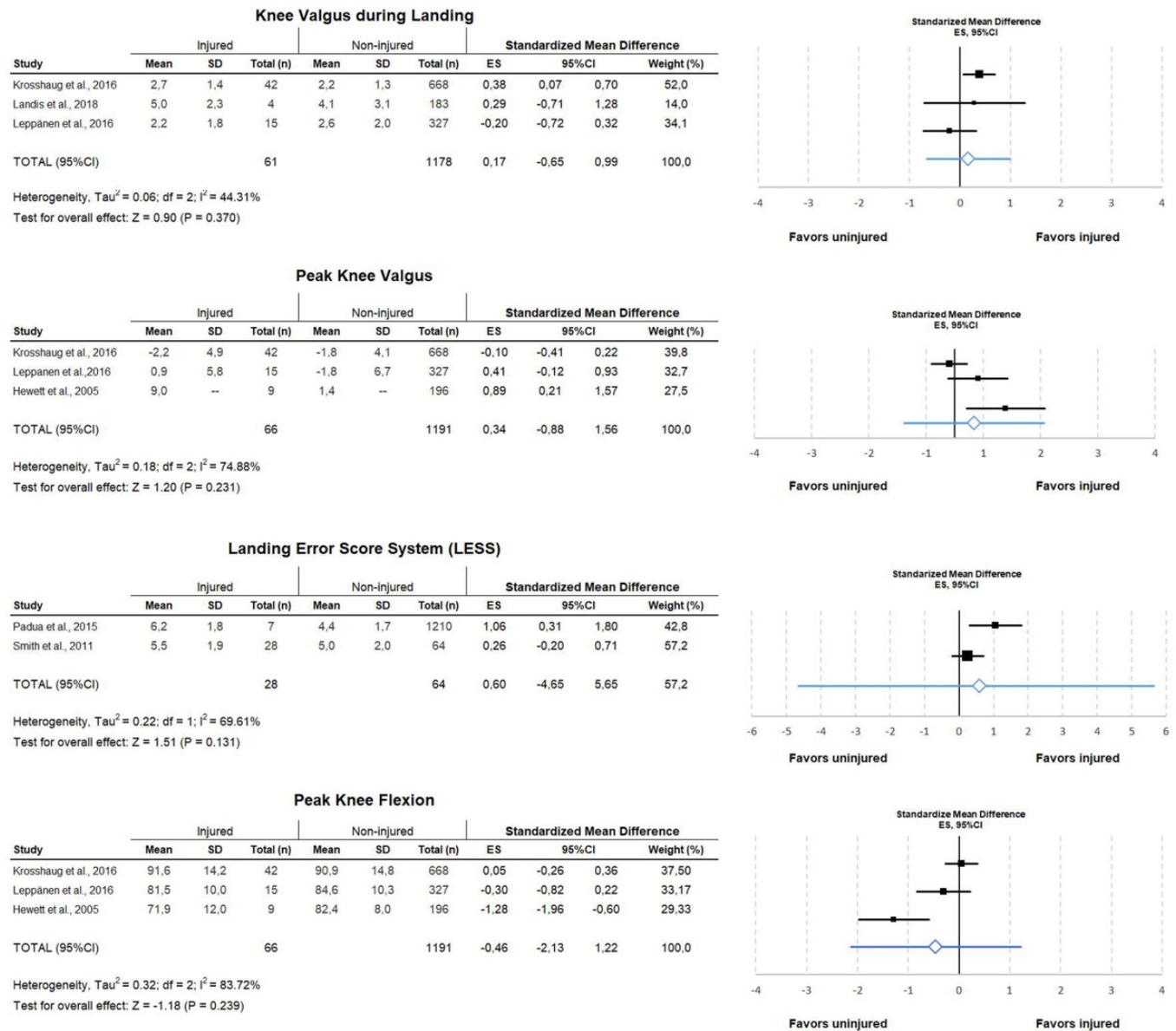
Knee Valgus during Landing

Study	Injured Mean	SD	Total (n)	Non-injured Mean	SD	Total (n)	ES	95%CI		Weight (%)
Krosshaug et al., 2016	2,7	1,4	42	2,2	1,3	668	0,38	0,07	0,70	52,0
Landis et al., 2018	5,0	2,3	4	4,1	3,1	183	0,29	-0,71	1,28	14,0
Leppänen et al., 2016	2,2	1,8	15	2,6	2,0	327	-0,20	-0,72	0,32	34,1
TOTAL (95%CI)			61			1178	0,17	-0,65	0,99	100,0

Heterogeneity, $Tau^2 = 0.06$; df = 2; $I^2 = 44.31\%$
Test for overall effect: Z = 0.90 (P = 0.370)

Peak Knee Valgus

Study	Injured Mean	SD	Total (n)	Non-injured Mean	SD	Total (n)	ES	95%CI		Weight (%)
Krosshaug et al., 2016	-2,2	4,9	42	-1,8	4,1	668	-0,10	-0,41	0,22	39,8
Leppanen et al.,2016	0,9	5,8	15	-1,8	6,7	327	0,41	-0,12	0,93	32,7
Hewett et al., 2005	9,0	--	9	1,4	--	196	0,89	0,21	1,57	27,5
TOTAL (95%CI)			66			1191	0,34	-0,88	1,56	100,0

Heterogeneity, $Tau^2 = 0.18$; df = 2; $I^2 = 74.88\%$
Test for overall effect: Z = 1.20 (P = 0.231)

Landing Error Score System (LESS)

Study	Injured Mean	SD	Total (n)	Non-injured Mean	SD	Total (n)	ES	95%CI		Weight (%)
Padua et al., 2015	6,2	1,8	7	4,4	1,7	1210	1,06	0,31	1,80	42,8
Smith et al., 2011	5,5	1,9	28	5,0	2,0	64	0,26	-0,20	0,71	57,2
TOTAL (95%CI)			28			64	0,60	-4,65	5,65	57,2

Heterogeneity, $Tau^2 = 0.22$; df = 1; $I^2 = 69.61\%$
Test for overall effect: Z = 1.51 (P = 0.131)

Peak Knee Flexion

Study	Injured Mean	SD	Total (n)	Non-injured Mean	SD	Total (n)	ES	95%CI		Weight (%)
Krosshaug et al., 2016	91,6	14,2	42	90,9	14,8	668	0,05	-0,26	0,36	37,50
Leppänen et al., 2016	81,5	10,0	15	84,6	10,3	327	-0,30	-0,82	0,22	33,17
Hewett et al., 2005	71,9	12,0	9	82,4	8,0	196	-1,28	-1,96	-0,60	29,33
TOTAL (95%CI)			66			1191	-0,46	-2,13	1,22	100,0

Heterogeneity, $Tau^2 = 0.32$; df = 2; $I^2 = 83.72\%$
Test for overall effect: Z = -1.18 (P = 0.239)

Figure 2. Meta-analysis forest plot of frontal and sagittal plane kinematic variables. ES, effect size.

evidence. We identified 7 variables with very conflicting evidence for an unknown association with future noncontact knee injuries (Appendix Table A3).
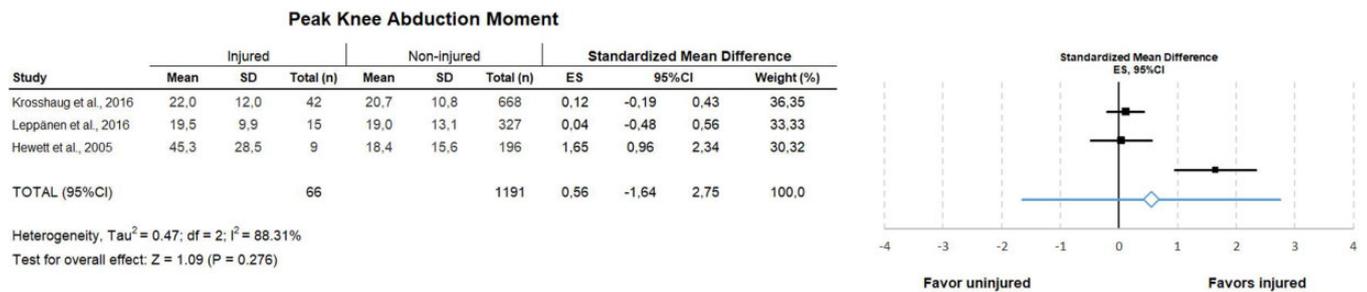
Quantitative Analysis: Meta-analysis

There were 5 meta-analyses performed across the 14 studies. The associations between 3 frontal plane kinematic variables (Figure 2), 1 sagittal plane kinematic variable (Figure 2), and 1 kinetic variable (Figure 3) with future acute noncontact injuries are graphically displayed. Among the frontal plane kinematics, high heterogeneity was found for peak knee valgus ($I^2 = 74.88\%$) and the LESS score ($I^2 = 69.61\%$) and low heterogeneity for knee valgus during landing ($I^2 = 44.31\%$). No significant associations were found for the aforementioned frontal plane variable with acute noncontact knee injuries ($P > .05$) (Figure 2). Peak knee flexion was the only sagittal plane kinematic variable evaluated, also with high heterogeneity and no significant association detected ($I^2 = 83.72\%$; $P > .05$) (Figure 2). For the kinetic variables, peak knee abduction moment showed high heterogeneity ($I^2 = 88.31\%$) and no significant associations with subsequent acute noncontact knee injuries ($P > .05$) (Figure 3).

Risk-of-Bias Assessment

A high risk of bias was found in 4 studies[11,18,24,40] and a moderate risk of bias in 8 studies.[6,7,15,18,25,29,35,36] Only 1 study was determined to have a low risk of bias.[16] According to the QUIPS tool, the most consistent area to elevate

Peak Knee Abduction Moment

Study	Injured			Non-injured			Standardized Mean Difference			
	Mean	SD	Total (n)	Mean	SD	Total (n)	ES	95%CI		Weight (%)
Krosshaug et al., 2016	22,0	12,0	42	20,7	10,8	668	0,12	-0,19	0,43	36,35
Leppänen et al., 2016	19,5	9,9	15	19,0	13,1	327	0,04	-0,48	0,56	33,33
Hewett et al., 2005	45,3	28,5	9	18,4	15,6	196	1,65	0,96	2,34	30,32
TOTAL (95%CI)			66			1191	0,56	-1,64	2,75	100,0

Heterogeneity, Tau^2 = 0.47; df = 2; I^2 = 88.31%
Test for overall effect: Z = 1.09 (P = 0.276)

Figure 3. Meta-analysis forest plot of kinetic variable. ES, effect size.

risk was study attrition (76.9% of studies) due to the lack of information about the follow-up period and completeness. Meanwhile, prognostic factor measurement was regarded the most consistent area to reduce risk (100% of studies) (Appendix Figure A1).

DISCUSSION

==The main findings of the present systematic review and meta-analysis showed that the kinematic and kinetic variables obtained from biomechanical evaluation of landing tasks in athletes did not allow prediction of acute noncontact knee injuries.== However, we observed an extremely high heterogeneity among the studies, which should be considered when interpreting these findings. Contributing to this controversy, most of the studies showed high risk of bias regarding study attrition and moderate to high risk related to study participation and study confounding.

Most of the studies did not report aspects related to dropouts (ie, number, reasons, or characteristics of those who dropped out) and data regarding the follow-up period and completeness. Also, many studies were unclear regarding the entire recruitment process (ie, period, place, or source of population) and/or did not consider important potential confounders in their investigations. As a favorable point to highlight, most of the studies reported complete information about the evaluation procedures and the outcomes obtained. In this sense, great homogeneity was observed in the intervention and procedures to evaluate participants. For example, 10 studies used a double-leg dropjump test to evaluate landing biomechanics. In this regard, a recent review affirmed that the drop-landing task may facilitate a lack of control in the center of mass height, resulting in biomechanical asymmetries between both lower limbs.[4] Owing to this limitation in the drop-jump task, authors of selected studies evaluated different kinematic and kinetic variables from the same test. Therefore, high variability was observed regarding the biomechanical variables that every study extracted from this test.

To organize the main biomechanical variables obtained in the selected studies and to clarify the available data, this review was structured regarding frontal and sagittal plane kinematics and kinetics during landing tasks based on the frequency with which the studies obtained these parameters. Therefore, this review observed 14 different variables after pooling all outcomes of the selected studies for the qualitative analyses. However, the observed variability allowed for extraction of only 5 variables for the quantitative analysis, all of which showed high heterogeneity (I^2 > 50%), except knee valgus during landing, which showed low heterogeneity (I^2 = 44.31%). The variability of data is the reason why the 5 meta-analyses in the present review included at most 4 studies for each variable.

Regarding frontal plane kinematics, this review found that knee valgus at initial contact (IC) and knee valgus during landing (obtained from the calculation [*knee valgus at IC*] − [*peak knee valgus*]) were the most frequently evaluated variables among the studies, demonstrating a very conflicting level of evidence regarding their association with future noncontact knee injuries. However, it seems that the studies with positive associations have attracted greater attention in the sports medicine world than those that did not find an association.[23] According to our results, the increasing load of knee structures was not sufficient to predict the damage of these structures, which does not allow us to confirm the predictive validity of these 2 frontal kinematic variables. In fact, in our review, almost half of the studies that evaluated different frontal plane kinematics did not find an association with future acute noncontact injuries. However, among the remaining studies that confirmed the predictive association between these variables and acute noncontact knee injuries, half had a high risk of bias. Consistently, the meta-analysis showed no significant association between frontal plane kinematics and subsequent acute noncontact knee injuries, demonstrating high heterogeneity in 2 of the 3 variables evaluated. Another variable identified in this review was the LESS score. In line with a recent review, our results suggest the necessity of more studies to confirm the predictive validity of the LESS score for noncontact knee injuries.[9] Although the qualitative analysis showed a very conflicting level of evidence for an unknown association with future acute noncontact injuries, the quantitative analysis confirmed this lack of association, with no significant effects.

Regarding the sagittal plane, because previous studies demonstrated its relationship with frontal plane variables, 7 studies also considered this plane for biomechanical analysis. This review identified 4 sagittal kinematic variables, of which knee flexion during landing and peak knee flexion were the most frequent biomechanical parameters measured among the studies. Our qualitative analysis showed no association for knee flexion during landing (with a

moderate level of evidence) and an unknown association for peak knee flexion (with a very conflicting level of evidence). In a similar way, the quantitative analysis for peak knee flexion did not show a significant association with future noncontact knee injuries. In line with our results, Norcross et al[22] suggested that sagittal plane biomechanical analysis is not enough to explain or predict future noncontact knee injuries. Although Norcross et al confirmed the importance of frontal plane kinematics to absorb energy during the initial phases of landing,[22] data extracted from selected studies did not allow for quantitative analysis of knee flexion at IC.

Finally, 4 kinetic variables were identified in this review, although none of them showed an association with a high enough level of evidence to ensure the predictive validity of this type of biomechanical parameter. Consistently, when quantitative analysis was possible, it did not show significant effects related to future acute noncontact knee injuries. In this sense, knee abduction moment was the only kinetic variable evaluated. Like the kinematic variables, knee abduction moment showed great heterogeneity values ($I^2 > 50.0\%$). When kinetic variables in landing tasks have been studied after ACL reconstruction, research has demonstrated altered values in the frontal and sagittal plane as well as in vGRF.[17] Although these parameters could be useful in monitoring the rehabilitation process, their predictive value should be demonstrated in future studies.

Therefore, in this review, all 14 variables showed no clear association with future acute noncontact knee injuries. All of the variables evaluated in this meta-analysis showed no significant associations, although the high risk of bias, heterogeneity, and small number of included studies should be considered.

Although kinematic and kinetic parameters during landing tasks lack the value to predict acute noncontact knee injuries, this finding does not detract from the importance of well-designed neuromuscular training programs that include drop-jump measurements. Previous studies have associated the use of these programs with decreased incidence of noncontact ACL injuries.[5] Clinicians should keep in mind the effectiveness of neuromuscular training programs but should not take biomechanical parameters from landing task evaluations as reference to evaluate injury risk.

The present review had some limitations. The small number of studies included in the meta-analysis hampered the extrapolation of results and limited definitive conclusions. The need to evaluate kinematic or kinetic variables of landing before noncontact knee injuries and to perform a subsequent follow-up considerably limited the number of studies selected. Further, the heterogeneity observed in the methods of the studies must be taken into account when interpreting the results of the present review. Limitations of this review also included publication and language bias: The selected studies had to be published and to be written in English or Spanish. In addition, this review focused on athletes. Therefore, these results cannot be considered for the sedentary population. For future studies, we recommend that authors select kinematic variables such as knee valgus during landing or knee valgus at IC for the frontal

plane, and knee flexion during landing or peak knee flexion for the sagittal plane, in order to add consistency to the evaluation of landing biomechanics in athletes. To diminish the risk of bias and ensure internal and external validity, authors should monitor the procedures related to recruitment, dropouts during the study, and potential confounders.

Sports and health professionals should be cautious when interpreting biomechanical variables from landing, owing to the lack of predictive capacity of these evaluations.

CONCLUSION

The kinematic and kinetic variables obtained from the biomechanical evaluation of landing tasks in athletes did not demonstrate any consistent ability to predict noncontact knee injuries. Furthermore, a high degree of heterogeneity and risk of bias characterized the studies included in this review.

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APPENDIX

APPENDIX TABLE A1
Search Strategies for all Databases[a]

MEDLINE (PubMed)
(1) athletes AND "knee injuries" AND "biomechanical phenomena"
(2) "knee injuries"[MeSH] AND "athletes" AND ("genu valgum"[MeSH] OR "knee valgus" OR "knee abduction" OR "dynamic valgus" OR "knee separation") AND ("biomechanical phenomena" OR "landing" OR "drop jump")

IBECS and LILACS (BVS)
(1) athletes AND "knee injuries" AND "biomechanical phenomena"
(2) "knee injuries"[MeSH] AND "athletes" AND ("genu valgum"[MeSH] OR "knee valgus" OR "knee abduction" OR "dynamic valgus" OR "knee separation") AND ("biomechanical phenomena" OR "landing" OR "drop jump")

Science Direct (Elsevier)
(1) athletes AND "knee injuries" AND "biomechanical phenomena"

CINAHL and SPORTDiscus (EBSCOHost)
(1) athletes AND "knee injuries" AND "biomechanical phenomena"
(2) athletes AND "knee injuries" AND "biomechanical phenomena" AND "genu valgum"
(3) "knee injuries"[MeSH] AND "athletes" AND ("genu valgum"[MeSH] OR "knee valgus" OR "knee abduction" OR "dynamic valgus" OR "knee separation") AND ("biomechanical phenomena" OR "landing" OR "drop jump")

IME
(1) athletes AND "knee injuries" AND "biomechanical phenomena"

SCIELO
(1) athletes AND "knee injuries" AND "biomechanical phenomena"

Cochrane
(1) athletes AND "knee injuries" AND "biomechanical phenomena"
(2) "knee injuries"[MeSH] AND "athletes" AND ("genu valgum"[MeSH] OR "knee valgus" OR "knee abduction" OR "dynamic valgus" OR "knee separation") AND ("biomechanical phenomena" OR "landing" OR "drop jump")

[a]MeSH, Medical Subject Headings.

APPENDIX TABLE A2
Characteristics of the Included Studies[a]

Lead Author (Year)	Sample and Sport	No. and Type of Knee Injuries	Test	Biomechanical Analysis	Frontal Plane Kinematic Factors	Other Kinematic and Kinetic Factors	Tracking Period
Hewett[11] (2005)	N = 205: female soccer, basketball, and volleyball players Age: 16.1 ± 1.7 y	n = 9: noncontact ACL injury Verified with arthroscopy or MRI	DJ from a 31-cm box (average of 3 trials)	3D motion analysis (25 retroreflective markers) with video cameras (EvaRT)	Knee valgus at IC, peak knee valgus	Knee flexion at IC, peak knee flexion, peak knee abduction moment, peak knee flexion moment, hip abduction moment	2002-2004 (2 y)
Paterno[29] (2010)	N = 56: female (n = 35) and male (n = 21) young athletes Age: 16.4 ± 3.0 y	n = 13: second noncontact ACL injury Verified with arthroscopy, MRI, or significant change (>3 mm) on the assessment of AP knee laxity	DJ from a 31-cm box (average of 3 trials)	3D motion analysis (37 markers) video cameras (Visual 3D)	Knee valgus during landing[b]	Knee abduction moment at IC, side-to-side difference in sagittal plane knee moment at IC, hip rotation moment at IC (all normalized by BW)	2007-2008 (1 y)
Goetschius[7] (2012)	N = 1855: soccer, field hockey, basketball, gymnastics, lacrosse, rugby, frisbee, and volleyball female athletes Age: 18.1 ± 1.7 y	n = 20: noncontact ACL injury Verified with MRI and arthroscopy	DJ from a 30-cm box (average of 3 trials)	2D motion analysis (no markers) video cameras (Dartfish)	Knee abduction moment probability score	NA	2008-2011 (3 y)
Smith[36] (2012)	N = 3876: female (n = 1855) and male (n = 2021) soccer, football, rugby, field hockey, basketball, gymnastics, lacrosse and volleyball athletes Age: 18.0 ± 1.7 y	n = 20: noncontact ACL injury Verified with MRI and arthroscopy	DJ from a 30-cm box (average of 3 trials)	2D motion analysis (no markers) video cameras (Dartfish)	LESS score	NA	2008-2011 (3 y)
Dingenen[6] (2015)	N = 44: elite female soccer (n = 26), handball (n = 7), and volleyball players (n = 11) Age: 20.5 ± 3.2 y	n = 7: noncontact knee injuries in soccer (n = 4), handball (n = 2), and volleyball (n = 1) players Verified with MRI and surgery required	Single-leg DJ from a 10-cm box (average of 3 trials each leg)	2D motion analysis (markers at ASIS, greater trochanter, medial and lateral femoral condyles, and medial and lateral malleolus) video cameras (Dartfish)	Peak knee valgus normalized by lateral trunk motion	Peak hip flexion	1 y
O'Kane[25] (2015)	N = 351: female elite youth soccer players Age: 11-14 y	n = 134: lower extremity injury in knee joint (n = 43 [2 ACL]) Diagnosed by the sports medicine physician with any available medical records	DJ from a 31-cm box (average of 3 trials)	2D motion analysis (markers at greater trochanter, center of patella, lateral malleolus, lateral knee) video cameras (Sportsmetrics)	Knee separation distance at IC, knee separation distance at peak knee valgus	NA	2008-2012 (4 seasons)

(continued)

APPENDIX Table A2 (continued)

Lead Author (Year)	Sample and Sport	No. and Type of Knee Injuries	Test	Biomechanical Analysis	Frontal Plane Kinematic Factors	Other Kinematic and Kinetic Factors	Tracking Period
van der Does[40] (2016)	N = 75: male (n = 49) and female (n = 26) elite or subelite basketball, volleyball, or korfball players Age: 21.9 ± 3.5 y	n = 6: acute knee injuries Medical-attention injuries registered by the physical therapist	Repeat countermovement jump (10 series of 3 maximal countermovement jumps) (average of the trials)	3D motion analysis (21 markers) video (Vicon Motion Analysis System)	Knee valgus during landing[b]	Peak vGRF, peak knee abduction moment, peak knee flexion moment, peak ankle dorsiflexion moment, and peak value and during-landing[b] value for knee flexion, hip flexion, and ankle dorsiflexion	1 season
Padua[27] (2015)	N = 829: male (n = 348) and female (n = 481) elite-youth soccer players Age: 13.9 ± 1.8 y	n = 7: noncontact ACL injury Verified during surgical reconstruction	DJ from a 30-cm box (average of 3 trials)	2D motion analysis (no markers) video cameras (Quicktime)	LESS score	NA	2006-2009 (3 seasons)
Krosshaug[15] (2016)	N = 710: premier league female handball players (n = 372) and female soccer players (n = 338) Age: 21.1 ± 3.7 y	n = 53: noncontact ACL injury in handball (n = 26) and soccer (n = 27) players Verified with MRI or arthroscopy	DJ from a 30-cm box (average of 3 trials)	3D motion analysis (markers at iliac crests and ASIS) infrared cameras (Oqus 4, Qualisys)	Knee valgus at IC, medial knee displacement	Peak knee flexion, peak vGRF (N), peak knee abduction moment (N·cm)	2007-2014 (7 y)
Leppänen[18] (2017)	N = 171: female elite junior basketball (n = 96) and floorball (n = 75) players Age: 15.4 ± 1.9 y	n = 15: noncontact ACL injury in basketball (n = 3) and floorball (n = 12) players Verified with MRI	DJ from a 30-cm box (average of 3 trials)	3D motion analysis (16 markers) video cameras (Vicon)	Knee valgus at IC, medial knee displacement	Knee flexion at IC, peak knee flexion, peak vGRF, peak knee abduction moment	2011-2014 (3 seasons)
Landis[16] (2018)	N = 187: female collegiate soccer (n = 63), basketball (n = 92), and volleyball (n = 62) players Age: 19.5 ± 1.2 y	n = 17: noncontact ACL injuries (n = 4) and other noncontact lower extremity injuries (n = 13) Injuries clinically assessed and diagnosed by a medical professional	DJ from a 31-cm box (average of 3 trials)	2D motion analysis (no markers) (software not specified)	Knee abduction moment probability score, knee valgus during landing[b]	Knee flexion during landing[b]	12-16 wk
Numata[24] (2018)	N = 291: collegiate female basketball and handball players Age: 15.0 ± 0.0 y	n = 27: noncontact ACL injury in basketball (n =15) and handball (n= 12) players Verified (method nonspecified)	Single-leg DJ from a 30-cm box (average of 3 trials each leg)	2D motion analysis (markers at ASIS and medial and lateral femoral condyles) video cameras (ImageJ)	Knee valgus at IC, peak knee valgus	NA	2009-2011 (3 y)
Smeets[35] (2019)	N = 39: Female soccer (n = 21), handball (n = 9), and volleyball (n = 16) players Age: 20.7 ± 3.2 y	n = 4: noncontact ACL injury Verified with MRI	DJ from a 30-cm box (average of 3 trials)	3D motion analysis (Visual 3D)	Knee valgus during landing	Knee flexion during landing, hip flexion during landing, knee muscle activity (EMG), knee abduction moment during landing	1 y

[a]All studies had a prospective cohort design except for Krosshaug et al[15] (prospective dynamic cohort). All studies were evidence level 2 as indicated by US Preventive Services Task Force guidelines: https://www.uspreventiveservicestaskforce.org/uspstf/grade-definitions. 2D, 2-dimensional; 3D, 3-dimensional; ACL, anterior cruciate ligament; AP, anterior-posterior; ASIS, anterior superior iliac spine; BW, body weight; DJ, drop-jump (based on protocol of Padua et al[27]); EMG, electromyography; IC, initial contact; LESS, landing error score system; MRI, magnetic resonance imaging; NA, not applicable; vGRF, vertical ground-reaction force.

[b]Result of (knee valgus at initial contact) – (peak knee valgus).

APPENDIX TABLE A3
Qualitative Results[a]

	n	Risk of Bias in the Included Studies[b]				Best-Evidence Synthesis	
		Low	Moderate	High	Association With Risk[c]	Association	Level of Evidence
Frontal-plane kinematic variables							
Knee valgus during landing[d]	1238	16	15, 18, 29, 35	40	↑ 15, 16, 29 = 18, 35, 40	Unknown	Very conflicting
Knee valgus at IC	1377		15, 18	11, 24	↑ 11, 24 = 15, 18	Unknown	Very conflicting
LESS score	4705		36	27	↑ 27 = 36	Unknown	Very conflicting
Peak knee valgus	496			11, 24	↑11, 24	Yes	Moderate
Knee valgus normalized by lateral trunk motion	44		6		↑ 6	Yes	Limited
Knee distance separation (normalized by hip distance ×100)	351		25		↑ 25 (only postmenarchal players)	Yes	Limited
Sagittal-plane kinematic variables							
Knee flexion during landing[d]	2235	16	35, 40		= 16, 35, 40	No	Moderate
Knee flexion at IC	376		18	11	= 11, 18	No	Limited
Peak knee flexion	1154		15, 18, 40	11	= 15, 40 ↓ 11, 18	Unknown	Very conflicting
Side-to-side difference knee flexion at IC	56		29		↑ 29	Yes	Limited
Kinetic variables							
Peak knee abduction moment	1200		15, 18, 35, 40	11	↑ 11 = 15, 18, 35	Unknown	Very conflicting
Knee abduction moment probability	2042	16	7		= 7, 16	No	Moderate
Peak knee flexion moment	280		40	11	↓ 40 =11	Unknown	Very conflicting
Peak vertical GRF	956		15, 18, 40		↑ 18, 40 = 15	Unknown	Very conflicting

[a]GRF, ground-reaction force; IC, initial contact; LESS, landing error score system.

[b]Numbers in the Risk of Bias columns are reference citations.

[c]Symbols indicate the following: ↑, association with increased risk for noncontact knee injuries; ↓, association with reduced risk for noncontact knee injuries; =, no significant association for noncontact knee injuries.

[d]Result of (initial contact knee angle) – (peak knee angle).
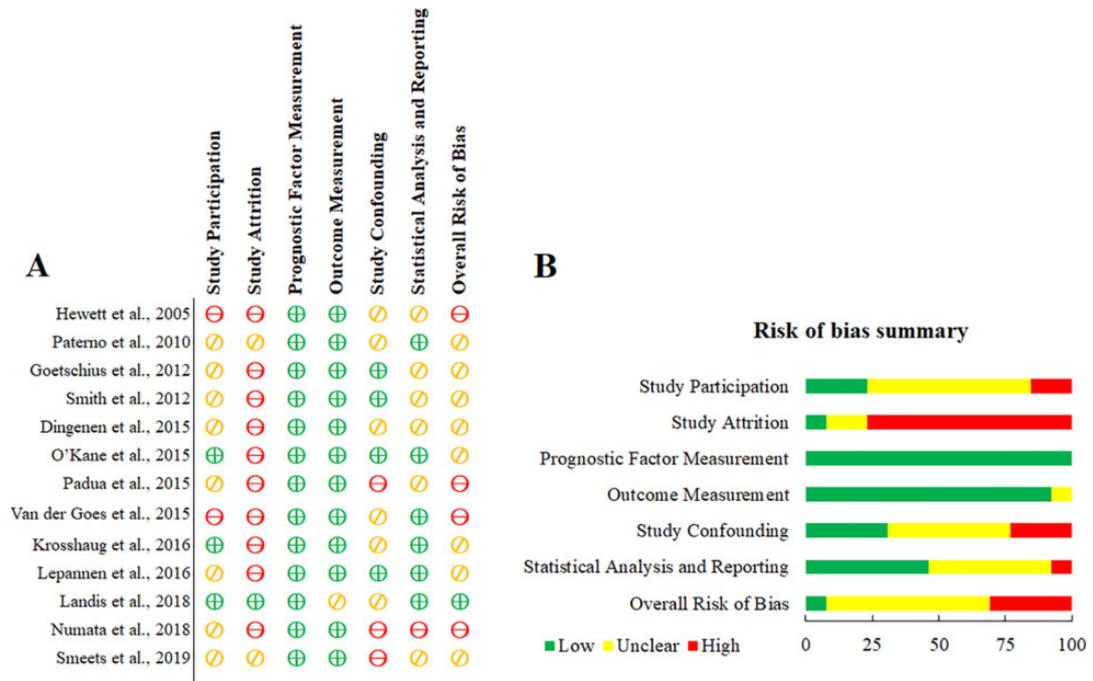
Appendix Figure A1. Risk-of-bias assessment. (A) Overall and (B) summary.