Review Paper

Fatigue-induced Changes in Lower Extremity Landing Kinematics: A Systematic Review and Meta-analysis

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ABSTRACT

Objectives: Fatigue may have a negative impact on joint biomechanics during landings. This systematic review aimed to collect and synthesize available data on the effects of fatigue on the biomechanics of the lower extremity limbs during various movements, such as landing, among physically active populations.

Methods: A systematic review of meta-analysis were conducted in accordance with preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, searching the PubMed, Scopus, Web of Science, and Google Scholar databases for original and peer-reviewed articles using selected keywords from inception to June 2025. The quality of the included studies was assessed using the Joanna Briggs Institute (JBI) checklist. Statistical analysis was conducted with comprehensive meta-analysis (CMA) software version 4. To evaluate data heterogeneity, the Q-test and I^2 statistic were applied. The Egger test was used to assess publication bias.

Results: After examining the titles and abstracts of 1692 studies from chosen databases, 44 articles were deemed suitable for inclusion in meta-analyses. Fatigue showed no significant effect on lower extremity kinematics during landing for hip flexion (P=0.947; 95% CI, -0.206%, 0.1925%), knee flexion (P=0.885; 95% CI, -0.135%, 0.156%), knee adduction (P=0.402; 95% CI, -0.060%, 0.149%), knee internal rotation (P=0.263; 95% CI, -0.091%, 0.334%), hip abduction (P=0.516; 95% CI, -0.099%, 0.197%), hip rotation (P=0.760; 95% CI, -0.39%, 0.286%), ankle dorsiflexion (P=0.372; 95% CI, -0.116%, 0.309%), and ankle supination (P=0.326; 95% CI, -0.23%, 0.692%). However, a significant effect was observed for ankle inversion (P=0.003; 95% CI, 0.114%, 0.537%). No significant differences were found between males and females across all kinematic variables. High heterogeneity was noted in most analyses (I^2 ranging from 28.877% to 83.642%), except for ankle inversion (I^2=0.000%). Egger's test indicated no significant publication bias across all variables (P>0.05).

Discussion: Contrary to common belief, fatigue does not appear to consistently alter hip and knee landing kinematics in healthy, active individuals, though it does increase ankle inversion, potentially elevating the risk of ankle sprains.

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Highlights

• Fatigue was not associated with consistent changes in hip, knee, or ankle joints during landing, except for ankle inversion.

• No significant differences were found between female and male active individuals.

• Ankle inversion may increase under fatigue.

Plain Language Summary

This study examined the impact of fatigue on the lower extremity joints of physically active individuals during landing. The findings showed that fatigue did not cause changes in the hip, knee, or ankle when landing. The only effect was on ankle inversion, which increased after fatigue.

Introduction

It is widely acknowledged that physical exercise is essential for maintaining overall health and wellbeing [1]. However, engaging in physical exercise can bring about injuries and may have some detrimental effects on overall performance of people [2]. To illustrate, injuries to the ankle and knee are frequent, particularly in activities that involve cutting and jumping movements [3]. During the landing phases of jumping exercises, substantial loads are typically placed on the leg extensor muscles, which work eccentrically to slow down the body's downward motion and dissipate the kinetic energy generated upon landing [4]. As a consequence, studies have investigated the biomechanics and pathomechanics of landing to improve comprehension of injury mechanisms, aiming to develop strategies for prevention and treatments [5-7].

Landing is well recognized as a key movement that reflects the neuromuscular system's capacity to control motion, especially in running and jumping activities [1, 8]. During landing, the knee plays a crucial role in absorbing impact forces by modulating muscle activity to control downward movement, while ankle dorsiflexion and hip flexion also significantly contribute to energy absorption [9]. When the lower extremity joints effectively manage descent through sagittal plane motion [10], landings tend to be safer because the ligaments responsible for lateral joint stability experience reduced loading [11]. Nevertheless, during prolonged activity, the body experiences a temporary decline in performance capacity, known as physical fatigue, which is an external factor impacting the neuromusculoskeletal system [12].

Neuromuscular control considerably contributes to maintaining dynamic joint stability and protecting the human body against various injuries [13, 14]; neuromuscular fatigue can impair this control and stability [15]. Prior studies demonstrate that neuromuscular fatigue can trigger various biomechanical alterations in the body, potentially increasing the risk of anterior cruciate ligament (ACL) injuries during landing [16, 17]. This injury may imply several impairments, including abnormal postural control, altered landing patterns, and neuromuscular deficits that can exacerbate the negative consequences of fatigue [18-20]. Yet, previous findings on this issue have some inconsistencies, and the impact of fatigue on lower limb injuries remains uncertain. For instance, in single-limb landings, researchers have observed that fatigue can lead to numerous biomechanical changes in the lower limbs, including decreased knee flexion and adduction moments [21]. Moreover, some studies have found that fatigue induces biomechanical changes that can be observed in both the lower extremity of the ACL reconstruction and the uninvolved one [18, 22].

Previous researchers have identified sagittal plane variables as factors that may contribute to the mechanism of lower extremity injuries, such as ACL [23, 24]. Research has shown that limited movement in the sagittal plane increases knee valgus angles and reduces energy absorption in the hip and knee joints among female soccer players [25]. These findings suggest that landing with limited motion in this plane could raise the risk of ACL injury. Additionally, other studies have demonstrated that reduced hip flexion and increased external knee flexion moments are associated with a higher likelihood of ACL injury [26]. It is shown that localized muscle fatigue in the lower extremity limbs has a significant association with greater alterations in postural stability in either the frontal or sagittal plane [27]. Another study suggests that the fatigue of the ankle dorsiflexors and plantar-flexors may have detrimental effects on postural stability in the sagittal plane only [28]. Moreover, lower extremity injuries can lead to alterations in angles and velocities, particularly during movements involving changes in direction, such as sidestepping, or during the landing phase of a jump [29]. Additionally, it has been observed that females have greater variation in knee joint angular velocity during the landing phase than males [30].

Despite extensive research on fatigue-induced changes in lower extremity kinematics during landing, inconsistencies persist due to methodological variations in fatigue protocols, kinematic analysis, and participant characteristics. While a recent article [31] has offered valuable insights into sex-specific responses to fatigue during landing tasks, the focus remains narrowly centered on gender-based comparisons and ACL-related outcomes. In contrast, this review expands the scope to provide a comprehensive synthesis of fatigue-induced changes in lower extremity landing kinematics across diverse fatigue protocols and study designs, regardless of sex or injury status. Our analysis emphasizes kinematic alterations as a function of fatigue, encompassing a broader spectrum of biomechanical variables. By aggregating and quantifying the impact of fatigue on lower extremity joint angles, our work provides a more comprehensive and versatile framework that can inform injury prevention, athletic training, and rehabilitation across various sports and populations. Therefore, this systematic review aimed to synthesize and gather available data on the effect of fatigue on the biomechanics of lower extremity limbs (including the hip, knee, and ankle) during landing in physically active individuals.

Materials and Methods

This review and meta-analysis study was registered prospectively in PROSPERO under the number CRD 42024502034.

Search strategy and keywords

This study used the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines [32]. All relevant articles were extracted using the search approach. Using a combination of phrases related to "lower extremity," "kinematics," "biomechanics," "fatigue," and "landing," we conducted a systematic search across Scopus, Web of Science, and PubMed from the databases' inception until June 2025 to identify relevant papers. Google Scholar was also searched. The references of pertinent papers were also carefully screened by three independent reviewers (Mohammad Salsali, Parisa Sayyadi, and Ebrahim Ebrahimi to see possibly more relevant literature and consulted with an expert (Rahman Sheikhhoseini) in the research area.

The following keyword combinations were used with the help of AND and OR operators as follows: ([Thigh OR Shank OR hip OR knee OR ankle OR foot OR feet OR "lower extremity" OR "lower limb" OR "lower-limb" OR "lower-extremity"] AND [fatigue* OR lassitude OR tiredness OR exhaustion) AND (Kinematics OR Biomechanics OR "human movement analysis" OR "motion analysis" OR "lower limb motion"] AND [jump* OR "touchdown" OR land* OR "take-off" OR Task*]).

Inclusion and exclusion criteria

A study was included in this review if it met the following criteria: 1) Examined the effect of fatigue on lower limb kinematics among physically active individuals, 2) was written in English, and 3) was published in a peer-reviewed journal. The following exclusion criteria were implemented: 1) studies were performed on individuals with neurological problems, ligament laxity, and lower extremity injury; 2) studies did not provide sufficient information for meta-analyses; and 3) studies were published as conferences, papers, abstracts, and unpublished dissertations.

Study selection

In this study, 3 authors (Mohammad Salsali, Parisa Sayyadi, and Elnaz Rajabi) independently examined and selected the articles' titles and abstracts according to the inclusion criteria and PRISMA standard methodology, utilizing a standardized Excel data extraction sheet [33]. All human studies and trials published until the end of the search period (June 2025) were included. The supervising author (Rahman Sheikhhoseini) addressed and assessed discrepancies between the researchers. Their searched records were imported into EndNote software, version 20. This software was also used to remove duplicate articles.

Data extraction and quality assessment

Two researchers (Mohammad Salsali and Ebrahim Ebrahimi) employed the Joanna Briggs institute (JBI) critical appraisal tools [34] to evaluate the potential for bias, selecting the specific tool according to the research design included in each study and the case-control analysis. Using a standard Excel data extraction sheet, the researchers independently collected data and subsequently compared their findings to evaluate coherence. Furthermore, the supervising author addressed and assessed any discrepancies between the researchers (Rahman Sheikhhoseini). The subsequent statistics were extracted from the included research based on the first author, year of publication, type of study, quality, sample size, subjects (including age, gender, and index data), the most important methods and tools used for data collection, and the most significant results obtained.

Data analysis

In this study, we used the comprehensive meta-analysis CMA software, version 4.0 (Biostat Inc., Englewood, New Jersey). The required data from eligible articles include the standard deviation, mean of pre- and post-tests, P values of the sample size, and mean difference. The effect size was calculated using Hedges' g to account for differences in measurement scales. The I^2 was employed to evaluate the data's heterogeneity and estimate the heterogeneity percentage. The Funnel Plot methods were used to assess the articles' publication bias risk. In the event of potential bias observed using this method and to investigate the extent to which the articles used in this field might affect the final results of this meta-analysis, we employed the trim-and-fill method.

Results

A total of 1866 articles were identified in the selected databases (Figure 1). Once the data were entered into End-Note software and duplicate records were removed, 1211 articles remained. After reviewing the abstracts and titles, 72 articles were selected for further analysis. Following this, the complete text of the 53 chosen articles was carefully analysed; ultimately, 45 papers were deemed suitable for the study. Additionally, 4 studies from the Google Scholar database were included, resulting in a total of 49 studies.

Study characteristics

Publication dates ranged from 2003 to 2024. Of the 49 studies and 3678 participants included in this systematic review, 20 studies included only females [7, 16, 17, 29, 35-49], 21 studies included only males [4-6, 11, 18, 38, 46, 50-63], and 8 studies included both male and female [3, 48, 55, 64-67] participants. Regarding the phase of landing, 1 study used impact phase [50], 1 study used the onset of ground reaction force (GRF) to peak knee flexion angle [45], 1 study used 50 ms before touchdown and touchdown [62], 1 study used 3 s after landing [56], 1 study used take-off and landing [6], and the other studies utilized initial contact phase. Also, the instrumentation of 1 study was electro goniometers [68], an analogue module of an ariel performance analysis system [42], VirtualDubMod [37], QuickTime Player [59], Electromyography [53], Kinovea [51], and the other studies used Vicon motion capture system and force plate. Online supplemental tables contain detailed information about each included study (Table 1).

Risk of bias

A methodological quality assessment was conducted across all included studies using a standardized checklist (JBI) comprising 9 criteria. Overall, the studies demonstrated moderate methodological quality, with quality scores ranging from 5 to 8 out of a possible 9. The most consistently met criteria were related to clarity in the study objective, the use of valid outcome measures, and the use of appropriate data collection methods. However, a notable and consistent source of bias was observed in criterion Q8 (Were outcomes measured in a reliable way?), which was not satisfied by any of the included studies, indicating a systematic gap in reporting or execution, likely associated with issues such as blinding or follow-up completeness. Additionally, variability was observed in criteria related to statistical analysis and participant selection, suggesting a potential for selection and performance bias. Despite these limitations, a substantial proportion of the studies (over 75%) met at least 6 quality criteria, supporting the overall reliability of the findings. Nonetheless, the presence of a moderate risk of bias across studies necessitates a cautious interpretation of the pooled results (Table 2).

Fatigue effects on kinematics of ankle dorsiflexion

Twenty-seven studies [3-6, 11, 16, 18, 29, 35-40, 46, 50, 51, 54-59, 63, 65, 76, 74] were included in the meta-analysis to investigate the effect of fatigue on the kinematics of ankle dorsiflexion, a key kinematic parameter of the lower extremities during landing. A total of 498 participants were involved in these studies. Forest plot analysis of the data revealed a non-significant change in ankle dorsiflexion due to fatigue effects (P=0.372; 95% CI, -0.116%, 0.309%). Assessment of heterogeneity revealed significant variability among the studies (P=0.000; I^2=77.979), suggesting substantial differences in study populations, fatigue protocols, or measurement methods. To explore potential moderators, we performed meta-regression analyses for sex, but the results showed that it did not significantly impact the observed effect sizes (P>0.05). Subgroup analyses by sex (male, female, and both) also indicated no significant differences in the effect of fatigue on ankle dorsiflexion across these groups. The funnel plot showed a symmetrical distribution of studies around the pooled effect size, and Egger's test yielded a non-significant intercept (P=0.59776).

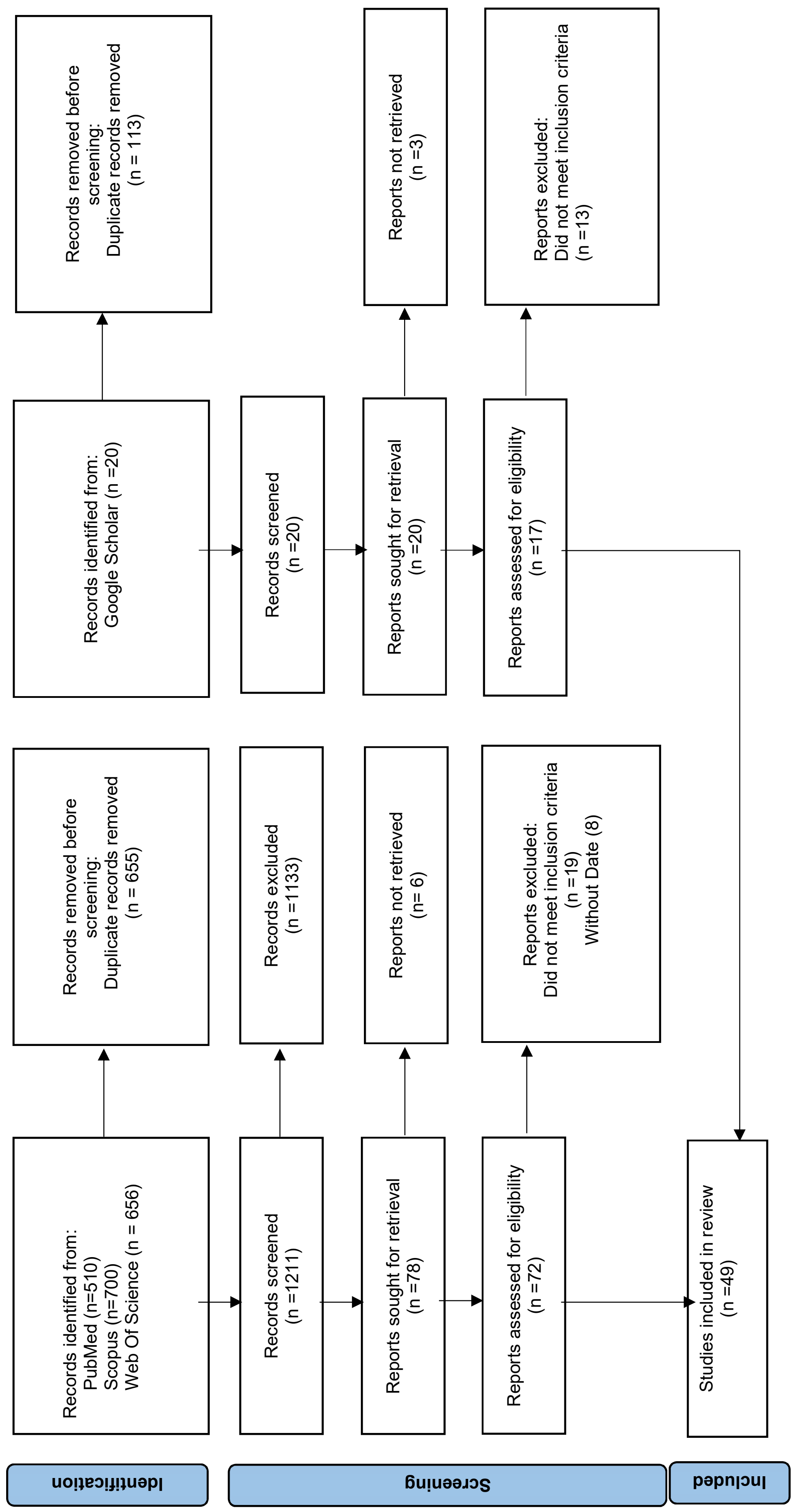

Figure 1. The PRISMA flow diagram illustrating the database process searching and reference identification

Table 1. Demographic information from the included studies

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
1	Madigan et al. 2003 [50]	Healthy subjects	12 (12/0) 27.9±5.4	Two single-leg landings and three single-leg squats	Impact phase	Single-leg landing	Motion analysis system	Hip flexion, knee flexion, ankle flexion, hip flexion maximum, knee flexion maximum, ankle flexion maximum	Maximum knee flexion and dorsiflexion in crease with fatigue
2	Carcia et al. 2005 [68]	Recreationally active college-age students	20 (10/10) 24±2.8	Isometric, bilateral hip-abductor-fatigue protocol	Initial contact	Double drop jump	Electro goniometers	Maximum frontal-plane tibiofemoral angle, frontal-plane tibiofemoral angle	After the fatigue protocol, participants landed in a greater valgus orientation than in the pre-fatigued state
3	Coventry et al. 2006 [5]	Active college subject	10 (10/0) 23.8±2.4	Sequence of a single-leg landing from an overhead trapeze bar set to afford a drop equal to 80% of the subject's two-leg jump height	Initial contact to maximal knee flexion	Jamp landing with two feet and single leg	Motion monitor electro-magnetic tracking	Hip, knee and ankle, peak flexion angle and, peak extension moment	Hip and knee, flexion increased and ankle plantarflexion decreased at touchdown with fatigue
4	Mclean 2007 [35]	NCAA athletes	20 (10/10) Male: 20.7±1.3	A series of continuous drills that loosely, reflected tasks synonymous with actual game play	Initial contact peak stance-phase	Double leg drop jumps from a 50-cm platform	Motion analysis	IC, hip flexion–extension, hip adduction–abduction, hip, internal–external rotation, knee extension–flexion, knee adduction–abduction, knee internal–external rotation, ankle dorsiflexion–plantarflexion), peak stance-phase (ankle internal–external rotation, ankle supination–pronation, hip flexion, hip adduction, hip internal	Females landed with more initial, ankle plantar flexion and peak-stance ankle supination, knee abduction, and knee internal rotation compared with men. They also had larger knee adduction, abduction, and internal rotation, and smaller ankle dorsiflexion moments.
5	Pappas et al. 2009 [48]	Recreational athletes	29 (14/15) (20-40)	Jumped over 5 consecutive 5-7 cm obstacles. This was repeated 20 times for a total of 100 jumps.	Initial contact	Jumps-bilateral drop landings from a 40 cm platform.	Motion analysis	Peak values of knee valgus	Knee flexion at peak VGRF, increased in males and decrease in females in the post fatigue condition

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
6	Borotikar et al. 2007 [16]	National College Athletic	22 (0/22) 21.2±2.5	Continuous sets of 5 double leg squats between jump trials, with the jump sequence	Initial contact and peak stance phase	Single leg landing	Motion analysis	Hip and knee flexion–extension, hip internal–external rotation, and ankle plantar–dorsi flexion angles, and peak stance phase	Fatigue caused significant increases in initial contact hip extension and internal rotation, and in peak stance knee abduction and internal rotation and ankle supination angles.
7	Wikstrom et al. 2008 [3]	Healthy subjects	20 (8/12) Men: 21.86±1.4 Women: 2.26±2.1	Plantar-flexion and dorsiflexion torques decreased below 50% of their respective PT values for 3 consecutive repetitions	Initial contact	Jump-landing	Motion analysis	Dorsiflexion, Knee flexion, knee valgum	There is no significant differences in joint kinematics after isokinetic and functional fatigue.
8	Benjaminse et al. 2008 [17]	Healthy and physically active subjects	30 (15/15) (18-30)	Exhaustive running	Initial contact	Single-leg stop-jumps	Vicon motion systems	Hip internal–external rotation, maximum hip internal–external, rotation, hip adduction–abduction, maximum hip adduction–abduction, knee valgus–varus angles	Less maximal knee valgus and decreased knee flexion
9	Kernozek et al. 2008 [36]	Recreational athletes from the La Crosse campus	30 (16/14) Women: 23±0.9 Men: 23.8±0.4	Parallel squat exercise (60% of 1 repetition maximum) until failure.	Initial contact	Single-legged 50-cm drop landing	Motion analysis	Maximum hip abductor angle, minimum hip abductor angle, maximum hip flexion angle, minimum hip flexion angle, maximum, knee flexion, angle, minimum, knee flexion angle	Fatigue caused men and women to land with more hip flexion. Men exhibited greater peak knee flexion angles post fatigue and larger peak knee varus angles irrespective of fatigue
10	Smith et al. 2009 [42]	Active volunteers	26 (12/14)18-35	A MVC of the lower extremities in a squat position	Initial contact 30 degrees of knee flexion	Bilateral drop jump landings from the 50 cm raised platform	Analog module of an ariel performance analysis system	Frontal plane knee, angle, maximum knee flexion.	Increased knee extension, and ankle plantar flexion
11	Gehring et al. 2009 [41]	Physically active subject	26 (13/13) Men: 25±2.4 Women: 22.6±1.5	Closed-kinetic-chain knee flexion and extension movements with other functional fatigue protocols	Initial contact	Double leg landing	Motion capture system	Knee joint flexion/extension knee abduction/adduction-angles maximum abduction/adduction and knee joint flexion during landing	Females landed with increased knee flexion velocities and knee joint abduction angles

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
12	Brazen et al. 2010 [37]	Healthy individuals	24 (12/12) 68.5±7	Ladder agility drills	At initial contact	Single-leg drop landings from a height of 0.36 m	VirtualDub-Mod	Sagittal ankle flexion, sagittal knee, flexion, frontal knee valgus angles	Increased knee flexion and ankle plantar flexion and higher peak vertical g round reaction forces
13	Edwards et al. 2010 [4]	Skilled beach and/or indoor volleyball players	14 (14/0) (26.5±5.6)	Repetitive jumping sets, was confirmed by decrements in vertical jump	Initial contact, peak ground reaction force	Single drop landing a 33-cm high bench	Motion analysis	Ankle angle at IC, Ankle angle at peak, Knee angle at IC, knee angle at peak, tibia angle at IC, tibia angle at peak	There were significant movement to fatigue condition interactions.
14	Geiser et al. 2010 [69]	Recreationally active	20 (0/20) 20.7±1.7	Isolated hip abductor fatigue protocol in side lying against isokinetic resistance,	Initial contact	Drop-jump	Motion analysis	Frontal plane knee angle, frontal plane knee moment, frontal plane hip angle, frontal plane hip moment	After the fatigue the knee angle was more adducted and there was a greater internal knee adductor moment
15	Thomas et al. 2010 [70]	Healthy volunteers	25 (13/12) Men: 20.31±0.85 Women: 20.33±1.33	Subjects performed a series of fve alternating QH maximum voluntary concentric contractions	Initial contact	Jump forward off and land on their dominant leg	Visual 3-D software (C-motion, Inc)	Hip flex/ext, hip add/abd, hip int/ext rotation, knee ext/flex, knee add/abd, knee int/ext rotation	Fatigued subjects displayed more hip internal rotation and knee extension and external rotation and at ground contact.
16	Ortiz et al. 2010 [49]	Fifteen physically active young adult women	15 (0/15) 24.6±2.6	A 30-second wingate anaerobic protocol	Initial contact	Single leg drop jump from a 40-cm box and a 20-cm, up-down, repeated hop task	Motion analysis	Peak knee joint flexion angles, and peak knee joint valgus anglespeak knee extension, valgus, vars moments	Knee flexion reduces after fatigue
17	Thomas et al. 2011 [38]	Healthy active volunteers	16 (0/16) (18-22)	Hip rotator fatigue was induced via alternating concentric contractions and triceps surae fatigue through concentric plantar flexion contractions on an isokinetic dynamometer.	Initial contact	Single leg landing	Visual 3-D software (C-motion, Inc)	Hip flexion/extension, hip add/abduction, hip add/abduction, knee add/abduction knee internal/external rotation	Hip IR angle significant increase.

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
18	Weinhandl et al. 2011 [54]	Healthy, recreationally active university students	Men= 6 (22±2) Women:6 (22±1)	Performed repetitive drop jumps until they could no longer reach 80% of their initial drop jump height.	Initial Contact	Double-land and then jump	Motion analysis	Knee flexion, hip flexion, ankle dorsi flexion	Increased knee extension, and ankle plantar flexion at initial contact after fatigue
19	Patrek et al. 2011 [61]	Physically active Women	20 (0/20) 21.0 6±1.3	Repetitive side-lying hip abduction	Initial contact and at 60 ms after initial contact	Single-leg landings from a height of 40 cm	Motion analysis	Knee flexion, knee abduction, hip flexion, hip abduction, peak knee flexion, peak, knee abduction, peak hip flexion, peak Hip abduction	Increase in hip-abduction Angle at initial contact and a small decrease in knee-abduction (valgus) angle at 60 milliseconds after contact
20	Quammen 2012 [66]	Volunteered soccer players	15 (0/15) 19.2±0.8	Slow linear oxidative fatigue protocol [SLOFP] and functional agility short-term fatigue protocol	Initial contact	Running-stop jump	Vicon	Knee flexion, knee abduction, knee rotation, hip flexion, and hip abduction, knee flexion-extension moment, knee abduction-adduction moment	Increased adduction moment, degreased hip flexion at peak vertical ground reaction force, decreased knee flexion
21	Liederbach et al. 2014a [43]	Elite modern and ballet dancers	40 (20/20)	50 step-ups onto a 30-cm box, followed by 15 maximal-effort single-legged vertical jumps.	Initial contact	Single-legged drop landings from a 30-cm platform	Motion analysis	Peak knee abduction angle, peak knee abduction moment, knee abduction angle at IC, peak hip adduction angle, hip adduction angle at IC, peak hip adduction moment, peak hip ir angle, hip ir angle at IC, peak hip ir moment	Increased peak knee valgus moment, increased lateral and forward trunk flexion, decreased the hip external rotation, increased the peak hip internal rotation, moment increased peak knee flexion, angles decreased knee flexion moments
22	Orishimo et al. 2014 [44]	Elite modern and ballet dancers	40 (20/20)	50 step-ups onto a 30-cm box, followed by 15 maximal-effort single-legged vertical jumps.	Initial contact	Single-legged drop landings from a 30-cm platform	Motion analysis	Peak knee abduction angle, peak knee abduction m, ment, knee abduction angle at IC, peak hip adduction angle, hip adduction angle at IC, peak hip adduction moment, peak hip IR angle	In executing a 30-cm drop landing, female team sport athletes displayed a greater knee valgus than did the other 3 groups. Dancers exhibited better trunk stability than did athletes.
23	Herrington et al. 2014 [71]	Asymptomatic subjects	15 (0/15) 20.4±1.4	Hip abductor maximal isometric contraction	Initial contact	Unilateral step landing	Motion capture system	Knee valgus angle, maximum knee valgus angle	Females showed a significant, increase in maximum knee valgus angle following the fatiguing

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
24	Thomas et al. 2015 [47]	Healthy subjects	16 (0/16) 23.38±4.11	Eight sets of double-leg squats followed by 3 dynamic landings	Initial contact	Single leg landing	Motion capture system (Vicon)	Sagittal and frontal plane knee angles peak knee flexion Joint moments	Results demonstrated smaller knee flexion, abduction angles and Knee abduction moment post-fatigue
25	Dickin et al. 2015 [11]	Healthy active females	11 (0/11) 22.58±3.09	Maximal isometric contractions on a Cybex dynamometer	Initial contact	Drop jump landed with both feet from the box	Vicon motion-analysis system	Angles of the ankle in the sagittal plane, as well as of the knee and hip in the frontal and sagittal planes	Increased at maximum hip and knee flexion angles and vertical ground reaction forces and joint moments, ground reaction forces and maximum knee valgus
26	Tamura et al. 2016 [29]	Healthy volunteers	34 (0/34) Fatigue (17) Control (17) Female: 20.7±1.8	Bike ergometer pedaling at 100 W per minute for 5 minutes or until they exceeded 17 (very hard) on the Borg scale	Initial ground contact to takeoff during the frrst landing.	Single-leg drop landing with dominant leg	Motion analysis system	Peak hip flexion, knee flexion, and ankle dorsiflexion angles	Increased peak hip and knee flexion angular velocities and hip flexion angular velocity
27	Haddas et al. 2016 [65]	Healthy and recurrent low back pain (LBP)	Thirty-three healty: 20.9±2.3 32 rLBP 21.2±2.7	Dynamic free squatting repetitions with 15% of body weight until task failure,	Initial ground contact to maximum Knee flexion	Drop vertical jump then landed simultaneously with each foot on a separate force platform	A motion capture system	Knee and ankle (flexion or dorsiflexion, abduction, external rotation)	Fatigue resulted in increased ankle inversion, knee abduction, maximum ankle dorsiflexion, maximum ankle inversion and maximum ankle rotation
28	Xia et al. 2017 [55]	Trained volunteers	15 (15-0) Men: 20.9±0.8	1. Run on the treadmill at 4 m/s until they reached a state of volitional fatigue 2. Shuttle running and vertical jumps within a height above 70% of their maximal vertical jump height	Initial contact	Bipedal drop land	Vicon motion capture system	Vertical GRF, initial contact anglem minimal joint angle, The occurrence time of θ min, maximal joint angular velocity	Results showed a more flexed landing posture due to an increase in hip and knee flexion angles in the post-fatigue condition.
29	Prieske et al. 2017 [45]	Volleyball players	20 (10/10) 18±2	Repeated vertical jump protocol	Onset of ground reaction forces (GRF) to peak knee flexion angle	Drop and countermovement jumps on stable and unstable surfaces	Motion analysis	Onset knee flexion, Peak knee flexion, Push up knee flexion, onset valgus angles, peak valgus flexion	Knee flexion angles were significantly lower, also result showed decrements in drop jump peak knee flexion angles under unstable conditions and in men only.

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
30	Lazaridis et al. 2017 [62]	Healthy male and prepubescent boys	26 (26/0) Male: 22–28 Boy: 10±0.7	Ten bouts of 10 consecutive countermovement jumps (CMJs) with 30-s rest interval between the bouts	Fifty ms before touch-down and touch-down	Double leg drop jumps from a 30-cm platform	Motion analysis	Peak isometric torque of knee extensors, Knee joint angle 50 ms before touch-down, knee joint angle at touch-down, knee joint angle at deepest point	Maximum knee flexion increased in a greater extend in adults than in boys
31	Wong et al. 2020 [50]	Collage athletes	12 (0./12) 21.33±1.49	Fifty step-ups onto a 30-cm box, followed by 15 maximal effort single-legged vertical jumps until the Borg CR-10 scale level 17	Initial ground contact	Forward drop jump to a vertical jump	3D motion-analysis	At initial ground contact, knee flexion angles, hip, flexion angles, trunk forward lean angle, during landing phase	Knee flexion at significantly increased under post-fatigue condition
32	Yu et al. 2020 [46]	Healthy subject	15 (15/0) 23.93±0.08	Ran on the treadmill at a speed of 6 km/h Every two minutes, the speed was increased by 1 km/h until 90% of heart rate	Push up landing	Vertical-jump landing	Vicon motion Force Platform	Peak joint angles and ROM, in the sagittal and frontal horizontal plane joint moments	Landing phase: increased peak inversion angle and peak external rotation angle of the ankle joint, peak abduction angle of the knee and hip joint /decreased knee peak flexion moment and hip peak extension moment
33	Higo et al. 2021 [56]	Healthy	12 (12/0) (23.3±2.9)	Lower-limb muscle fatigue: isokinetic contractions with an angular velocity of 180°/s over a range of motion of 90° to 0° at the knee joint for 10 min on landing leg	Three seconds after landing	One-legged landing	Three-dimensional (3D) motion	Hip and knee/ankle joint angles, knee valgus angles maximum joint moments of hip and knee extension and ankle plantarflexion	Decreased the maximum trunk flexion angle
34	Zhang et al. 2021 [39]	College athletes	18 (9/9) (21.3±1)	Drill cycle	At initial contact	one drop landing from a platform 40 cm high	Motion Analysis	Ankle plantarflexion angle, knee flexion angle, knee add/abduction angle, hip flexion angle, peak ankle dorsiflexion angle, peak knee flexion angle, peak knee abduction angle, peak hip flexion angle, peak hip abduction angle	Fatigue reduced ankle inversion

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
35	Wang et al. 2021 [57]	Collegiate basketball athletes	15 (15/0) (22.1±1.7)	Shuttle runs combined with multiple vertical jumps	Initial contact	Initiated by dropping with both legs from a 60 cm platform and then landing with each leg on the separated force plates	Motion analysis	Initial contact angle and minimum angle (of the hip, knee and ankle joints	Significant increase in the initial contact and minimum angles of the ankle were observed in HS compared with CS.
36	Harato et al. 2021 [63]	Basketball player	25 (0/25) 15 collegiate athletes (20±1.5) 10 recreational athletes (20.9±1.2)	Double-legged squats, with arms parallel to the ground, to a depth of 90° knee flexion	Initial contact and at toe-of from the jump (TO)	Double-legged drop landing and executed a vertical jump after landing	Motion analysis system	Knee flexion angle peak knee flexion angle t knee abduction angle peak knee abduction angle, the knee internal rotation angle, peak knee internal rotation angle	Female collegiate athletes: increased peak knee flexion; female recreational athlete: increased peak knee flexion angle and knee abduction angle and peak knee abduction moments
37	Harato et al. 2021 [72]	Healthy athletes	Eleven healthy athletic adults	Double-legged squats, with arms parallel to the ground, to a depth of 90° knee flexion	Initial contact and at toe-of from the jump (TO)	Double-legged drop landing and executed a vertical jump after landing, and Golf swing motion	Motion analysis system	Knee flexion angle, peak knee flexion angle t knee abduction angle peak knee abduction angle, the knee internal rotation angle, peak knee internal rotation angle	As fatigue of trunk muscles will alter swing movement and kinematic chain, trunk muscle training can be one of key strategies to maintain swing performance.
38	Alanazi et al. 2021 [18]	Soccer players (ACLR and healthy, non-injured)	Thirty-six underwent ACLR (8-10) 26.11±3.95 control group (sex matched) 25.83±3.51	30-s Wingate anaerobic protocol	Initial contact and the moment of maximum knee flexion	Forward jump to head a soccer ball and land on the force platforms	Vicon motion systems	Peak ankle dorsiflexion angle, peak plantar flexion moment, peak knee flexion angle, peak knee extension moment, peak hip flexion angle, and peak hip extension moment	Fatigue increased flexion of hip, knee and ankle joints and increased extension moments of hip, knee and ankle joints
39	Kim et al. 2021 [67]	Healthy and physically active	10 (10/10) 26.6±1.35	Hip abduction	Initial contact	Single-leg landing	Motion analysis	Peak Knee flexion, peak knee abduction, peak knee internal rotation, peak hip flexion, peak hip abduction, peak hip internal rotation, peak knee extension moment, peak knee external rotation moment, peak hip extension moment,	Knee internal rotation, and hip adduction moments were significantly increased after the fatigue protocol Knee abduction moment was significantly decreased after the fatigue protocol

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
40	Lin et al. 2022 [6]	Collegiate basketball players	12 (12/0) 22.8±2.7	Raised up to the trunk extension position at a rate of 25 repetitions per minute until they could not continue	Takeoff and landing	Jumped to make a jump shot, finally landing on the force plates	Vicon 3D motion analysis system	Flexion and extension of knee and hip dorsiflexion and plantar of ankle	Ankle plantar flexion increased, and their knee flexion angles were reduced when landing.
41	Kamitani et al. 2023 [58]	Healthy elite soccer field players	20 (0/20) 23.15±3.03	Pedaling on an ergometer from a 35-cm platform	Initial contact	Drop vertical jumps	Images from the videos were captured	Max hip flexion, max knee flexion, max ankle dorsiflexion	Fatigue decreases hip flexion angle and ankle dorsiflexion angle
42	Zhang et el. 2023 [60]	Collegiate volleyball players	18 (18/0) 19.9±1.6	Three stations, which were volleyball specific agility test, lunge digging, and continuous blocking jumping	Initial contact	Single-leg landing	Motion analysis	Ankle inversion angle	Fatigue or not, soft and semi-rigid brace reduced the ankle inversion
43	Nardon et al. 2024 [73]	Healthy males	Twenty-four healthy males	A single bout of cycling at a constant workload, maintaining a cadence of 65–70 rpm	Initial contact	Single leg drop jumps	Software qualisys track manager	Knee moments, Hip joint moments, ankle moments, ankle, hip and knee joint angles	The increased hip and knee extension, as well as the increased knee abduction we observed after the execution of the fatiguing exercise
44	Asaeda et al. 2024 [52]	Healthy adult males	Twenty-two male participants	Isokinetic hip abduction/adduction (hip fatigue task [HFT]) and knee extension/flexion (knee fatigue task [KFT]).	Initial contact	Single-leg drop landings	Motion analysis device and two force plates	Hip abduction/adduction, knee extension/flexion	This study revealed distinct kinematic and kinetic changes specific to each fatigue task, particularly in the frontal plane for hip joint tasks and the sagittal plane for knee joint tasks
45	Asaeda et al. 2024 [53]	Healthy males	Sixteen healthy males	The isokinetic movement was adopted as the fatigue task. The participant performed the isokinetic knee extension/flexion movement (KFT)	Initial contact	Single-leg landing	Electromyography and three-dimensional motion analysis systems	HFT and KFT	The analysis revealed that the occurrence of DKV varies depending on the peripheral fatigue task, and the effects on average DKV during landing and DKV at peak vGRF vary depending on the peripheral fatigue task.

No.	Author(s), Year	Sample Description	Sample Size (Men/Women) Age (y) Mean±SD	Fatigue Protocol	Phase	Task	Instrumentation	Variables	Outcomes
46	Li et al. 2024 [59]	Volleyball players	Ten young male volleyball players	Maximum touch height experiment, and the highest of the three jumps represented the jumping ability	Initial contact	Single leg landing	Motion analysis device and two force plates, and OpenSim	Hip, knee, and ankle joints	The ankle dorsiflexion angle at initial contact was significantly decreased in the post-fatigue group compared to the non-fatigue one.
47	Asadpour et al. 2024 [51]	Basketball players	Twenty-seven basketball players with dynamic knee valgus	the fatigue protocol consisted of 40 minutes of basketball play, carried out legally and considering all rest periods	Initial contact	Counter-movement jumps	Kinovea	Hip, knee, and ankle joints	The results showed that the application of the fatigue protocol during landing in the sagittal plane led to a significant decrease in the maximum knee flexion angle in the guard group, initial ankle contact in the forward group, initial ankle contact in the center group, and maximum ankle plantar flexion in the center group.
48	Tian et al. 2024 [64]	Dancers	Thirty dancers (mean age: 23.4 years)	The fatigue protocol consisted of plyometric exercises and repetitive dance-specific movements	Landing initial contact	Landing	Motion analysis device and two force plates,	Joint angles at the hip, knee, and ankle were measured during the landing's initial contact, peak force, and stabilization phases	Post-fatigue, hip and knee flexion increased significantly at initial contact reflecting compensatory adjustments for impact absorption.
49	Medeiros et el. 2024 [40]	Runners	Eighteen females: 18 (25.7±3.63) females: 25.7±3.63	Three isometric exercises and three dynamic exercises performed consecutively	Initial contact	Single-leg drop-landing	Electromyographic	Ankle, knee, and hip joints in the sagittal plane and the knee and hip in the frontal plane, angular displacement, vGRF	There was an increase in the tibialis, anterior and soleus mean iEMG in F1, a reduction in TA and GM maximum iEMG in F2, and an increase in the BF minimal iEMG in F2.

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Abbreviation: MVC: Maximum voluntary isometriccontraction; HFT: Hip-joint fatigue task; KFT: Knee-joint fatigue task; TA: Tibialis anterior; GM: Gastrocnemius medialis; BF: Biceps femoris.w

Fatigue effects on kinematics of ankle inversion

Five eligible studies [35, 38, 46, 60, 65] have investigated the impact of fatigue on the kinematics of ankle inversion. A total of 102 participants took part in these studies. The forest plot analysis revealed that the studies showed varied but generally minor changes in ankle inversion, with a statistically significant effect across the pooled data (95% CI, 0.114%, 0.537%; P=0.003). The heterogeneity analysis indicated no significant heterogeneity among the studies (P=0.516, I^2=0.000). To evaluate publication bias, we conducted Egger's regression test, which yielded a non-significant intercept (P=0.65654).

Fatigue effects on kinematics of ankle supination

Four studies [16, 35, 46, 65] involving a total of 93 participants were analyzed to examine the effects of fatigue on the kinematics of ankle supination. The combined effect size indicated a modest and statistically non-significant shift in ankle supination/pronation following fatigue (P=0.326; 95% CI, -0.23%, 0.692%). Heterogeneity analysis confirmed considerable variation among the studies (P=0.002, I^2=76.011), likely attributable to differences in study methodologies, fatigue interventions, or participant demographics. We performed Egger's regression test to assess publication bias, which showed a non-significant intercept (P=0.84139).

Fatigue effects on kinematics of knee flexion

Forty-five studies [3-6, 11, 12, 16-18, 29, 35-39, 41-51, 53-59, 61-65, 68-70, 72, 73], including a total of 906 participants, were considered in the meta-analysis to examine how fatigue affects the kinematics of knee flexion. The forest plot analysis demonstrated a range of outcomes across the studies, with no significant overall effect found in the combined data (P=0.885, 95% CI, -0.135%, 0.156%). Analysis of heterogeneity revealed considerable differences among the studies (P=0.000, I^2=72.707). We performed subgroup analyses by sex, but the factor did not significantly influence the effect sizes. To check for publication bias, we conducted Egger's regression test, and it indicated a non-significant intercept (P=0.38787).

Fatigue effects on kinematics of knee adduction

Twenty-nine studies [3, 16, 17, 35, 36, 38-43, 45-49, 53, 54, 62, 64, 66, 68-75], with a total of 672 participants, were incorporated into the meta-analysis to explore the impact of fatigue on the kinematics of knee adduction. Data analysis using CMA and forest plot analysis demonstrated a minor and statistically non-significant difference in knee adduction/abduction following fatigue (P=0.402, 95% CI, -0.060%, 0.149%). Also, heterogeneity evaluation revealed moderate inconsistency among the studies (P=0.069, I^2=28.877). Subgroup analyses based on sex revealed no significant changes in the effect sizes. Moreover, Egger's regression test yielded a non-significant intercept (P=0.60201).

Fatigue effects on kinematics of knee internal rotation

Nine studies [16, 35, 38, 46, 53, 65, 66, 67, 70] examined the possible effects of fatigue on the kinematics of knee rotation. The total number of participants in these studies was 231. The overall pooled estimate was P=0.263 with 95% CI, -0.091%, 0.334%. Also, after examining the heterogeneity, the results showed that the heterogeneity was significant (P=0.087, I^2=42.023). To examine publication bias, we conducted Egger's regression test. It showed a non-significant intercept (P=0.93192). In addition, subgroup analysis based on sex was insignificant.

Fatigue effects on kinematics of hip flexion

Twenty-six studies [5, 6, 11, 16, 18, 29, 35, 36, 38-40, 46, 7, 50, 51, 54-59, 61, 64, 66, 67, 70], involving a total of 501 participants, were included in the meta-analysis to investigate the impact of fatigue on hip flexion. The forest plot analysis showed a range of outcomes across the studies, with no significant overall effect observed in the combined data (P=0.947, 95% CI, -0.206%, 0.192%). Heterogeneity assessment indicated significant variability among the studies (P=0.000, I^2=73.481). Likewise, the subgroup analysis revealed that sex has a minimal influence on the effect sizes. We evaluated a funnel plot to examine publication bias and conducted Egger's regression test. The funnel plot displayed a symmetrical distribution of studies around the pooled effect size, and Egger's test yielded a non-significant intercept (P=0.44254).

Fatigue effects on kinematics of hip abduction

Seventeen studies [11, 17, 35, 36, 38, 39, 43, 44, 46, 52, 53, 61, 66, 67, 69, 70], with a total of 382 participants, were included in the meta-analysis to explore the effect of fatigue on hip abduction. The overall pooled effect size indicated a non-significant change in hip adduction/abduction following fatigue (P=0.516; 95% CI, -0.099 %, 0.197%) . Heterogeneity assessment showed significant differences among the studies (P=0.034, I^2=39.998). With the moderate number of studies, we performed subgroup analyses by sex, but there was no significant influence on the effect sizes. Also, Egger's test yielded a non-significant intercept (P=0.24714).

Table 2. Critical appraisal results of eligible systematic reviews

	Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Overall Score
1	Madigan et al. 2003 [50]	Y	N	Y	Y	Y	Y	Y	N	Y	7
2	Carcia et al. 2005 [68]	Y	Y	Y	N	Y	N	Y	N	Y	6
3	Coventry et al. 2006 [5]	Y	N	Y	Y	Y	Y	Y	N	Y	7
4	Mclean et al. 2007 [2007]	Y	N	N	Y	Y	Y	Y	N	Y	6
5	Pappas et al. 2007 [48]	Y	N	Y	N	Y	N	Y	N	Y	5
6	Borotikar et al. 2008 [16]	Y	N	Y	Y	Y	Y	Y	N	Y	7
7	Wikstrom et al. 2008 [74]	Y	N	N	Y	Y	Y	Y	N	Y	6
8	Benjaminse et al. 2008 [17]	Y	N	Y	N	Y	N	Y	N	Y	5
9	Kernozek et al. 2008 [36]	Y	N	Y	N	Y	N	Y	N	Y	5
10	Smith et al. 2009 [42]	Y	N	Y	N	Y	N	Y	N	Y	5
11	Gehring et al. 2009 [41]	Y	N	Y	N	Y	N	Y	N	Y	5
12	Brazen et al. 2010 [37]	Y	N	Y	N	Y	N	Y	N	Y	5
13	Edwards et al. 2010 [4]	Y	N	Y	Y	Y	Y	Y	N	Y	7
14	Geiser et al. 2010 [69]	Y	Y	Y	N	Y	N	Y	N	Y	6
15	Thomas et al. 2010 [70]	Y	N	N	Y	Y	Y	Y	N	Y	6
16	Ortiz et al. 2010 [49]	Y	Y	Y	N	Y	N	Y	N	Y	6
17	Thomas et al. 2011 [38]	Y	N	Y	Y	Y	Y	Y	N	Y	7
18	Weinhandl et al. 2011 [54]	Y	Y	Y	N	Y	N	Y	N	Y	6
19	Thomas et al. 2015 [47]	Y	Y	Y	Y	Y	Y	Y	N	Y	8
20	Patrek et al. 2011 [61]	Y	Y	Y	N	Y	N	Y	N	Y	6
21	Quammen et al. 2012 [66]	Y	N	Y	Y	Y	Y	Y	N	Y	7
22	Liederbach et al. 2014 [43]	Y	N	Y	N	Y	N	Y	N	Y	5
23	Orishimo et al. 2014 [44]	Y	N	Y	N	Y	N	Y	N	Y	5
24	Herrington et al. 2014 [71]	Y	Y	Y	N	Y	N	Y	N	Y	6
25	Dickin et al. 2015 [11]	Y	N	Y	Y	Y	Y	Y	N	Y	7
26	Tamura et al. 2017 [29]	Y	N	Y	Y	Y	Y	Y	N	Y	7
27	Haddas et al. 2016 [65]	Y	Y	Y	Y	Y	Y	Y	N	Y	8
28	Xia et al. 2017 [55]	Y	N	Y	Y	Y	Y	Y	N	Y	7
29	Prieske et al. 2017 [45]	Y	Y	N	N	Y	N	Y	N	Y	5
30	Lazaridis et al. 2017 [62]	Y	N	N	Y	Y	Y	Y	N	Y	6
31	Wong et al. 2020 [7]	Y	N	Y	Y	Y	Y	Y	N	Y	7
32	Yu et al. 2020 [46]	Y	N	Y	Y	Y	Y	Y	N	Y	7

	Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Overall Score
33	Higo et al. 2021 [56]	Y	Y	Y	Y	Y	Y	Y	N	Y	8
34	Zhang et al. 2021 [39]	Y	N	Y	N	Y	N	Y	N	Y	5
35	Wang et al. 2021 [57]	Y	N	Y	Y	Y	Y	Y	N	Y	7
36	Harato et al. 2021 [63]	Y	N	Y	Y	Y	Y	Y	N	Y	7
37	Hakukawa et al. 2021 [72]	Y	N	Y	Y	Y	Y	Y	N	Y	7
38	Kim et al. 2021 [67]	Y	Y	Y	N	Y	N	Y	N	Y	6
39	Alanazi et al. 2021 [18]	Y	Y	Y	Y	Y	Y	Y	N	Y	8
40	Lin et al. 2022 [6]	Y	N	Y	Y	Y	Y	Y	N	Y	7
41	Kamitani et al. 2023 [58]	Y	N	Y	Y	Y	Y	Y	N	Y	7
42	Zhang et al. 2023 [60]	Y	N	Y	Y	Y	Y	Y	N	Y	7
43	Nardon et al. 2024 [73]	Y	Y	Y	Y	Y	Y	Y	N	Y	8
44	Asaeda et al. 2024 [52]	Y	N	Y	Y	Y	Y	Y	N	Y	7
45	Asaeda et al. 2024 [53]	Y	N	Y	Y	Y	Y	Y	N	Y	7
46	Li et al. 2024 [59]	Y	N	Y	Y	Y	Y	Y	N	Y	7
47	Asadpour et al. 2024 [19]	Y	N	Y	Y	Y	Y	Y	N	Y	7
48	Tian et al. 2024 [64]	Y	N	Y	Y	Y	Y	Y	N	Y	7
49	Medeiros et al. 2024 [40]	Y	N	Y	Y	Y	Y	Y	N	Y	7

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Fatigue effects on kinematics of hip rotation

Twelve studies [16, 17, 35, 38, 43, 44, 46, 52, 53, 67, 70, 73], comprising a total of 293 participants, were included in the meta-analysis to evaluate the influence of fatigue on hip rotation. The overall pooled effect size demonstrated a non-significant alteration in hip rotation following fatigue (P=0.760; 95% CI, -0.391%, 0.286%). Heterogeneity testing revealed significant variability among the studies (P=0.000, I^2=83.642). To assess publication bias, we conducted Egger's regression test, and it demonstrated a non-significant intercept (P=0.04839).

Discussion

The findings of this study suggest that fatigue does not substantially affect knee, hip, or ankle joint angles across the sagittal, frontal, or horizontal planes. However, a notable exception was observed in ankle inversion, where a significant effect of fatigue was detected, highlighting a potential area of concern for performance changes. These results contribute to understanding the impact of fatigue on joint kinematics during landing, providing valuable insights for strength and conditioning professionals and informing injury prevention strategies. While this study focused on kinematic variables, it is vital to recognize that changes in kinetics and muscle activity (electromyography) may be more sensitive indicators of fatigue-induced alterations. The limited impact of fatigue observed in joint angles suggests that gross kinematic changes alone may not fully show the biomechanical consequences of fatigue.

Multiple factors might have obscured significant biomechanical predisposing factors for lower extremity injuries during fatigued sessions. Enhanced muscular control, particularly eccentric control of the joint [75], and compensatory neuromuscular strategies [76] are potential mechanisms that can prevent dynamic instability in the lower limbs. A review examining fatigue-induced biomechanical changes in single-limb landings showed that vertical ground reaction forces and hip and knee joint moments were reduced after fatigue [77]. Another study by Jayalath et al. demonstrated that fatigue affects ankle biomechanics by reducing dorsiflexion from initial contact to maximum knee flexion at landing [78]. Importantly, the lack of statistically significant findings should not be misinterpreted as an absence of biomechanical or clinical relevance. Instead, the substantial variability observed across studies likely reflects subject-specific adaptation strategies in response to fatigue. Fatigue does not impact all individuals uniformly; rather, it can provoke a range of neuromuscular responses depending on each individual's conditioning level, motor control strategies, previous injury history, and even psychological factors such as risk perception or movement confidence [79]. A review by Liu et al. demonstrates a significant change in hip external rotation and knee flexion angle after fatigue [31]. Although the study by Liu reported significant changes in knee flexion and hip external rotation angles following fatigue, their conclusions were based on a relatively limited dataset comprising only 14 included studies. Specifically, their analysis of knee flexion relied on just 10 studies, while only 3 studies contributed data on hip external rotation. In contrast, our meta-analysis incorporated a substantially larger evidence base, including 49 studies in total, with 45 studies analyzing knee flexion and 12 studies examining hip external rotation. This broader inclusion not only strengthens the statistical power and generalizability of our findings but also suggests that the significance levels observed in smaller datasets may shift when analyzed with more comprehensive data.

Additionally, the human body possesses adaptive mechanisms that can act to preserve movement patterns despite the presence of fatigue. These compensatory responses can involve neuromuscular adjustments, such as modified muscle activation patterns or increased co-contraction, which help maintain joint stability and mitigate unfavorable kinematic deviations [80]. Also, the lack of consistent directional change across studies in the meta-analysis may reflect these individualized strategies for mitigating fatigue-induced impairments, rather than a true absence of effect. Moreover, in athletic contexts, this rigid control pattern may act as a short-term protective mechanism but may also predispose individuals to overuse or load-related injuries if sustained over time [81]. These stiffening responses illustrate how motor control adjustments under fatigue can mask changes in observable kinematics [82] while substantially altering the underlying kinetic profile of movement.

Additionally, central nervous system mechanisms also play a role in compensating for fatigue. The brain may adapt motor commands to preserve task performance by reorganizing motor unit recruitment, altering movement strategies, or prioritizing stability over efficiency [83]. These central adaptations may limit the extent of observable kinematic changes, effectively masking fatigue-induced perturbations at the joint level. Thus, the absence of significant group-level kinematic alterations should not be interpreted as evidence of no fatigue effect. Instead, it may reflect a complex interplay of individualized neuromechanical strategies and central compensatory processes that act to maintain motor performance under fatigue.

A notable alteration was detected in the ankle inversion. This outcome aligns with earlier studies that associate fatigue with disruptions in neuromuscular coordination and diminished joint stability, especially in the ankle region. In addition, increased ankle inversion following fatigue is clinically significant, as it directly elevates the risk of lateral ankle sprains [84]. Also, the peroneus longus plays a vital role in resisting excessive inversion during landing; when fatigued, its delayed activation and reduced force output compromise this protective mechanism. A study by Gutierrez et al. demonstrates that fatigue can decrease the median frequency and strength of the peroneus longus, a key muscle responsible for resisting ankle inversion during dynamic tasks, such as landing [85]. In a similar vein, Delahunt et al. demonstrated that fatigue impairs sensorimotor performance, resulting in delayed neuromuscular activation and a heightened tendency toward inversion deviations, thereby increasing the risk of instability and injury [86]. Moreover, fatigue-induced alterations in ankle inversion may impact knee and hip kinematics and kinetics by upstreaming the kinetic chain. Specifically, increased ankle inversion may restrict normal subtalar pronation, reducing the foot's ability to absorb impact forces efficiently [87]. This limited motion leads to reduced tibial internal rotation during the early stance phase, which may disrupt the natural coupling between the ankle and knee joints [88]. This is because altered ankle mechanics can change joint loading patterns and force transmission, which may put more strain on proximal joints, such as the knee and hip, and increase the risk of injury [89, 90]. Furthermore, the ankle joint, especially in the frontal plane, is particularly vulnerable to instability under fatigue conditions, largely due to its relatively smaller supporting muscles and strong dependence on reflex-based stabilization. McKeon and Hertel highlighted that fatigue can impair the finely tuned neuromuscular coordination required to maintain ankle stability during dynamic tasks, thereby increasing the likelihood of excessive inversion and potential injury [91]. In contrast to ours, Liu et al. showed no significant changes across the ankle joint after fatigue [31]. The key distinction between our study and that of Liu et al. lies in the scope of ankle joint analysis. While their meta-analysis focused solely on peak ankle dorsiflexion, it did not examine other critical kinematic parameters, such as ankle inversion. Moreover, their conclusions regarding ankle biomechanics were derived from only 3 studies, significantly limiting the generalizability of their findings. In contrast, our review incorporates 36 studies that collectively provide a far more comprehensive assessment of ankle kinematics, including inversion and other angular displacements across multiple planes of motion.

One possible explanation for the absence of significant effects on knee internal rotation and adduction is the measurement challenges. The limitations of existing motion capture methods make it particularly challenging to accurately measure knee internal rotation. Internal rotation is typically difficult for inertial measurement unit sensors to detect, and even marker-based motion capture systems like Vicon have problems because of skin artifacts, which occur when the skin moves in relation to the underlying bone [92]. Additionally, there is a lack of standardization in measurement protocols, including variations in marker placement, skeletal models, and methods for calculating joint angles (e.g. direct versus inverse kinematics models), which further complicates comparisons across studies. The small magnitude of knee internal rotation angles, coupled with relatively large errors from skin movement, may obscure true kinematic differences caused by fatigue [93]. Similar methodological errors cause some variability in knee adduction measurements, even though they are less impacted by these problems [94]. In contrast, knee flexion angles, which involve a larger range of motion, are less sensitive to marker placement errors and provide more consistent results across different laboratories [95].

Furthermore, because knee moments are less dependent on small angular changes and instead represent the pressures acting on the joint, they may offer deeper insights into fatigue-induced changes in joint loading. However, as with kinematic measurements, the comparability of results may be limited by the lack of consistency in knee moment calculations among laboratories [96]. Also, due to differences in muscle activation patterns, arthrokinematic motions (such as anterior-posterior translation), and other biomechanical considerations, the same osteokinematic motion can produce substantially different loading conditions within the knee [97]. Future research should include kinetic and electromyographic data to better understand how fatigue affects lower extremity biomechanics, as these differences might not be adequately captured by kinematic analysis alone.

Substantial heterogeneity was evident across all variables, attributed to the vast array of fatigue protocols employed in the studies, which encompassed plyometric exercises, local muscle exercises with isokinetic dynamometers, stair climbing, jumping, and treadmill activities. The diversity in exercise types and variations in intensity and duration likely contributed to the observed heterogeneity among the studies. Moreover, individual differences in fitness level, training background, and neuromuscular control strategies may contribute to the variability in responses. This finding underscores the importance of establishing standardized protocols and providing more precise descriptions of exercise characteristics in future research to enhance comparability and facilitate a more comprehensive understanding of fatigue effects. In addition, the lack of publication bias in all variables except for ankle dorsi moment indicates the plausibility of the results. The conclusions should be interpreted as context-dependent rather than universal. However, further studies are needed on this variable to confirm these findings.

Several limitations related to this review should be noted. Firstly, the study was restricted to English-language articles, potentially overlooking valuable insights from non-English publications. Secondly, the focus was solely on studies involving healthy individuals, excluding research on injured populations. Thirdly, most of the variables demonstrated substantial heterogeneity, which may have influenced the overall findings. Methodological differences in kinematic measurements, particularly for knee internal rotation and adduction, where changes in motion capture equipment, marker positioning, and computational models can introduce significant variability, may exacerbate this heterogeneity. Besides, since identical osteokinematic motions may obscure differences in muscle activation or arthrokinematic movements that influence injury risk, relying solely on kinematic data restricts the ability to capture changes in joint loading. Lastly, the study only considered research investigating the acute effect of fatigue, neglecting potential long-term effects. It is also important to recognize that most studies included in this meta-analysis examined specific, often isolated, time points during landing tasks, typically pre- and post-fatigue conditions defined by operational thresholds. This methodological constraint limits the generalizability of findings across the full temporal profile of fatigue development. These limitations necessitate careful consideration when interpreting the results and inform future research directions.

Conclusion

Contrary to common belief, fatigue does not appear to consistently alter hip and knee landing kinematics in healthy, active individuals, though it does increase ankle inversion, potentially elevating the risk of ankle sprains. Various compensatory mechanisms are employed to mitigate the effects of fatigue across different populations. Future studies are needed to examine individual differences in the kinematics of landing following a fatigue protocol.

Ethical Considerations

Compliance with ethical guidelines

There were no ethical considerations to be considered in this research.

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Authors' contributions

Study design and data collection: Mohammad Salsali, Parisa Sayyadi, Elnaz Rajabi, Rahman Sheikhhoseini, and Ebrahim Ebrahimi; Writing: Mohammad Salsali, Parisa Sayyadi, Rahman Sheikhhoseini, Ebrahim Ebrahimi, and Trent M. Guess; Final approval: All authors.

Conflict of interest

The authors declared no conflict of interest.

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