

Systematic Review

Effects of Cognitive Demands on ACL Injury-Related Knee Kinematics: A Systematic Review with Meta-Analysis

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Featured Application

The findings of this systematic review may provide a theoretical foundation to inform future injury prevention and return-to-sport programmes by identifying which cognitive demands modify knee biomechanics during sport-specific tasks. However, as this review did not directly evaluate clinical outcomes or intervention protocol, these practical implications should be framed as hypotheses to be tested in future intervention studies. Specifically, clinicians, coaches and researchers may benefit from incorporating ecologically valid paradigms into biomechanical assessments and neuromuscular training protocols, including unanticipated decision-making tasks, sport-specific visual stimuli, time-constrained responses and dual-task condition. Nonetheless, it must be acknowledged that direct evidence regarding actual injury rate reduction through these strategies remains insufficient.

Abstract

Interest in the relationship between cognitive demands and anterior cruciate ligament (ACL) injuries has increased, particularly during change-of-direction and jump-landing tasks. This study examined how different cognitive demands influence ACL-related biomechanical variables at initial ground contact. A systematic review with meta-analysis was conducted according to the Cochrane Handbook for Systematic Reviews of Interventions and the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. PubMed, Scopus and Web of Science were searched up to 23 May 2025. Cognitive demands were classified into four groups: decision making, divided attention, perturbation and uncertainty. JASP software was used for the meta-analysis. A total of 6213 records were identified, and 59 studies were included. Significant differences were found only in the decision making group when analysing the female cohort, with greater knee flexion angles under anticipated conditions in the sagittal plane (SMD = 0.21, 95% CI = 0.01, 0.40, $p = 0.039$), whereas no differences were observed in the male cohort, the overall group or the frontal plane across any of the subgroups ($p \geq 0.163$). No significant differences were found for divided attention, perturbation or uncertainty in either the sagittal or frontal plane. These findings indicate that cognitive demands modify knee kinematics only in the sagittal plane for females with a small effect size. While these laboratory-based insights offer potential hypotheses for neuromuscular training and assessment protocols (such as incorporating unanticipated and dual-tasks conditions) further clinical studies are required to confirm their effectiveness in actual injury prevention.



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1. Introduction

Anterior cruciate ligament (ACL) injuries are a common setback in an athlete's career [1]. Most of the injuries occur during manoeuvres such as changes of direction, pivoting, jumps, landings and decelerations [2,3] during the first 50 ms after the initial contact with the ground [4,5]. Furthermore, it has been observed that the ACL suffers the greatest strain between the first 48 to 61 ms after initial contact [6]. Many team sports are concerned about this issue since it is such a widespread injury [7–11]; however, this is not confined to team sports, as it is also an issue in individual sports [12,13]. Several epidemiological studies have been conducted to better understand how these injuries occur by analysing the injury mechanism.

The ACL injury mechanisms described are non-contact injuries (no contact with any other player), indirect contact injuries (contact on any part of the body but the injured knee) and direct contact injuries (contact to the injured knee) [14]. In team sports, despite all players sharing the same space, most of the ACL ruptures occurred without contact with other players and during competition matches [15]. This trend is clearly evident in football [16] and handball [10]. Nevertheless, in other sports such as basketball it was found that indirect injuries are the most common mechanism [9,17]. In American football and rugby non-contact injuries are also common but, due to the nature of the sports, there are a great number of injuries after contact, and specifically in some playing positions, the majority of the injuries occurred via direct contact mechanisms [3,18–20].

Non-contact injuries are the most commonly studied since the prevalence is higher and there are some risk factors that can be addressed with preventive training programmes [21], but despite all the research related to this issue the number of injuries has not decreased since the 2000s [22]. This may be because ACL injuries are multifactorial and of a complex nature (e.g., dynamic knee valgus, hip muscle weakness and unanticipated environmental events among others) [23]. One of the new perspectives currently being investigated is how cognitively demanding task conditions are linked to ACL injuries [24], as it has been observed that neurocognitive errors are common during non-contact ACL injuries [25]. Neurocognition can be understood as the cognitive processes or functions related to neural mechanisms that occur in the brain and any alterations of these mechanisms [24]. Some neurocognitive aspects that may influence variables previously linked with an increased risk of ACL injury are visual attention, processing speed/reaction time and dual tasking [26]. Furthermore, it has been observed that athletes with a lower cognitive performance (e.g., measuring inhibition control, reaction time and processing speed [24,26]) are at a higher risk of suffering an injury during cognitive-challenging movements [27].

Several reviews have been conducted [27–31] reflecting the increase in interest in how cognitive challenging tasks may alter ACL-injury related risk markers. Additionally, various meta-analyses have shown how these demanding conditions may affect lower limb biomechanics associated with ACL injury [32–34]. For example, unplanned movements modify knee abduction and tibial internal rotation moments during landing and/or sidestep-cutting [33] and peak or mean knee flexion angle during changes of direction [34]. However, to our knowledge, there are no meta-analyses conducted on knee angle variables at initial contact with the ground, which is a crucial phase for these injuries [4]. While identifying how cognitive demands modify knee kinematics may offer valuable hypotheses for future neuromuscular training protocols, direct prospective evidence linking these laboratory outcomes to actual injury risk reduction seems to be currently lacking. There-

fore, the aim of this study was to analyse how different cognitive demands may affect ACL injury-related biomechanical variables at initial contact with the ground. A previous review divided cognitive demands into two groups: decision making (number of choices, its complexity and available time to react) and divided attention (attentional demand and attention capacity) [29]. Additionally, some studies also analyse if perturbation [35] and uncertain conditions [36] may affect the kinematics related to ACL injuries. Consequently, it seems that four groups of different cognitive demands could be established: decision making, divided attention/dual task, perturbation and uncertainty.

2. Methods

A systematic review with meta-analysis was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) [37]. The completed PRISMA 2020 checklist is provided as Supplementary File S1 [38]. This study was previously registered in the International Prospective Register of Systematic Reviews (PROSPERO) database with the code CRD42024617048.

2.1. Search Strategy

A systematic literature search was performed for articles published up to 23 May 2025 in three databases: PubMed (MEDLINE), Scopus and Web of Science. The search strategy consisted of four group of terms combined using a Boolean search strategy with the operators “AND” and “OR” based on previous reviews searches [27,30,33,34]. The search syntax was as follows: (1) “anterior cruciate ligament” OR “ACL” OR “knee” OR “lower limb” OR “lower extremity” OR “leg” OR “ankle” OR “hip” OR “injur*”; (2) “cognit*” OR “neurocognit*” OR “perturbation” OR “attention*” OR “decision-making” OR “visual-motor” OR “visual-spatial” OR “unplanned movement” OR “reaction time” OR “dual-task” OR “anticipat*” OR “inhibition” OR “executive function” OR “neuromotor function”; (3) “biomechanic*” OR “mechanic*” OR “kinematic*” OR “kinetic*” OR “valgus” OR “abduction” OR “flexion” OR “movement quality”; (4) “sport” OR “physical activity” OR “land*” OR “jump*” OR “sidestep*” OR “side-step*” OR “cut” OR “cutting” OR “motor task” OR “performance” OR “functional test” OR “change of direction” OR “COD” OR “deceleration*”. Detailed syntax used for each database is presented in Figure S1.

2.2. Inclusion Criteria

Inclusion and exclusion criteria were based on previous studies [30,33,34]. Inclusion criteria were: (1) to be published in English or Spanish; (2) with healthy non-injured participants at the time of the data collection; (3) ages between 16 and 45 years; (4) using an experimental (randomised controlled trials), quasi-experimental or single-case design; (5) analysing biomechanical variables associated with ACL injuries where contexts and environments are modified to impose a cognitive demand; (6) including tasks with both low and high cognitive demand; (7) with no alteration in the metabolic, neurological, motivational or emotional conditions of the participants; and (8) reporting knee angles in the sagittal and/or frontal plane at initial contact with the ground.

On the other hand, the exclusion criteria were: (1) participants who were injured, could not perform the tasks without pain, had any impairment that could affect the results (i.e., chronic ankle instability) or were having medical treatment during data collection; (2) the tasks did not imply any cognitive demand (e.g., decision making, divided attention, perturbation or uncertainty); and (3) the data presented did not compare between low and high cognitive demands or only compared them including the data without separating injured and non-injured participants.

Studies with fatigue protocols and/or training programmes were not excluded if the data presented compared between cognitive tasks and baseline tasks prior to those interventions [33,34]. In the cases where the protocol included participants with impairments that could affect the performance of the task and a control group, only the data of the groups that met the inclusion/exclusion criteria were retrieved [33]. ACL-reconstructed participants cleared to return to sport and performing tasks without pain or discomfort were included and pooled into the same analytical group as non-injured participants.

2.3. Data Extraction

Once the search was completed, every record was downloaded and the duplicates were removed. Then, two authors (DO-S and MR-d) independently screened every title and abstract to analyse the study eligibility. If no agreement was reached in any study a third author (AB-S) was consulted until a unanimous decision was reached. If studies were selected, then the full text was searched to finally decide whether to include them in the analysis or not. If a full text could not be found, a request was made to the corresponding authors. After the final list of included articles was reviewed, some additional studies were included after retrieving them from other reviews. When a study did not provide the necessary data to meet the inclusion/exclusion criteria (e.g., data of injured and control participants presented as the mean value of both groups) and/or to be included in the meta-analysis (e.g., no standard deviation), it was excluded. Prior to the final exclusion, corresponding authors were contacted to request the missing information.

2.4. Classification of Cognitive Demanding Categories

Included studies were classified based on the specific operational paradigm used to impose cognitive demands during motor execution. Studies offering multiple experimental comparisons between different cognitive demanding conditions and a baseline were eligible for inclusion in more than one category provided that multiple cognitive demands were not performed within the same trial. Specifically, four distinct categories were defined: (1) decision making, which encompassed paradigms requiring real-time visual or auditory cue processing to select and execute a motor action based on an external stimulus provided during task execution (e.g., changing direction upon seeing a directional arrow during the approach run or selecting a landing strategy in response to a visual cue presented mid-flight); (2) divided attention, which included protocols requiring participants to simultaneously perform a secondary task alongside the primary motor action, thereby dividing attentional resources between both tasks (e.g., executing mental arithmetic during a jump-landing or catching/dribbling a ball while completing a cutting manoeuvre); (3) perturbation, which comprised methodologies applying a physical force or mechanical disruption requiring rapid neuromotor adjustments (e.g., absorbing the impact of a ball or a rope-pull prior landing); and (4) uncertainty, which included paradigms where temporal or spatial predictability was manipulated such that participants could not anticipate when or where an environmental change would occur (e.g., landing with unknown drop timing or height or trial without knowing when the surface condition would change).

2.5. Study Quality and Quality of Evidence

An adapted version of a checklist proposed by Downs and Black [39] was used to determine the methodological quality of the studies as previously used in similar systematic reviews on this topic [28,33,34]. This checklist assesses the quality of randomised and non-randomised controlled trials, with 27 items divided into four categories, namely reporting quality, external validity, internal validity and power, and has a high validity and good inter-rater reliability [39,40]. This checklist was subsequently reduced to 17 items divided into the same four categories and each one was awarded 1 point if the criteria were met.

Four categories were established to determine the overall study quality: excellent (16–17 points), good (12–15 points), fair (9–11 points) and poor (<9 points) [31,33].

The risk of bias assessment was determined with the Cochrane Handbook for Systematic Reviews of Interventions tool modified for randomised trials [41] as previously used in a similar systematic review [30]. A familiarisation and control bias was added while the conduct bias was deleted since it is very difficult or even impossible to successfully blind participants and investigators in a supervised exercise intervention [30,42]. To avoid familiarisation bias, it was necessary to conduct a familiarisation session in the studies, and not just to rely on the fact that the participants practised sports in which the analysed task was normally performed. As previously noted, for studies incorporating a fatigue protocol or training programme, only pre-intervention values were extracted. Consequently, the fatigue and training program bias domain was omitted from the risk-of-bias assessment.

2.6. Statistics

Data were collected as mean $\pm$ standard deviation to analyse the difference between baseline and cognitive demanding tasks. Statistical analysis was performed using JASP (version 0.98.1; JASP Team, Amsterdam, The Netherlands). To account for potential within-study dependency arising from papers contributing multiple comparisons and to prevent the artificial inflation of sample sizes and study weights, multilevel random-effects meta-analytic models (3-level structure) were implemented. This approach partitions total variance into sampling variance (level 1), variance between comparisons within the same study (level 2) and variance between studies (level 3). This properly adjusts the statistical weight assigned to each paper regardless of its number of comparisons. JASP mathematically incorporates all nested comparisons into the model, adjusting for data dependency without artificially inflating the effective sample size, while visually summarising each study as a single entry in the forest plots for graphical conciseness.

Continuous outcomes were evaluated using the standardised mean difference (SMD) with corresponding 95% confidence intervals (CIs) [43,44]. To account for the within-participant repeated-measures design, within-subject correlations were incorporated into SMD calculations, assuming a correlation of $r = 0.5$ in accordance with Cochrane recommendations [43]. Effect sizes were interpreted as follows: <0.2 trivial, 0.2–0.5 small, 0.51–0.8 moderate and >0.8 large effect size [45]. Model parameters and the variance between studies and comparisons were estimated via restricted maximum likelihood (REML), applying the Knapp–Hartung adjustment to calculate the pooled effect sizes with adjusted standard errors. Between-study heterogeneity was assessed using Cochran’s Q test [43]. The level of significance was established at $p < 0.05$ for all analyses. Publication bias was visually assessed using residual funnel plots for analyses with a sufficient number of included estimates ($k \geq 10$). For subgroups or outcomes with limited estimates ($k < 10$), formal publication bias assessments were omitted in accordance with Cochrane guidelines, as small sample sizes limit the power and validity of asymmetry evaluations [43]. Finally, the certainty of evidence for each pooled knee-kinematic outcome was assessed using the GRADE framework. The assessment considered risk of bias, inconsistency, indirectness, imprecision, and publication bias.

3. Results

3.1. Search Results

The initial search on the three databases resulted in a total of 6213 records (1636 in PubMed, 2798 in Scopus and 1779 in Web of Science). Of these, 123 were assessed for eligibility and, after scanning references lists of previous reviews, 71 studies were included. Finally, a total of 59 studies were included for analysis since data could not be retrieved in

12 studies even after contacting the corresponding authors. A detailed description of the search and selection process appears in Figure 1.

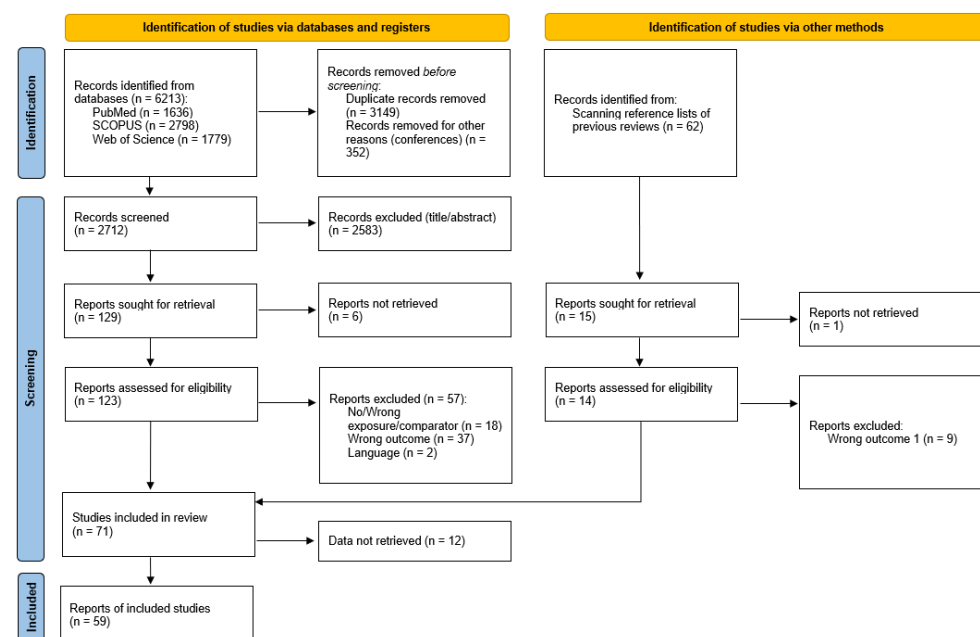


Figure 1. PRISMA 2020 flow diagram.

3.2. Characteristics of the Studies Included

A total of 1351 participants (568 men, 738 women and 45 not specified) were evaluated in the 59 studies included for analysis; all their characteristics are presented in Table 1. Most of the studies (64.4%) included participants that usually participate in sports that include jump-landing actions and changes of direction. Two included military participants and 19 did not specify the activities in which the participants were enrolled.

Table 1. Characteristics of the studies included in the meta-analysis.

Study	Group	Participants Characteristics	Sport
Abe et al. [46]	DA + UNC	N = 20 (M = 10 & W = 10) 21.5 ± 2.1 y; N.S. kg; N.S. m non-injured	N.S.
Akbari et al. [47]	DA	N = 24 (M = 6 & W = 18) 20.0 ± 1.1 y; 61.0 ± 8.5 kg; 1.66 ± 0.07 m non-injured	Soccer
Almonroeder et al. [48]	DM + DA	N = 20 (M = 0 & W = 20) 21.5 ± 1.8 y; 64.1 ± 11.2 kg; 1.70 ± 0.10 m non-injured	Basketball
Almonroeder et al. [49]	DA	N = 20 (M = 0 & W = 20) 21.5 ± 1.8 y; 64.1 ± 11.2 kg; 1.70 ± 0.10 m non-injured	Basketball
Arumugam et al. [50]	DM	N = 20 (M = 4 & W = 16) 24.2 ± 4.2 y; 67.5 ± 10.1 kg; 1.70 ± 0.08 m unilateral ACL reconstruction, at the end stage or completed rehabilitation, and able to perform hop tests without pain or discomfort	N.S.

Table 1. Cont.

Study	Group	Participants Characteristics	Sport
Aziminia et al. [51]	DM	N = 18 (M = 18 & W = 0) 22.7 ± 2.2 y; 71.4 ± 8.5 kg; 1.77 ± 0.04 m non-injured	Futsal
Bedo et al. [52]	DM	N = 31 (M = 0 & W = 31) 21.9 ± 2.7 y; 64.2 ± 8.9 kg; 1.67 ± 0.06 m (16 professional and 15 collegiate) non-injured	Handball
Bill et al. [53]	DM + DA	N = 51 (M = 0 & W = 51) 19.2 ± 3.4 y; 67.0 ± 7.7 kg; 1.70 ± 0.06 m (overall) 21.0 ± 3.7 y; 68.5 ± 7.2 kg; 1.70 ± 0.07 m (cluster 1 n = 14) 18.3 ± 1.8 y; 69.2 ± 8.0 kg; 1.72 ± 0.05 m (cluster 2 n = 37) non-injured and 7 with previous ACLR	Handball
Borotikar et al. [54]	DM	N = 24 (M = 0 & W = 24) 21.2 ± 2.5 y; 67.5 ± 7.4 kg; 1.76 ± 0.05 m non-injured	Basketball, soccer and volleyball
Brazalovich et al. [55]	DA	N = 29 (M = 22 & W = 7) 20.5 ± 1.2 y; 78.3 ± 14.3 kg; 1.75 ± 0.09 m non-injured	Reserve Officers’ Training Corps/Military
Brown et al. [56]	DM	N = 26 (M = 13 & W = 13) N.S. y; N.S. kg; N.S. m non-injured	N.S.
Byrne et al. [57]	DM	N = 60 (M = 60 & W = 0) 21.0 ± 4.1 y; 80.4 ± 9.4 kg; 1.84 ± 0.07 m non-injured	Australian football
Chan et al. [58]	DA	N = 13 (M = 0 & W = 13) 21.8 ± 2.6 y; 61.7 ± 8.1 kg; 1.68 ± 0.05 m non-injured	Basketball
Cortes et al. [59]	DM	N = 13 (M = 0 & W = 13) 19.3 ± 0.9 y; 61.3 ± 5.6 kg; 1.68 ± 0.05 m non-injured	Soccer
Dai et al. [60]	DA	N = 38 (M = 19 & W = 19) 21.4 ± 1.4 y; 71.7 ± 13.4 kg; 1.75 ± 0.10 m non-injured	Action sports
Dempsey et al. [61]	DM	N = 12 (M = 12 & W = 0) N.S. y; 80.2 ± 12.5 kg; 1.84 ± 0.05 m 9 completed the study non-injured	Australian football, rugby and soccer
Dowling et al. [62]	DA	N = 22 (M = 11 & W = 11) 23.6 ± 2.7 y; N.S. kg; N.S. m non-injured	Sidestep cutting manoeuvres sports (soccer, lacrosse and ultimate frisbee)
Fedie et al. [63]	DA	N = 38 (M = 19 & W = 19) 19.9 ± 1.6 y; 84.8 ± 9.7 kg; 1.88 ± 0.09 m (men) 20.7 ± 1.8 y; 72.2 ± 9.4 kg; 1.76 ± 0.07 m (women) non-injured	Basketball

Table 1. Cont.

Study	Group	Participants Characteristics	Sport
Fong et al. [64]	DM	N = 10 (M = 10 & W = 0) 26.4 ± 1.8 y; 70.9 ± 15.6 kg; 1.73 ± 0.72 m non-injured	N.S.
Fuerst et al. [65]	DM	N = 13 (M = 13 & W = 0) 25.0 ± 3.0 y; 79.0 ± 9.0 kg; 1.84 ± 0.07 m non-injured	Basketball
Gambelli et al. [66]	DA	N = 9 (M = 3 & W = 6) 30.5 ± 8.0 y; 62.5 ± 13.1 kg; 1.67 ± 0.03 m non-injured	N.S.
Han et al. [67]	UNC	N = 44 (M = 22 & W = 22) 23.4 ± 2.6 y; 70.5 ± 10.7 kg; 1.74 ± 0.10 m (control n = 22) 23.0 ± 2.4 y; 69.7 ± 13.4 kg; 1.74 ± 0.10 m (copers n = 22) copers and non-injured	N.S.
Helm et al. [68]	DA + UNC	N = 18 (M = 10 & W = 8) 24.0 ± 4.5 y; 64.0 ± 7.0 kg; 1.71 ± 0.07 m non-injured	N.S.
Hou et al. [69]	DM	N = 15 (M = N.S. & W = N.S.) 24.3 ± 5.7 y; N.S. kg; N.S. m non-injured	N.S.
Imai et al. [70]	DA	N = 20 (M = 0 & W = 20) 20.2 ± 1.3 y; N.S. kg; N.S. m non-injured	Basketball, volleyball, ski and badminton
Khalid et al. [71]	DM	N = 12 (M = 6 & W = 6) 19.7 ± 1.9 y; 61.0 ± 9.6 kg; 1.68 ± 0.08 m (overall) 20.2 ± 1.8 y; 66.6 ± 6.0 kg; 1.74 ± 0.03 m (men) 19.3 ± 2.0 y; 55.4 ± 9.6 kg; 1.61 ± 0.04 m (women) non-injured	Soccer
Ko et al. [72]	DA	N = 20 (M = 10 & W = 10) 25.0 ± 4.0 y; 74.0 ± 11.0 kg; 1.76 ± 0.06 m (men) 22.0 ± 2.0 y; 57.0 ± 6.0 kg; 1.62 ± 0.04 m (women) non-injured	N.S.
Konishi et al. [73]	DM	N = 32 (M = 16 & W = 16) 21.0 ± 2.4 y; 71.2 ± 14.2 kg; 1.77 ± 0.18 m (control n = 16) 21.5 ± 2.0 y; 66.6 ± 12.0 kg; 1.75 ± 0.81 m (training group n = 16) non-injured	Jumping/cutting sport
Lei et al. [74]	DM + DA	N = 12 (M = 12 & W = 0) 21.3 ± 2.3 y; 67.4 ± 10.2 kg; 1.74 ± 0.06 m non-injured	Football
Lempke et al. [75]	DA	N = 41 (M = 21 & W = 20) 23.2 ± 2.5 y; 80.4 ± 10.2 kg; 1.81 ± 0.08 m (men) 21.8 ± 1.0 y; 61.2 ± 9.4 kg; 1.64 ± 0.08 m (women) non-injured	N.S.
Li et al. [36]	DA + UNC	N = 33 (M = 17 & W = 16) 22.5 ± 3.0 y; 72.0 ± 10.1 kg; 1.73 ± 0.08 m non-injured	Basketball, volleyball and soccer

Table 1. Cont.

Study	Group	Participants Characteristics	Sport
Lin et al. [76]	DA	N = 30 (M = N.S. & W = N.S.) 20.0 ± 2.0 y; 68.9 ± 9.0 kg; 1.76 ± 0.08 m non-injured	Basketball, volleyball and badminton
Lynall et al. [77]	DM	N = 15 (M = 6 & W = 9) 19.7 ± 1.6 y; 71.0 ± 10.4 kg; 1.72 ± 0.10 m non-injured	N.S.
Mache et al. [78]	DM	N = 29 (M = 16 & W = 13) 22.0 ± 3.0 y; 79.0 ± 9.9 kg; 1.80 ± 0.05 m (men) 22.0 ± 3.0 y; 60.8 ± 6.2 kg; 1.72 ± 0.05 m (women) non-injured	Activities with intense jumping
McCarren et al. [79]	DA	N = 24 (M = 18 & W = 6) 20.4 ± 1.3 y; 78.1 ± 15.0 kg; 1.75 ± 0.10 m non-injured	Military / Army ROTC
McLean & Samorezov [80]	DM	N = 20 (M = 0 & W = 20) 19.2 ± 1.7 y; N.S. kg; N.S. m non-injured	Volleyball, soccer and basketball
Meinerz et al. [81]	DM	N = 18 (M = 0 & W = 18) 19.7 ± 0.8 y; 66.1 ± 2.1 kg; 1.67 ± 0.06 m non-injured	Soccer
Mejane et al. [82]	DA	N = 19 (M = 0 & W = 19) 25.0 ± 2.4 y; 82.2 ± 13.5 kg; 1.77 ± 0.06 m non-injured	Crossfit, running, basketball and soccer
Monfort et al. [83]	DA	N = 15 (M = 15 & W = 0) 20.7 ± 2.0 y; 76.5 ± 8.9 kg; 1.78 ± 0.07 m non-injured	Soccer
Moritz et al. [84]	DA + UNC	N = 10 (M = 0 & W = 10) 22.0 ± 4.0 y; 57.0 ± 5.0 kg; 1.67 ± 0.06 m non-injured	N.S.
Mornieux et al. [85]	PER + UNC	N = 12 (M = 7 & W = 5) 24.0 ± 2.0 y; 70.0 ± 11.0 kg; 1.71 ± 0.10 m non-injured	N.S.
Munoz-Martel et al. [86]	DA	N = 14 (M = 10 & W = 4) 28.0 ± 5.0 y; 67.0 ± 11.0 kg; 1.75 ± 0.10 m 12 completed the study non-injured	N.S.
Oliveira et al. [87]	PER	N = 22 (M = 22 & W = 0) 28.0 ± 4.0 y; 71.0 ± 10.0 kg; 1.71 ± 0.07 m non-injured	Team sports (soccer, basketball, handball, ice hockey)
Rikken et al. [88]	DM	N = 15 (M = 15 & W = 0) 22.1 ± 2.3 y; 84.5 ± 11.9 kg; 1.88 ± 0.11 m non-injured	Basketball
Saadat et al. [89]	DM	N = 21 (M = 0 & W = 21) 21.0 ± 2.0 y; 63.0 ± 8.0 kg; 1.68 ± 0.07 m non injured	Jump-landing and directional change sports
Simpson et al. [90]	UNC	N = 23 (M = 11 & W = 12) 22.6 ± 2.5 y; 83.9 ± 13.4 kg; 1.77 ± 0.07 m (men) 20.8 ± 1.4 y; 62.7 ± 7.6 kg; 1.63 ± 0.05 m (women) non-injured	N.S.

Table 1. Cont.

Study	Group	Participants Characteristics	Sport
Song et al. [91]	PER	N = 32 (M = 16 & W = 16) 21.5 ± 2.2 y; 71.6 ± 12.9 kg; 1.72 ± 0.10 m non-injured	Jump-landing sports (basketball, soccer, volleyball and American football)
Song et al. [92]	PER	N = 28 (M = 14 & W = 14) 22.0 ± 2.9 y; 71.3 ± 13.5 kg; 1.70 ± 0.10 m non-injured	N.S.
Song et al. [93]	PER	N = 32 (M = 16 & W = 16) 22.7 ± 3.1 y; 71.3 ± 11.9 kg; 1.70 ± 0.10 m non-injured	Jump-landing sports (soccer, basketball, American football, etc.)
Song et al. [35]	PER	N = 31 (M = 16 & W = 15) 22.9 ± 3.2 y; 74.2 ± 11.4 kg; 1.73 ± 0.07 m non-injured	Jump-landing action sports
Wang et al. [94]	DA	N = 15 (M = 8 & W = 7) 23.5 ± 1.0 y; N.S. kg; 1.70 ± 0.07 m non-injured	Basketball, soccer, volleyball and badminton
Weltin et al. [95]	PER	N = 24 (M = 12 & W = 12) 23.2 ± 3.0 y; 76.4 ± 6.8 kg; 1.80 ± 0.06 m (men) 23.2 ± 2.6 y; 60.7 ± 7.3 kg; 1.67 ± 0.05 m (women) non-injured	Team sports
Yang et al. [96]	DM	N = 20 (M = 20 & W = 0) 21.5 ± 1.3 y; 68.3 ± 8.5 kg; 1.78 ± 0.03 m non-injured	Soccer
Yom et al. [97]	PER	N = 17 (M = 0 & W = 17) 21.1 ± 1.3 y; 61.5 ± 9.9 kg; 1.67 ± 0.06 m non-injured	N.S.
Yom et al. [98]	DM	N = 18 (M = 0 & W = 18) 21.4 ± 1.8 y; 62.9 ± 4.4 kg; 1.69 ± 0.04 m non-injured	N.S.
Zamankhanpour et al. [99]	DA	N = 32 (M = 0 & W = 32) 24.0 ± 3.6 y; 56.9 ± 7.4 kg; 1.63 ± 0.05 m (control n = 15) 22.8 ± 3.9 y; 59.0 ± 7.9 kg; 1.64 ± 0.07 m (DKV n = 17) non-injured	N.S.
Zhang et al. [100]	UNC	N = 12 (M = 12 & W = 0) 23.7 ± 2.7 y; 70.1 ± 4.6 kg; 1.78 ± 0.02 m non-injured	Basketball
Zhu et al. [101]	DM	N = 24 (M = 0 & W = 24) 23.4 ± 1.5 y; 57.3 ± 3.1 kg; 1.65 ± 0.02 m non-injured	Basketball
Zou et al. [102]	DM	N = 21 (M = 0 & W = 21) 18.4 ± 1.4 y; 60.1 ± 5.5 kg; 1.66 ± 0.05 m non-injured	Soccer

Abbreviations: ACLR, anterior cruciate ligament reconstruction; DA, divided attention; DKV, dynamic knee valgus; DM, decision making; W, women; M, men; N, sample number; N.S., not specified; PER, perturbation; UNC, uncertainty; y, years.

Twenty-six studies were classified as decision making, 25 as divided attention, eight as perturbation and eight as uncertainty. The tests included in these studies were divided into two groups (running and jump-landing). Specifically, 25 analysed drop jump-landing, 19 running task, six horizontal jump, five vertical jump, two lateral jump, one hop test and one step down. Detailed methodology of the included studies is displayed in Table S1.

3.3. Assessment of Methodological Quality and Risk of Bias

Table S2 details the methodological quality of the studies, of which 11 showed excellent quality (16–17), while 47 had good quality (12–15) and only one fair quality (9–11). No studies were excluded for methodological quality.

Figure S2 shows the traffic light plot of the risk of bias assessment and Figure 2 shows the summary plot.

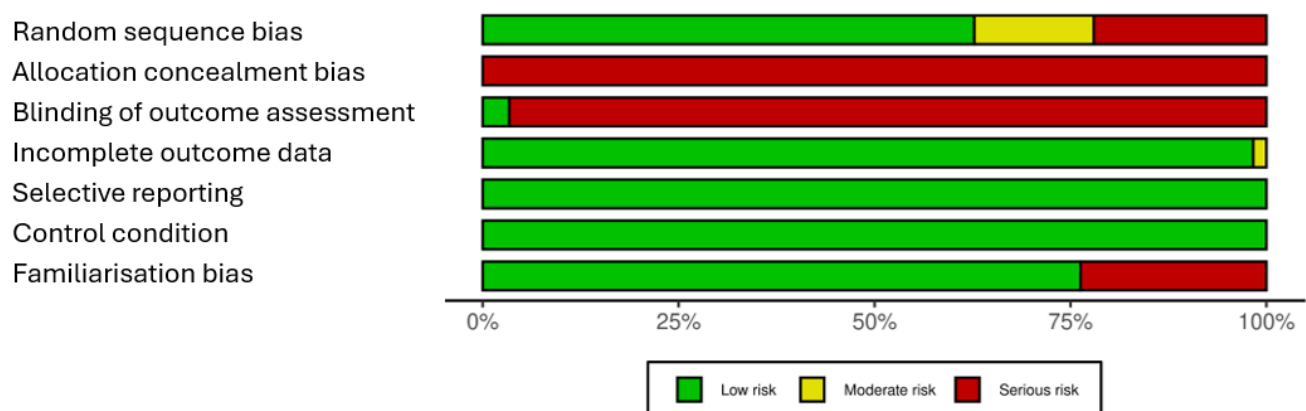


Figure 2. Risk of bias assessment of the included studies assessed with the RoB 2 tool.

3.4. Meta-Analysis Results

While individual studies appear a single time in the forest plots, several contributed multiple comparisons based on specific subgroup stratifications or experimental parameters (e.g., stimulus timing or cohort demographics) which are detailed in Table 2.

Table 2. Explanation of multiple comparisons included in the studies in the meta-analysis.

Study	Comparisons
Almonroeder et al. [49]	Divided attention: a. Carry ball b. Carry and pass ball
Arumugam et al. [50]	Decision making: a. Medial diagonal direction b. Lateral diagonal direction
Bedo et al. [52]	Decision making: a. Dominant leg b. Non-dominant leg
Bill et al. [53]	Decision making and divided attention: a. Group/Cluster 1 b. Group/Cluster 2
Borotikar et al. [54]	Decision making: a. Dominant leg b. Non-dominant leg

Table 2. Cont.

Study	Comparisons
Brazalovich et al. [55]	Divided attention: a. No vision b. Virtual reality
Brown et al. [56]	Decision making: a. Men dominant leg 600 ms stimulus b. Men dominant leg 500 ms stimulus c. Men dominant leg 400 ms stimulus d. Men non-dominant leg 600 ms stimulus e. Men non-dominant leg 500 ms stimulus f. Men non-dominant leg 400 ms stimulus g. Women dominant leg 600 ms stimulus h. Women dominant leg 500 ms stimulus i. Women dominant leg 400 ms stimulus j. Women non-dominant leg 600 ms stimulus k. Women non-dominant leg 500 ms stimulus l. Women non-dominant leg 400 ms stimulus
Dai et al. [60]	Divided attention: a. Counting by 1 s b. Counting by 7 s
Fedie et al. [63]	Divided attention: a. Fake pass b. Intercept pass
Fong et al. [64]	Decision making: a. Left direction b. Right direction c. Forward direction d. Vertical direction
Fuerst et al. [65]	Decision making: a. Medium difficulty cut b. Hard difficulty cut c. Medium difficulty turn d. Hard difficulty turn
Han et al. [67]	Uncertainty: a. Control b. Coper
Helm et al. [68]	Uncertainty: a. Hard surface b. Soft surface
Imai et al. [70]	Divided attention: a. Dominant leg b. Non-dominant leg
Konishi et al. [73]	Decision making: a. Control b. Training group
Lei et al. [74]	Decision making: a. Real environment b. Virtual reality

Table 2. Cont.

Study	Comparisons
Lempke et al. [75]	Divided attention: a. Jump landing b. Dominant leg cut c. Non-dominant leg cut
Li et al. [36]	Divided attention and uncertainty: a. 11 cm b. 22 cm c. 33 cm
Lynall et al. [77]	Decision making: a. Dominant leg b. Non-dominant leg
Mache et al. [78]	Decision making: a. Drop landing men b. Drop jump men c. Drop landing women d. Drop jump women
McLean & Samorezov [80]	Decision making: a. Fatigued limb b. Non-fatigued limb
Moritz et al. [84]	Uncertainty: a. Surprise hard surface b. Random hard surface
Mornieaux et al. [85]	Perturbation: a. Known sliding surface b. Known counteracting surface c. Unknown sliding surface d. Unknown counteracting surface Uncertainty: a. Stable surface b. Sliding surface c. Counteracting surface
Saadat et al. [89]	Decision making: a. Left jump congruent b. Left jump incongruent c. Right jump congruent d. Right jump incongruent
Song et al. [91]	Perturbation: a. Left leg upper trunk left perturbation b. Left leg upper trunk right perturbation c. Right leg upper trunk left perturbation d. Right leg upper trunk right perturbation e. Left leg lower trunk left perturbation f. Left leg lower trunk right perturbation g. Right leg lower trunk left perturbation h. Right leg lower trunk right perturbation
Song et al. [92]	Perturbation: a. Natural landing b. Soft landing c. Falling landing

Table 2. Cont.

Study	Comparisons
Song et al. [93]	Perturbation: a. Upper trunk ipsilateral perturbation b. Upper trunk contralateral perturbation c. Lower trunk ipsilateral perturbation d. Lower trunk contralateral perturbation
Song et al. [35]	Perturbation: a. Anterior perturbation b. Posterior perturbation
Weltin et al. [95]	Perturbation: a. Right perturbation b. Left perturbation
Zamankhanpour et al. [99]	Divided attention: a. Control group b. Dynamic knee valgus group
Zhu et al. [101]	Decision making: a. 45° cut b. 90° cut

Subgroup meta-analyses by sex were conducted exclusively for the decision making condition, as it was the only category with a sufficient number of studies with sex-disaggregated data.

3.4.1. Decision Making

In the sagittal plane, subgroup analysis revealed a statistically significant difference in females (SMD = 0.21, 95% CI = 0.01, 0.40, $t(11.20) = 2.33$, $p = 0.039$), whereas no significant effect was found in males (SMD = 0.01, 95% CI = −0.31, 0.34, $t(7.62) = 0.10$, $p = 0.921$), both sexes combined (SMD = 0.15, 95% CI = −0.11, 0.40, $t(3.30) = 1.74$, $p = 0.171$) or the total pooled dataset (SMD = 0.11, 95% CI = −0.04, 0.25, $t(22.70) = 1.54$, $p = 0.138$) (Figure 3). No significant differences were observed in the frontal plane for males (SMD = −0.08, 95% CI = −0.28, 0.13, $t(5.15) = −0.95$, $p = 0.384$), females (SMD = −0.08, 95% CI = −0.31, 0.16, $t(7.94) = −0.74$, $p = 0.481$), both sexes combined (SMD = −0.03, 95% CI = −0.21, 0.15, $t(1, 72) = −0.88$, $p = 0.485$) or the full dataset (SMD = −0.08, 95% CI = −0.21, 0.04, $t(16.28) = −1.47$, $p = 0.161$) (Figure 4).

3.4.2. Divided Attention

Regarding the divided attention cognitive demand, no statistically significant differences were observed across any of the evaluated conditions, neither in the sagittal (SMD = 0.08, 95% CI = −0.12, 0.27, $t(22.40) = 0.82$, $p = 0.419$) (Figure 5) nor in the frontal plane (SMD = −0.01, 95% CI = −0.10, 0.08, $t(8.77) = −0.22$, $p = 0.833$) (Figure 6). In both planes, overall heterogeneity was statistically significant ($p < 0.001$).

3.4.3. Perturbation

Analysis of perturbation yielded no significant main effects or subgroup differences in either anatomical movement plane. In the sagittal plane, non-significant results were observed (SMD = −0.04, 95% CI = −0.15, 0.07, $t(4.25) = −1.01$, $p = 0.366$) (Figure 7), while findings in the frontal plane were also non-significant (SMD = −0.13, 95% CI = −0.44, 0.18, $t(2.18) = −1.68$, $p = 0.225$) (Figure 8). Heterogeneity remained statistically significant in both analyses ($p < 0.001$).

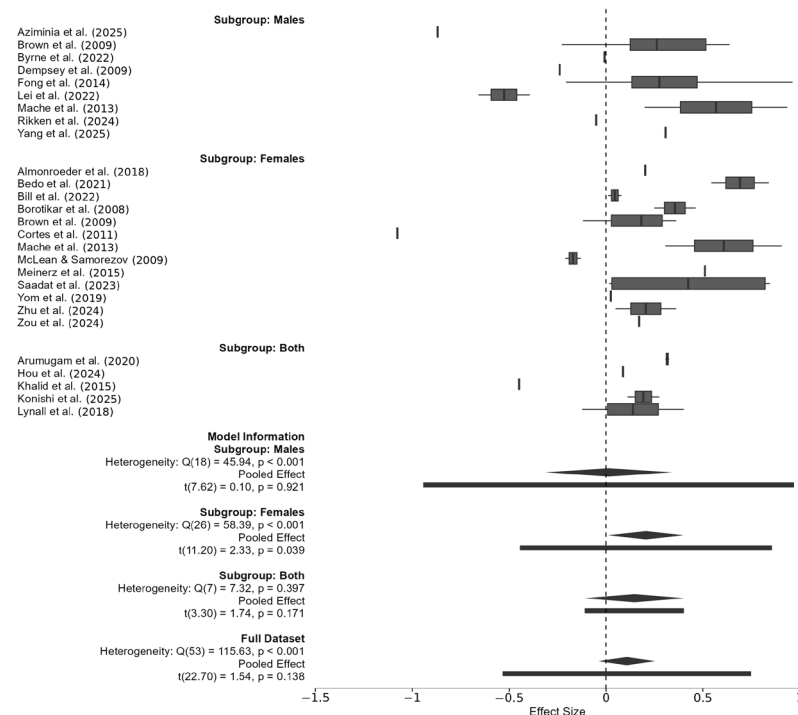


Figure 3. Effects of anticipated versus unanticipated on the sagittal plane in the decision making group. Positive effect sizes represent higher values in the anticipated condition, while negative represents higher values in the unanticipated condition [48,50–54,56,57,59,61,64,69,71,73,74,77,78,80,81,88,89,96,98,101,102].

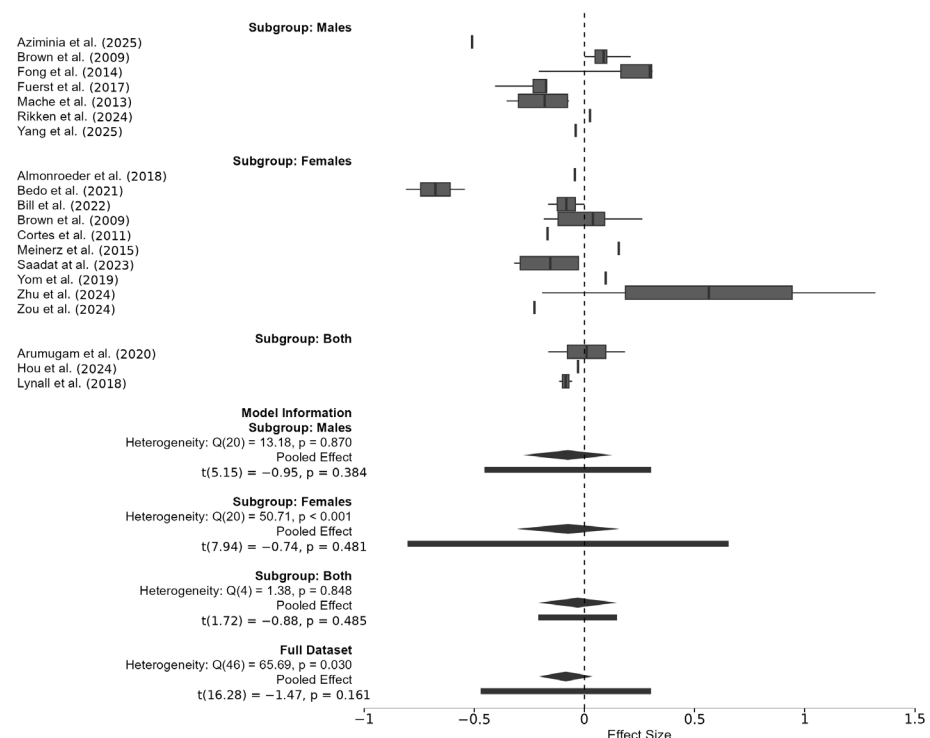


Figure 4. Effects of anticipated versus unanticipated on the frontal plane in the decision making group. Positive effect sizes represent higher values in the anticipated condition, while negative represents higher values in the unanticipated condition [48,50–53,56,59,64,65,69,77,78,81,88,89,96,98,101,102].

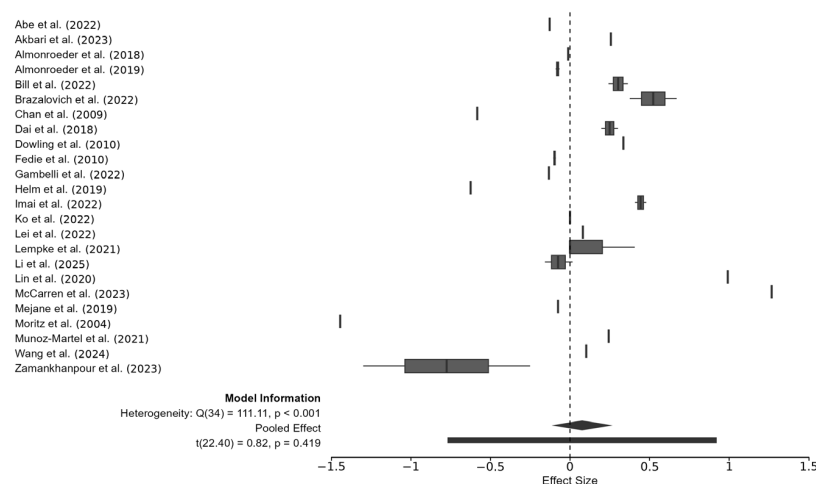


Figure 5. Effects of single task versus dual task on the sagittal plane in the divided attention group. Positive effect sizes represent higher values in the single task condition, while negative represents higher values in the dual task condition [36,46–49,53,55,58,60,62,63,66,68,70,72,74–76,79,82,84,86,94,99].

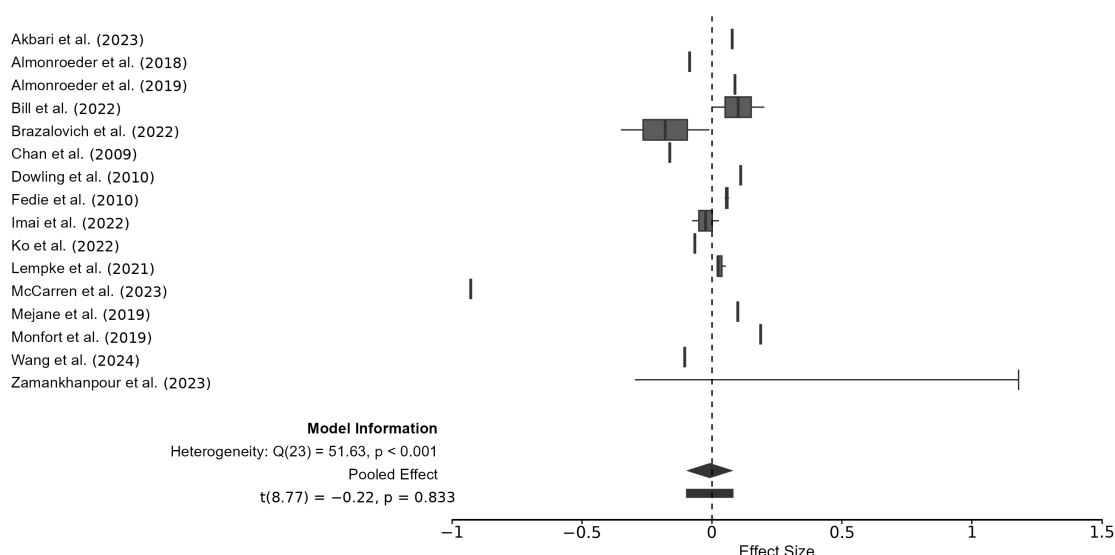


Figure 6. Effects of single task versus dual task on the frontal plane in the divided attention group. Positive effect sizes represent higher values in the single task condition, while negative represents higher values in the dual task condition [47–49,53,55,58,62,63,70,72,75,79,82,83,94,99].

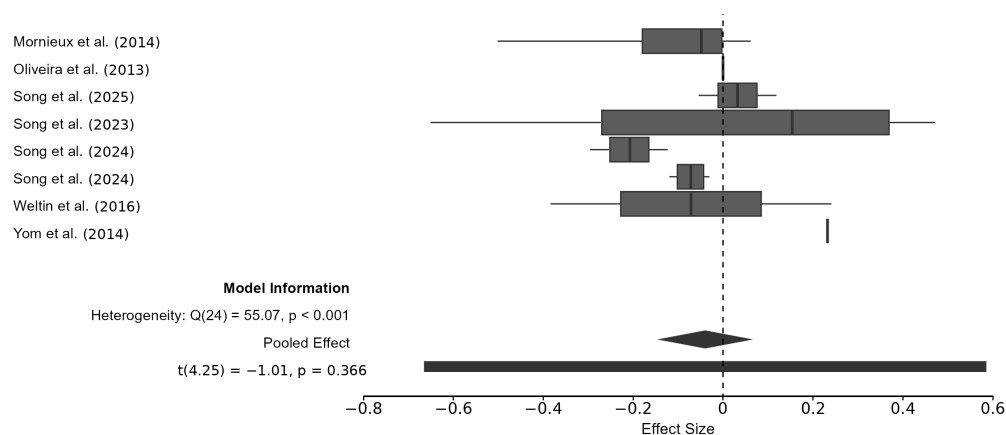


Figure 7. Effects of no perturbation versus perturbation on the sagittal plane in the perturbation group. Positive effect sizes represent higher values in the no perturbation condition, while negative represents higher values in the perturbation condition [35,85,87,91–93,95,97].

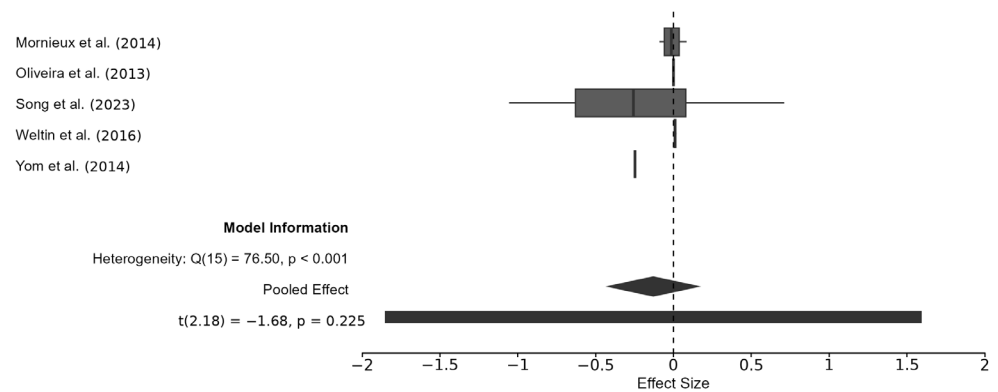


Figure 8. Effects of no perturbation versus perturbation on the frontal plane in the perturbation group. Positive effect sizes represent higher values in the no perturbation condition, while negative represents higher values in the perturbation condition [85,87,91,95,97].

3.4.4. Uncertainty

The results of the uncertainty meta-analysis showed no significant differences between conditions in the sagittal plane ($SMD = 0.25$, $95\% \text{ CI} = -0.32, 0.81$, $t(6.93) = 1.04$, $p = 0.333$) (Figure 9), with significant heterogeneity ($p < 0.001$). In the frontal plane (Figure 10), no significant differences appeared ($SMD = -0.19$, $95\% \text{ CI} = -2.26, 1.88$, $t(1.00) = -1.16$, $p = 0.454$), where no significant heterogeneity was found ($p = 0.662$).

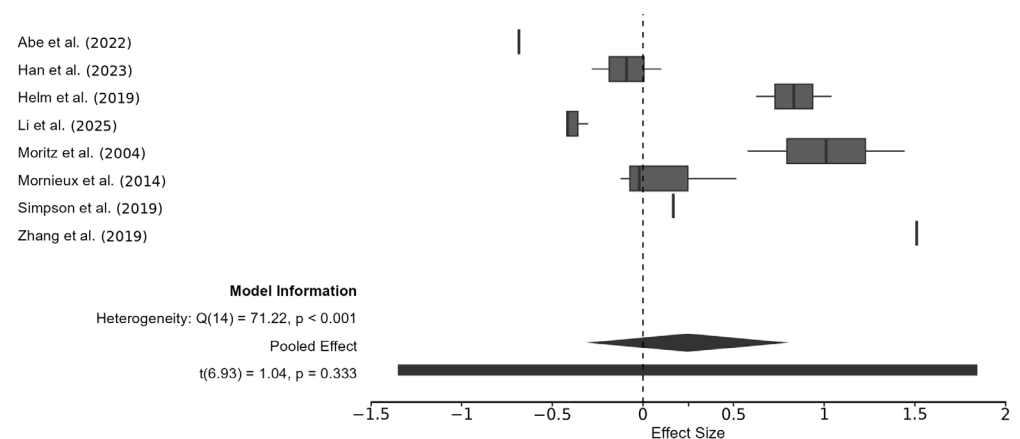


Figure 9. Effects of certainty versus uncertainty on the sagittal plane of the uncertainty group. Positive effect sizes represent higher values in the certainty condition, while negative represents higher values in the uncertainty condition [36,46,67,68,84,85,90,100].

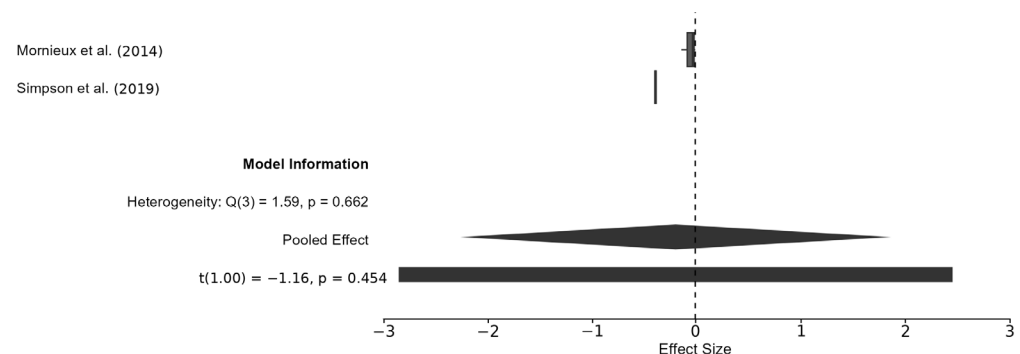


Figure 10. Effects of certainty versus uncertainty on the frontal plane in the uncertainty group. Positive effect sizes represent higher values in the certainty condition, while negative represents higher values in the uncertainty condition [85,90].

3.5. Publication Bias and Certainty of Evidence

Visual inspection of the residual funnel plots was conducted for the overall results in the decision making and divided attention tasks across both movement planes, as well as for females' subgroup in both planes of divided attention. Additionally, subgroup analysis for males in the decision making task in the sagittal plane was visually evaluated. Across all evaluated outcomes and subgroups, study residuals were symmetrically distributed around the zero line, with the vast majority of estimates falling within the pseudo-95% confidence bounds (Figure S3).

The GRADE assessment indicated very low certainty of evidence for all biomechanical outcomes included in the meta-analysis (Table S3). This was mainly driven by the observational design of the included studies; the serious risk of bias identified across studies (primarily due to the impossibility of blinding participants and assessors inherent to biomechanical testing protocols); and the presence of substantial statistical heterogeneity (inconsistency) in several key variables.

4. Discussion

The aim of this systematic review with meta-analysis was to examine how different cognitive demands may influence kinematic variables associated with potential ACL injury risk at initial contact with the ground in four categories. In the meta-analysis, 59 studies were evaluated with a total of 1351 participants. The variables analysed were knee flexion in the sagittal plane and knee valgus in the frontal plane at the first moment the foot contacted the ground. The principal finding was that the decision making group showed differences in the sagittal plane, but not in the frontal plane. Meanwhile, no differences were found in the divided attention group, the perturbation group, or the uncertainty group in any of the planes. Therefore, our meta-analysis results show that lower limb biomechanics may be affected during athletic tasks if decisions have to be made.

The effect of decision making on ACL injury-related biomechanics has already been analysed in two meta-analyses, finding that unplanned sidestepping/changes of direction and dual task affect injury-related biomechanical aspects of the lower limb [32,34]. Our meta-analysis was conducted only on knee kinematics at initial contact with the ground. Only one meta-analysis analysing kinematic variables relevant to ACL injury risk during unplanned tasks has analysed variables at initial contact, but it included only two studies in the sagittal plane and one in the frontal plane [32] so no clear results could be assessed. However, our meta-analysis included 25 studies in the sagittal plane and 19 in the frontal plane, and overall results found no difference between conditions. Nevertheless, we found that females presented a higher knee flexion angle during anticipated conditions. Consequently, this resulted in a stiffer position (i.e., with the knee in a more extended position) during initial contact with the ground under unanticipated conditions, which aligns with the biomechanical mechanism through which ACL injuries occur [14]. However, the effect size was small, and heterogeneity was high, likely because variations in jump-landing and running protocols across studies may have influenced the results. The mean difference in knee flexion between conditions was 1.57° (18.56° in the anticipated condition vs. 16.99° in the unanticipated condition). Although this difference reached statistical significance, from a clinical perspective this change alone seems to have limited or trivial direct impact. In a previous meta-analysis, Ebner et al. [34] reported that peak and mean knee flexion values increase in unanticipated conditions combining male and female samples. Hence, it seems that in the combined population, decision making does not affect knee kinematics at initial foot contact with the ground, although it does influence peak and mean values in the sagittal plane. These authors only included changes of direction, whereas our study did not limit the type of task analysed. Despite the possible differences

between tasks included (14 studies used running tasks and 12 jumping/landing tasks), the results show the same tendency. On the other hand, we also found that decision making does not affect the kinematics on the frontal plane. Ebner et al. [34] did not find differences on the peak valgus angle either. The different approaching speed among studies could have affected the results in this meta-analysis [32], as the protocols ranged between 3.1 and 5.5 m/s. Some studies did not even establish the approaching speed before the start of the test. Overall, despite the methodological variability across studies, decision making as an isolated cognitive demand appears to influence knee kinematics at initial contact specifically in females, although this effect remains small.

How the divided attention and/or external factors may influence the variables associated with ACL injury susceptibility included 25 studies in the meta-analysis. Although some studies display significant differences with this cognitively challenging condition [76,79], the results of our meta-analysis did not find any difference in either the sagittal or the frontal plane. Although paying attention to different stimuli may impose a cognitive demanding state, it seems it is not enough to modify knee kinematics at initial contact. However, in the knee kinetics it has been observed that knee abduction moment is higher while dual tasking [34]. Therefore, a higher ground reaction force may be more relevant for evaluating biomechanical risk factors for ACL injury than just the kinematics [103]. In contrast, with the studies included in the decision making group, the cognitive demanding task varied among studies which may have affected the results. The cognitive demands differed among the effects of virtual reality or not looking during the task, the inclusion of a ball similar to a match-specific action, the distraction of performing a different task at the same time (i.e., subtracting numbers) and ground configuration. This may explain the statistically significant heterogeneity found in our analysis. Not only were different cognitive demands imposed, but also we found a greater diversity in the tasks used than in the previous group as 19 studies included jumping/landing tasks while only six included running tasks. These differences between motor tasks and cognitive demands may have affected the results displayed. Therefore, future meta-analyses with more studies could focus solely on assessing methodologies associated with each specific cognitive demanding task. Both studies that found differences included tasks where some decisions had to be made as well. In Lin et al.'s [76] study participants had to perform a single-leg landing after touching one of the lights illuminated during a vertical jump. In addition, McCarren et al. [79] studied how having to decide whether to shoot six of the seven targets influenced a drop jump landing. Therefore, even when these studies were considered in this group, we find again that when some decision has to be made it may be the key factor in altering lower limb kinematics. It appears that combining different cognitive demands has a greater effect on the ACL injury-related variables.

In the perturbation group we found that the stimulus applied was similar among studies, as some of them added a contact or pull of the participants while making the action and others moved the surface during the task. However, we also found significant heterogeneity. This could be explained by differences in sample sizes as well as in the specific task imposed. Even though all except one study included jump-landing tasks, some protocols required participants to simply land after the perturbation, while others required them to land and cut, which may have affected the results. Despite some authors finding that kinematic variables in the frontal and sagittal planes are significantly modified at initial contact after perturbation [91], the results of our meta-analysis show no differences in any of the planes. These actions are commonly seen in ACL injuries in sports like basketball and football, as the player is contacted during the action (e.g., cutting or jumping) and the injury occurs during the landing [7,17]. In the studies included in the meta-analysis, participants only had to pay attention to the task performed; hence, maybe the inclusion

of a second cognitive demand such as an overhead goal may influence these injuries [76]. In addition, during real sports environments athletes may not expect the perturbation which could be an important cause for the injury development. Therefore, controlled laboratory environments may prepare the participant to expect a possible perturbation even if they do not know if it will happen. Previous work by Olivera et al. [87] found that when the participants were not aware that the floor may move the knee flexion and rotation were significantly modified during a change of direction. Thus, uncertainty and lack of anticipation have a significant influence on movement biomechanics and prior knowledge of a perturbation may modify participants' motor behaviour.

Finally, in the uncertainty group no significant differences were found either despite some individual studies finding differences in the variables analysed [46,68,84,100]. The studies included analysed different actions (different motions, movements and motor tasks) and different conditions (e.g., no knowledge of the height of falling [46], knowledge of the ground's characteristics [68,84] and knowledge of the moment of falling [100]), and yet in practically all of them some differences were found in the variables analysed, so it seems that uncertainty may modify biomechanical factors linked to ACL injuries. Except for Li et al. [36] and Zhang et al. [100] (basketball, volleyball and soccer) none of the other studies specified the sport or activity in which the participants were enrolled. This could result in participants having no previous background in activities similar to those analysed, which could have affected the results. Despite a previous familiarisation with the test, it could be assumed that without a previous background in the motor tasks the participants could have performed the test more slowly or with less intensity to be able to control their movement. On the contrary, the studies included in this meta-analysis involve only jumping/landing tasks, which implies a good methodological homogeneity among the tasks performed. Nevertheless, the statistical heterogeneity found between both planes was truly diverse with a non-significant heterogeneity in the frontal plane, but significant in the sagittal plane. The sagittal plane included more results, but the high heterogeneity may have influenced them. Statistical heterogeneity may be affected by variability in methodological heterogeneity [43]. In this group, three of the studies included did not randomise the condition order [46,84,90], while another one did not specify if it was randomised [100]. This means that half of the studies analysed did not establish a protocol to randomise condition order, which could have affected the results. Further investigation with a specific population and methodological homogeneity could improve knowledge on how uncertainty during the task may or may not alter knee biomechanics associated with ACL injury. As we have hypothesised above, the combination of different cognitive tasks may have a greater influence on altering kinematics of the leg linked to ACL injuries. This should be more related to the specific actions found during competitions, rather than in a controlled laboratory. To better understand this, future studies could combine different cognitive demand actions.

This study is not free of limitations. In the first place, six studies that may have met the inclusion criteria were not included since it was not possible to retrieve the full text. Additionally, 12 more were not included in the analysis since the variables analysed were not clearly described in the study and could not be retrieved by any other method. This means that a total of 18 more studies could have been included in the analysis which may have modified the results found. Another limitation is the different protocols that were used (e.g., different approach speed in running test) which could affect the outcomes. However, the literature is limited, and we could not exclude studies based on this criterion. Even when all studies reported kinematic variables at the same nominal time point, the methodology used to define this measurement timing actually differed. More than half of the studies established the reference frame using a force threshold, whereas others

defined it as the initial foot–ground contact identified visually via video analysis or did not specify the measurement criteria. Furthermore, even among studies employing a force threshold, methodologies varied: some used a fixed value (ranging from 5 to 30 N, with 10 N being the most common), while others relied on a percentage increase in body weight. Therefore, it should be considered that despite efforts to analyse a time window closer to the moment of ACL injury [4], the precise measurement timing was not uniform across the included studies. In the future, similar protocols should be established to analyse these variables. For instance, the same running distance, approach speed and time from the appearance of the stimulus until the execution of the motor task. In the perturbation group some investigations without telling the participants the possibility of this external factor would make the test more sport specific as a perturbation is not always expected during a competition. In addition, in the uncertainty group a similar population should be analysed to see if this is not a factor that alters the results. In general, studies could be conducted including different cognitive tasks at the same time. To reduce heterogeneity among studies, future meta-analyses could focus on comparing studies with similar protocols (e.g., approach distance, jump height and specific cognitive demands) within well-defined populations (e.g., considering sex, sport and level of play). This could be implemented once the volume of published literature permits it, as the current lack of sufficient number of studies detailing all this information prevented us from performing such subgroup analyses. Additionally, key individual-level cognitive, sensory and environmental factors (e.g., educational background, baseline cognitive and sensory function, sleep, fatigue, psychological state and sporting expertise with the cognitive task) were inconsistently reported across the included studies. Consequently, quantitative subgroup analyses based on these factors were not feasible, and current evidence cannot definitively distinguish whether the observed biomechanical responses stem from the experimental conditions themselves or from participants' individual traits and prior experience. Furthermore, while the term neurocognition is utilised in this review to describe the cognitively demanding tasks evaluated, it does not imply that participant-level cognitive capacities or traits were directly measured in the original studies. Future research should systematically report and control for these individual variables to better isolate their impact on cognitive–biomechanical performance. In addition, a specific limitation regarding the risk-of-bias assessment warrants mention. As observed in Figure 2, allocation concealment and outcome blinding domains show high-risk ratings. However, this reflects an intrinsic methodological constraint of movement science experimentation rather than flaws in study execution. In the majority of the included paradigms, it is impossible to blind participants to the imposition of a secondary task or a decision making task. Therefore, these specific domains should be interpreted cautiously within this field of research. Given that the overall methodological quality assessed via the Downs & Black checklist [39] remained consistently high across studies, our confidence in the meta-analytic conclusions remains robust. Finally, variables associated with ACL risk at initial contact and peak values have commonly been studied; however, it has been observed that the moment of injury is shortly after the first contact with the ground [4]. Since the injury frame has previously been considered around the 40 ms after initial contact [5], some authors have started to analyse this time frame in their video analysis [7,14]. Since no differences seem to appear at these two moments, more studies should implement a time frame closer to the moment of injury (e.g., 40 ms after initial contact).

5. Conclusions

This meta-analysis presents 59 studies assessing how cognitively demanding tasks affect lower limb biomechanics related to ACL injuries during athletic tasks evaluated in

laboratory environments. In females, decision making conditions were associated with a small difference in sagittal-plane knee kinematics during running and jump-landing tasks, with lower knee flexion at initial contact under unanticipated than anticipated conditions. When analysing males alone or combining both sexes, no differences were found. No statistically significant pooled differences were identified for frontal-plane knee kinematics, either in the overall analysis or in the sex-stratified analyses. Moreover, other cognitive challenging actions, such as divided attention, perturbation and uncertainty, did not seem to modify the variables analysed during running and jump-landing tasks analysed in controlled environments.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16168120/s1>, Figure S1: Detailed search strategies used for PubMed, Scopus and Web of Science. Figure S2: Traffic light plot of the risk of bias assessment of the included studies using the modified Cochrane RoB 2 tool. Figure S3. Residual funnel plots for selected meta-analyses and subgroup analyses. Table S1: Summary of data extracted from the studies included in the meta-analysis. Table S2: Methodological quality assessment of the studies included in the meta-analysis. Table S3. GRADE certainty-of-evidence assessment for knee kinematic outcomes. Supplementary File S1: PRISMA 2020 Checklist.

Author Contributions: D.O.-S., A.B.-S. and J.A.-V. conceived the idea for this review. D.O.-S. conducted the literature search. D.O.-S., A.B.-S., P.A. and M.R.-d. selected the articles for inclusion in the review. D.O.-S. wrote the first draft of the manuscript. J.A.-V., A.B.-S. and P.A. revised the original and the revised manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACL	Anterior cruciate ligament
CI	Confidence interval
COD	Change of direction
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REML	Restricted maximum likelihood
RoB	Risk of bias
SMD	Standardised mean difference

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