Title: The Impact of Fatigue on Lower-Limb Biomechanics in Individuals with Dynamic Knee Valgus: A Systematic Review and Meta-Analysis

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Abstract

Objective: This structured review seeks to examine the effects of fatigue on lower-limb biomechanics in individuals exhibiting Dynamic Knee Valgus (DKV).

Methods: We conducted a comprehensive review using Scopus, Web of Science, and PubMed, spanning from the launch of these databases until January 5, 2025. To measure the effect of fatigue, we employed Hedges' g as the effect size, calculating 95% confidence intervals (CIs) through either random-effects or fixed-effects models. A random-effects model was used when I^2 values exceeded 50%. Both reviewers evaluated the risk of bias by applying the Newcastle-Ottawa Scale (NOS) for quality assessment.

Results: Following the screening phase, six studies involving an aggregate of 171 subjects were incorporated into the review. Findings from the meta-analysis revealed that the fatigue intervention resulted in an amplified knee valgus angle in the dominant limb (effect size; -0.78, 95% CI= -1.56_-0.01, P = 0.001), alongside a notable increase in the knee valgus angle of the non-dominant limb (effect size; -0.56, 95% CI= -0.78_-0.21, P = 0.001).

Conclusion: The results indicated that fatigue-inducing protocols substantially heightened the DKV angle in both the dominant and non-dominant lower limbs of the subjects. The increase in knee valgus angles due to fatigue highlights a critical area for intervention and monitoring. By addressing these changes, professionals can enhance injury prevention strategies, optimize athletic performance, and improve rehabilitation outcomes for individuals with DKV. Nonetheless, the results of this study must be viewed with caution because of the diversity in fatigue protocols, differences in biomechanical assessment methods, and the challenges posed by small sample sizes.

Keywords: Knee Valgus; Biomechanics; Fatigue; Kinetics; Kinematics.

Highlights:

- Fatigue increases DKV angle in both dominant and non-dominant legs.
- First meta-analysis on fatigue's effect on lower-limb biomechanics in DKV.
- High methodological quality support's reliability of the findings.

Plain Language Summary:

This systematic review examines how fatigue affects knee movement in individuals with Dynamic Knee Valgus (DKV), a condition marked by the inward angling of the knees. Researchers analyzed six studies involving a total of 171 participants, sourcing data from four major databases up to January 5, 2025. The findings revealed that fatigue significantly increased the inward angle of the knees in both the non-dominant and dominant legs. This suggests that fatigue may exacerbate DKV, potentially increasing the risk of injury. Overall, the review emphasizes the importance of considering fatigue when evaluating knee biomechanics in individuals with DKV, highlighting the necessity for targeted interventions to mitigate injury risk.

Introduction

Dynamic Knee Valgus (DKV) is a distinct lower limb motion pattern defined by several factors, including femoral adduction and inward rotation, knee abduction, and forward movement of the tibia, outward rotation of the tibia, along with ankle eversion [1]. This movement pattern is distinguished by medial shift of the knee that extends beyond the alignment of the foot and thigh, indicating valgus knee posture [2]. Therefore, evaluating the factors affecting DKV can increase our knowledge in preventing sports injuries.

DKV alters lower limb kinematics, leading to abnormal knee joint angles and compensatory movements at the hip and ankle, which can further disrupt normal biomechanics [3, 4]. The altered alignment associated with DKV increases ground reaction forces (GRFs) transmitted through the lower extremities, heightening stress on the knee joint and potentially contributing to overuse injuries [5, 6]. Additionally, DKV often results in reduced knee flexion during landing tasks, diminishing the natural shock-absorbing capabilities of the knee and increasing the risk of injury during high-impact activities [7]. Research, including video analyses of athletes during competitive games and cadaveric studies, highlights the significance of knee valgus in the mechanism of ACL trauma [3, 8]. The condition also influences muscle activation patterns, leading to altered recruitment of stabilizing muscles such as the quadriceps, hamstrings, and gluteal muscles, which can create imbalances and decrease knee joint stability [9]. This increased valgus moment at the knee, coupled with the biomechanical inefficiencies caused by DKV, is closely linked to a heightened risk of anterior cruciate ligament (ACL) injuries [6], as well as other injuries like meniscal tears and patellar tendinopathy due to abnormal loading patterns.

Fatigue is a critical factor that significantly affects DKV during sports and landing tasks [10]. As fatigue accumulates, there is a notable decline in neuromuscular control and strength, which can exacerbate the inward collapse of the knee joint [11]. This deterioration in muscular function leads to altered lower limb kinematics, characterized by increased knee valgus angles [12]. Specifically, fatigued athletes may exhibit reduced ability to maintain proper alignment and stability of the knee, resulting in compensatory movements at the hip and ankle that further disrupt normal biomechanics [13].

Moreover, fatigue influences muscle activation patterns, often leading to insufficient recruitment of key stabilizing muscles such as the gluteals and quadriceps [14]. This insufficient activation can increase the valgus moment at the knee, further amplifying the risk of injury [15]. The effects of fatigue are particularly pronounced during high-impact activities, where the ability to absorb shock and maintain optimal knee flexion is compromised [16]. Consequently, the combination of fatigue and DKV not only heightens the risk of ACL injuries but also predisposes athletes to other overuse injuries [17]. Consequently, comprehending the relationship between fatigue and DKV is crucial for creating effective training and rehabilitation strategies that aim to improve performance and reduce the risk of injury in athletes.

Findings from review studies indicate that DKV considerably influences kinetic and kinematic parameters [3, 18]. Furthermore, the findings of these studies also suggest that fatigue exerts a notable effect on kinematic and kinetic factors, consequently increasing injury incidence [19, 20]. However, no review has directly examined how fatigue impacts individuals exhibiting DKV. Thus, this thorough review aims to explore the effect of fatigue on lower-limb mechanics in individuals with dynamic knee valgus.

Existing research on DKV has established that it significantly influences kinetic and kinematic parameters, indicating a clear link between DKV and altered biomechanics [3, 18]. However, while findings from review studies suggest that fatigue also exerts a notable effect on these parameters, leading to an increased incidence of injuries [19, 20], there remains a critical gap in the literature. Specifically, no review has directly examined the interplay between fatigue and DKV in individuals, leaving a crucial aspect of this relationship unexplored. This study is necessary to fill this gap by providing a comprehensive analysis of how fatigue impacts lower-limb mechanics in individuals exhibiting DKV. Understanding this interaction is vital for several reasons. First, it can elucidate the mechanisms through which fatigue exacerbates the risks associated with DKV, potentially leading to targeted interventions for injury prevention. Second, by focusing specifically on individuals with DKV, this review can inform clinical practices and rehabilitation strategies tailored to this population. Overall, this investigation is essential for advancing our knowledge of the biomechanical implications of fatigue in the context of DKV, ultimately contributing to enhanced athlete safety and performance. Thus, this systematic review aims to examine how fatigue affects lower-limb mechanics in individuals with dynamic knee valgus (DKV).

Method

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and rigor in reporting [21].

Search strategy

We conducted a systematic search throughout Scopus, Web of Science, and PubMed from the database's inception until January 5, 2025. Initially, keywords were extracted from MeSH descriptors and subsequently refined to guarantee the incorporation of all pertinent research. Moreover, Google Scholar was utilized to broaden the search for relevant publications across multiple platforms. Following the selection process, we manually examined the references of the chosen studies to uncover any potentially missed citations.

Search keywords

The digital repositories were explored using various keyword groupings, as follows: (1) "Dynamic knee valgus" OR "knee abduction" OR "knee kinetics" OR "frontal plane projection angle" OR "knee biomechanics" OR "valgus alignment" OR "valgus knee deformity"; (2) Fatigue OR "neuromuscular fatigue" OR "muscular exhaustion" OR "systemic fatigue" OR exertion, OR "physical strain" and (3) Biomechanics OR kinematics OR "counter-movement jump" OR "landing task" OR landing OR "lower extremit" OR "lower limb" OR "lower-limb" OR "lower-extremit".

Eligibility criteria

The inclusion parameters were as follows: 1. Study Population: Participants with dynamic knee valgus (with any age range with both genders); 2. Intervention: Fatigue assessment protocol; 3. Comparison: Fatigue protocol versus non-fatigue protocol; 4. Outcomes: Kinetic or kinematic assessments; 5. Study Design: Pre- and post-fatigue protocol investigations; 6. Language: Peer-reviewed publications available in English.

Two independent reviewers, X.X. and X.X., carried out the search and then individually screened the titles and abstracts according to the established criteria. Any differences in opinion were addressed through discussion. Also, supervisor author did take the initiative to address these discrepancies [22].

Data extraction

The study data were independently collected by researchers (X.X. and X.X.) based on several criteria, including the lead author's name, participant information, assessment instruments, primary outcome measures, and an overall evaluation of the study's quality (Table 1).

Table 1. Overview of Sample Characteristics in Individual Studies.

Source, year	Study design	Sample size (N)	Sex	Age [years]	Participants characteristics	Fatigue protocol	Protocol characteristics	Outcomes measure	Assessment
Curi et al, (2024) **[23]**	Pre-test/post-test	Valgus= 14 Non-valgus= 13	F	Valgus=26.78±4.98 Non-valgus=25.84±3.64	Runners	Core muscle fatigue	Three isometric and Three dynamic exercises	- Electromyographic activity - Angular amplitudes - Vertical ground reaction force	- Single-leg drop landing test
Asadpour & Norasteh (2024) **[24]**	Pre-test/post-test	27	M	20.77±3.06	Basketball Players	Basketball fatigue protocol	Basketball fatigue protocol lasted for 40 minutes	-Angular amplitudes	- Tuck jump
Asadpour & Norasteh (2024) **[25]**	Pre-test/post-test	Guard= 9 Forward= 9 Center= 9	M	Guard= 19.77±2.68 Forward= 20.22±2.90 Center= 22.33±3.27	Basketball Players	Basketball fatigue protocol	Basketball fatigue protocol lasted for 40 minutes	-Angular amplitudes	- Tuck jump
Akbarieh Kaleybar (2021) **[26]**	Pre-test/post-test	Valgus= 21 Non-valgus= 21	F	Valgus= 23.14±1.54 Non-valgus=22.46±2.26	Gymnast Players	Plyometric program	The exercises involved both running and jumping activities	-Time to Stabilization	-Jump landing
García-Luna et al, (2020) **[27]**	Pre-test/post-test	ACL-IPP= 10 SSFP= 8	M	ACL-IPP= 12.68±0.86 SSFP= 12.73±0.95	Soccer Players	Soccer-specific fatigue protocol	The protocol involved a ball possession activity between two teams, each consisting of two players, within a confined area measuring 15 × 15 meters	- Angular amplitudes	- Single-Leg Squat (SLS) Test
Sharif et al, (2016) **[28]**	Pre-test/post-test	Valgus= 15 Non-valgus= 15	F	NR	Healthy subjects	Non-specific fatigue protocol	The fatigue protocol consists of a sequence of jumping exercises followed by running in a shuttle format	--Angular amplitudes	- Countermovement jump

SD: Standard deviation; M: Male; F: Female; SSFP: Soccer-Specific Fatigue Protocol; ACL-IPP: ACL Injury Prevention Protocol; NR: Not reported.

Quality of evidence

Both reviewers assessed the risk of bias utilizing the Newcastle-Ottawa Quality Assessment Scale (NOS). Additionally, a checklist created by Herzog, Álvarez-Pasquin (29) for cross-sectional studies was utilized. The NOS evaluates the risk of bias by awarding star ratings for each criterion fulfilled, with a total possible score of ten stars distributed as follows: for selection five stars, for comparability three stars, and for outcomes two stars [30]. Each star signifies a reduced risk of bias for that specific criterion. According to Herzog, Álvarez-Pasquin (29), studies were classified according to their quality as follows: unsatisfactory (0–4 stars), satisfactory (5–6 stars), good (7–8 stars), and very good (9–10 stars). Studies deemed low quality were excluded from the comprehensive analysis in accordance with the NOS checklist guidelines. The creators of the NOS confirmed its face and criterion validity, as well as its inter-rater reliability [31-33].

Statistical Analyses

Heterogeneity was evaluated using the I^2 index, which was interpreted according to these thresholds: 0%–30% signifying no heterogeneity; 30%–50% indicating a small degree of heterogeneity; 50%–75% representing moderate heterogeneity; and 75%–100% reflecting substantial heterogeneity. As a result, both fixed and random-effects models were employed to analyze variation among studies in this review. A random-effects model was applied when I^2 values surpassed 50% [34]. Hedges' g effect size was applied to quantify the effect of fatigue [35]. In addition, Egger's regression analysis was performed to assess publication bias [36, 37]. Ultimately, statistical calculations were performed using Comprehensive Meta-Analysis software version 2.0 (Biostat Inc, Englewood, NJ).

Results

A total of 986 potentially relevant articles were retrieved from four digital repositories. Additionally, 24 records were detected through reference list examination. After excluding 224 duplicate studies, 786 potentially applicable summaries were screened, leading to 745 exclusions. This resulted in 41 full-Text papers for comprehensive review, of which 35 were removed due to failure to meet the inclusion criteria (see Figure 1). Ultimately, 6 studies involving 171 participants were incorporated into this systematic review.

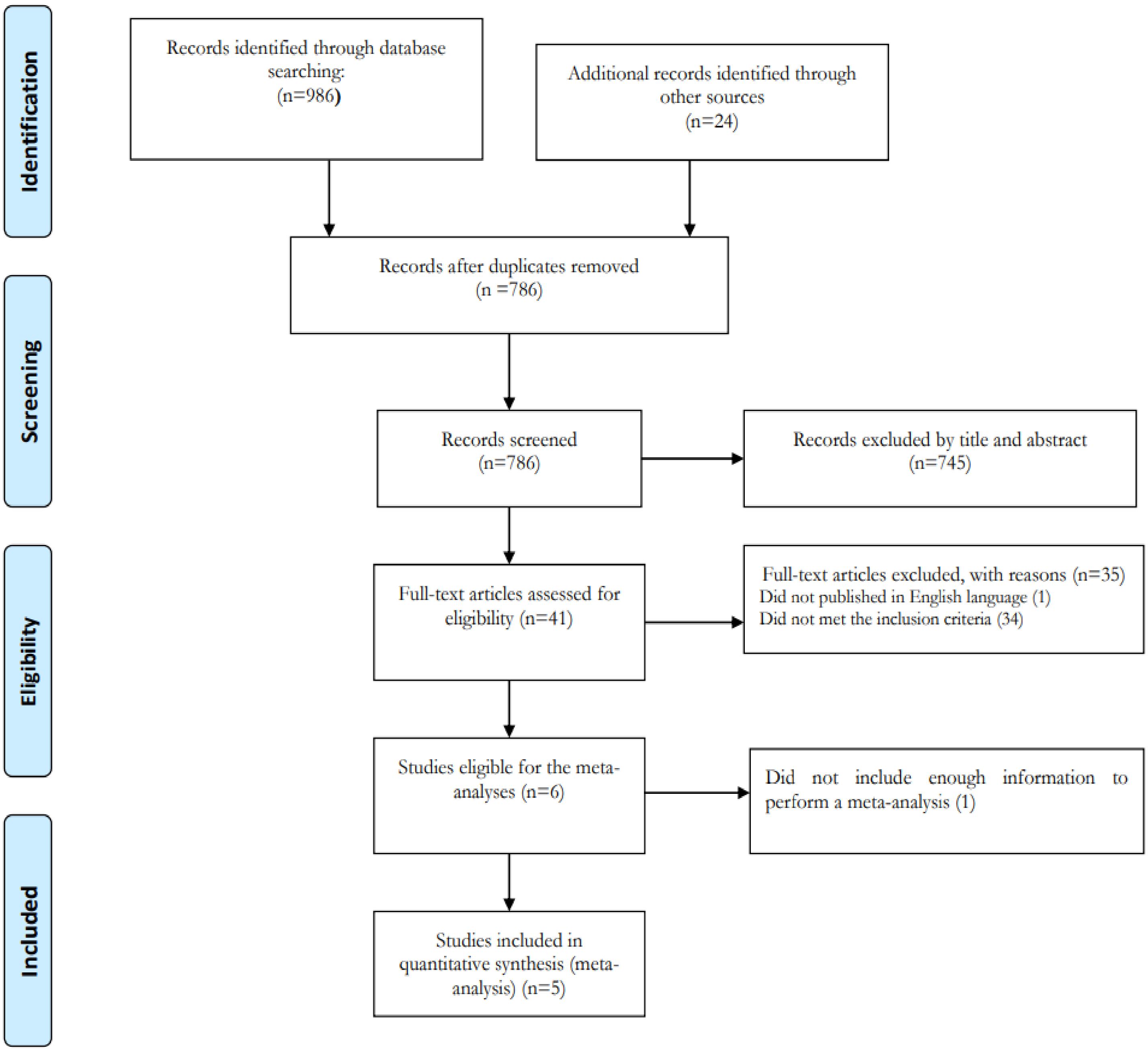

Figure 1. Flow diagram of systematic literature search.

Publication characteristics

Among the six studies selected for analysis in the systematic review, the participant demographics were as follows: two studies focused on basketball players, one on runners, one on gymnasts, one on soccer players, and one on non-athletes. To assess dynamic knee valgus, various tests were employed, including the tuck leap, unilateral drop landing, single-leg squat, and countermovement leap. The studies implemented diverse fatigue protocols, which ranged from fatigue-simulating games to plyometric and localized muscle fatigue protocols.

The participants' ages ranged from 12 to 30 years. Several outcomes were utilized to assess the influence of fatigue on lower limb biomechanics. Kinematic measurements were taken using the Motion Analyzer and Kinovea, focusing on two key phases: initial contact and maximum knee flexion. Kinetic assessments were conducted with a Force Plate device, which measured the time to stability. Additionally, electromyography was employed to analyze the electrical activity of the muscles.

Quality of evidence

According to the findings derived from the NOS evaluation, 6 studies were subjected to systematic review and meta-analysis, exhibiting favorable qualities: 4 studies (67%) received a rating of highly rated (9-10 stars), while 2 studies (33%) were rated moderately rated (7-8 stars). Therefore, the research analyzed in the systematic review was considered to have good methodological quality (Table 2).

Table 2: Quality of Evidence Assessment of Individual Studies – Consensus Score

	Selection					Comparability		Outcome		
Authors	**Representativeness of the Sample a**	**Sample Size b**	**Non-Respondents c**	**Exposure Quantification d**		**Comparability of Outcome Groups e**		**Outcome Assessment f**	**Statistical Test g**	**Quality h**
Curi et al, (2024) [23]	*	*	*	**		**		*	*	Very good
Asadpour & Norasteh (2024) [24]	*	*	*	**		**		*	*	Very good
Asadpour & Norasteh (2024) [25]	*	*	*	**		**		*	*	Very good
Akbarieh Kaleybar (2021) [26]	*	-	*	**		**		*	–	Good
García-Luna et al, (2020) [27]	*	*	*	**		**		**	–	Very good
Sharif et al, (2016) [28]	*	-	*	**		**		*	–	Good

a) **Representativeness of the Sample**: Studies should choose samples that are either fully or partially representative of the target population. b) **Sample Size**: The appropriateness and justification of the selected sample size were examined. c) **Non-responders**: A star was awarded if the characteristics of respondents and non-responders were similar and the response rate was satisfactory. No stars were given if the response rate was considered unsatisfactory or if there was a lack of information regarding the response rate. d) **Exposure Quantification**: Two stars were granted if the study utilized a valid measurement tool to evaluate risk factors. One star was awarded for using an available or described but invalid measurement tool. e) **Comparability of Outcome Groups**: This criterion evaluated whether the study accounted for confounding variables among individuals in different outcome groups. f) **Outcome Assessment**: The method of outcome assessment was assessed based on whether it included independent blinding, record linkage, self-reporting, or lacked description. Two stars were awarded for independent blinded assessments or record linkage, while one star was given for self-reported outcomes. g) **Statistical Test**: One star was assigned if the statistical test used for data analysis was clearly described, appropriate, and included a measure of association, such as confidence intervals and p-values. h) **Quality**: Study quality was rated using a star system: nine to ten stars indicated "very good" quality, seven to eight stars indicated "good" quality, five to six stars indicated "satisfactory" quality, and zero to four stars indicated "unsatisfactory" quality.

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Data Synthesis

The Impact of Fatigue Protocol on Dominant Limb Knee Valgus Angle

Four intervention conditions were evaluated regarding the influence of the fatigue protocol on the dominant limb knee valgus angle. Overall, the fatigue protocol resulted in an increase in the dominant limb knee valgus angle (effect size; -0.78, 95% CI= -1.56_-0.01, P = 0.001), demonstrating substantial variability across studies (I^2 = 79.81%, p = 0.002) (see Figure 2). Both the graphical examination of scatter plots and the findings of Egger's test revealed no considerable publication distortion (p = 0.50).

Model	Study name	Outcome	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Curi et al, (2024)	Dominant Leg	0.07	0.38	0.14	-0.67	0.81	0.18	0.86
	Garca-Luna et al, (2020).1	Dominant Leg	-2.31	0.65	0.42	-3.57	-1.04	-3.58	0.00
	Asadpour & Norasteh (2024).1	Dominant Leg	-0.29	0.27	0.07	-0.82	0.25	-1.05	0.29
	Asadpour & Norasteh (2024).3	Dominant Leg	-1.16	0.29	0.09	-1.74	-0.59	-3.95	0.00
Fixed			-0.65	0.17	0.03	-0.99	-0.32	-3.81	0.00
Random			-0.80	0.41	0.17	-1.60	-0.01	-1.97	0.05

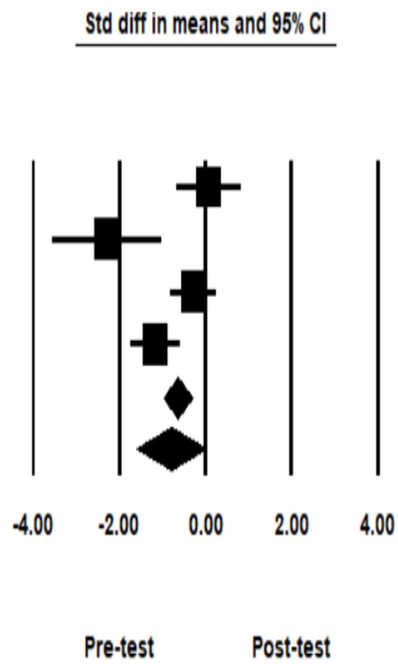

Figure 2. Forest plot of the effect of fatigue protocol on dominant limb knee valgus angle.

The Impact of Fatigue Protocol on Non-Dominant Limb Knee Valgus Angle

Three intervention conditions were assessed to determine the impact of the fatigue protocol on the non-dominant limb knee valgus angle. Overall, the fatigue protocol resulted in an increase in the non-dominant limb knee valgus angle (effect size; -0.56, 95% CI= -0.78_-0.21, P = 0.001), with minimal variation between studies (I² = 0.00%, p = 0.773) (see Figure 3). Both the graphical assessment of scatter plots and the conclusions from Egger's test demonstrated no meaningful publication deviation (p = 0.51).

Model	Study name	Outcome	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Garca-Luna et al, (2020).2	Non-Dominant Leg	-0.83	0.52	0.27	-1.85	0.19	-1.59	0.11
	Asadpour & Norasteh (2024)2	Non-Dominant Leg	-0.43	0.28	0.08	-0.97	0.11	-1.57	0.12
	Asadpour & Norasteh (2024)4	Non-Dominant Leg	-0.64	0.28	0.08	-1.18	-0.09	-2.29	0.02
Fixed			-0.57	0.18	0.03	-0.93	-0.21	-3.11	0.00
Random			-0.57	0.18	0.03	-0.93	-0.21	-3.11	0.00

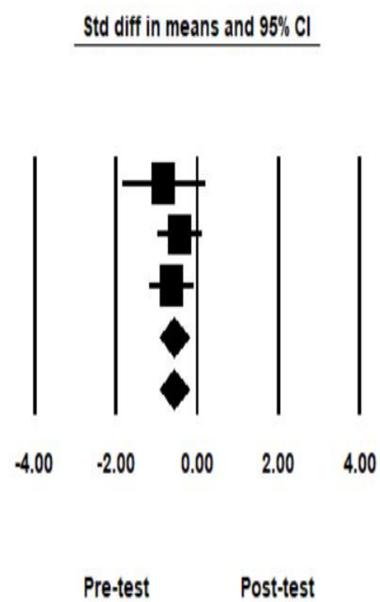

Figure 3. Forest plot of the effect of fatigue protocol on non-dominant limb knee valgus angle.

Discussion

The present comprehensive literature review and meta-analysis aimed to assess the effect of fatigue on the biomechanical function of the lower extremities in individuals with DKV. The findings indicated that fatigue protocols notably elevated the DKV angle in both the primary and secondary legs of the participants. To our knowledge, no prior investigation or extensive meta-study has examined the degree to which fatigue protocols influence lower-limb biomechanics in those with DKV. Other systematic reviews have demonstrated that fatigue significantly influences kinematic and kinetic parameters, resulting in an increased injury rate [19, 20]. Additionally, studies have utilized various biomechanical outcomes to evaluate the effect of fatigue protocols on fatigue-induced changes in movement patterns of lower-limb in individuals with DKV. Consequently, this study concentrated exclusively on meta-analyzing the combined effect of fatigue protocols on DKV in the primary and secondary sides, as other outcomes were deemed unsuitable for meta-analysis. Moreover, the studies included in this review exhibited high methodological quality, suggesting that the results of this meta-analysis are both trustworthy and of superior quality.

In addition, Egger's test was utilized to examine potential reporting bias, revealing no bias among the research findings. However, one of the two outcomes examined within this comprehensive review displayed significant research constraints and variability across several areas, including assessment tools and methods, protocol type, extent and magnitude, supervision by therapists or trainers, participant groups, timeframes, and characteristics of the induced fatigue. While variability in evaluation instruments was managed through classification of factors, additional constraints contributed to increased variability in the studies. Consequently, it is advisable for future research in this area to consider these variables to achieve more precise conclusions about the effects of fatigue on the biomechanical function of the lower extremities in individuals with DKV.

Findings from four intervention arms [23-25, 27] showed that fatigue protocol increased dominant limb valgus positioning of the knee. Also, the results of three intervention arms [24, 25, 27] showed that fatigue protocol increased non-dominant limb valgus positioning of the knee. Research conducted by Madigan and Pidcoe (38) regarding fatigue-related impacts during forward landing maneuvers found indicating that fatigue led to a heightened valgus positioning, which corresponds with our present findings. Likewise, Chappell, Creighton (39) investigated the kinetic and kinematic effects of fatigue on the knees of a cohort of 20 athletes (10 males and 10 females) engaged in a stop-and-jump activity, revealing that exhaustion elevated the knee valgus position in both groups, which is consistent with our findings. Additionally, Santamaria and Webster (19) evaluated how fatigue influences lower-limb movement mechanics while executing unilateral landings. They reported a notable decrease in peak knee valgus, angular displacement, and knee flexion across genders athlete's post-fatigue. Notably, they found that women exhibited less inward leg rotation, joint angular deviation, and duration of knee flexion at peak displacement compared to males' post-exertion, aligning with our study's findings. Overall, the findings from these studies reinforce the conclusions of the present study.

One of the investigations incorporated in this comprehensive review examined fatigue's influence on time to stability (TTS) [26]. The results indicated that post-exertion TTS was markedly extended compared to pre-exhaustion levels. TTS refers to the duration required for an individual to return reaction forces from the ground in vertical, medial-lateral, and anterior-posterior planes to baseline standing values [40]. A quicker TTS is generally considered a beneficial and protective characteristic. Within this framework, fatigue is acknowledged as a contributing element to lower-limb injuries, including ACL damage. This increased risk is likely due to alterations in movement mechanics and adaptive responses [41].

Neuromuscular regulation is essential for maintaining dynamic stability in joints. This process involves the activation of dynamic constraints that respond to movements and the loading of joints, thereby ensuring effective functional stability. The TTS metric serves as a valuable indicator of neuromuscular control, employing force plate measurements to evaluate postural stability during activities such as jump landings. [42]. Additionally, it assesses how fatigue influences proprioception and neuromuscular regulation. An extended TTS reflects a sluggish response to maintaining stability, which can hinder postural control during landings. Studies indicate that fatigued individuals tend to depend more on their ankle muscles and associated strategies rather than engaging their knee muscles. This shift may compromise knee stability and elevate the risk of ACL injuries [26].

Additionally, results from one of the studies included in this systematic review show that fatigue significantly affects muscle electromyographic activity [23]. All voluntary movements result from a complex interaction between the brain, spinal cord, peripheral nerves, muscles, and joints. Any injury or dysfunction in these components can adversely affect performance, especially in athletic settings [43]. A significant factor affecting the regulation of lower limb joints is neuromuscular fatigue. This form of fatigue arises from a combination of physiological mechanisms at both central and peripheral levels, disrupting neuromuscular afferent pathways and reducing proprioceptive capabilities. The resulting dysfunction in neuromuscular efferent pathways manifests as delayed muscle responses [44].

Fatigue mechanisms can significantly influence the biomechanical patterns associated with DKV, particularly through impaired gluteal function [43] [45]. Research suggests that fatigue can result in decreased activation and strength of the gluteal muscles, which are essential for stabilizing the pelvis and ensuring proper alignment of the lower extremities during dynamic movements [43]. When these muscles become fatigued, their capacity to counteract valgus forces at the knee decreases, leading to greater knee collapse during activities like landing or cutting [10]. This compromised gluteal function can alter movement patterns, leading to greater reliance on less stable muscle groups, thereby increasing the risk of injury [46].

In response to stress, initial muscle contractions are activated to stabilize joints, serving as a protective mechanism against injury. These contractions contribute to enhanced joint stability and mitigate the risk of collapse, which could result in irreversible damage [47]. In summary, this mechanism is essential for neuromuscular regulation and joint stability. Furthermore, the dynamic stability of the body, especially at critical joints like the knee, depends on the coordinated neuromuscular control of all body segments involved in movement. A prolonged deterioration in neural function during physical activities can jeopardize the integrity of lower limb joints, particularly the knee [48]. Research indicates that fatigue arising from heightened knee movement in the anterior and lateral planes may play a significant role in knee injuries, particularly those involving the ACL. This fatigue leads to a depletion of the body's energy reserves, subsequently elevating the risk of injury. [43].

Contrastingly, some studies have shown that fatigue may not universally affect landing mechanics. For example, Zhang et al. (2021) found that while fatigue altered certain kinematic parameters, it did not significantly impact vertical ground reaction forces during landing tasks in a sample of trained athletes [49]. In a similar vein, Johnson and Lee (2019) observed that fatigue significantly elevated the knee abduction angle at initial contact (IC) and the peak abduction torque at 40 milliseconds after IC in recreational female athletes. However, these changes were not observed in collegiate female athletes, indicating that individual differences and training status may influence how fatigue affects landing mechanics [50]. These conflicting results highlight the complex relationship between fatigue and biomechanics, indicating that further research is necessary to elucidate the conditions under which fatigue influences DKV patterns. The practical applications of this research are significant. By identifying the specific mechanisms through which fatigue affects lower-limb mechanics, targeted neuromuscular training programs can be developed to enhance gluteal activation and strength [51]. Such programs could include exercises focusing on hip abduction and external rotation, which are crucial for maintaining knee stability [52]. Additionally, incorporating fatigue protocols into training regimens may help athletes adapt to the demands of their sports, ultimately reducing the risk of injuries associated with DKV [53]. Furthermore, understanding the interplay between fatigue and DKV can inform rehabilitation strategies for individuals recovering from knee injuries, ensuring that interventions are tailored to address the specific biomechanical challenges posed by fatigue in this population.

Limitations and future scope

This research highlighted multiple methodological constraints requiring further exploration. Notably, none of the authors mentioned allocation concealment in their studies, implying that selection bias may not have been completely controlled. Additionally, the current study focused solely on lower-limb biomechanics, neglecting other aspects such as motor function and upper-limb movement patterns. Thus, it is recommended that future systematic reviews investigate these additional parameters.

Conclusion

The present systematic review sought to assess the effect of fatigue on biomechanics of lower-limb in individuals with DKV. The results indicated that fatigue protocols significantly raised the DKV angle in both the non-dominant and dominant legs of the participants studied.

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