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ORIGINAL RESEARCH

The effect of calf muscle fatigue on cutting maneuver kinematics in female athletes with and without dynamic knee valgus

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Abstract

Background: Calf muscle fatigue has been shown to affect movement patterns and may contribute to increased injury risk, particularly in the knee joint. **Objective:** This study aims to investigate the effect of calf muscle fatigue on lower limb kinematics during cutting maneuvers in female athletes with and without dynamic knee valgus (DKV). **Methods:** This case-control study included female athletes with (n = 12) and without dynamic knee valgus (n = 12). The cutting maneuver kinematics were measured with 10 cameras motion analysis before and after calf muscle fatigue, which was induced using an isokinetic dynamometer through repeated maximal plantarflexion contractions at the time point corresponding with peak knee valgus angle. A two-way mixed-design analysis of variance was conducted to analyze within-group differences between the pre-test and post-test results. **Results:** The findings indicated that calf muscle fatigue was associated with a significant decrease in knee flexion (p = .006) and increases in valgus angle (p = .003) and external rotation angle (p = .028), during the cutting maneuver. Also, calf muscle fatigue significantly increased ankle inversion (p = .028) and decreased hip flexion (p = .030) in the DKV group. Moreover, a significant difference was observed in the effect of fatigue between the two groups, such that the ankle inversion (p = .021) and hip flexion angle (p = .006) changed more in the DKV group than in the group without DKV. **Conclusions:** This study showed significant effects of calf muscle fatigue on the lower limb kinematics of female athletes. These alterations in movement patterns, especially in athletes with DKV, may contribute to a higher risk of injury, particularly anterior cruciate ligament injuries, due to compromised joint stability and altered biomechanics.

Keywords: athletes, kinematics, fatigue, dynamic knee valgus, female

Introduction

The possibility of knee injury in sports may increase due to misalignments in lower-limb structures (da Silva & Pereira, 2017). Dynamic knee valgus (DKV), characterized by internal rotation and adduction of the femur with a simultaneous contralateral pelvic drop, exemplifies a biomechanical deviation across three planes of movement (Dischiavi et al., 2019). Several factors have been investigated as potential triggers for changes in knee movement. Two recent factors showing some evidence include reduced ankle dorsiflexion and a lack of strength or impaired activation of the hip abductor and adductor muscles (Lima et al., 2018). This is particularly evident for weakness in the hip abductors and external rotators (Suzuki et al., 2015). It should be noted that the prevalence of DKV is more prominent in females (Marotta et al., 2020). This misalignment is predominantly pointed out in the frontal plane, with knee abduction load forecasting 70–80% of anterior cruciate ligament (ACL) injury risk (Zamankhanpour et al., 2024). A prospective study of 291 female high school athletes found that those who sustained non-contact ACL injuries exhibited significantly greater knee valgus angles during single-leg drop jumps compared to uninjured controls (Numata et al., 2018). In addition, knee valgus movement is a common risk factor for acute and chronic lower limb injuries. Significant research has been conducted to identify modifiable factors that affect knee movement in the frontal plane (Asadpour & Norasteh, 2024a).

Identifying these factors can help target injury prevention and rehabilitation programs (Barber-Westin & Noyes, 2017). Among the potentially modifiable factors, lower-limb muscle fatigue is significant. It has been demonstrated that muscle fatigue is a complicated, multidimensional phenomenon that influences an individual's task performance (da Costa Curi et al., 2024), including reduced muscle strength, proprioception impairment (Mohammadi et al., 2013), reduced balance, and coordination (Paillard, 2012). Some studies have demonstrated that lower-limb muscle fatigue increases knee valgus moments, a known biomechanical risk factor for ACL injuries (Asadpour & Norasteh, 2024b). During DKV, the medial collateral ligament, medial patellar ligament, and ACL are primarily

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used to prevent excessive knee valgus (Fidai et al., 2020). When lower-limb fatigue impairs neuromuscular control, the ligaments' ability to absorb and respond to ground reaction forces is reduced (Chang, 2024), which increases tensile stress on the medial collateral ligament and ACL (Westerblad et al., 2010).

Furthermore, some studies have shown that muscle fatigue causes changes in the kinematics of the lower extremity. For example, a study examining the lower-limb fatigue on the kinematic variables declared that lower-limb fatigue can increase tibia external rotation and ankle inversion, leading to kinematic changes and increasing the risk of ACL injury (Hosseini et al., 2025). In another study conducted by Liu et al. (2023), it was shown that muscle fatigue may increase the knee buckling moment and valgus moment, which may lead to the risk of ACL injury. Additionally, a study investigating the effect of fatigue on knee biomechanics during the sidestep cutting maneuver showed fatigue was associated with reduced knee flexion during early stance, along with a notable decrease in activation of the vasti muscles (Bedo et al., 2024). Also, da Costa Curi et al. (2024) showed that following fatigue, both with and without DKV groups exhibited a significant decrease in the minimum and maximum knee angles in the frontal plane.

Cutting movements are common in various sports and require precise neuromuscular coordination to ensure optimal performance and injury prevention. It has been shown that female athletes are 2 to 8 times more susceptible to ACL injuries than male athletes in sports that require quick deceleration, like soccer, basketball, and handball (Bram et al., 2021). This increased susceptibility has been linked to a combination of anatomical factors, hormonal influences affecting ligament laxity, and neuromuscular control differences (Saber et al., 2024). These movements frequently necessitate rapid directional changes (Havens & Sigward, 2015), conditions in which DKV is typically more prominent biomechanically. Research indicates that individuals with DKV have elevated knee abduction angles and moments during deceleration tasks (Schmidt et al., 2019), hence heightening their vulnerability to knee ligament damage.

While DKV has traditionally been linked to proximal factors like hip muscle weakness and insufficient neuromuscular control, emerging evidence indicates that distal segments, especially the ankle and foot, can significantly affect knee joint mechanics. The calf muscles, particularly the soleus and gastrocnemius, are crucial in controlling ankle dorsiflexion and stabilizing the tibia during dynamic movements. Fatigue of these muscles may impair ankle stability and alter frontal and transverse plane mechanics, leading to compensatory motions at the knee. Therefore, this study examines how calf muscle fatigue affects the kinematics of the lower limb during a cutting maneuver in female athletes with and without DKV. We hypothesized that calf fatigue would cause more significant alterations in lower limb kinematics, especially increased knee valgus, external rotation, and ankle inversion in female athletes with DKV than in those without DKV. Comprehending these fatigue-induced kinematic alterations is essential for developing tailored therapies to prevent knee injuries, particularly ACL injuries, in female athletes with DKV who are at an elevated risk.

Methods

Participants

This controlled laboratory study included female athletes with and without dynamic knee valgus (WDKV) participating in sports requiring jumping and landing movements. They were selected using convenience sampling and divided into DKV (n = 12) and WDKV groups (n = 12). Based on a study (Liu et al., 2023) with α = .05 and β = .90, and considering the difference in knee flexion angle at initial contact (mean ± *SD*: pre-fatigue 69.77 ± 12.92, post-fatigue 66.90 ± 9.82) between the two groups, the sample size estimation was initially calculated as 10 participants per group using the G*Power software (Version 3.1; https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower). This sample size estimation was performed based on the t-test family and differences between two dependent means. However, to account for potential dropouts, 12 participants were considered in each group.

The inclusion criteria for the study were as follows: being female, aged between 18 and 30 years, and having a history of engaging in physical activity three times per week for the past three years. Athletes who exhibited significant medial knee displacement during the Single Leg Squat (SLS) test were classified as having DKV (Zamankhanpour et al., 2023), using 2D video analysis. Markers were placed on the anterior superior iliac spine, center of the patella, and center of the ankle. The frontal plane projection angle was calculated, and a valgus angle greater than 10° was considered significant (Asaeda et al., 2024). Exclusion criteria included any clinical condition that restricted physical activity; failure to finish the test; the previous history of lower extremity surgery; having any lower limb pain at the time of the test; taking medication that may affect vigilance and attention; any lower extremity injury within the previous 6 months that required the individual to alter their training program or refrain from participating in sports for at least one week and presence of any significant postural malalignment in the spine, based on the New York posture rating (McRoberts et al., 2013). At first, for ethical considerations based on the Declaration of Helsinki, all stages of the study were explained to the subjects, and then written informed consent was signed by all participants. Secondly, individuals were informed that in case of any issues during the tests, all necessary actions would be taken by the examiner, a sports science expert studying for a master's degree in kinesiology.

The subjects were instructed on how to perform each test. It should be noted that to standardize conditions and eliminate footwear effects, all tests were performed barefoot. All steps were explained to the participants. Before starting the tests, the procedure was presented to them. All tests were conducted in the Sport Sciences Research Institute laboratory in Tehran, Iran. Before starting the investigation, study approval was obtained from the Biomedical Research

Ethics Committee of Allameh Tabataba'i University (Ethics code: IR.ATU.REC.1402.100, Date: 2023/12/27).

Procedure

The SLS test was employed to ascertain whether or not the subjects had the DKV. The dominant leg was identified before the SLS. Participants dropped onto one leg three times using a 30-cm step to determine their dominant leg. A leg utilized for landing in two or more trials is considered dominant. The SLS test was conducted using Sciascia and Kibler's instructions (Sciascia & Kibler, 2006). The barefoot athletes were instructed to place their hands on their hips and stand on one leg while bending the opposing knee to a 90° angle. They were then instructed to squat with the stance leg to knee flexion of 30 degrees. They returned to fully extended knees after briefly holding this position. Participants performed the SLS test three times on each leg. The investigator records any atypical movements, such as the Trendelenburg sign, arm flailing, and valgus collapse of the supporting knee. If more than two abnormal movements were observed during the test with the dominant leg in the stance position, the SLS test was deemed positive. In the SLS test, participants obtained scores categorized as either positive or negative. A positive SLS result may suggest inadequate lower extremity mechanics, insufficient core strength, or weakness in the hip abductors.

Motion analysis was used to examine the lower extremities' kinematics while cutting. We followed the manufacturer-recommended procedure for calibrating the motion analysis capture device before testing, after calibrating the device, and before conducting the pre-test. The ankle, knee, and hip angles were measured in three planes of motion at the moment of maximum knee valgus during the cutting maneuver. A participant's heel, first, second, and fifth metatarsal heads, iliac crests, posterior superior iliac spines, lateral and medial femoral condyles, and lateral and medial malleoli were all marked with reflective markers, which were affixed bilaterally. Markers for the S2, T10, and C7 vertebrae, the bilateral acromion process, and the sternal notch were also used to model the trunk spatially. Moreover, four cluster markers affixed to a hard shell were positioned on the thighs and shins. Kinematic data were collected at a sampling frequency of 250 Hz using infrared high-speed motion capture cameras in a 10-camera Kestrel 1300 Plus system (Motion Analysis Corporation).

Participants were required to perform a cutting maneuver as a pre-test and post-test before and after the calf muscle fatigue protocol. To minimize the potential effect of coaching on the natural execution of the maneuver, no instructions were provided regarding the correct or incorrect techniques for the cutting maneuver. Participants were only given a brief explanation of how to perform the task to familiarize them with the procedure. A designated area for the cutting maneuver was marked on the ground, with lines drawn at 45° angles. For the pre-test execution, participants were instructed to sprint from a distance of 7 m towards the cutting area at their preferred speed, approaching a 45° angle. Upon reaching the designated location for the cutting maneuver, participants placed their dominant leg in the center of the marked area, and based on whether the left or right leg served as the support, they pivoted to the right or left along the prescribed path. Participants were asked to perform three practice trials to prepare for the primary test. Once participants felt comfortable executing the cutting maneuver, they were instructed to complete three successful trials. Only cutting maneuvers executed toward the participants' dominant side were measured and included in the analysis.

The Biodex System 2 isokinetic device (Biodex Medical Systems) was used for measurement of muscular strength and to induce calf muscle fatigue, and at the beginning and end of the fatigue protocol, participants were asked to rate their perceived exertion of the activity in their calf muscles using the Borg scale (0 = *no fatigue*, 10 = *maximum imaginable fatigue*), with a score of 8 or above indicating muscle fatigue (Williams, 2017).

Fatigue protocol

Participants were positioned supine on the system, with the setup adjusted to achieve 135° of hip flexion, 55° of knee flexion, and complete contact of the dominant foot with the footplate, ensuring no restriction on ankle motion. A support was placed under the distal thigh to bear the limb's weight and provide relaxed support at the knee. To minimize the impact of assistor movements, the participant's movement was restricted using straps across the forefoot, ankle, distal thigh, waist, and chest. The non-dominant foot was placed on a support at the end of the dynamometer bed, in front of the motor unit, to prevent body twisting during contraction.

Initially, to assess strength, each participant was instructed to exert maximum effort, utilizing their full strength and speed throughout the entire range of motion of the ankle joint. The isokinetic test protocol for ankle movements was conducted at 120 °/s. The test was performed in concentric/eccentric mode for the ankle's plantar flexion movements. In the first set, participants performed three submaximal voluntary contractions to familiarize themselves with the protocol and warm-up. In the second set, participants were asked to perform the main maximum-effort trials in three non-consecutive repetitions, with 10-s rest intervals between repetitions and 30-s rest intervals between angular velocities and modes, exerting their maximum force. Verbal encouragement and visual feedback were provided to ensure maximal effort. Peak torque during the second set, when the participant performed their maximum voluntary contraction for plantar flexion, was recorded. Fifty percent of this value was used as the criterion for fatigue. After the strength test, the fatigue protocol was applied, consisting of 20 repetitions across three sets, with an angular velocity of 180 °/s, a torque of 150 Nm, and 30-s rest intervals between sets (Brouner et al., 2014). This fatigue protocol was repeated as long as the considered fatigue level was reached.

Data collection

Following the calf muscle fatigue protocol, the post-test data collection was conducted in the same manner as the pre-test.

The acquired data were analyzed using MATLAB software (Version 2015a; MathWorks Inc.) with custom scripts written by a biomechanics expert. The joint angles of the hip, knee, and ankle at the time of maximum knee valgus were extracted as the primary variables for the study. A fourth-order, zero-phase-shift Butterworth filter with a low-pass cut-off frequency of 15 Hz was applied for kinematic data. We used standard linear interpolation methods to fill in missing data that occurs infrequently and is shorter than 20 frames. Also, Cortex program (Version 8.1.0.2017 64-bit; Motion Analysis Corporation) was used for gap filling.

Data analysis

The Shapiro-Wilk test was utilized to evaluate the normality of the data distribution. A two-way mixed-design analysis of variance was conducted to analyze within-group differences between the pre-test and post-test results and examine between-group differences. Effect sizes for the analysis of variance analyses were calculated using η^2, with values of .01, .06, and .14 interpreted as representing small, medium, and large effects, respectively. All data were analyzed using IBM SPSS Statistics (Version 26, IBM Corp.). The $p < .05$ was considered significant.

Results

Table 1 displays the demographic characteristics of participants in both groups. There was no significant difference between demographic data among the study groups. The Shapiro-Wilk test results indicated that the data followed a normal distribution.

The findings indicated that calf muscle fatigue was associated with a significant decrease in knee flexion (mean difference –3.51, 95% confidence interval (CI) [–5.85, –1.17], $p = .006$) and increases in valgus angle (mean difference 2.10, 95% CI [0.83, 3.37], $p = .003$) and knee external rotation (mean difference 1.42, 95% CI [0.09, 2.75], $p = .028$) regardless of group. Also, calf muscle fatigue significantly increased ankle inversion (mean difference 1.94, 95% CI [0.56, 3.84], $p = .028$) and decreased hip flexion (mean difference –3.55, 95% CI [–7.26, 0.14], $p = .03$). Moreover, significant time × group interactions were found in ankle inversion (mean difference –6.06, 95% CI [–9.59, –2.54], $p = .021$) and hip flexion angle (mean difference –0.51, 95% CI [–6.01, 4.99], $p = .006$) increasing more in the DKV group than in the WDKV group (Table 2).

Discussion

The present study demonstrated that calf muscle fatigue in the calf muscles directly affects the kinematics of the lower limb in female athletes. Calf muscle fatigue was associated with increased knee valgus and knee external rotation angles across all participants. Additionally, fatigue reduced hip flexion angle and increased ankle inversion, but the time × group interaction was only significant for ankle inversion and hip flexion. Fatigue is a factor that can influence movement patterns and alter their biomechanical nature (Aquino et al., 2022). It can temporarily reduce the muscles' ability to maintain or generate the expected force or power during physical activities.

Generally, kinematic changes imposed on the ankle joint can lead to alterations in the upper joints (Boden et al., 2009). A study investigating the effects of ankle dorsiflexor fatigue on lower limb biomechanics showed that following fatigue, a significant increase in ankle inversion was observed after both forehand and backhand landings, and our results were consistent with theirs (Tong et al., 2023). Fatigue reduces the range of motion, compromising the body's ability to absorb impact forces. Moreover, fatigue of the plantarflexors and supporting calf musculature can reduce active control of subtalar and tibial motion, increasing medio-lateral instability at the foot and thereby encouraging compensatory inversion or pronation (Marcolin et al., 2022). Additionally, decreased control over the ankle can lead to eversion, causing more significant lateral displacement of the body and ultimately reducing dynamic stability after lower-limb fatigue (Lin et al., 2011). Muscular imbalances and weakness in the calf muscles, including the medial head of the gastrocnemius, anterior tibialis, and posterior tibialis, may reduce the ability to control foot pronation and knee valgus, potentially leading to an increase in knee valgus.

During cutting maneuvers, the increased knee valgus and tibial rotation typically result in ligamentous injury and may elevate the stress on these structures (Munro et al., 2012). Concerning this subject, a study that used a standardized exercise protocol and vertical jumps as a fatigue protocol demonstrated that exercise contributes to increased DKV in young athletes, with female athletes and those over 15 years of age experiencing the most significant effects (Fidai et al., 2020), and our results were consistent with theirs. It can be interpreted that higher fatigue levels were associated with a greater degree of DKV, potentially

Table 1 Means, standard deviations, and statistical significance of *t*-tests for basic demographic characteristics and average power of dorsiflexion and plantarflexion

Characteristics	DKV	WDKV	*p*
Age (years)	22.83 ± 2.33	23.51 ± 1.76	.311
Body height (cm)	167.60 ± 4.47	164.00 ± 5.31	.195
Body mass (kg)	66.20 ± 7.21	64.41 ± 9.48	.476
Body mass index (kg/m^2)	24.52 ± 3.12	23.52 ± 2.71	.961
Average power of dorsiflexion (W)	43.03 ± 24.96	50.90 ± 26.82	.432
Average power of plantarflexion (W)	88.41 ± 24.36	89.97 ± 23.63	.865

Note. DKV = dynamic knee valgus; WDKV = without dynamic knee valgus.

Table 2 Means and standard deviations (in degrees) and ANOVA statistics for angular variables

Variable	Time	DKV	WDKV	ANOVA			
				Effect	*F*	*p*	η^2
Ankle							
Plantar flexion	Pre	−20.51 ± 6.19	−21.02 ± 7.46	T	0.582	.454	.026
	Post	−21.94 ± 5.57	−21.49 ± 7.29	T × G	0.148	.704	.007
Inversion	Pre	9.87 ± 5.43	7.90 ± 2.37	T	5.553	.028	.202
	Post	13.87 ± 3.89	7.80 ± 4.42	T × G	6.142	.021	.218
External rotation	Pre	−5.65 ± 1.64	−4.91 ± 2.17	T	0.004	.950	.000
	Post	−5.50 ± 2.01	−5.13 ± 1.40	T × G	0.120	.735	.005
Knee							
Flexion	Pre	34.25 ± 6.25	35.19 ± 6.20	T	9.391	.007	.299
	Post	30.13 ± 4.83	32.28 ± 4.00	T × G	0.281	.601	.013
Valgus angle	Pre	11.90 ± 2.15	8.44 ± 2.33	T	11.34	.003	.340
	Post	14.24 ± 2.38	10.31 ± 3.11	T × G	0.138	.714	.006
External rotation	Pre	9.54 ± 3.02	6.96 ± 2.21	T	5.509	.028	.200
	Post	12.17 ± 3.38	7.17 ± 2.04	T × G	3.963	.059	.153
Hip							
Flexion	Pre	24.91 ± 7.77	33.80 ± 9.33	T	5.384	.030	.197
	Post	26.05 ± 7.58	25.54 ± 5.20	T × G	9.410	.006	.300
Adduction	Pre	9.80 ± 6.54	8.55 ± 3.62	T	0.993	.330	.043
	Post	11.16 ± 5.50	10.37 ± 3.89	T × G	0.021	.886	.001
Internal rotation	Pre	10.19 ± 4.65	11.16 ± 3.32	T	0.461	.504	.021
	Post	11.99 ± 3.85	10.71 ± 4.46	T × G	1.278	.270	.055

Note. ANOVA = analysis of variance; DKV = dynamic knee valgus; WDKV = without dynamic knee valgus; T = time; G = group.

elevating the risk of ACL injuries in these athletes (Numata et al., 2018). Moreover, another study by Asaeda et al. (2024) following the peripheral fatigue protocol showed that knee-joint fatigue increases DKV during landing, while hip-joint fatigue promotes knee adduction and internal rotation, with both tasks elevating quadriceps activity. On the contrary, a study reported that although the hip abductors' fatigue may slightly increase the hip's internal rotation, these changes are not substantial enough to significantly impact knee valgus or other kinematic variables such as knee flexion (Patrek et al., 2011). The findings of our study do not align with the results of the mentioned study. The difference may be due to variations in the targeted muscles and the side-lying hip abduction as a fatigue protocol, which differs from ours.

Regarding the hip joint, it was shown that reducing hip flexion and decreasing the capacity to absorb shock during lower limb impact in cutting maneuvers and landing tasks increases the risk of ACL injury (O'Connor et al., 2015).

Cutting maneuvers, such as increasing knee valgus angle and decreasing hip flexion, alter the movement pattern between the hip and knee joints, increasing stress and heightened risk of ACL injury. Therefore, it appears that the combination of fatigue and cutting maneuvers, through changes in the movement patterns and range of motion at the hip and knee joints, elevates the risk of injury to these joints (Smith et al., 2014). In another study, Hosseini et al. (2025) found a significant decrease in hip joint flexion following the lower-limb fatigue protocol. In a study, it was shown that fatigue increased DKV and gluteus medius activity in all runners, while runners with DKV showed greater hip excursion (da Costa Curi et al., 2024). Our study's findings align with the mentioned studies. It should be noted that reduced flexion during landing is considered a potential injury mechanism due to the increased anterior shear force exerted on the ACL. Finally, calf muscle fatigue may exacerbate knee instability in athletes with DKV, leading to a higher likelihood of excessive knee valgus during the cutting maneuver. Effective interventions, such as strengthening exercises and fatigue resistance training, may help mitigate the effects of calf muscle fatigue and enhance the overall stability and safety of cutting maneuvers, particularly for female athletes prone to knee injuries. Incorporating joint stabilization strategies in training programs could have important clinical implications, helping to reduce the likelihood of acute injuries and improve long-term joint health in at-risk athletes.

This study has several limitations that should be considered. Most critically, our sample size was relatively small and restricted to female athletes. Equally important, we did not collect kinetic measures (e.g., ground reaction forces or joint moments), which constrains our ability to link observed kinematic changes directly to loading mechanisms relevant to ACL injury risk. Moreover, the research did not focus on a specific sport, as athletes from various disciplines were included. Potential differences in approach speed or cutting angles between groups or between pre- and post-fatigue conditions were not observed. These factors could independently affect lower limb kinematics and may confound the interpretation of fatigue-related changes. Additionally, the study primarily involved young athletes, and the results may not apply to other age groups, particularly older athletes. The study also utilized a limited set of assessment tools, exclusively relying on single-leg squats to evaluate DKV, which may not provide a comprehensive understanding of the impacts of this condition on overall movement performance. Furthermore, the research was conducted cross-sectionally, meaning that the effects of calf muscle fatigue were examined only in the short term, potentially overlooking the long-term effects on lower extremity kinematics and kinetics. A methodological limitation is that kinematic analysis was restricted to the moment of maximal knee valgus angle. In addition, ACL injuries often occur within the first 100 ms after initial contact, and continuous approaches such as statistical parametric mapping could provide more detailed insight into how fatigue alters joint motion throughout stance. Finally, the study focused solely on calf muscle fatigue, whereas in real-world athletic settings, fatigue typically occurs across multiple muscle groups simultaneously, which may lead to different outcomes. Future research should incorporate kinetic analyses alongside kinematics, target sport-specific cohorts, and expand beyond isolated calf fatigue to multi-muscle or whole-limb fatigue protocols.

Conclusions

This study's findings underscore calf muscle fatigue's significant effects on female athletes' lower limb kinematics. These alterations in movement patterns, especially in athletes with DKV, may contribute to a higher risk of injury, particularly ACL injuries, due to compromised joint stability and altered biomechanics. Importantly, this study provides new insights by quantifying how calf muscle fatigue alters kinematics in athletes with and without DKV, highlighting differential effects between groups.

Conflict of interest

The authors report no conflict of interest.

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