Effects of Lower Extremity and Core Muscles Fatigue Protocols on Landing Mechanics and Performance in Female Athletes

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Abstract- Fatigue decreases muscle strength and functional capacity, disrupting neuromuscular coordination by impairing load control .This negatively impacts the kinetics and kinematics of the ankle, knee, and hip joints, resulting in reduced performance and an increased risk of injury, particularly to the anterior cruciate ligament (ACL). This study aimed to compare the effects of fatigue protocols for lower extremity and core muscles on landing mechanics and performance of female athletes. This study used a cross-sectional, comparative, pretest-posttest design with a control group. A total of 105 female athletes, aged 11 to 49, were selected via convenience and purposive sampling. Participants were divided into three groups: core muscle fatigue, lower extremity muscle fatigue, and a control group. Data were gathered using the Landing Error Scoring System (LESS), Y-Balance, and 45-degree trunk flexion tests. Data were analyzed using descriptive statistics, Shapiro-Wilk test, Levene's test, one-way ANCOVA, and the Bonferroni post hoc test. A *P* of 0.05 or lower was considered statistically significant. ANCOVA results showed significant differences among the groups for the LESS (*P*=0.001) and 45 ° trunk flexion test (*P*=0.001). There was no significant difference between the two experimental groups regarding the LESS (*P*=1.00). However, a significant difference was observed between the two experimental groups in the trunk flexion test (*P*=0.001). Fatigue had a greater effect size on landing mechanics ($\eta p^2=0.209$) than on the trunk flexion test ($\eta p^2=0.143$). However, no significant difference was observed between the groups regarding the Y-Balance Test (*P*=0.996). The study revealed that fatigue protocols targeting lower extremity and core muscles had a negative impact on kinematic parameters associated with ACL injuries during jump-landing in female athletes. Additionally, core muscle fatigue significantly impacted the 45º trunk flexion test, while lower extremity muscle fatigue had no significant effect on it.

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Introduction

The prevalence of knee and ankle injuries is very common among athletes, particularly thoseengaging in sports such as soccer, football, basketball, and American football, where athletes frequently perform cutting and jumping maneuvers. These sports exhibit the highest injury rates (1,2). Knee injuries account for 60% of all sports injuries, with the anterior cruciate ligament (ACL) injuries constituting nearly half of these cases (3).

ACL injuries are a significant issue in sports, accounting for 16% to 32% of all knee injuries and contributing to 43% of the overall injury burden during sports seasons (4-6). Women are particularly susceptible to ACL injuries, with females being up to eight times more likely to experience these injuries compared to men. The ACL plays a crucial role in knee function by stabilizing the joint during full extension and preventing rotational forces and anterior tibial displacement (7-9). While extensive research has explored biomechanical and

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hormonal factors, unidentified variables remain that require further investigation (10). Hormonal factors, both internal and external, affect ACL laxity and may modify the injury risk profile, particularly in women (10,11). Most ACL injuries in female athletes occur without contact from another player (5). These injuries are multifactorial, arising from the interaction of modifiable and non-modifiable risk factors (5,12,13). Increasing the knee flexion angle at initial contact can reduce impact forces and the knee loading during landing (14). Knee valgus, or the inward positioning of the knee during landing, is associated with various knee injuries, including ACL and patellofemoral joint injuries (15,16).

Core stability and function are essential for the dynamic control of the trunk, enabling the generation, regulation, and transfer of forces. Furthermore, they play a vital role in managing dynamic movements in the distal segments of the lower extremity kinetic chain (17). Several studies have found a correlation between poor core trunk stability and non-contact ACL injuries in athletes (18,19). Specifically, weakness in neuromuscular control can lead to increased hip adductor and knee valgus torques during landing from a jump. Dynamic knee stability depends on the control of the central part of the body, and evidence indicates a relationship between poor neuromuscular control and ACL injuries (19). Despite the complex etiology of sports injuries, the elevated risk in female athletes has been primarily attributed to neuromuscular factors, including fatigue (20). Neuromuscular fatigue is characterized by a decline in maximal voluntary force production due to exercise-induced fatigue (21). Research indicates that fatigue-related impairments in muscle activation patterns can alter lower extremity kinematics, increasing injury susceptibility (21). Fatigue diminishes muscular strength and disrupts neuromuscular control across various movements.

Additionally, studies reveal that lower extremity fatigue contributes to biomechanical alterations, including reduced knee flexion and increased knee valgus during both double- and single-legged squat maneuvers (21,22). Khosravi *et al.,* and Sebyani *et al*., investigated the impact of core muscle functional fatigue on kinematic parameters associated with ACL injury risk. The former study examined the effects during a single-leg stop-jump task in female athletes (23), while the latter focused on a cutting maneuver in collegiate male athletes. The results of these studies indicated that core muscle fatigue significantly influenced knee flexion angle, knee valgus, and the maximum degree of flexion and valgus during these dynamic movements (24). Similarly, Seyedi *et al*., examined how core muscle fatigue affects lower extremity kinematic variables during squatting in female bodybuilders. Their findings indicated that fatigue in the core muscles led to altered alignment of the lower extremities, which heightened the risk of injury for female bodybuilders (25). Additionally, Mirkarimpour *et al*., assessed the effect of functional fatigue on landing mechanics using the LESS. Their results demonstrated that exercise-induced functional fatigue leads to alterations in landing mechanics.

Since females tend to land with external rotation and a more upright posture (26), their susceptibility to ACL injuries is increased. Additionally, most lower extremity injuries occur during landing or upon impact with the ground after a jump, with fatigue being a significant contributing factor (26). Therefore, investigating the effects of different fatigue protocols on performance and comparing their impacts in female athletes is crucial. Such analysis is essential for optimizing training protocols that aim to enhance performance and prevent injuries. In this regard, the present study aims to compare the effects of lower extremity and core muscle fatigue protocols on landing mechanics and performance among female athletes.

The null hypothesis is as follows: there is no significant difference between the core muscle fatigue, lower extremity fatigue, and control groups in landing mechanics, trunk flexion test, and Y-Balance, considering pre-intervention measures as covariates. The alternative hypothesis is as follows: there is a significant difference between the core muscle fatigue, lower extremity fatigue, and control groups in landing mechanics, trunk flexion test, and Y-Balance, considering pre-intervention measures as covariates.

Materials and Methods

This study utilized a cross-sectional, comparative, pretest-posttest design with a control group. The study population consisted of female athletes aged 11 to 49 years living in Tehran, Iran, during 2023. Participants were selected from various sports disciplines, including basketball, futsal, Pilates, and karate. To qualify, athletes had to have a minimum of three consecutive years of training experience in their specialized field and engage in regular physical activity at least three times a week. The exclusion criteria were as follows: any injury during the testing period, a history of surgery, a history of injury or severe musculoskeletal deformities in the limbs and spine, neuromuscular disorders, balance disorders, joint complications in the lower extremity, engaging in vigorous physical activity within 48 hours prior to the fatigue tests, and unwillingness to continue participating in the tests.

The sample size, calculated using G*Power (with an effect size of 0.4, α=0.05, and power=0.8), was 105 participants. The subjects were divided into three groups: core muscle fatigue, lower extremity muscle fatigue, and a control group. The study was approved by the Sport Sciences Research Institute of Iran (Approval Code: SSRI.REC-2309-2414).

Prior to any assessments, written informed consent was obtained from all participants, and their personal information, including age, height, weight, sports experience, and history of injury or disease, was collected. This study was conducted in a suitable environment over a single session. First, the researchers instructed all subjects on how to perform the tests. After a 5-minute warm-up, the performance and landing mechanics were assessed using the Y-balance test, trunk flexion test (45 degrees), and the LESS under normal conditions, without fatigue. The tests were administered randomly, with one-minute rest periods provided between each test.

The subjects' performance was measured and recorded using a camera and a stopwatch. Following this, the fatigue protocols for the lower extremity and core muscles were administered to the two experimental groups, while the control group did not undergo any fatigue protocols. After the fatigue protocols were completed, the performance and landing mechanics were reassessed in participants within ten seconds of completing the protocols. Finally, the statistical data obtained from all three groups were analyzed.

Fatigue protocols

Fatigue protocol for core muscles (Assessed by the plank test)

In this test, subjects lie face down on the ground, positioning their forearms so that both elbows touch the surface at a 90-degree angle. The distance between their elbows should match the width of their shoulders, while their feet are placed hip-width apart. The forearms should remain in a neutral position between pronation and supination, with hands clenched into fists. The pelvis must be elevated above the ground. To ensure proper alignment, an imaginary line should be drawn connecting the outermost part of the acromial end of the scapula, the greater trochanter of the femur, and the lateral malleolus. Subjects were instructed to keep their necks straight, looking down towards the ground, ensuring their heads remained in a neutral position throughout the test. They were required to maintain this posture until reaching a state of fatigue. Prior to the official testing, subjects were familiarized with the procedure through a trial.

During the test, participants were encouraged to persevere until they felt unable to continue due to fatigue. The test was terminated if the pelvis dropped to the ground, created an angle above the ground, or if the subjects could not maintain the correct position for two consecutive seconds (27).

Additionally, participants' fatigue levels were assessed using the 10-point Borg scale (CR-10). Borg (28) attempted to address the issue of whole-body fatigue by developing a scale ranging from 0 to 10. This scale ranges from 0 (no exertion at all) to 10 (maximal exertion) (29). The Borg CR10 Scale has been validated for measuring fatigue (30). Therefore, this scale was used to measure muscle fatigue and individuals' perception of physical effort during the plank test. When the rating reached 10, indicating maximal exertion, the individual was considered to have reached their limit of fatigue.

Fatigue protocol of lower extremity muscles

The lower extremity fatigue protocol consisted of ten repetitions of single-leg squats with knee flexion to 90 degrees, two maximum vertical jumps on one leg, and twenty repetitions of stepping up and down a 31 cm step using the dominant leg. This sequence of exercises constituted one set of the protocol (31).

After each set, participants were asked to rate their fatigue levels using the Borg (CR10) scale (0-10), where 0 indicated no fatigue, and 10 represented maximum fatigue. When a participant reported a fatigue level of 10, the single-leg hop test was conducted to confirm the presence of fatigue (29,31,32). To assess fatigue-related performance changes, the single-leg hop test was performed before and after the fatigue protocol. In this test, participants stood on one leg and attempted to hop as far as possible in a straight line, landing on the same leg. This test served as an objective measure of lower extremity muscle fatigue. If a participant was unable to achieve at least 80% of their pre-fatigue hop distance, they were classified as fatigued, based on the study criteria. The single-leg hop test was repeated three times, and the mean of the three trials was recorded as the final measure of lower extremity fatigue for each participant. (32). Immediately after completing the fatigue protocol, a post-test was performed under the same conditions as the pre-test for each subject.

The functional tests

The landing error score system (LESS)

LESS was used to assess the landing error. To conduct this test, subjects were instructed on proper landing techniques and then asked to jump with both legs from a 30-cm platform to a designated spot marked at 50% of their height away from the platform. After landing, they immediately performed a maximal vertical jump. Subjects were not allowed to pause between landing on the ground and performing a vertical jump (33). No feedback on technique was provided; however, if they did not jump off the platform with both legs or if their legs did not pass the designated mark after jumping, they were required to repeat the task. To ensure comfort during the test, subjects were allowed to practice the jump-landing task 2-3 times before indicating their readiness for the final attempt. The jump-landing tasks were recorded using two video cameras positioned 3 meters away and 1.5 meters high to capture the movements in both the sagittal and frontal planes. The videos recorded by the examiner were analyzed using the standardized scoring form of the LESS. The LESS consists of 17 items, each scored such that 0 indicates a correct movement and 1 represents an incorrect movement. The total score for all items determines the final score for each subject. Based on the landing technique of each subject, the scores were categorized into four groups: excellent (LESS< 4), good (4≤ LESS≤ 5), average (6≤ LESS≤ 7), and poor (LESS> 7). A higher LESS score indicates a greater number of landing errors (33). This test demonstrates strong performance capabilities for clinically assessing risky landing mechanics. A recent systematic review concluded that the overall LESS score exhibits excellent to good reliability across various measures: intrarater reliability (intraclass correlation coefficient [ICC], 0.82 to 0.99), interrater reliability (ICC, 0.83 to 0.92), and intersession reliability (ICC, 0.81) (34). The validity of the overall LESS score in relation to 3-dimensional (3D) jump-landing biomechanics was found to be robust when individuals were stratified into four quartiles based on their LESS scores (34).

The Y balance test (YBT)

The Y-Balance Test (YBT) is a well-established assessment tool for identifying dynamic balance deficits associated with lower extremity injuries, such as ACL rupture, patellofemoral pain syndrome, and chronic ankle instability (35,36). Its widespread use in musculoskeletal evaluations is attributed to its cost-effectiveness, portability, ease of administration, and strong interrater and test-retest reliability, with an intraclass correlation coefficient (ICC) ranging from 0.85 to 0.93 (37,38). Given the high prevalence of ACL injuries in sports, the YBT is frequently employed as an objective tool for monitoring post-reconstruction functional recovery and rehabilitation progress (39,40).

During the YBT, the subject begins by standing on her dominant leg at the center of the Y, positioning her foot to form an angle between 90 and 135 degrees. If the right leg was the subject's dominant leg, the YBT was performed in a counter-clockwise direction; if the left leg was dominant, the test was conducted in a clockwise direction. During the test, any of the following actions constituted an error: if the reaching leg touched the ground, if the subject used her hand for support, or if the reaching leg bore any weight upon contact with the ground. In such cases, the test was repeated after a two-minute rest. The subjects performed the YBT three times before and after the fatigue protocol. Their balance scores were obtained considering the leg length, measured as the distance from the anterior superior iliac spine (ASIS) to the medial malleolus. The final YBT score was calculated as the mean of the three repetitions performed in all three directions using the following formula (41).

Dynamic balance score=distance traveled in three directions/leg length*100

Endurance test of trunk flexor muscles

The trunk flexion test (45 degrees) was utilized to assess the functional endurance of the core muscles, including the anterior abdominal muscles. In this test, the subjects were first instructed to sit against a 45-degree board, with their backs resting against the board and their hip joints bent at a 90-degree angle. Their hands were crossed over their chests. An assistant was employed to stabilize the subject's body by keeping the ankle in a stable position using her hand. To perform the test, the athlete leaned against the 45-degree board and moved the board 10 cm away from her back, with the instruction to maintain this position for as long as possible. The duration for which the subject could hold this position was recorded using a stopwatch. The test was stopped as soon as the subject's back made contact with the board. The intraclass correlation coefficient for the trunk flexion test was found to be 0.97 (42).

Statistical analysis

Both descriptive and inferential statistics were applied to analyze the data. All statistical analyses were performed using SPSS version 26. The main assumptions for conducting statistical tests, such as the normality of data distribution and the homogeneity of variance, were assessed and confirmed using the Shapiro-Wilk test and Levene's test, respectively. The analysis of covariance

(ANCOVA) test was used to compare the results between groups. Subsequently, the Bonferroni post-hoc test was utilized to further assess the differences between the two population means. Since there were three groups, the significance level of 0.05 was divided by the number of groups for the Bonferroni post-hoc test, and a *P* of ≤ 0.017 was considered statistically significant.

Results

The demographic characteristics of the study participants, such as age, height, and weight, the mean, standard deviation, median, and Interquartile Range (IQR) of the study variables, as well as the results of the homogeneity test are provided in Table 1. The results of the ANOVA test revealed that, aside from the age variable, there were no significant differences in height and weight among the three groups, indicating homogeneity in these characteristics.

Table 1. The demographic characteristics of the study participants (standard deviation±mean, median, and interquartile range (IQR))

Variables	*P*		All participants (n=105)	Control group (n=33)	Lower extremity muscles' fatigue group (n=36)	Core muscles' fatigue group (n=36)
Age	0.001	(Mean±Standard deviation)	21.48±11.62	14.39±4.03	23.25±12.40	26.22±12.60
		Interquartile Range (IQR)	16	3	23.5	24.5
		Median	15	13	16	21
Height	0.164	(Mean±Standard deviation)	160.48±6.52	158.70±7.52	160.25±6.46	161.36±5.35
		Interquartile Range(IQR)	7	8	6.75	5.75
		Median	161	160	162	160.5
Weight	0.856	(Mean±Standard deviation)	54.63±7.32	53.61±7.22	55.08±7.66	55.11±7.17
		Interquartile Range(IQR)	9	9	9.75	9
		Median	54	52	54	55

Assessing the normally distributed data

Before analyzing the data, the Shapiro-Wilk test was employed to assess the normality of the distribution. The data exhibited a normal distribution. The mean and standard deviation of study variables are shown in Table 2.

Table 2. Mean and standard deviation of the study's variables

Variables	Test	The total number of the study participants (n=105)	Control group (n=33)	Lower extremity muscles' fatigue group (n=36)	Core muscles' fatigue group (n=36)
YBT	pre-test	93.12±12.33	89.89±11.00	93.34±14.06	95.86±11.20
	post-test	95.03±11.14	92.55±10.52	95.04±12.71	97.26±9.74
LESS	pre-test	4.8±1.55	5.30±1.76	4.64±1.44	4.5±1.36
	post-test	5.99±1.53	5.73±1.81	6.11±1.51	6.11±1.28
The trunk flexion test (45 degrees)	pre-test	139.12±95.61	87.57±31.77	153.36±115.25	172.14±95.52
	post-test	105.12±69.47	89.45±36.62	123.50±97.109	101.11±55.58

The results of the ANCOVA in relation to the functional tests are presented in Table 3. This table demonstrates significant differences among the groups concerning the LESS (*P*=0.001). Following that, the results of the Bonferroni post hoc test indicated a significant difference between the core muscles fatigue group and the control group (*P*=0.001), as well as between the lower extremity muscle fatigue group and the control group (*P*=0.001) in terms of the LESS. There was no significant difference between the two experimental groups regarding the LESS (*P*=1.00).

There was a significant difference among the groups in the trunk flexion test (*P*=0.001). The results of the Bonferroni post hoc test revealed significant differences between the experimental groups (*P*=0.003) and between the core muscle fatigue group and the control group (*P*=0.001). Additionally, there was no difference between the lower extremity muscle fatigue group and the control group in this regard (*P*=1.00). Effect size was calculated as partial eta squared (ηp^2) and interpreted according to the following range: $\eta p^2 > 0.01$ was a small effect size; $\eta p^2 > 0.06$ was medium; whereas $\eta p^2 > 0.14$ was large. Given the varying effect sizes across groups in functional tests, it can be concluded that fatigue has a more substantial effect on both landing mechanics ($\eta p^2=0.209$) and trunk flexion test ($\eta p^2=0.143$). However, no significant difference was observed between the groups regarding the Y-Balance Test (*P*=0.996).

Table 3. The results of ANCOVA tests

Variable	mean square	df	F	*P*	ηp^2
LESS	10.642	2	13.362	0.001	0.209
YBT	0.943	2	0.035	0.966	0.070
The trunk flexion test (45 degrees)	14889.309	2	8.418	0.001	0.143

Discussion

The present study aimed to compare the effects of lower extremity and core muscle fatigue protocols on landing mechanics and performance among female athletes. Our results demonstrated that, after controlling for the pre-test effect, significant differences were found among the three groups in terms of the LESS scores and the endurance of the trunk flexor muscles. The results of the present study indicated that following the fatigue protocol implemented in the two experimental groups, the mean scores of the LESS increased. After controlling for the pre-test scores, a significant difference was observed among the three groups in terms of the LESS scores; however, no significant difference was found between the two experimental groups. Given the varying effect sizes across groups in functional tests, it can be concluded that fatigue had a more substantial effect on landing mechanics ($\eta p^2=0.209$) than on the trunk flexion test ($\eta p^2=0.143$. However, no significant difference was observed between the groups regarding the Y-Balance Test (*P*=0.996). Movement patterns are key modifiable factors that can affect the risk of ACL and lower extremity injuries by changing the forces (43). As mentioned previously, the LESS is a clinical test that evaluates landing biomechanics during a jump-landing task in order to assess the risk of ACL injury (33). Since landing error relies on the coordination of feedback and movement strategies involving the hip, knee, and ankle joints, any deficiencies in landing mechanics can compromise the strength and mechanical stability of any joint or structure within the kinematic chain of the lower extremity (44-46). A lack of core and hip muscle strength, particularly in the abductors and external rotators, contributes to the development of dynamic knee valgus, a biomechanical position that increases the risk of non-contact ACL injuries (47). ACL injuries are often associated with excessive flexion and abduction movements, with factors such as neuromuscular control, anatomical structure, hormonal influences, and biomechanical alignment playing significant roles in their occurrence(48). Studies indicate that an increased knee flexion angle upon foot contact with the ground can reduce the impact force and load on the knee during landings (43,49). Conversely, a reduction in the knee flexion angle at foot strike is directly associated with an increase in stress on the ACL, thereby elevating the risk of injury (43). Differences in landing mechanics between genders have been identified as a key risk factor for injury. Female athletes typically land with less knee flexion and greater quadriceps activation, which increases the anterior shear force on the tibia, thus placing more stress on the ACL (50,51).

It appears that fatigue can reduce the functional capacity and ability of the muscles, causing disturbances in the simultaneous activation of agonist and antagonist muscles, alterations in movement patterns, and a decline in the performance and efficiency of the neuromuscular system. Additionally, fatigue increases the risk of injury. It involves a combination of physiological mechanisms that occur at both central and peripheral fatigue levels, ultimately resulting in a decrease in force or power-producing capacity (52). Therefore, it can be concluded that when lower extremity muscles become fatigued during sports activities, this fatigue likely leads to a decrease in the flexion angles of the knee, hip, and trunk. This alteration in muscle function and movement patterns can increase stress on the ACL, subsequently elevating the risk of injury (43).

The results of the current study are consistent with some previous studies, including Vermeulen *et al.,* who investigated the effect of fatigue on jump-landing biomechanics. The results indicate a prevailing body of evidence suggesting more trunk flexion during standardized jump-landing tasks following lower extremity muscle fatigue (53). Based on the findings from previous studies and the current research, it can be concluded that fatigue in both the core and lower extremity muscles can lead to decreased performance, compromised landing mechanics, misalignment of the lower extremity joints, and increased risk of injury (54,55). Additionally, insufficient coordination of the core muscles can lead to compensatory movement patterns, increasing the risk of ACL reinjury (48). A systematic review study indicated that inadequate core stability, diminished hip abduction strength, excessive knee valgus, and heel-first landing may contribute to a higher risk of ACL injury in young athletes (56). Core muscle fatigue, particularly in the gluteus maximus and medius, impairs pelvic control in the frontal plane, causing inward rotation of the hip and misalignment, which negatively affects functional test scores (57).

Additionally, fatigue in the rectus abdominis and iliopsoas muscles can disrupt pelvic control in the sagittal plane, influencing hip and trunk flexion angles, as well as landing error scores (58). Some studies have shown that fatigue in the core trunk muscles can lead to increased scores on the LESS in real-time (LESS-RT). Since jump-landing tasks are common in many sports, fatigue in the core muscles may contribute to a higher incidence of landing errors, potentially serving as a significant factor in lower extremity injuries among athletes (43,49). The findings of the current study revealed that core muscle fatigue significantly alters landing mechanics and endurance performance of trunk flexor muscles. In this regard, Gandomi and Najafi reported that fatigue-induced reduction in knee flexion during landing, along with elevated landing error scores, may increase the risk of lower extremity injuries in athletes (44). Similarly, Abyar *et al*., demonstrated that peripheral fatigue in core muscles compromises joint stability, strength, and endurance, which aligns with our findings (57).

Fatigue is thought to negatively impact other injury risk factors, as it is linked to reduced muscle strength, impaired neuromuscular control, poor coordination, decreased postural stability, and altered proprioception, particularly in the ankle joint (59-62). However, the exact mechanisms by which fatigue influences injury risk remain unclear, and there is ongoing debate about whether fatigue serves as an independent risk factor or modifies other risk factors. Some studies have shown that fatigue increases peak angles in the knee and hip during landing, while others suggest that fatigue reduces landing forces compared to the non-fatigued condition (63). These inconsistencies in the findings emphasize the need for further research on this issue (64). Madigan *et al*., reported a decrease in ground reaction force and an increase in knee flexion post-fatigue. They attributed the discrepancy to differences in fatigue protocols, noting that other studies have used various activities such as running, stopping, and cutting maneuvers (65).

To mitigate the impact of lower extremity and core muscle fatigue on landing mechanics, targeted training programs are crucial. Quadriceps-hamstring co-contraction can provide a protective effect on the ACL and reduce peak anterior shear force (66). Furthermore, coaches are encouraged to incorporate core-strengthening exercises, such as planks, which are one of the most important core exercises, into their training sessions. These exercises are essential for improving core stability, which in turn enhances motor control and coordination. It is also advisable to perform these exercises toward the end of a workout, as this approach helps minimize fatigue before engaging in activities that require rapid directional changes, ultimately reducing the risk of ACL injuries.

Limitations

Despite the researchers' efforts to control various aspects of the study, several limitations were present. The wide age range (11-49 years) is one, as the growth spurt, maturation, and physical and hormonal changes during adolescence may influence the results, with younger and older athletes responding differently to fatigue. Additionally, the single-sex sample may affect the generalizability of the findings. Furthermore, the difference in the types of contractions used in the fatigue protocols between the groups could also impact the comparison between them. Furthermore, the short-term nature of the study limits the ability to draw conclusions about the long-term effects of fatigue on injury risk.

The results of the present study demonstrated that peripheral fatigue of core muscles impaired trunk flexor function, especially in terms of stability, in female athletes. Furthermore, the fatigue protocols applied to the lower extremity and core muscles may negatively affect kinematic parameters related to ACL injury during jump-landing in female athletes. The comparison between the groups in terms of performance revealed that fatigue had a more substantial effect on LESS than on the other functional tests. In this regard, future research can investigate the potential impact of integrated fatiguemitigating exercises on athletes' landing mechanics to reduce the incidence of sports-related injuries. Additionally, it is suggested to assess the long-term effects of fatigue on injury risk.

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