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ORIGINAL ARTICLE

Comparison of the Effect of Core Trunk and Lower Limb Muscle Fatigue on Landing Kinematics and Fear of Movement in Young Athletes with and without Anterior Cruciate Ligament Reconstruction

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K E Y W O R D S

Anterior cruciate ligament reconstruction;
Fatigue;
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Kinematics

A B S T R A C T

Comparison of the effect of core trunk and lower limb muscle fatigue on landing kinematics and fear of movement in young athletes with and without anterior cruciate ligament reconstruction. In this study, 84 people participated and were divided into 8 groups of 12: case (two groups of 12 with anterior cruciate ligament reconstruction) and control (two groups of 12 matched healthy people). The participants in the study were randomly divided into two groups: central muscle fatigue (Groups 1) and lower limb fatigue (Groups 2). Each subject was administered the landing error and single-leg landing tests, as well as the Tampa Fear of Motion Score Questionnaire, and the results were recorded as pre-test data. Then, each subject was subjected to fatigue intervention according to the group, and then a post-test was conducted. The results showed that in the post-fatigue stage, there was a significant difference in all research variables between the ACLr1 group with control 1 and control 2, as well as control 1 with ACLr2 and ACLr2 with control 2. ($P<0.50$). However, no significant difference was observed in the ACLr1 group with ACLr2 and control 1 with control 2 ($P>0.50$). The results of intra-group comparisons showed that in the post-fatigue stage, there was a significant difference in all research variables between the ACLr1 group with Control 1 and Control 2, as well as Control 1 with ACLr2 and ACLr2 with Control 2 ($P<0.50$). However, no significant difference was observed in the ACLr1 group with ACLr2 and control 1 with control 2 ($P> 0.50$). In a general conclusion, the results showed that central and lower limb fatigue leads to changes in landing performance in individuals with ACL reconstruction, which makes it necessary to consider the role of fatigue on landing kinematics and its role in return-to-sports criteria and prevention of re-injury.

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Introduction

The unique structural and functional features of the human knee joint enable it to adapt to various activities, but the mechanisms the precise preservation of its integrity is still under investigation. In addition, how to regulate knee joint function despite the reduction human mobility is still unknown (1,2). The knee joint, which is prone to injury due to its complexity and demands, is particularly vulnerable to risks such as anterior cruciate ligament (ACL) injury, which is a severe injury and can lead to long-term absence from sports, pain, disability, and the risk of knee arthritis. Research is primarily focused on identifying risk factors for ACL injury, environmental conditions, and anatomy athletes, hormonal levels, and neuromuscular mechanics have been focused on, with a focus on modifiable neuromuscular aspects (3,4). In recent studies, due to the interconnected nature of sports activities performed in a closed motor chain, researchers have often used biomechanics joints are analyzed to assess the biomechanics of an affected joint as well as the adjacent upper and lower joints (5,6). Bouisset who pioneered the claim that pelvic and trunk stability is crucial for all limb movements (7). Later, Hodges and Richardson they found the trunk muscles are activated before upper and lower limb movements to create a stable footing (8). This is the context for this concept established that proximal stability is essential for distal movement (9). The main assumption of this concept is that greater stability is in the central region the body becomes better able to adapt and anticipate changing conditions, improving organ function, improving overall performance, and reducing the risk of injury. Researchers have investigated the causes of lower extremity injuries and have shown a significant association between injury risk and core instability. (10,11)

Fatigue appears to be a key neuromuscular factor in ACL injury, as it can cause changes in neural control create lower limb muscular and biomechanical stability during functional tasks. Numerous studies have addressed the consequences of fatigue and its impact. They have investigated movement coordination, muscle reaction time, and proprioception (12). Recent research aimed at replicating functional movements similar exercises have been performed to better understand the impact of fatigue on lower limb joints. Some findings show that fatigue causes It induces neuromuscular and biomechanical changes and potentially increases the risk of non-contact ACL injuries during functional activities. (13) Consequently, the integration of fatigue considerations into ACL injury prevention programs is recommended, despite extensive research, ACL tears remain common in athletic events. Notably, individuals who have previously torn or reconstructed their ACL face a significant risk of re-injury, which emphasizes the importance of addressing fatigue in rehabilitation programs after ACL injury (14,15). Given the emphasis of recent studies on examining various factors affecting ACL injury outcomes, including fatigue, multiple studies are necessary to clarify its specific effects on these indicators.

Anterior cruciate ligament (ACL) injuries are one of the most common and debilitating knee injuries, affecting approximately 85 in 100000 people are between the ages of 16 and 39 (16,17). The ACL is the primary stabilizer of the knee, controlling anterior movement of the tibia and rotation and it limits the medial aspect of the knee and its defect leads to anterior and rotational instability (16,18). The most common non-mechanical injury modes during impact, turning, cutting, and jumping maneuvers, the knee is slightly bent and in a valgus position (19). ACL tear consequences has significant short-term and long-term implications. Many athletes never return to the same level of performance while rates of re-injury and osteoarthritis remain high (20). The reconstructed ACL is at a higher risk of injury than the intact ligament, with studies showing a 25% re-injury rate in people with ACL reconstruction, which can lead to knee instability and knee osteoarthritis (20). Walden et al. showed that 86% of professional soccer players had a history of ACL reconstruction three years after surgery were able to return to sports, while only 65% of them were able to return to pre-injury levels. (21)

Various studies have suggested that the cause of ACL injury is multifactorial and results from the interaction of modifiable and non-modifiable risk factors (22). One potentially modifiable factor that has received attention in recent years in research is the role of neuromuscular fatigue is (23). Fatigue is defined as the inability to maintain and sustain the necessary strength to perform physical activity. Studies have shown a high percentage of sports injuries occur late in the competition or during training. (24)

Fear of movement is known to be a variable affecting the process of returning to sports. Researchers consider fear of movement to be one of the important factors in not returning to previous exercise and activity levels (25). Kvist et al. (2004) reported that 24% of athletes did not return to their pre-injury activity levels until 4 years after surgery due to fear of re-injury. Studies have shown that athletes who did not return to their pre-ACL injury activity level were significantly more likely to recover than athletes who did those who had returned to pre-injury activity had a higher level of fear of movement. Fear of movement has negative effects on quality of life and progressing the cure. (27)

studies show that fatigue leads to a severe decrease in muscle strength, changes in lower limb muscle activation patterns, and changes in the biomechanics of the trunk, hips, and knees and the increase in ground reaction forces during landing or cutting which is hypothesized to increase the likelihood of non-contact ACL injury (14,28). Various studies have investigated the effect of fatigue on kinematic, kinetic, and neuromuscular factors of the knee joint in different planes of motion in healthy athletes as a risk factor for ACL injury. These fatigue protocols include repetitive movements, functional activities, isokinetic and isometric contractions (29). Review of the work different fatigue protocols have shown different results. Some fatigue protocols lead to changes in movement patterns in the frontal pages, sagittal, and transverse, which can be attributed to a decrease in hip and knee flexion angles, an increase in dynamic knee valgus angles, and an increase in anterior knee shear forces were noted and some fatigue protocols did not show any difference after fatigue application. In addition, the different results due to applying local fatigue to different organs and general fatigue, as well as applying fatigue in a laboratory environment and sports environment has been observed. (17, 23, 29)

Despite numerous studies to identify risk factors for ACL injury, high rates of this injury are still observed in athletes (29,30). Recent research has investigated the impact of fatigue on ACL injury and post-ACL reconstruction kinematics and activity neuromuscular and kinetic studies are needed to further understand this injury (29,30). The results of some studies have shown that the effect fatigue has different effects on kinematic, kinetic, and neuromuscular variables in healthy, injured, and reconstructed samples, and on the other hand, no significant changes have been reported (29,30). Although there are limited studies on individuals who have undergone ACL reconstruction, these individuals may be more vulnerable to the biomechanical effects of fatigue (29). Many athletes who undergo ACL reconstruction surgery, are continuing their sports activities that require a lot of support for the knee joint. Returning to sports and athletic activity exposes the ACL to high tensile loads that may compromise the integrity of the reconstructed ligament. Jumping and landing are essential requirements of many sports and are also a risk factor for ACL injury. Furthermore, many studies have reported that altered landing strategies persist after ACL reconstruction which can be reduced knee flexion, increased knee valgus angle, altered trunk and thigh kinematics, decreased muscle response time, and decreased knee joint motion were noted. (30,32)

Because biomechanical changes play a significant role in the risk of secondary injury, there is a need to develop objective, performance-based assessments designed to identify potential biomechanical deficits of the lower extremity during the final phase of rehabilitation after ACLR before the athlete returns to high-level sport. Exercise demands Identifying altered movement patterns after ACLR may be critical to maximizing post-surgical performance improvement and reducing the risk of secondary ACL injury. (30,33) Therefore, biomechanical analysis of jumping and landing movements can provide us with very useful information about risk factors for ACL injury. One of the available and low-cost visual analysis tools is the Single-Leg Landing Test and Landing Error Scoring Test (LESS). These tests have high performance with excellent reliability and validity, along with a 3D analysis system, which serves as a field tool capable of predictive in identifying individuals at high risk of injury. (30,34)

Despite the acceptance of the role of fatigue and its possible impact on jump-landing kinematics in healthy individuals, there is limited research and little information on its role in individuals with ACL reconstruction. Furthermore, none of the neuromuscular training interventions that have been successful in reducing ACL injury rates target fatigue resistance, and there is no evidence to suggest that these ACL injury reduction programs should be modified to focus on this parameter. (29,35) Also, a study examining the effect of central fatigue and the lower limbs were not found on the Tampa fear of movement scores. Therefore, in order to safety return to sports, we need sufficient information about the changes caused by the effect of fatigue on athletes with ACL injuries, therefore, the purpose of the present study was to compare the effect of fatigue on core muscles comparison of the effect of core trunk and lower limb muscle fatigue on landing kinematics and fear of movement in young athletes with and without anterior cruciate ligament reconstruction.

Materials and Methods

Considering the comparison of two healthy and injured groups, the present study is a case-control study. The statistical population of the present study was male athletes young people aged 18 to 30 years underwent anterior cruciate ligament reconstruction. Purposeful and accessible sampling method similar items. The sample size of the present study was based on previous studies that examined the effect of fatigue on the biomechanics of lower limb landing with a level significance 0.05 and power 0.80 with ANOVA Repeated Measures research design with 4 groups and 2 repetitions in G software power was calculated and the total sample size was calculated as 48 people. Therefore, in this study, 12 people of 4 groups were divided into case and control groups. It should be noted that, considering the comparison of two types of central and lower limb fatigue protocols in two groups of athletes with and without ACL reconstruction, four groups were defined for the present study.

Inclusion criteria for the group with anterior cruciate ligament reconstruction included an age range of 20 to 30 years, at least 9 months after ACL reconstruction surgery, completion of rehabilitation, having a sports history of at least 5 years, and returning to sports at an intermediate to high level. Metrics exclusion criteria for the ACL reconstruction group included injury and other lower limb complications such as patellofemoral pain syndrome, ankle sprains, etc. history of lower limb surgery other than ACL surgery, history of diseases associated with weakness in the balance and vision, the presence of severe structural abnormalities. Also, the criteria for entering the study in the healthy group included the age range of 20 to 30 years, being active in sports continuously in one discipline sports, having at least 5 years of continuous sports experience and exclusion criteria from the study in the healthy group were; history of anterior cruciate ligament injury, history of lower limb injury in the past 6 months, no pain, and no structural abnormalities in the lower limb.

In order to find research subjects through announcements and in coordination with sports medicine centers, orthopedic and physiotherapy offices in Tehran, male subjects with a history of anterior cruciate ligament reconstruction were purposefully identified. After communicating with the subjects and explaining the goal subjects were selected according to the study's inclusion and exclusion criteria.

After selecting the subject according to the inclusion and exclusion criteria, the research process was fully explained and, if consent was obtained, the participant was informed consent to participate in the study was obtained from the subjects who entered the study. Then, the subjects visited the research site located in the clinic Dr. Dayani Physiotherapy in Tehran, initial measurements and assessments, including completing demographic information, pre-fatigue tests (single-leg landing and LESS) and then applying the fatigue protocol, and post-fatigue tests immediately after the fatigue protocol they were applied. It should be noted that in order to randomly divide the subjects into central and lower limb fatigue groups, the groups were divided using sealed envelopes. Also, before starting the test process, the subjects warmed up for 15 minutes.

The lower limb fatigue protocol was performed using the protocol presented in the study by Padua and Barnett (32,36). In this fatigue protocol, subjects performed repetitive squatting at a speed of 25 squats per minute with a metronome beat using a weighted barbell (30% of the subject's body weight), they did it at an angle of 0 to about 60 degrees. Fatigue training would stop when the subject squats at a set speed of 25 in 4 cycles If the squat fell behind in the minute or failed to complete 2 consecutive squat cycle. The subjects verbally were Encouraged to keep pace with the metronome, observing the subject's lag in the squat cycle to measure fatigue, the Borg rating scale was used. The Borg scale is a subjective scale that ranges from 6 (no perceived stress) to 20 (maximum perceived pressure). (37)

The central fatigue protocol presented in the present study includes 4 consecutive sets of 6 exercises, and the time to complete this protocol is approximately 24 minutes. In this protocol, each subject performed each exercise for 40 seconds and rested for 20 seconds between each exercise they rested. (38) These exercises in each set include:

Exercise 1: The subject is in a sitting position and performs trunk rotation while holding a 2kg medicine ball.

Exercise 2: In this exercise, the subject lies on a gym ball with a two-kilogram weight in hand, and the examiner holds the leg, the subject is held firmly and the subject moves downwards and upwards.

Exercise 3: In this exercise, the subject lies on his stomach on a gym ball and holds a two-kilogram weight with his hand over his chest, and then bends downwards and rises upwards.

Exercise 4: In this exercise, the subject sits on a sit-up table with a negative slope and holds a 2kg weight on his chest, then he picks it up and then goes down and returns to the original sitting position.

Exercise 5: In this exercise, the subject, while holding the gym ball between her legs at a 90-degree hip flexion angle, lowers her legs to the right and to the ground once by moving the lumbar-pelvic region, then returns to the starting position and then moves to the left.

Exercise 6: In this exercise, the subject uses the elastic which is placed on a wall or bar with a band that is stable while the person's legs are fixed and motionless, rotates from the torso in the opposite direction of the hand holding the elastic.

Instruments

Tampa Fear of Motion Questionnaire (TSK): The TSK consists of 17 statements related to fear of motion and injury that participants rate on a 4-point Likert scale (from 1 = “strongly disagree” to 4 = “strongly agree”). Scores are from 17 to 68, higher scores indicate greater fear of movement and re-injury. This questionnaire has been reviewed and validated in studies. Interpretation of Tampa Scale for Kinesiophobia (TSK) scores for athletes with anterior cruciate ligament (ACL) reconstruction helps identify the level of fear of movement or re-injury (39). The interpretation of the scores is as follows;

-Score 17-28 Fear of move athletes in this range are likely to be well mentally prepared for rehabilitation and return to sport. They might get require minimal psychological intervention.

-Score: 29-35 Moderate fear of movement. Athletes may have concerns about movement and re-injury.

-Score: 36-68 Extreme fear of movement. Athletes in this area have significant concerned about movement and re-injury.

Height and weight measurement: In order to accurately measure the height and weight of the subjects, a digital stadiometer, model Saka, made in Germany, was used. A measurement of 1 cm was used for height and 0.01 kg for weight.

Video camera: In order to record images of the LESS tests and single-leg landing, two Japanese Sony brand video cameras, model mode DSR62 were used. In order to record test images from two cameras in frontal view and sagittal view at a distance, those were placed in 3 meters away from the subject. After warming up, 6 markers were placed on anatomical points on the subjects' bodies. The lateral aspect of the femur, the greater trochanter and the lateral epicondyle of the thigh, the superior anterior iliac spine, the tibial tuberosity, and the distal part of the ankle were located between the medial and lateral malleolus. Valgus and knee flexion angles were measured using Kinovea software (40,41). The analysis was carried out three successful landings were recorded and if imbalance or excessive movement in the arms and torso was observed the test was repeated again.

- Landing Error Scoring System Test (LESS): The LESS test is used to identify movement pattern changes during landing after a jump. This test evaluates the subject's landing technique based on 9 images and 13 questions. The LESS test is performed as follows: the person stands on a box in 30 cm height, in front of the box there is a target line that is drawn at half the height of the subject. We teach the person to jump forward from the box with both feet in such a way that land with both feet slightly past the target line and immediately jump up to maximum height after landing. To record and analyze the LESS test, two standard Japanese 60 Hz Sony DSR62 video cameras were used. One camera was placed in front of the subject and the other was in the side view and recorded the test steps. (30)

Data analysis

SPSS version 14 software was used to analyze the data. Using descriptive statistics of the subjects' demographic information fabrics was analyzed. The Shapiro-Wilk test was used to examine the normal distribution of the data. After confirming the normal distribution. Data and variance analysis were performed using a mixed analysis of variance test and Bonferroni post hoc test for intra- and intergroup comparisons before and after fatigue exercises were used.

Results

Table 1 shows the demographic characteristics of the research groups.

Table 1. Demographic studies of subjects divided into two groups.

Variable	Group	Number	Average ± standard deviation	P value
Age (Years)	ACLr1	12	23.0±08.52	0.73
	Control 1	12	24.0±0.76	
	ACLr2	12	23.0±91.65	
	Control 2	12	23.0±33.73	
Height (meter)	ACLr1	12	180.1±50.37	0.38
	Control 1	12	179.1±08.17	
	ACLr2	12	178.0±0.93	
	Control 2	12	180.1±50.26	
Weight (kilogram)	ACLr1	12	78.1±41.31	0.10
	Control 1	12	75.1±75.40	
	ACLr2	12	74.0±33.49	
	Control 2	12	78.1±0.49	
Body mass index (kg m^2)	ACLr1	12	24.0±05.17	0.19
	Control 1	12	23.0±60.26	
	ACLr2	12	23.0±45.20	
	Control 2	12	23.0±91.20	

According to Table 1, the mean and standard deviation of the variables of age, height, weight, and body mass index of the individuals can be seen. Also, there were no statistically significant differences between the different groups in these three characteristics. Table 2 shows the mean and standard deviation of the variables separately in the pretest and posttest.

Table 2. Mean and standard deviation of variables by groups

stage		**pre-test**	**Post-test**
Group	variable	Mean ± standard deviation	Mean ± standard deviation
ACLr1	Fear of movement	35.2 ± 66.60	39.2±91.46
	LESS	6.1 ± 583.16	8.1±75.05
	Knee valgus angle	12.1 ± 94.60	15.1±49.66
	Knee flexion angle	130.2 ± 60.16	135.2±42.50
Control 1	Fear of movement	24.2±50.54	28.2±83.55
	LESS	3.0±0.85	5.1±08.08
	Knee valgus angle	6.1±44.27	8.1±07.16
	Knee flexion angle	126.2±35.31	127.3±74.16
ACLr2	Fear of movement	34.2±91.77	41.2±83.51
	LESS	6.1±41.37	8.1±33.23
	Knee valgus angle	12.1±01.73	15.1±99.42
	Knee flexion angle	130.3±63.30	137.3±02.09
Control 2	Fear of movement	23.2±33.30	28.2±08.02

	LESS	2.0±41.90	3.1±83.02
	Knee valgus angle	6.1±75.47	8.1±74.40
	Knee flexion angle	126.2±68.29	127.3±54.98

To examine the normal distribution of data in each of the 4 groups, the Shapiro-Wilk statistical test was used.

Table 3. Results of the Shapiro-Wilk test related to research variables by groups in different stages of the research

stage		**pre-test**	**Post-test**
Group	variable	significance	significance
ACLr1	Fear of movement	0.513	0.295
	LESS	0.282	0.069
	Knee valgus angle	0.872	0.148
	Knee flexion angle	0.982	0.810
Control 1	Fear of movement	0.624	0.824
	LESS	0.100	0.48
	Knee valgus angle	0.836	0.602
	Knee flexion angle	0.331	0.500
ACLr2	Fear of movement	0.828	0.223
	LESS	0.100	0.072
	Knee valgus angle	0.284	0.741
	Knee flexion angle	0.499	0.200
Control 2	Fear of movement	0.353	0.674
	LESS	0.015	0.066
	Knee valgus angle	0.645	0.953
	Knee flexion angle	0.594	0.799

As can be seen in Table 3, the results of the Shapiro-Wilk test show that the data distribution is normal. (P>5.50)

To compare the effect of fatigue of the core muscles of the trunk and lower extremities on research variables in young athletes with cruciate ligament reconstruction the mixed analysis of variance test was used for the anterior and healthy athletes, considering the normality of the data distribution and the homogeneity of the variances. (Table4)

Table 4. Results of the mixed analysis of variance test related to the research variables.

Variable	Source of the work	Sum of Squares	Degrees of freedom	Mean of Squares	F	Significance	Eta squared
Fear of movement	stage	615.09	1	615.09	338.125	<0.001*	0.885
	stage*group	28.36	3	9.45	5.19	0.004*	0.262
	Error	80.04	44	1.81	-	-	-
	Group	3411.36	3	1137.12	108.20	<0.001	0.881
	Error	426.375	44	10.509	-	-	-
LESS	stage	86.260	1	86.360	412.17	<0.001*	0.904
	stage*group	2.03	3	0.677	3.23	0.031*	242
	Error	9.208	44	0.309	-	-	-
	Group	383.198	3	127.73	92	<0.001*	0.798
	Error	1537676.926	33	46596.35	-	-	-
Knee Valgus angle	stage	154.73	1	154.73	324.05	<0.001*	0.884
	stage*group	19.20	3	6.40	13.82	0.001*	0.485
	Error	20.38	44	0.46	-	-	-
	Group	1050.96	3	350.32	89.38	<0.001*	0.85
	Error	20.38	44	0.46	-	-	-
Knee Flexion angle	stage	271.690	1	271.690	82.53	<0.001*	0.652
	stage*group	128.67	3	42.89	13.03	0.001*	0.470
	Error	144.83	44	3.29	-	-	-
	Group	973.81	3	324.60	27.37	<0.001	0.651
	Error	426.375	44	10.509	-	-	-

According to Table 4, the mixed analysis of variance test showed that the effect of time is significant in the values related to the research variables. Also, the results of the mixed analysis of variance test showed that the effect of time in the group was significant in the values related to the research variables. According to the results obtained from the mixed analysis of variance test, the Bonferroni post hoc test was used to more accurately examine the differences between groups in the values of the research variables at different stages of the research. The results showed that in the post-fatigue stage, there was a significant difference in all research variables between the ACLr1 group with control 1 and control 2, as well as control 1 with ACLr2 and ACLr2 with control 2 (P<0.05) However, no significant difference was observed in the ACLr1 group with ACLr2 and control 1with control 2. (P>0.05)

In order to examine within-group changes in the research variables before and after fatigue, Bonferroni post hoc test was used. The results showed that all groups experienced a significant increase in the fear of movement scores, LESS, and knee valgus angle in the post-test compared to the pre-test (P<0.05). Also, there was a significant increase in knee flexion angle in ACLr1 and ACLr2 groups after fatigue application compared to before fatigue application (P<0.05) but no significant change was observed in control group 1 and control 2. (P>0.05)

Discussion

In the post-fatigue stage, the LESS test score, flexion angle, and valgus were significantly lower than those in the ACLr1 group compared to the control group, a significant difference was between ACLr2 and control 1, as well as between control 2 and ACLr2, and between ACLr2 and control 1, but in the ACLr1 group with ACLr2 and no significant difference was observed between control 2 and control 1, the results showed. The results of the present study with the Kuenze et al. results (2018), Gokler et al. (2014), Bell et al. (2014) reported an increase in LESS test scores after fatigue in individuals with ACL reconstruction. Gokler et al. (2014) showed that athletes with ACL reconstruction showed higher scores (poorer performance) after applying fatigue on a scale compared to healthy individuals (30). Bell et al. (2014) also showed that people with ACL reconstruction achieved higher scores on the LESS test compared to healthy people (42). Kuenze et al. (2018) also reported poor performance in individuals with ACL reconstruction, with this rate being higher in women. (43)

The results of this study emphasize the significant impact of fatigue on landing kinematics in athletes with a history of ACL reconstruction. Fatigue, what in the core muscles of the trunk and lower extremities exacerbate the landing performance deficit in these individuals compared to their healthy counterparts.

The current results of this study with Willems et al. (2023), Kim et al. (2021), Webster et al. (2012), based on changes in landing kinematics and a decrease in the flexion angle and an increase in the knee valgus angle. Thomas et al. (2015) showed that knee flexion and valgus angles were different before and after neuromuscular fatigue with repeated squats in subjects with ACL reconstruction compared to the healthy group. Also, after fatigue, the ACL reconstruction group showed lower flexion angles and greater valgus (44). Willems et al. (2023) showed that the athletes with ACL reconstruction showed reduced hamstring muscle activation and increased knee valgus during jumping after fatigue (45). In this regard, Asayda et al. (2024) showed that fatigue leads to increased knee valgus (46). In a study conducted in 2012 by Webster and colleagues, the effect of fatigue on lower limb kinematics was examined in subjects with and without ACL reconstruction. The findings of this study were consistent with current research. The study included 15 male participants who had undergone ACL reconstruction surgery 15 to 19 months earlier. A bilateral, repetitive squat protocol was used to induce fatigue. There was a significant difference in the hip flexion angle at the moment of foot contact with the ground between the two groups, along with a decrease in knee flexion amplitude following fatigue, the results showed (47). Kim et al. (2021) showed that fatigue of the hip abductor muscles leads to changes in the kinematics of single-leg landing. (48)

Fatigue negatively affects neuromuscular control, which is crucial for maintaining proper landing kinematics. The control is often compromised due to the surgery and subsequent rehabilitation process in athletes with ACL reconstruction. Research has shown that fatigue can lead to movement changes such as increased knee valgus, decreased knee flexion, and compromised balance during landing, which are risk factors for further injury.(45) Core stability is essential for optimal performance in various athletic activities, including landing. Core muscles provide the foundation for limb movement. Fatigue in these muscles can lead to an unstable chain reaction that affects the entire kinetic chain and increases the risk of an improper landing. Fatigue in the core muscles can lead to reduced trunk control, which leads to compensatory movements that increase the load on the lower extremities. (45,49) the studies have shown.

Lower extremity fatigue specifically affects muscles vital for shock absorption and knee stabilization during landing. Athletes with ACL reconstruction often demonstrate quadriceps weakness and altered muscle activation patterns that are exacerbated by further fatigue (30. According to this study the lower limb fatigue led to worse landing performance for athletes with ACL reconstruction, which is consistent with previous findings that these individuals may have compensatory strategies that lead to impaired movement in conditions of fatigue.

Comparative analysis between the two groups under different fatigue conditions provides valuable insight. The poorer performance of the ACL reconstruction group in the lower limb fatigue condition, compared to their performance in the central fatigue condition, suggests that lower limb fatigue may be more likely to contribute to decreased performance in individuals with ACL reconstruction compared to central fatigue. Therefore, the findings of this study highlight the need for targeted interventions to assess and address fatigue-related motor deficits in athletes with ACL reconstruction. Rehabilitation programs should include strategies to increase core and lower extremity endurance. Specific exercises aimed at improving core stability, as well as lower limb strength and neuromuscular control, can reduce the adverse effects of fatigue on landing mechanics.

Regarding the results of the fear variable, the results of the present study are similar to the results of McPherson's studies. et al. (2019), Webster et al. (2018), Sun. 4 et al. (2017), Lentz et al. (2015), Ardern et al. (2014), Tripp. et al. (2007) are consistent with the increase in fear of movement after functional activities and fatigue. McPherson et al. (2019) conducted a study aimed to investigate psychological readiness for return to sport with knee kinematics in athletes after ACL reconstruction. The relationship between psychological preparedness, including fear of movement, and knee kinematics in athletes after ACL reconstruction, this study examined. They found that individuals with higher levels of fear of movement showed impaired knee kinematic patterns during dynamic tasks, suggesting that psychological factors significantly influence movement patterns and may be exacerbated by fatigue (50). Webster et al. (2018) showed that muscle fatigue, especially in the lower extremities, can contribute to increased fear of movement, thus delaying return to exercise. (51) Kim et al. (2015) evaluated the effects of core stability and lower extremity fatigue on movement patterns in athletes with ACL reconstruction. This study showed that both types of fatigue negatively affect movement patterns, increase fear of movement, and alter biomechanics in ways that can make athletes more susceptible to re-injury. (57) Ardern et al. (2014) showed that higher levels of fear of movement were associated with a lower likelihood of returning to pre-injury exercise levels, particularly in conditions of physical fatigue (53). Tripp et al. (2007) showed that fear of re-injury and negative psychological states, exacerbated by fatigue, significantly contribute to fear of movement and affect motor confidence and return to sport. (54)

Kinesiophobia, is a common issue among athletes recovering from ACL reconstruction, as an excessive, defined irrational, and disabling fear of movement and physical activity resulting from a sense of vulnerability to painful injury or re-injury. This can significantly impact their rehabilitation progress, return to sports, and overall quality of life. Tampa Scale for agoraphobia is often used to measure this fear and assess its impact on athletes' movement patterns and confidence in their physical abilities. (55) Lower limb fatigue can severely affect an athlete's performance and mental state. Fatigue in the muscles responsible for knee stabilization, such as the quadriceps and hamstrings, can reduce proprioceptive feedback and neuromuscular control, leading to instability and increased fear of moving. This study found that athletes with ACL reconstruction had higher levels of fear compared to healthy athletes. They showed signs of movement when their lower limbs were tired. This finding is supported by research showing that lower limb fatigue can impair joint position sense and increase the risk of perceived instability, which in turn increases fear of movement (55).

While core stability is critical for overall body biomechanics, fatigue in the core trunk muscles can also influence the level of fear of movement, although to a lesser extent than lower extremity fatigue in athletes with ACL reconstruction. Core muscles are essential for maintaining posture and balance, and their fatigue can lead to compensatory strategies that increase the perceived effort and risk of movement. Fatigue in the core muscles exacerbated the fear of movement in athletes with ACL reconstruction, although to a lesser extent than fatigue in the lower extremities, this study showed. Research by Gildea et al. (2015) supports the idea that core muscle fatigue can impair postural control and alter dynamic movement patterns, contributing to fear of movement.

A comparative analysis of the effects of lower limb and core fatigue on the level of fear of movement shows that lower limb fatigue has a more pronounced effect while both types of fatigue negatively affect athletes with ACL reconstruction. This may be due to the direct involvement of the lower limb muscles in knee joint stability and the psychological connection of these muscles to the site of injury. In contrast, core fatigue, while still influential, may be less directly related to knee stability and thus slightly less influential on fear of movement. (56,57)

Conclusions

According to the results of the present study, it can be stated that lower limb and central fatigue leads to increased LESS test scores, decreased knee flexion angle, increased valgus angle, and fear of movement score, and it seems that this effect was greater in the lower limb fatigue group than in the central fatigue group. Therefore, increased fatigue can lead to an increased risk of ACL re-injury and secondary complications. Therefore, it is important to pay attention to comprehensive rehabilitation programs that focus on endurance and correct compensatory patterns caused by fatigue on landing kinematics in athletes with ACL reconstruction.

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Conflict of interests

No conflict.

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