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The impact of a secondary cognitive task on variables associated with ACL loading during landing: a systematic review and meta-analysis

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ABSTRACT

This article aimed to perform a meta-analysis and systematic review on the effect of dual-task landing on potential ACL loading. Repeated measures assessments of landings with concurrent, unrelated cognitive tasks were included. Databases were searched (SPORTDiscus, ScienceDirect and PubMed, searched June 2023). Results were synthesised and presented using custom R code. Twenty-five articles were included, 12 eligible for the meta-analysis, involving single or double-leg landings alongside various cognitive tasks. Funnel plots, regression testing and selection modelling detected no publication bias. The systematic review identified most authors concluded dual-task landing potentially increased ACL loading, due to small, inconsistent, biomechanical impacts on the trunk and lower extremity consistent with potentially increased ACL loading. However, robust variance estimation showed no significant effect ($g = -0.001$, 95% CI $[-0.093, 0.09]$, $p = 0.97$) on frontal or transverse plane knee loading, only identifying a small decrease in IC knee flexion angles ($g = -0.13$, $p = 0.03$). Diverse research methodologies make summarising this research area difficult. While dual-task landings can evoke mechanical changes associated with potentially increased ACL loading, this increased loading is not consistently seen. Further research with consistent methodologies is required to clarify this. This paper was registered (PROSPERO: CRD42023425191).

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Introduction

Video analyses of anterior cruciate ligament (ACL) injuries identify that they occur during high-impact movements such as landing and cutting, often characterised by little to no sagittal plane range of motion (ROM) of the hip, knee and ankle (Brophy et al., 2015; Hewett et al., 2009; Koga et al., 2018; Krosshaug et al., 2007; Stuelcken et al., 2016; Waldén et al., 2015). This impairs ground reaction force (GRF) absorption and increases

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load on the knee (Boden & Sheehan, 2022; Boden et al., 2009; Dai et al., 2015; Donelon et al., 2020; Donnelly et al., 2017; Song et al., 2023). Video analyses also often show mechanics known to prompt knee abduction loading, such as lateral trunk flexion, internal hip rotation, hip adduction and external ankle rotation (Donelon et al., 2020; Hinshaw et al., 2019; Jones et al., 2015; Kristianslund et al., 2014; Powers, 2010; Weir et al., 2019), correspondingly showing the knee in an abducted and sometimes rotated position at injury (Boden et al., 2009; Brophy et al., 2015; Cochrane et al., 2007; Hewett et al., 2009; Koga et al., 2010, 2018; Olsen et al., 2004; Stuelcken et al., 2016; Waldén et al., 2015). *In vitro* and *in vivo* assessments of landing and cutting show knee abduction and tibial rotational loading directly load the ACL, more so in combination (Bates, Schilaty, Krych, et al., 2019; Bates, Schilaty, Nagelli, et al., 2019; Englander et al., 2019; Kiapour et al., 2016; Roldán et al., 2017; Schilaty et al., 2018).

Following the above, researchers have developed prospective methodologies to try and identify mechanics that may predispose future ACL injury. However, this research has produced inconsistent and conflicting findings (Straub & Powers, 2025). Some show that ACL injuries are predisposed by increased lateral trunk flexion as well as initial contact (IC) knee abduction and internal rotation angles, peak knee abduction angles or peak abduction moments (Bates et al., 2020; Corban et al., 2023; Dingenen et al., 2015; Hewett et al., 2005; Numata et al., 2018; Zazulak et al., 2007; Zebis et al., 2022). However, other prospective studies have found neither trunk, hip or knee mechanics to identify future ACL injuries (Cronström et al., 2020; Goerger et al., 2015; Krosshaug et al., 2016; Leppänen et al., 2017, 2021; Nilstad et al., 2023; Smeets et al., 2019; Smith et al., 2012; Zebis et al., 2022). This may indicate a difference between these prospective methodologies and ACL injury situations.

Video analyses also identify that most ACL injuries occurred with an opposing player in close proximity, possibly disrupting coordination or prompting higher risk movement (Boden et al., 2009; Brophy et al., 2015; Stuelcken et al., 2016). Video analyses that looked at this more directly, qualitatively judged that players' attention was directed externally towards the target, ball or opponents at the point of injury (Krosshaug et al., 2007; Olsen et al., 2004). Tracking the movement of an opponent or ball is an example of a cognitive task (Hughes & Dai, 2023; Perrey, 2022) and when performed alongside a movement creates a dual-task, given the tasks can be performed and measured separately (Giessler-Gonzalez et al., 2025; Mas-Mas et al., 2023; McIsaac et al., 2015). Therefore, ACL injuries may occur during dual-task movements, which would be a difference between prospective methodologies ACL injury situations; no cognitive demands (Almonroeder et al., 2018; Dai et al., 2018; Lin et al., 2020; Schnittjer et al., 2021; Stephenson et al., 2018).

Motion analyses across the last 25 years have begun to assess dual-task landing and cutting movements. An early study by Besier et al. (2001) used a light task to indicate cut direction immediately before initial contact and reported that reduced planning time led to increased frontal and transverse plane knee loading. Subsequent research has assessed movements such as drop jumps, countermovement jumps and land-and-cuts, alongside tasks such as arithmetic, memory and object tracking (Almonroeder et al., 2018; Dai et al., 2018; Kajiwaru et al., 2019; McLean et al., 2010; Mejane et al., 2019). This has shown that a secondary task can impact trunk, hip, knee and ankle mechanics that may increase ACL loading. This effect may be impacted by factors such as cognitive ability (Herman & Barth, 2016) and fatigue (Borotikar et al., 2008; Mejane et al., 2019). Previous meta-

analyses and systematic reviews have assessed dual-task cutting (Almonroeder et al., 2015; Brown et al., 2014; Giesche et al., 2021; Wilke et al., 2020), concluding secondary tasks prevent movement planning and prompt mechanical changes associated with ACL injury. However, to the best of the authors' knowledge, no such review or analysis has been published on dual-task landing. A meta-analysis would allow a quantitative analysis of any effects of secondary tasks on variables associated with ACL loading and any confounding variables. A systematic review would allow a qualitative methodological assessment, highlighting key considerations, potential threats to validity and areas for future research. Therefore, the aim of this study is to perform a meta-analysis and systematic review of the current literature assessing the impact of dual-task landings on potential ACL loading via biomechanical adaptations thought to contribute to ACL loading.

Materials and methods

This study followed the updated 'Preferred Reporting Items for Systematic Review and Meta Analyses' (PRISMA) guidelines (Page et al., 2021). The meta-analysis and systematic review methods were detailed in a preregistration document (PROSPERO ID: CRD42023425191).

Eligibility criteria

Studies were included in the systematic review if they met the following criteria: (1) The full English text of the article was available, (2) the study used a repeated measures design, (3) participants in the study were healthy and active, (4) dual-task landing performance was compared to a control condition, entailing the same movement performed as a single task, (5) the dual-task condition consisted of a landing movement with a *concurrent unrelated* secondary task, defined as a task with requirements and goals independent of the landing task, (6) the secondary task was non-physical in nature, requiring predominantly mental effort such as an arithmetic task (Hughes & Dai, 2023; Perrey, 2022), (7) the data collected has been associated with potential increases ACL loading in previous research, being related to knee joint loading, GRF absorption and/or landing stability. This includes multiplanar kinetics and/or kinematics of the trunk, hip, knee and ankle as well as GRF and stability data. All data meeting these criteria was included in the systematic review. Studies were also included in the meta-analysis if they met the above criteria and included in their analysis assessments of one or more of the following: peak knee abduction angles, peak knee abduction moments, peak knee internal rotation angles, peak knee internal rotation moments, initial contact knee flexion angles, peak knee flexion moments and peak vGRF. These variables have been directly related to ACL loading during landing movements (Bakker et al., 2016; Bates et al., 2015; Bates, Schilaty, Krych, et al., 2019; Kiapour et al., 2016; Laughlin et al., 2011).

Previous reviews have assessed dual-task cutting/sidestepping (Almonroeder et al., 2015; Brown et al., 2014; Giesche et al., 2021; Wilke et al., 2020). The current study, concerned with landing, only included these movements if the change of direction occurred following a jumping movement and data analysis was restricted to the landing/weight acceptance phase, to be comparable to a landing (Malloy et al.,

2016). These studies were also included if they entailed a condition absent the change of direction. Other exclusion criteria included the following: (1) grey literature, review articles and comments, (2) participants with a current or previous injury or impairment that may impact landing mechanics, (3) dual-tasks consisting of two physical or two cognitive tasks, (4) no control condition present or no comparison with a control condition made, (5) control and dual-task landing assessed using independent or between-groups study designs, (6) data collected was not associated with potential ACL loading.

Within the systematic review, a single statistical synthesis was performed, in the form of a meta analysis. All studies that met the inclusion criteria were included in the systematic review and those that also met the additional criteria above were included in the meta-analysis.

Information sources and search strategy

Studies were identified from searching the following electronic databases: SPORTDiscus (searched via EBSCOhost 13 October 2023), ScienceDirect (searched directly via ScienceDirect.com 15 October 2023) and PubMed (searched via NIH.gov 19 October 2023). A preliminary search of literature identified landing movements and secondary tasks were described using multiple terms and so a broad search strategy was devised (Table 1). All search terms were used in a single search with no limits or filters applied to yield the most literature. A final search was performed a year later to ensure all relevant articles have been retrieved. The reference lists of all inclusions, notable exclusions and relevant review articles retrieved were examined to highlight any further research articles. These were then searched for directly via the electronic databases identified above.

Study selection process

As this research formed part of a PhD thesis, all studies were screened for inclusion against the criteria by the same researcher (RK). Study screening was done manually,

Table 1. The search strategy used.

Group	Search Terms
Movement	OR Landing OR Drop Jump OR Jump landing OR Jump
AND	
Cognitive task	OR Cognitive task OR Cognitive demand OR Secondary task OR Secondary cognitive task OR Dual task OR Dual-task OR Unplanned OR Divided attention OR Decision making OR Unanticipated
AND	
Other	Biomechanics

using the title, then the abstract and finally the full text to ensure the eligibility criteria were met. All exclusions were recorded and notable ones marked.

Data collection

Data was collected from all identified papers the same researcher (RK). Data collected was stored and organised in Microsoft Excel, ahead of transfer to the analysis software. Where variables were expressed in a range of different units, significant changes were also expressed in percentages to aid comparison. The outcome that data was collected for was potentially increased ACL loading during the dual-task landing condition, informed by significant mechanical changes previously associated with ACL loading between the control and dual-task landing conditions. All results compatible with this outcome were sought. Data concerning the secondary cognitive task was sought, including the task requirements, the cognitive demands imposed and when, relative to the landing movement. Other data collected included the following: (1) number of participants, (2) participant demographic (age and sex), (3) landing movement employed (landing leg(s), jump type), (4) authors conclusions and any explanations given. This data was displayed in two tables, the first displaying study methodological information and the second presenting study results and findings.

Study risk of bias assessment

Study quality was assessed by the same researcher (RK) using the Downs and Black checklist (Downs & Black, 1998), a valid and reliable tool for assessing methodological quality and risk of bias. A modified version designed to assess sources of bias in non-randomised biomechanical studies was used (Almonroeder et al., 2015; Santamaria & Webster, 2010) with two additional items from the original checklist added, covering the identification and control of potential confounding variables (Downs & Black, 1998). This tool assessed four domains: reporting bias, external validity, internal validity and power, to provide an overall risk of bias. This assessment carries a maximum score of 15, with scores of ≥ 12 indicating *high methodological quality*, 10–11 indicating *moderate quality* and ≤ 9 indicating *low quality*. In the meta-analysis, study quality and any potential confounding variables identified in the literature were assessed as potential moderators, using meta-regression (Gucciardi et al., 2022; Hagger, 2022).

Meta-analysis

All meta-analyses were conducted using R Version 4.2.2 (R Core Team, 2023), using the packages Metafor (Viechtbauer, 2010) and Robumeta (Fisher et al., 2017). Robust variance estimation (RVE) with correlated study weighting was used to perform the analysis (Fisher et al., 2017; Hedges et al., 2010; Tipton, 2013, 2015) as a valid and reliable method of analysis in the presence of dependant effect sizes. Further, RVE was used in conjunction with a small sample adjustment that mitigates type 1 error inflation due to low or moderate study numbers (Tipton, 2015; Tipton & Pustejovsky, 2015). Standardised mean differences were used as the outcome effect measure. Standardised mean differences

were calculated to account for any different units used (Hagger, 2022; Lin & Aloe, 2021), with the Hedge's g correction applied to mitigate any small-sample bias from within studies (Pustejovsky & Rodgers, 2019). Effect sizes were defined as 0.2 = small, 0.5 = medium and 0.8 = large effect. A random-effects method was used due to the variation in study methodologies (Hagger, 2022). Effect sizes were displayed in a table and on forest plots along with confidence intervals calculated at 95% error. Confidence intervals were calculated using a t -distribution method. Statistical significance was set at $p < 0.05$. Heterogeneity was assessed via methods of moments estimator using I-square (I^2) and T-square (T^2) statistics (Gucciardi et al., 2022; Hagger, 2022), categorised as low (25%), moderate (50%) and high (75%) variation. An initial overall effect was calculated and then subsequent sub-group analyses were performed on each variable. These were a combination of study-level variables and within study contrasts dependant on whether studies assessed only one or multiple of the variables. Potential causes of heterogeneity were assessed in the form of moderator analyses using meta-regression (Gucciardi et al., 2022; Hagger, 2022). This included all levels of the movement performed, the type of secondary task, secondary task timing, participant sex and study quality. Study quality was assessed at the study level; the remaining analyses were a combination of study-level variables and within study contrasts dependant on whether studies entailed one or multiple levels of the variables. Sensitivity analyses would be conducted in the event of substantial heterogeneity being identified.

Reporting bias assessment

Potential publication bias was assessed within the meta-analysis by one researcher (RK), prior to any subgroup analyses. Following best practice guidelines, potential publication bias across studies was assessed using multiple methods (Hagger, 2022). Firstly, contour-enhanced funnel plots were created to allow an initial visual analysis of any asymmetries potentially due to publication bias (Peters et al., 2008). Secondly, the Egger sandwich test was selected to detect any potential publication bias; a regression test modified to handle dependant effect sizes without inflated type one error rates (Rodgers & Pustejovsky, 2021). It has been used previously in robust variance estimation (RVE) analyses (Bediou et al., 2018; Coles et al., 2019; Stevens et al., 2018). Finally, the three-parameter selection model (3PSM) was used (Carter et al., 2019; Hedges, 1992; McShane et al., 2016) due to its demonstrated bias identification and adjustment ability (Carter et al., 2019; Pustejovsky & Rodgers, 2019) including in the presence of dependant effect sizes (Rodgers & Pustejovsky, 2021). This selection model was applied to the data, using maximum likelihood methods, to provide the three parameters: bias adjusted effect size, bias adjusted heterogeneity and the degree of selection bias. Secondly, cluster-bootstrapping was applied to yield valid standard errors of these estimates, accounting for the dependency within the data. A modified standard error of effect size estimates was used in the latter two analyses to avoid inflated type one error rates due to the correlation between the standardised mean differences and conventional standard error (Pustejovsky & Rodgers, 2019; Rodgers & Pustejovsky, 2021).

Certainty assessment

An assessment was made to determine the certainty of the outcome (the potentially increased ACL loading during dual-task landings) in the body of research overall. Certainty was assessed using the quality assessment scores for each study and whether a majority of studies reported the same outcome effect and if any disagreeing outcomes proposed contradictory explanations. High certainty would entail the majority of studies scoring high quality and reporting the same/similar outcome/s and any that differ and propose explanations that do not contradict those offered by the majority. Low certainty would entail low methodological quality scores and/or no majority outcome effect with differing, contradicting explanations. This will be reported in text.

Results

Study selection

As shown in [Figure 1](#), initial searching identified 4012 articles and, following the screening process, this was reduced to 21 eligible articles. In reading these, a further eight articles were identified and screened with four included in this review. This process resulted in 25 articles for inclusion in the systematic review with 12 of these eligible for the meta-analysis.

Notable exclusions

A number of papers met all but one inclusion criteria. Several employed a dual-task single-leg land and cut but did not restrict analyses to the landing/weight acceptance phase (Borotikar et al., 2008; Brown et al., 2009; Kipp et al., 2013; McLean & Samorezov, 2009; McLean et al., 2010; Meinerz et al., 2015; Mejane et al., 2019). Eleven did not employ control conditions without a cognitive task to permit assessment of dual-task

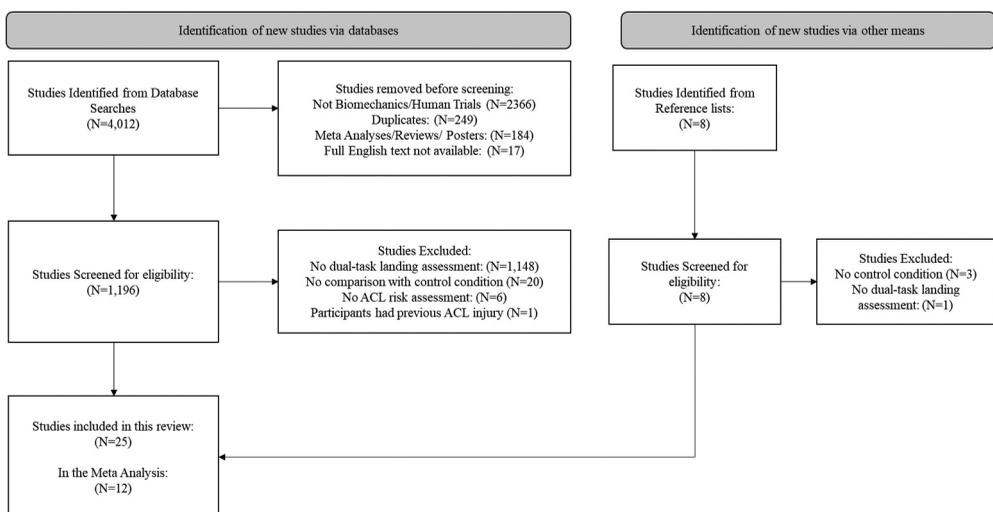


Figure 1. A flowchart detailing the search and screening process.

effects (Bertozzi et al., 2023; Cortes et al., 2012; Herman & Barth, 2016; Malloy et al., 2016; Niederer et al., 2020; Niemeier et al., 2019; Peel et al., 2021; Romanchuk, Del Bel, et al., 2020; Romanchuk, Smale, et al., 2020; Wilke et al., 2021). One assessed individuals who had previously suffered ACL injuries (Ashigbi et al., 2021). One averaged landing data across dual-task and single-task control conditions (Heinert et al., 2021). Three were excluded due to the outcome measures recorded not allowing inference of potential ACL loading, being reaction time and EMG data (Lempke et al., 2020; Leukel et al., 2012; Lynall et al., 2021).

Study characteristics

The key characteristics of the 25 studies included in the systematic review are displayed in Supplementary Table S1. Nine studies assessed males (Amoli et al., 2021; Fong et al., 2014; Friebe et al., 2022; Giesche et al., 2020, 2022; Ren et al., 2022; Shinya et al., 2011; Whyte et al., 2018a, 2018b), 4 assessed females (Almonroeder et al., 2018; Fischer et al., 2021; Imai et al., 2022; Yom et al., 2019), 10 assessed both (Biese et al., 2019; Dai et al., 2018; Holmes et al., 2023; Kajiwara et al., 2019; Lempke et al., 2021; Mache et al., 2013; Schnittjer et al., 2021; Sell et al., 2006; Shumski et al., 2023; Stephenson et al., 2018) and, of these, 5 made a comparison between the sexes (Lempke et al., 2021; Mache et al., 2013; Schnittjer et al., 2021; Sell et al., 2006; Shumski et al., 2023). Two studies did not provide participant sex (Lin et al., 2020; Watson et al., 2020). Fourteen studies (56%) assessed double-leg landings, most commonly dropping or jumping from a platform or hanging bar to perform a landing or secondary jumping movement. One study used repeated tuck jumps (Schnittjer et al., 2021) and one a standing broad jump (Sell et al., 2006). The remaining 11 studies (44%) assessed single-leg landings, made up of standing vertical jumps (Amoli et al., 2021; Friebe et al., 2022; Giesche et al., 2020, 2022; Shinya et al., 2011), a running stop jump (Fong et al., 2014), a broad jump (Whyte et al., 2018a, 2018b), drops from a platform (Kajiwara et al., 2019; Lin et al., 2020) and a hop (Watson et al., 2020). Seven studies entailed changes of direction. Two of these entailed conditions absent any changes of direction from which data was extracted, forward and vertical jumps following a stop jump (Fong et al., 2014) and a vertical jump following a forward jump from a platform (Stephenson et al., 2018). Four restricted their analyses to the landing/weight acceptance phase (Fischer et al., 2021; Whyte et al., 2018a, 2018b; Yom et al., 2019), and the remaining one completed post hoc data analysis to isolate effects due to the secondary task (Sell et al., 2006). Fifteen studies (60%) used short secondary cognitive tasks which were performed during the jump landing movement. In all but two cases, these entailed visual signals presented which provided instructions on the landing movement to be performed. Two studies used short tasks that had no bearing on the movement, a reaction button-press task (Shinya et al., 2011) and a target touch (Lin et al., 2020). Nine studies (36%) used longer secondary tasks that were performed alongside the jump landing movement. These were most commonly mental arithmetic tasks entailing subtraction or additions of random numbers (Amoli et al., 2021; Dai et al., 2018; Imai et al., 2022; Lempke et al., 2021; Schnittjer et al., 2021; Shumski et al., 2023). Beyond those, there were visuospatial and recall/memory tasks (Biese et al., 2019; Ren et al., 2022; Watson et al., 2020). Finally, one study incorporated both short and longer secondary cognitive tasks, separately and combined (Fischer et al., 2021).

Risk of bias

Supplementary Table S2 displays the Downs and Black (1998) modified checklist scores for each study. Ratings categorised 18 studies (72%) as high, 5 studies (20%) as moderate and 2 studies (8%) as low methodological quality. All/almost all studies scored positively on items 1 (clear aim/hypothesis; 100%), 2 (Outcomes clearly described; 100%), 3 (Subjects described; 92%), 4 (Interventions clearly described; 100%), 5 (findings described; 100%), 7 (Estimation of variability; 88%), 8 (probability values reported; 80%), 11 (data analysis as planned; 100%), 12 (appropriate analysis; 100%) and 13 (valid and reliable outcome measures; 100%). Two studies failed to provide all subject characteristics by not identifying sex (Lin et al., 2020; Watson et al., 2020), three didn't provide estimates of variability (Shinya et al., 2011; Whyte et al., 2018a, 2018b) and five failed to provide all probability values (Giesche et al., 2022; Mache et al., 2013; Ren et al., 2022; Shinya et al., 2011; Stephenson et al., 2018). Only three studies listed potential confounding variables (Friebe et al., 2022; Giesche et al., 2020; Schnittjer et al., 2021) and 13 studies (52%) adequately controlled for these. Nine studies (36%) utilised participants not representative of the population, using participants of only one sex (or not providing sex), but hypothesised and concluded with regard to general landing performance (Fong et al., 2014; Friebe et al., 2022; Giesche et al., 2020; Lin et al., 2020; Ren et al., 2022; Shinya et al., 2011; Watson et al., 2020; Whyte et al., 2018a; Yom et al., 2019). Ten studies (40%) did not perform a power analysis (Almonroeder et al., 2018; Fong et al., 2014; Friebe et al., 2022; Holmes et al., 2023; Kajiwara et al., 2019; Lempke et al., 2021; Mache et al., 2013; Sell et al., 2006; Shinya et al., 2011; Watson et al., 2020). Overall, the body of research seems to present *high* methodological quality, with 18 studies (72%) achieving this.

Results of individual studies

See Supplementary Table S3. Most research assessed discrete variables, kinematic variables were more commonly assessed than kinetic variables, with the knee being most researched, followed by the hip and then the ankle. Below, statistically significant effects between single- and dual-task landing conditions are reported, from the perspective of the dual-task condition. The percentages of assessments that saw a significant effect are given in brackets.

Knee

Five papers (63%) identified significantly decreased IC flexion (Dai et al., 2018; Imai et al., 2022; Lin et al., 2020; Mache et al., 2013; Stephenson et al., 2018) of between 1.9 and 5.8 degrees resulting in 16–23 degrees of flexion. Two studies (33%) identified increased IC abduction, in the form of 1.1–1.6 degrees decreased knee adduction resulting in 0.8–2.8 degrees of adduction (Mache et al., 2013; Stephenson et al., 2018) and no studies identified increases in either internal or external IC rotation. In terms of peak, only one study (14%) identified 1.7 degrees of decreased flexion, resulting in 56.7 degrees (Fischer et al., 2021), and four studies (50%) identified increased abduction (Almonroeder et al., 2018; Mache et al., 2013; Stephenson et al., 2018; Yom et al., 2019) of between 0.91 and 1.5 degrees, resulting in angles between 1.4 degrees of adduction and 13.6 degrees of

abduction. One study (20%) identified 1.0 degree of increased internal rotation (Kajiwara et al., 2019) and only one study assessed and identified (100%) an increase in external rotation (Mache et al., 2013) of 2.5 degrees, resulting in between 1.3 and 6.3 degrees of rotation. Finally, considering peak moments, one study (50%) identified 0.43 Nm/Kg of increased flexion (Imai et al., 2022), two studies (29%) identified 0.06 BW x BH and 0.43 Nm/Kg of increased abduction (Imai et al., 2022; Sell et al., 2006) and one study (50%) identified 0.13 Nm/Kg of increased internal rotation (Imai et al., 2022). No differences in external rotation moments were identified.

Hip

Two studies (50%) identified decreased IC flexion of 2.3 and 3.3 degrees, resulting in 12 and 21 degrees (Imai et al., 2022; Mache et al., 2013); two studies (67%) identified increased adduction (Mache et al., 2013; Yom et al., 2019) of 1.1 and 2.1 degrees, resulting in 6.1 and 6.2 degrees. No increases in internal rotation were observed. Considering peak angles, one study (33%) identified increased adduction (Mache et al., 2013) but as 2.1 degrees decreased abduction, resulting in 2.6 and 4.3 degrees of abduction. No changes were observed in flexion or internal rotation. As for peak moments, one study (50%) identified 0.4 Nm/Kg of increased flexion (Imai et al., 2022) and two studies (67%) identified increased adduction (Imai et al., 2022; Mache et al., 2013) of between 0.21 and 0.38 Nm/Kg, and 0.1% BWxBH. No increases in internal rotation were seen.

Ankle

No studies identified changes in IC or peak plantar flexion, external rotation or eversion. For peak moments, one study (50%) identified a 0.6 and 1.7% BW x BH decrease in plantarflexion (Mache et al., 2013), one study (100%) identified 0.06 and 0.1 Nm/Kg increased dorsiflexion moments (Imai et al., 2022) and one study (33%) saw 0.03 and 0.07 Nm/Kg increase in eversion moments (Imai et al., 2022). No studies assessed external ankle rotation.

Other

Four studies (67%) identified decreased stability (Giesche et al., 2020, 2022; Lin et al., 2020; Ren et al., 2022). Three studies (75%) identified between 13% and 15% increases in COP path length (Giesche et al., 2020, 2022; Ren et al., 2022). Two studies (67%) identified decreased vertical stability index scores (Lin et al., 2020; Ren et al., 2022), one study (33%) identified decreased mediolateral stability index scores (Ren et al., 2022) and one study (25%) identified a longer time (22.1 ms) to stabilisation (Ren et al., 2022). No studies identified decreased antero-posterior stability. Eight (57%) papers identified increased peak vertical GRF (vGRF) in dual-task landings (Dai et al., 2018; Friebe et al., 2022; Imai et al., 2022; Kajiwara et al., 2019; Lempke et al., 2021; Lin et al., 2020; Ren et al., 2022; Shinya et al., 2011); this ranged from increases of 5–42%. Two papers (50%) identified increased vertical loading rate (Friebe et al., 2022; Lin et al., 2020), one reporting 5% and the other only providing the data graphically, and three papers (75%) identified increased peak posterior GRF (Dai et al., 2018; Sell et al., 2006; Yom et al., 2019) of 7.5%, 16% and 13%, respectively. Imai et al. (2022) looked at angles and moments at peak vGRF, identifying decreased hip (2.5 degrees) and knee flexion (3.1 Degrees) angles as well as increased hip internal rotation (0.02

Nm/Kg), knee abduction (1.01 Nm/Kg) and knee flexion (0.28 Nm/Kg) moments during dual-task landings. Some papers also looked at angular displacement (Lin et al., 2020; Stephenson et al., 2018; Yom et al., 2019); one identified increased hip (2 degrees) and knee (1.8 degrees) abduction. Also, some papers assessed knee extension moments (Mache et al., 2013; Stephenson et al., 2018) as well as anterior tibial translation (Kajiwara et al., 2019); however, the only significant difference identified was one instance of a decreased knee extension moment (1.8% BW x BH) during dual-task landings.

Other analyses

Two studies performed qualitative analyses of dual-task landings (Biese et al., 2019; Schnittjer et al., 2021); one found no difference between conditions (Biese et al., 2019) and one found impaired movement during dual-task landings (Schnittjer et al., 2021) with a 25% increase in knee abduction presence. Two studies analysed dual-task landings using statistical parametric mapping (Whyte et al., 2018a, 2018b); both identified increased lateral and decreased sagittal trunk flexion, decreased hip flexion, increased hip external rotation moments, increased knee extension moments and decreased ankle plantar-flexion moments. One study (Whyte et al., 2018b) also identified decreased hip abduction angles, increased hip abduction moments, decreased knee varus angles, increased knee abduction moments, decreased ankle dorsiflexion, eversion and external rotation angles, decreased inversion moments, decreased ankle force absorption and finally decreased lateral GRF, whereas the other (Whyte et al., 2018a) identified increased trunk rotation, increased hip abduction and internal rotation angles, increased adduction and external rotation moments, increased knee internal rotation angles, decreased external knee rotation moments and increased extensor work, increased plantarflexion angles and decreased external ankle rotation moments.

Study-specific conclusions

Twelve studies made conclusions referring to potential injury risk. All except one concluded a possible increased ACL injury risk during dual-task landing, and the remaining one concluded kinematic changes thought to decrease the risk of ACL loading (Fong et al., 2014). However, they only assessed knee kinematics at initial contact and so may have seen differences throughout the landing phase. Five studies concluded potentially increased ACL strain/loading during dual-task landing movements. The remaining eight studies made conclusions referencing performance changes. Three of these identified changes thought to potentially increase ACL loading, decreased stability, increased peak vGRF and decreased peak knee flexion angles (Fischer et al., 2021; Giesche et al., 2022; Lempke et al., 2021). Three studies did not identify performance changes, possibly due to a simple secondary task (Biese et al., 2019) or participants adopting different landings (Holmes et al., 2023; Shumski et al., 2023). Finally, two studies saw performance changes associated with decreased ACL loading, decreased peak GRF (Amoli et al., 2021) and increased landing stability (Watson et al., 2020). The secondary tasks may have been insufficiently challenging or may have increased arousal (Watson et al., 2020) and possibly required landings to be performed automatically, which was beneficial for the highly skilled athletes in the study (Amoli et al., 2021).

Overall, the majority of the research concludes potentially increased ACL injury risk or loading during dual-task landings.

Meta-analysis

Study characteristics

Supplementary Table S4 displays studies included in the meta-analysis. All but one assessed double-leg landings via range of movements, most commonly a jump-land-jump. These were performed alongside a variety of secondary tasks, most commonly a visual indication of the movement to be performed. Where possible, data on males and females was separated, the remaining are listed as including both sexes. All but two had a high methodological quality score ($12 \leq$). A negative effect size represents a decrease in the dual-task condition.

Overall effect

Figure 2 displays the meta-analysis and subgroup analyses on a forest plot. Ninety-one effect sizes were included in the meta-analysis of the overall effect of secondary tasks on knee abduction and internal rotational loading during landing. This demonstrated a negligible, statistically insignificant effect ($g = -0.017$, 95% CI $[-0.144, 0.111]$, $p = 0.77$). Low between study heterogeneity was demonstrated ($\tau^2 = 0$, $I^2 = 0\%$).

Subgroup analyses

Eighteen effect sizes from seven studies were included in the subgroup analysis of peak knee abduction angles. This demonstrated a negligible, statistically insignificant effect ($g = 0.046$, 95% CI $[-0.076, 0.168]$, $p = 0.35$). Low between study heterogeneity was demonstrated ($\tau^2 = 0$, $I^2 = 0\%$).

Sixteen effect sizes from six studies were included in the subgroup analysis of peak knee abduction moments. This demonstrated a negligible-to-small, statistically insignificant effect ($g = 0.056$, 95% CI $[-0.235, 0.346]$, $p = 0.63$). Low between study heterogeneity was demonstrated ($\tau^2 = 0.01$, $I^2 = 13.7\%$).

Twelve effect sizes from five studies were included in the subgroup analysis of peak knee internal rotation angles. This demonstrated a negligible, statistically insignificant effect ($g = -0.03$, 95% CI $[-0.173, 0.112]$, $p = 0.51$). Low between study heterogeneity was demonstrated ($\tau^2 = 0$, $I^2 = 0\%$).

Fourteen effect sizes from six studies were included in the subgroup analysis of initial contact knee flexion angles. This demonstrated a negligible, statistically significant effect ($g = -0.13$, 95% CI $[-0.217, -0.037]$, $p = 0.03$). Low between study heterogeneity was demonstrated ($\tau^2 = 0$, $I^2 = 0\%$).

Fourteen effect sizes from six studies were included in the subgroup analysis of peak knee flexion angles. This demonstrated a negligible, statistically insignificant effect ($g = -0.014$, 95% CI $[-0.592, 0.031]$, $p = 0.37$). Low between study heterogeneity was demonstrated ($\tau^2 = 0$, $I^2 = 0\%$).

Nine effect sizes from seven studies were included in the subgroup analysis of peak vGRF. This demonstrated a negligible, statistically insignificant effect ($g = -0.056$, 95% CI $[-0.039, 0.154]$, $p = 0.19$). Low between study heterogeneity was demonstrated ($\tau^2 = 0.004$, $I^2 = 33\%$).

Only two included studies assessed peak knee internal rotation and flexion moments; therefore, these subgroup analyses were not performed.

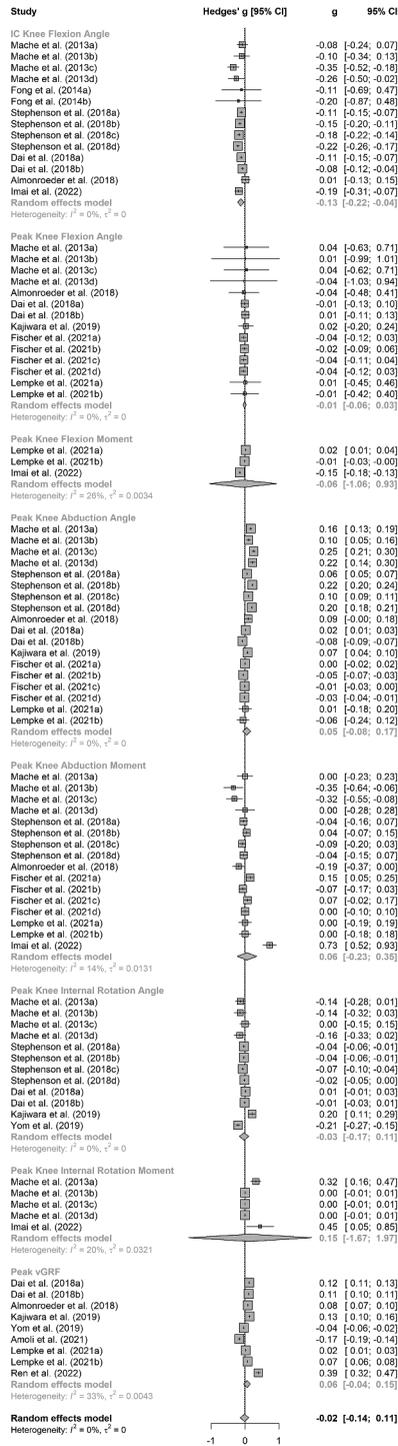


Figure 2. A forest plot displaying both overall and subgroup analyses.

Table 2. Moderator analyses.

Moderator	Studies	Number of Effect Sizes	Effect Estimate	95% CI.L	95% CI.U	P Value	Significance
Movement	12	91	-1.67	NaN	NaN	NaN	N/A
Secondary Task	12	91	0.39	NaN	NaN	NaN	N/A
Sex	12	91	0.01	-0.13	0.15	0.7	No
Secondary Task Timing	12	91	-0.03	-0.29	0.22	0.62	No
Study Quality	12	91	0.94	-1.23	3.12	0.3	No

Moderator analysis

Table 2 displays the meta-regression analyses performed to determine potential moderators.

Neither participant sex, the timing of the secondary task nor study quality was shown to have any significant impacts upon the results ($p > 0.05$). Analysis of the potential effect of different secondary tasks or movements was not possible, yielding not a number (NaN) due to insufficient sample sizes.

Risk of bias across studies

As shown in **Figure 3**, there is little asymmetry in the funnel plot. There are a couple of outliers, showing significant positive effect sizes; however, Egger's sandwich test identified no significant funnel plot asymmetry ($p = 0.86$). Finally, **Table 3** displays the outputs from the 3PSM, as well as the standard errors and confidence intervals obtained from bootstrapping.

A selection parameter estimate identified a 72% probability of non-significant results being reported. However, this parameter is accompanied by the largest margin of error and confidence intervals. Plus, adjusting for this potential selection bias, the model reported a similar overall effect size and heterogeneity as the meta-analysis. This, with the above two bias detection methods, does not indicate that significant selection bias is present.

Certainty of evidence

Most (72%) of included studies were ascribed a *high* methodological quality score and most (76%) supported a conclusion of potentially increased ACL loading during dual-task landing. However, this is due to a variety of biomechanical impacts that were often small, seen inconsistently across studies, and the meta-analysis of nine studies identified these changes did not significantly impact frontal or transverse plane knee loading. Therefore, this allows only low certainty in the outcome of potentially increased ACL loading during dual-task landing. Variable changes being larger, more consistent and/or significantly increased knee loading would allow higher certainty.

Discussion

The meta-analysis did not identify dual-task landings to significantly impact knee abduction, internal rotation loading, peak knee flexion angles or peak vGRF. The only significant impact was a small decrease in IC knee flexion angles during dual-task landings by an average of 3.5 degrees (Dai et al., 2018; Imai et al., 2022; Mache et al.,

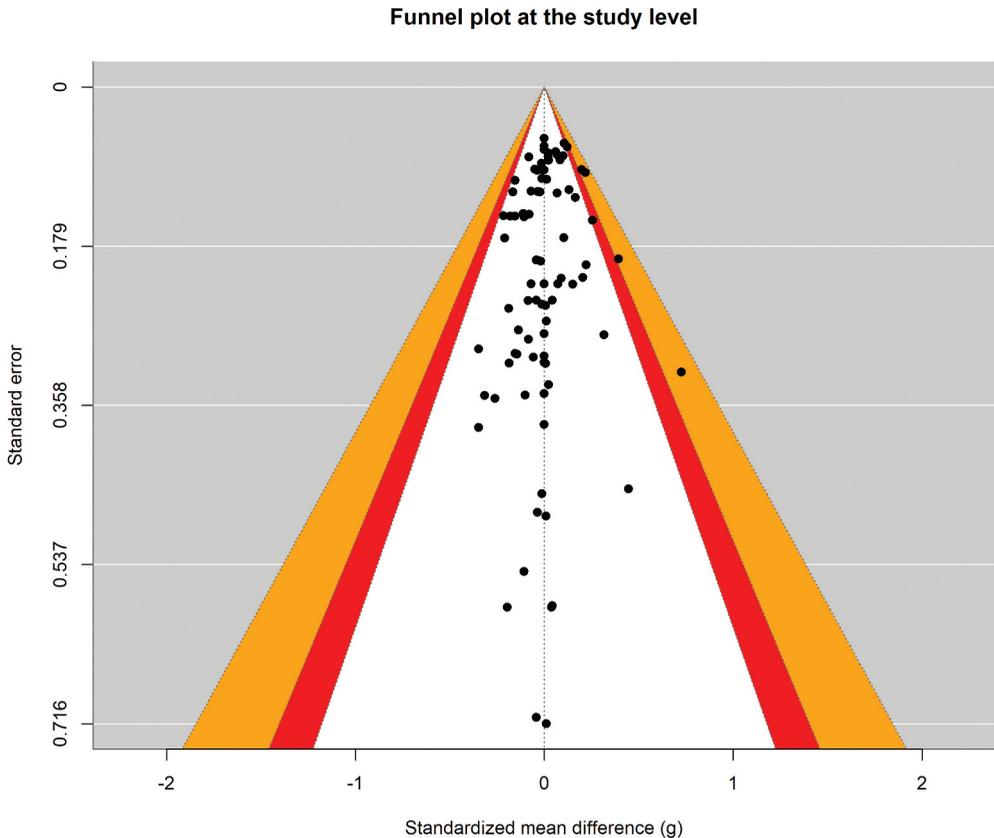


Figure 3. A contour-enhanced funnel plot, displaying standardised mean differences (g) and standard error. Red and orange sections indicate significance levels of $p < 0.05$ and $p < 0.01$, respectively.

Table 3. Outputs from the boot-strapped 3PSM.

Parameter	Statistic	Std Error	95% BCA-L	95% BCA-U
mean	0.0158	0.0126	-0.0112	0.0373
tau	0.003	0.008	0.0008	0.0463
sel	0.72	16.6	0.1848	5.313

2013; Stephenson et al., 2018). During landings, decreased knee flexion angles place the knee in a vulnerable position maximising both ACL length and quadriceps drawer loading at the knee (Bakker et al., 2016; DeMorat et al., 2004; Li et al., 2005; Nunley et al., 2003; Roldán et al., 2017; Taylor et al., 2011). Decreased IC knee flexion during landing of 4.5 degrees has been shown to contribute to an 11% increase in ACL loading (Laughlin et al., 2011), though in the presence of decreased IC hip flexion and peak hip and knee flexion values. The current study identifying only decreased IC knee flexion suggests little to no impacts on ACL loading due to knee mechanical changes. Conversely, the systematic review identified that most authors concluded a possible increased risk of ACL injury/loading during dual-task landings. Conclusions of potentially increased ACL loading during dual-task landings are supported by the evidence; being based on significant, though small, variable changes that are associated with

increased ACL loading (Almonroeder et al., 2018; Sell et al., 2006; Stephenson et al., 2018; Whyte et al., 2018a, 2018b). However, conclusions that injury risk is potentially increased are not consistent with the evidence; these studies were not prospective in design and so could not assess incidents of injury nor the risk of injury; significant variable changes were infrequently reported, typically small, and did not result in increased knee frontal or transverse plane loading. Researchers ought to be more cautious when making claims about injury risk, reserving such judgements for prospective study designs that can assess this.

Methodological considerations

Types of dual-task landing

Dual-task landing literature presents distinct ‘types’ of dual-task landings which have not been formally identified. This review proposes three, two of which being ‘unplanned’ and ‘divided attention’. Unplanned landings entail a short cognitive task to reduce or prevent pre-planning of movement, such as a light that activates during flight to indicate jump direction upon landing (Fischer et al., 2021; Stephenson et al., 2018). This assesses reaction time and processing speed (Fischer et al., 2021; Friebe et al., 2022; Kajiwara et al., 2019; Stephenson et al., 2018; Yom et al., 2019) and any subsequent movement error is attributed insufficient time to plan it (Friebe et al., 2022; Giesche et al., 2022; Kajiwara et al., 2019; Stephenson et al., 2018; Yom et al., 2019). This necessitates the use of quick and simple cognitive tasks which have limited ecological validity (Almonroeder et al., 2018; Hughes & Dai, 2023; Mache et al., 2013) and may not establish a truly unanticipated paradigm (Almonroeder et al., 2018; Brown et al., 2009). Divided attention landings often entail longer, more complex cognitive tasks performed alongside a landing, such as a verbal arithmetic task (Dai et al., 2018). This assesses attention division between two different tasks (Dai et al., 2018; Fischer et al., 2021; Kernozek et al., 2021; Lin et al., 2020; Schnittjer et al., 2021) and any movement impairment is a result of insufficient attention dedicated to the landing task. This follows the limited capacity theories of attention (Bayot et al., 2018; Kahneman, 1973; Tombu & Jolicoeur, 2003); attention directed towards the secondary task decreases that available for neuromuscular control of the landing (Dai et al., 2018; Lin et al., 2020; Ren et al., 2022; Schnittjer et al., 2021). This methodology allows more ecologically valid, longer cognitive tasks and task complexity to be manipulated (Almonroeder et al., 2018; Dai et al., 2018; Imai et al., 2022; Norte et al., 2020; Stephenson et al., 2018). Unplanned and divided attention cognitive demands can be applied together, forming ‘Unplanned-Divided-Attention’ landings. One included study assessed this, signalling jump direction mid-flight *and* requiring this be performed alongside a memory recall task (Fischer et al., 2021). This elicited a slight but statistically significant decrease in peak knee flexion angles compared to the single-task and unanticipated landings, possibly suggesting increased cognitive demands during this condition.

Potential confounding variables

The inconsistent biomechanical outcomes across included studies could be due to confounding variables; however, a lack of research makes this difficult to assess. Differing cognitive demands on participants may impact dual-task performance.

Included unplanned landings employed a range of secondary task timings, giving participants between 0 and 400 ms to pre-plan their movement. Reducing this time increases the demand imposed and may further increase potential ACL loading when dual tasking (Stephenson et al., 2018). Similarly, increasing the task complexity during divided attention landings will also increase the demand imposed and has been shown to have no impact during jump landing (Dai et al., 2018); however, increased knee abduction during tuck jumps (Schnittjer et al., 2021) and an excluded study identified that it impaired single-leg landing stability (Wilke et al., 2021). Differing levels of physical demand may also impact dual-task landing effects. Jump-land-jumps and drop-jumps entail greater physical demands compared to drop landings due to the subsequent jumping movement (Cruz et al., 2013; Hovey et al., 2021; Moolyk et al., 2013; Shultz et al., 2012) which may contribute to impaired dual-task landing performance (Mache et al., 2013). Facilitating a change of direction entails greater impact forces and frontal plane joint loading (Cortes et al., 2011; Jones et al., 2014; Kristianslund & Krosshaug, 2013) and may also contribute to increased impacts of a dual-task (Fong et al., 2014; Stephenson et al., 2018). During single-leg landings, limb dominance may factor into dual-task landing movements. One included study identified increased peak GRF, increased hip rotation moments and decreased ankle internal rotation angles only in the non-dominant limb (Imai et al., 2022). However, other dual-task landing research has identified little to no difference between limbs (Holmes et al., 2023; Lempke et al., 2021; Mercado-Palomino et al., 2020). Therefore, it may be that increasing the cognitive and/or physical task demands increases the total demand on the participant and contributes to ACL loading in dual-task movements.

Another variable is task prioritisation. When dual-tasking, attention cannot be split evenly between tasks; one is prioritised (Shumway-Cook et al., 1997; Yogev-Seligmann et al., 2012). This concept has been researched within gait and limb loading (Chan & Sigward, 2023; Patel et al., 2014; Yogev-Seligmann et al., 2012), however not within dual-task landings. Included studies suggest that impaired dual-task landing performance is due to participants prioritising the cognitive task (Dai et al., 2018; Lin et al., 2020), while little to no impacts on landing are attributed to *it* being prioritised (Biese et al., 2019; Lempke et al., 2021). This conforms to the 'posture first' theory which states that people prioritise the physical task when dual-tasking to prevent injury and falls (Shumway-Cook et al., 1997; Yogev-Seligmann et al., 2012). Understanding this requires assessment of secondary task performance; minimal impacts on landing may indicate insufficient cognitive demand (Biese et al., 2019; Shinya et al., 2011; Wilke et al., 2021) or the landing being prioritised (Biese et al., 2019; Lempke et al., 2021). Impaired landing mechanics may indicate the secondary task being prioritised (Dai et al., 2018; Lin et al., 2020) or impaired performance of both tasks (Lempke et al., 2021; Schnittjer et al., 2021; Wilke et al., 2021). Prioritisation of the secondary task may impair dual-task landing mechanics and contribute to ACL loading.

Participant sex may also impact dual-task landings. Included studies show that females may perform dual-task landings with decreased peak knee flexion angles, increased peak knee abduction and rotation angles, increased tibial shear force and increased knee extension moments, possibly experienced increased ACL loading (Mache et al., 2013; Sell et al., 2006). However, other included studies looking at stiffness (Shumski et al., 2023), a qualitative assessment of tuck jumps (Schnittjer et al., 2021) and the kinematics

and kinetics of a jump landing (Lempke et al., 2021) identified no differences between the sexes. Fatigue is similar; two included studies assessed this and found no impact (Whyte et al., 2018a, 2018b). However, an excluded study identified a combination of fatigue and a secondary cognitive task significantly increased peak knee abduction during landing (Mejane et al., 2019) and cutting research has shown that fatigue worsens dual-task performance and potentially increases ACL loading (Borotikar et al., 2008; McLean & Samorezov, 2009). There is currently no consensus of how sex or fatigue impacts dual-task landing.

Limitations of the evidence and future research

No included studies made a direct assessment of injury risk, for example via prospective study designs. Future research ought to incorporate dual-task movements into prospective research to allow a more direct link between dual-task demands and injury risk to be investigated. Beyond this, more research is required into ankle, hip and trunk mechanics, as they impact potential knee loading but are often not assessed. Future research needs to employ consistent methodologies in terms of the movement assessed and the secondary task employed to mitigate any potential confounding variables and allow a more consistent body of research to develop. Considering potential confounding variables, some included studies did not control for these, such as grouping and assessing males with females (Biese et al., 2019; Dai et al., 2018; Kajiwara et al., 2019; Stephenson et al., 2018); future research ought to match other included studies and control for sex, jump direction and limb dominance (Fischer et al., 2021; Imai et al., 2022; Lempke et al., 2021; Mache et al., 2013; Sell et al., 2006). Further, potential confounding variables need more investigation, for example, comparing different dual-task movements, different secondary tasks or assessing task prioritisation. Included studies' cognitive tasks have limited ecological validity; possibly the most valid being a 3D digital object tracking task (Ren et al., 2022), analogous to tracking the ball/opponents in sport. Future research could use video clips of sport (Basevitch et al., 2020; Natsuhara et al., 2020) or interaction with a physical ball (Amoli et al., 2021; Kernozek et al., 2021) or explore virtual reality (Brown et al., 2009; DiCesare et al., 2020; Gokeler et al., 2016) to allow secondary cognitive tasks better match the demands seen in sport. Finally, more research is also required into secondary task performance; only eight (32%) of included studies assessed this which, as stated, allows assessment of task prioritisation.

Limitations of this review

This is a relatively new research area, with scope for methodological development. There is little data, gathered from a range of different methodologies. Only 12 studies met the criteria for inclusion in the meta-analysis, which makes identification of significant effects challenging. The initial searching of the three databases and the subsequent search through retrieved reference lists may not have identified all possible articles for inclusion; searching of more comprehensive databases may have entailed greater coverage (Gusenbauer, 2019). Also, most studies that met the inclusion criteria entailed sagittal plane movements, absent any change of direction, which hinders assessment of frontal or transverse plane joint loading. This is a possible factor into the largely insignificant meta-

analysis results. Finally, only one researcher screened articles, extracted the data and performed the statistical synthesis. This increases the risk of bias and error.

Conclusion

Dual-task landing research has significantly grown over the past 20 years; a variety of movements and secondary tasks have allowed a diverse body of research to develop. Most research in the systematic review concluded potentially increased ACL loading during dual-task landings based on a wide range of mechanical changes to the trunk and lower extremity. However, the meta-analysis identified that these small mechanical changes did not significantly impact knee abduction or internal rotation loading. This body of research supports the assertion that dual-task landings can elicit a range of small mechanical changes that are logically consistent with increased knee loading. However, this increased knee loading has not been consistently observed. This research also indicates that task demands, task prioritisation, different landing movements, participant sex and fatigue *may* impact dual-task landing mechanics and any subsequent knee loading. Further research is required with consistent methodologies to clarify results and to assess potential confounding variables. Prospective research is needed to assess any impacts of dual-task landings on ACL injury risk. Therefore, while secondary cognitive tasks appear to be present during ACL injuries, it is premature to conclude that they significantly contribute to ACL loading and subsequent injury risk.

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Registration and protocol

The review was registered at the International prospective register of systematic reviews (PROSPERO) registration ID: CRD42023425191. A protocol was not prepared.

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