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Comparison of Eight Weeks of Theraband Resistance Training and Hopping Exercises on Proprioception and Postural Stability Under Muscle Fatigue Conditions in Men at Risk of Anterior Cruciate Ligament Injury

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Original Article

Abstract

Introduction: Neuromuscular fatigue is a significant risk factor for anterior cruciate ligament (ACL) injury. The purpose of the present study was to compare the effects of fatigue induced following a period of Theraband resistance training and hopping exercises on proprioception and postural stability in men at risk of ACL injury.

Materials and Methods: In this semi-experimental study, 30 men aged 18–28 years who met the inclusion criteria were randomly assigned to three groups of 10 participants each: resistance training, hopping exercises, and a control group. Proprioception was measured using the Biodex isokinetic dynamometer, and time-to-stability was assessed using a force plate. The training groups participated in their respective exercise programs for 8 weeks. Pre- and post-test data were analyzed using repeated-measures analysis of variance (ANOVA) and Tukey's post hoc test in SPSS software.

Results: Statistical analysis revealed significant differences between pre- and post-test values for both proprioception ($P = 0.001$, $\eta^2 = 0.14$) and time-to-stability ($P = 0.03$, $\eta^2 = 0.09$). Furthermore, the resistance training group demonstrated greater improvement in time-to-stability than the hopping group. In contrast, the hopping group showed better improvement in proprioception than the resistance training group.

Conclusion: Based on the findings, resistance training can lead to greater improvements in time-to-stability. At the same time, hopping exercises can result in increased proprioception among men at risk of ACL injury. Overall, given the improvements observed in proprioception and time-to-stability under fatigue conditions, these exercises appear to mitigate some of the risk factors associated with ACL injury.

Keywords: Anterior cruciate ligament; Proprioception; Balance; Resistance training; Hopping exercises

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Introduction

The knee joint, as the largest synovial joint in the body, is considered one of the most vulnerable joints during sports activities because powerful muscles, long bones, and high torques increase the likelihood of injury (1). Among the various types of knee injuries, anterior cruciate ligament (ACL) injuries are the most common and play a key role in maintaining joint stability and preventing anterior displacement of the tibia relative to the femur (2). Studies have reported that the incidence of ACL injury among football players is approximately 0.30 cases per 1000 match

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hours (3). In addition to imposing high treatment costs, this injury may lead to reduced or discontinued participation in sports activities and even the loss of an entire season of professional competition. Furthermore, ACL injury is associated with an increased risk of secondary complications such as osteoarthritis (more than 10-fold), meniscal tears, and psychological problems (4), which further highlights the importance of timely prevention and management of this injury.

In addition to causing mechanical instability in the knee joint, anterior cruciate ligament rupture impairs proprioception and neuromuscular control. This ligament contains mechanoreceptors that transmit information related to joint position and movement to the central nervous system. Therefore, injury to this ligament results in reduced accuracy of joint position sense and impaired proprioception (5–7). Loss of function in these receptors weakens coordination among the muscles surrounding the knee and causes delayed muscle responses, which reduce control of sudden movements and the joint's dynamic stability (6, 8). Moreover, disruption of the coordination between the sensory and motor systems affects both static and dynamic balance, making it difficult to maintain the body's center of gravity over the base of support (7, 9). The consequences of these impairments include an increased risk of secondary injuries such as meniscal tears, development of osteoarthritis, graft or ligament re-rupture, and reduced sports performance; in addition, psychological effects such as anxiety and decreased self-confidence are also observed in injured individuals (4, 6, 8). Thus, ACL injury not only affects the knee joint but is also multidimensional, influencing the athlete's performance, safety, and overall health. Most injuries, not only those related to the anterior cruciate ligament, occur during the final stages of sports activities, coinciding with muscular fatigue. Since muscles help maintain joint stability, neuromuscular fatigue may also be a risk factor for non-contact ACL injuries (4). Fatigue of the leg muscles leads to decreased knee and hip flexion, increased ground reaction forces, and greater knee valgus angle, all of which increase stress on the ACL and increase the risk of injury (5).

Specific exercises play an essential role in the rehabilitation and prevention of anterior cruciate ligament injuries. Among these exercises, hopping and TheraBand resistance exercises have been identified as two effective methods for improving proprioception, enhancing neuromuscular control, and increasing knee joint stability (10, 11). Hopping exercises, by providing intense stimulation of sensory receptors and rapid activation of motor units, improve coordination, responsiveness, and muscular control around the knee joint, helping individuals return to sports activities more safely (12). On the other hand, resistance exercises using TheraBand, by strengthening the muscles of the lower extremities, especially those around the knee, and stimulating sensory receptors, play an effective role in improving proprioception and dynamic balance (11, 13). The use of these exercises is important not only in rehabilitation after injury but also in prevention programs and preseason conditioning, as regular performance can significantly reduce the risk of non-contact ACL injuries and improve sports performance (14).

Despite numerous studies on the prevention and rehabilitation of anterior cruciate ligament injury, there remains insufficient evidence on the effects of fatigue on proprioception and postural stability, and on the comparative effects of different exercises on these variables. Most previous studies have examined the effects of hopping exercises or TheraBand resistance exercises separately. In contrast, fatigue is a main factor contributing to impaired neuromuscular performance and an increased risk of non-contact knee injuries (15–17). Since fatigue can reduce joint stability by causing muscle weakness, decreased neuromuscular coordination, and impaired proprioception, examining the neuromuscular system's response under fatigued conditions following different exercises is of particular importance (8, 18). Therefore, the present study is necessary because it has the potential to provide more effective strategies for preventing ACL injuries and improving knee joint stability by comparing the effects of TheraBand strength and hopping exercises on proprioception and postural stability. Accordingly, the research hypothesis is that both types of exercise improve proprioception and postural stability in men at risk of anterior cruciate ligament injury. However, their effects under fatigue conditions may differ. Therefore, the main aim of the present study is to compare the effects of fatigue following periods of TheraBand strength and hopping exercises on proprioception and postural stability in men at risk of anterior cruciate ligament injury.

Materials and Methods

The present study was a semi-experimental study with a pretest–post-test design. The statistical population consisted of students from Kharazmi University, Karaj campus. In this study, the sample size was estimated as 30 participants using G*Power software (G-Power 3.1.5 freeware, University of Düsseldorf, Düsseldorf, Germany), considering high power (0.8), a medium effect size (0.28), and alpha (0.05). The inclusion criteria were a positive tuck jump test, at least 2 years of sports activity, no injuries to the knee and ankle regions, an age range of 18–28 years, body mass index between 20 and 25, and male athletes only. The exclusion criteria included unwillingness to continue participation in the study, spinal fracture and surgery within the past 3 years, neurological disorders within the past 12 months, and any injury or abnormality affecting the study. These individuals were assigned, using simple randomization via www.random.org, to three groups of 10 participants (control group, hopping group, and TheraBand strength group). Participants were allocated to groups by an independent person who was unaware of their conditions. In addition, this study had no sample attrition at the end.

Before the pretest and post-test assessments in all three groups, the fatigue protocol was applied to the participants, and then the assessments were conducted. This study was also conducted in accordance with the ethical principles of research involving humans. Before the start of the study, ethical approval was obtained from the National System of Ethics in Biomedical Research (ethics code: IR.KHU.REC.1403.154). The objectives, implementation stages, benefits, and possible risks of the study were fully explained to all participants, and written informed consent was obtained from them. Participation in the study was entirely voluntary, and participants had the right to withdraw at any stage without consequences. All participants' personal information was treated as confidential, and the results were reported in aggregate. In addition, all assessments and training sessions were conducted under the researchers' supervision and in compliance with safety principles to minimize the risk of injury.

To identify individuals at risk for anterior cruciate ligament injury, the tuck jump test was used. The tuck jump is a highly valid test that reveals biomechanical components and neuromuscular deficits present in athletes' jumping and landing techniques. It is also a valid and reliable method for evaluating and identifying neuromuscular deficits associated with ACL injury. This test consists of performing continuous jumps with maximum height for 10 seconds and provides comprehensive information about individuals at risk of ACL injury. In addition to identifying the ligament-dominance deficit related to dynamic knee valgus, this test can also identify deficits in trunk, leg, and quadriceps dominance. In the present study, the participants were instructed to place their feet in the center of the designated area on the ground. This area was rectangular and consisted of four smaller rectangles, each measuring 40 × 35 cm. The necessary instructions for correct execution of the test were then provided, including raising the knees to hip-joint height and, after each jump, attempting to land in the same starting position. It was also emphasized that upon landing, the feet should be shoulder-width apart, aligned, and should contact the ground simultaneously. After that, the participants began performing repeated jumps in the designated area for 10 seconds. In the present study, individuals who exhibited internal rotation of the thigh and knee during landing and whose feet were not shoulder-width apart upon landing were identified as having dynamic knee valgus deficiency and as persons at risk of anterior cruciate ligament injury (19).

To assess proprioception, the Biodex System 3 isokinetic dynamometer (Biodex System 3, USA) was used, the validity and reliability of which were reported as acceptable by Drouin et al. (2004) (20). For this purpose, proprioception testing was performed after the participants sat on the chair and were fastened with a safety belt, in accordance with the protocol of Gerus et al. (21). Participants were asked to estimate 45 degrees of knee extension; in this condition, 90 degrees of knee flexion was considered as the zero angle or the starting point of movement. For each participant, measurements were taken three times, and the mean difference from the target angle was recorded. In the first stage, after the device reached the 45-degree angle, it was locked for 10 seconds, and the participants focused on that point. In the next stage, while wearing a blindfold, they had to press the lever button they held in their hand when they felt they had reached that point.

To assess time to stabilization, a force plate (Bertec Corporation, USA) was used, the validity and reliability of which were reported as acceptable by Walsh et al. (2006) (22). The testing protocol was performed in accordance with Gribble et al. (23). To determine time to stabilization, 50% of each participant's maximum jump height was first calculated. At this stage, the participant stood barefoot, laterally beside the wall, with the heels on the floor and the lateral malleolus in contact with the wall. Then, the arms were fully extended overhead, and the highest reachable point was marked. Next, the participant jumped upward with maximum effort and landed on the ground with both feet. The difference between the highest reachable point and the point touched after the jump was considered the maximum vertical jump height. This process was repeated three times, and the highest value was recorded as the final value. After determining the maximum jump height, a marker equivalent to 50% of this height was installed above the force plate. Then, the participants stood barefoot at a distance of 70 cm from the center of the force plate. During the jump–landing task, the participant jumped with both feet and attempted to touch the designated marker with the hand on the side of the dominant leg. After the hand contacted the marker, landing had to be performed only with the dominant leg on the center of the force plate. Finally, immediately after landing, the participant was required to place their hands on the pelvis, keep their head up, and focus their gaze straight ahead. The participant had to remain in this position without moving for 20 seconds to record data on time to stabilization. Time to stabilization was considered as the point at which the amplitude of the ground reaction force signals reached within ±5% of the stable value (23, 24).

To induce participant fatigue, the protocol by Orshimo et al. (25) was used. To create controlled muscular fatigue in the lower extremity, the participants performed 10 repetitions of single-leg squats to 90 degrees of knee flexion, 2 maximal single-leg vertical jumps, and 20 repetitions of stepping up and down from a 31-cm step. These exercises constituted one set of the fatigue protocol. After each set, the level of fatigue was recorded based on the Borg Rating of Perceived Exertion (Borg RPE Scale) (0 to 10). If a score of 10 was reported, the single-leg side hop test was performed to ensure that the desired fatigue had been reached. In this test, the participant covered the maximum possible distance with one leg and landed on the same leg. Inability to cover at least 80% of the pretest distance was considered the criterion for achieving the desired fatigue. The mean of three consecutive attempts was calculated as the quantitative index of fatigue, and the test was repeated under conditions similar to the pretest in order to evaluate the degree of performance decline.

The training protocol of this study included two types of exercise programs, namely hopping (Table 1) and resistance exercises with TheraBand (Table 2), which were performed for 8 weeks, 3 sessions per week, and 60 minutes per session. The control group also continued their daily activities, and no protocol was applied to them.

In the hopping exercise section, the participants performed various movements including forward hopping, lateral hopping, forward–backward hopping, square hopping, zigzag hopping, and a Latin figure-eight path. In this study, training intensity was operationally defined as training volume (the product of the number of sets and the number of repetitions), and exercises were progressively increased each week by adding new movements and increasing their complexity, thereby increasing the training load. Training intensity increased progressively by 10%, from a light level in the initial week (intensity 70) to a very heavy level in the final week (intensity 130).

Table 1. Hopping Exercise Protocol

Exercise	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Lateral hopping with two legs, arms free	3×10	–	–	–	–	–	–	–
Forward–backward hopping with two legs, arms free	2×10	2×10	–	–	–	–	–	–
Forward hopping with two legs, arms free	2×10	2×10	–	–	–	–	–	–
Lateral hopping with two legs, hands on chest	–	2×15	–	–	–	–	–	–
Lateral hopping with one leg, arms free.	–	4×5	–	–	–	–	–	–
Lateral hopping with one leg, hands on chest	–	–	3×10	3×10	–	–	–	–
Forward–backward hopping with one leg, arms free	–	–	2×10	–	–	–	–	–
Forward–backward hopping with one leg, hands on chest	–	–	–	2×10	–	–	–	–
Forward hopping with one leg, arms free	–	–	–	3×10	2×10	–	–	–
Zigzag hopping with two legs, arms free	–	–	2×10	–	–	–	–	–
Zigzag hopping with one leg, arms free	–	–	–	2×10	–	–	–	–
Square hopping with two legs, arms free	–	–	–	2×10	–	–	–	–
Square hopping with one leg, arms free	–	–	–	–	2×10	2×10	–	–
Square hopping with one leg, hands on chest	–	–	–	–	–	–	2×10	2×10
Forward hopping with one leg, hands behind the head	–	–	–	–	2×10	2×10	–	–
Lateral hopping with one leg, hands behind head	–	–	–	–	2×10	2×10	3×10	3×10
Forward hopping with one leg, hands on chest	–	–	–	–	2×10	2×10	–	–
Forward hopping with one leg, hands behind the head	–	–	–	–	–	–	2×10	2×10
Zigzag hopping with one leg, hands behind head	–	–	–	–	–	–	2×10	2×10
Figure-eight hopping with two legs, arms free	–	–	–	–	2×10	2×10	–	–
Figure-eight hopping with one leg, arms free	–	–	–	–	–	–	2×10	2×10

Table 2. TheraBand Exercise Protocol

Exercise	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Hip extension in quadruped position	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Hip external rotation	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Seated quadriceps strengthening with a band	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Standing hip abduction with a band	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Quadruped exercise with a band	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Squat with TheraBand	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Bridge with hip abduction	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Hip adduction with TheraBand	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
ACL injury prevention with TheraBand	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25
Abdominal crunch with band	3×10	3×10	3×15	3×15	3×20	3×20	3×25	3×25

The aim of performing these exercises was to improve muscular strength, balance, neuromuscular coordination, and functional stability of the lower extremity (26, 27).

In the resistance exercise section with TheraBand, the participants, after a 10-minute warm-up, performed strengthening exercises for the lower-extremity and core muscles for 40 minutes in standing, sitting, and supine positions, followed by 10 minutes of cool-down movements. The intensity of the exercises was progressively adjusted from simple, light movements to more complex, heavier movements, and overload was applied by increasing the number of training sets and exercises.

At the same time, the band color remained the same throughout the training sessions. These exercises were designed based on the protocol of the TheraBand Academy of Health and Performance and modeled on the study of Ansari et al. (11, 28). The main purpose of performing these exercises was to increase muscular strength and explosive power through greater involvement of muscle fibers and utilization of the elastic properties of the muscles

For data analysis, SPSS software version 27 (IBM Corp., Armonk, NY, USA) was used. First, the Shapiro–Wilk test was applied to examine the normality of data distribution. Then, Levene's test was used to assess the homogeneity of variances among the groups. To compare changes in the dependent variables among the study groups, mixed-model ANOVA was used. In the case of a significant difference among the groups, Tukey's post hoc test was applied to determine the exact location of the differences. The significance level was set at $P < 0.05$ for all tests.

Results

The demographic characteristics of the participants are presented in Table 3. The TheraBand group had greater height and body weight than the other groups. The results of the Shapiro–Wilk and Levene's tests are also reported in Table 4. Descriptive statistics, including the mean and standard deviation of pre-test and post-test scores for all three groups (Control, Hopping, and TheraBand) across both variables (proprioception and time to stabilization), are presented in Table 5.

The results presented in Table 6 showed that the time effect and the time × group interaction effect between the pretest and post-test were significant for the proprioception variable ($F = 17.65$, $P = 0.001$, $\eta^2 = 0.39$); ($F = 15.33$, $P = 0.001$, $\eta^2 = 0.53$), whereas the group effect was not significant $p>0.05$. The results of the Tukey test (Table 7), despite showing a significant time effect, did not indicate a significant difference between any two groups. The within-group test results (Table 8) for proprioception also showed that the hopping group had a larger effect size than the other groups.

The results of the mixed-model ANOVA for time to stabilization showed significant differences in the time effect and the time × group interaction effect ($F = 5.10$, $P = 0.030$, $\eta^2 = 0.15$); ($F = 5.04$, $P = 0.010$, $\eta^2 = 0.27$), while the group effect was not significant ($P > 0.05$). Although the main effect of time showed a slightly higher F value, the time × group interaction demonstrated a smaller significance value.

Table 3. Demographic Information and Mean ± Standard Deviation of Participants

Variable	Control group (N=10)	Hopping Group (N = 10)	TheraBand Group (N = 10)	P value
Height (cm)	174.10 ± 5.44	176.80 ± 4.75	178.70 ± 4.24	0.152
Age (years)	23.1 ± 2.38	22.9 ± 2.49	21.5 ± 2.22	0.645
Weight (kg)	72.00 ± 4.83	74.20 ± 5.78	74.70 ± 3.71	0.318
BMI (m2/kg)	23.81 ± 2.25	23.71 ± 1.04	23.42 ± 1.45	0.278

Table 4. Results of the Shapiro–Wilk and Levene's Tests in the Control, Hopping, and TheraBand Groups

Variable	Time	Group	Normality (Shapiro-Wilk)	Homogeneity of Variance (Levene's Test)
Proprioception	Pretest	Control	0.341	0.515
		Hopping	0.898	
		TheraBand	0.657	
	Post-test	Control	0.995	0.067
		Hopping	0.531	
		TheraBand	0.379	
Time to Stabilization	Pretest	Control	0.718	0.600
		Hopping	0.244	
		TheraBand	0.693	
	Post-test	Control	0.956	0.415
		Hopping	0.368	
		TheraBand	0.367	

Table 5. Descriptive Statistics (Mean and Standard Deviation) of Pre-test and Post-test for the Three Groups and Both Variables

Variable	Group	Stage	Mean ± SD
Proprioception (degree)	Control	Pretest	5.22 ± 2.08
		Post-test	6.32 ± 2.11
	Hopping	Pretest	7.37 ± 3.03
		Post-test	3.77 ± 1.19
	TheraBand	Pretest	7.77 ± 3.28
		Post-test	5.85 ± 3.02
Time to stabilization (s)	Control	Pretest	2.26 ± 0.52
		Post-test	2.48 ± 0.26
	Hopping	Pretest	2.35 ± 0.53
		Post-test	1.95 ± 0.34
	TheraBand	Pretest	2.25 ± 0.40
		Post-test	1.78 ± 0.37

Similar to the proprioception variable, the Tukey post hoc test (Table 7) did not reveal any significant differences between the groups. The within-group test results indicated that the TheraBand group showed greater improvement than the other groups and reported a larger effect size (Table 8).

Discussion

The present study aimed to compare the effects of fatigue following a period of TheraBand strength training and hopping exercises on proprioception and postural stability in men at risk of anterior cruciate ligament (ACL) injury. The findings indicated that, compared with the pretest, there were significant differences in proprioception and time to stabilization. The hopping group demonstrated greater improvement in proprioception compared with the TheraBand group. In contrast, the TheraBand group showed greater improvement in time to stabilization and reported a larger effect size than the hopping group.

The results of the mixed-model ANOVA and paired t-test showed that proprioception significantly improved on the post-test compared with the pretest, which is consistent with the findings of Zahedi (2018) (8). Zahedi investigated the effects of two types of plyometric exercises—hopping and jumping—on knee joint position sense (proprioception) in men following ACL reconstruction and confirmed their positive effects. It appears that hopping exercises stimulate mechanoreceptors within muscles, tendons, and the joint capsule, particularly muscle spindles and Golgi tendon organs. Repeated stimulation of these receptors during high-impact weight-bearing activities increases their sensitivity and enhances the central nervous system's ability to detect joint position and movement (29). On the other hand, strength training—especially exercises targeting the lower-extremity and core muscles—improves neuromuscular control by increasing motor unit recruitment, enhancing muscular coordination, and promoting co-contraction of muscles surrounding the joint, thereby improving joint stability and the accuracy of proprioceptive feedback (30).

Table 6. Results of Inferential Statistics Including the Effects of Time, Group, and Time × Group Interaction with F Values, Degrees of Freedom, Significance Level, and Effect Size

Variable	Source of Variation	F	Degrees of Freedom	P value	Effect Size
Proprioception	Time Effect	17.65	(1, 27)	< 0.001*	0.39
	Group Effect	0.78	(2, 27)	0.46	0.05
	Time × Group Interaction	15.33	(2, 27)	< 0.001*	0.53
Time to Stabilization	Time Effect	5.10	(1, 27)	0.03*	0.15
	Group Effect	3.08	(2, 27)	0.06	0.12
	Time × Group Interaction	5.04	(2, 27)	0.01*	0.27

*Indicates a significant difference at the level of $P < 0.05$

Table 7. Results of Tukey Post Hoc Test Among the Control, Hopping, and TheraBand Groups

Variable	Group Comparison	Mean Difference	P value	95% Confidence Interval
Proprioception	Control – TheraBand	1.03	0.597	-3.67 to 1.59
	Control – Hopping	0.19	0.981	-2.43 to 2.83
	TheraBand – Hopping	1.23	0.484	-3.39 to 3.87
Time to Stabilization	Control – TheraBand	0.35	0.057	-0.005 to 0.71
	Control – Hopping	0.24	0.232	-0.11 to 0.60
	TheraBand – Hopping	0.11	0.727	-0.47 to 0.24

*Indicates a significant difference at the level of P < 0.05

Table 8. Results of Within-Group Tests (T values, Significance Level, and Effect Size) in the Control, Hopping, and TheraBand Groups

Variable	Group	T	P value	Effect Size
Proprioception	Control	1.6	0.13	0.5
	Hopping	5.1	< 0.001*	1.6
	TheraBand	4.7	< 0.001*	1.4
Time to Stabilization	Control	1.2	0.22	0.4
	Hopping	2.5	0.03*	0.8
	TheraBand	2.9	0.01*	0.9

*Indicates a significant difference at the level of P < 0.05

In addition, regular performance of these exercises may induce plastic adaptations in both the peripheral and central nervous systems, leading to faster and more efficient processing of proprioceptive information. Ultimately, this contributes to improved joint position sense, postural stability, and overall sensorimotor function. Wang et al. (2023) also examined the effects of isokinetic muscle-strengthening exercises on knee muscle strength, proprioception, and balance in athletes following ACL reconstruction. They reported that adding regular isokinetic strengthening exercises to rehabilitation programs can improve proprioception in individuals after ACL reconstruction, supporting the findings of the present study (31).

The results also showed that time to stabilization improved significantly from pre- to post-test, with the TheraBand group experiencing better outcomes. This finding is consistent with Hosseinzadeh (2022), who demonstrated that hopping and strength-balance exercises can effectively improve balance in individuals with ankle sprain (32). Additionally, Akbari et al. (2015) reported that balance training can lead to relative improvements in dynamic stability indices during the early stages of rehabilitation after ACL reconstruction (33).

The improvement in time to stabilization among participants who performed hopping and strength exercises may be attributed to the combined effects of enhanced proprioception and increased muscle strength. Hopping exercises, through rapid and dynamic movements, challenge the body's balance systems and strengthen the neuromuscular pathways involved in joint stabilization. Simultaneously, strength training enhances the musculoskeletal system—particularly the core and lower-extremity muscles—providing a stronger foundation for maintaining posture (34). Collectively, these adaptations lead to better control of the body's center of gravity and improved coordination during static and dynamic postural tasks.

Hopping exercises stimulate both sensory and motor systems, increasing coordination between sensory receptors and muscular motor responses (34). During hopping exercises, muscles must contract in a coordinated manner within very short time intervals to prevent falls or loss of balance. This repeated practice improves movement pattern regulation. Strength and plyometric exercises also promote optimal joint stiffness by increasing co-activation of agonist and antagonist muscles, which in turn enhances joint stability against external forces (35).

Limitations

The present study had several limitations, including a relatively small sample size and the absence of long-term follow-up of participants. In addition, the study population was limited to men, which restricts the generalizability of the findings to other age groups and to female populations. Another limitation was the lack of full control over potential confounding variables, such as participants' daily physical activity levels.

Furthermore, although the tuck jump test is considered a valid tool for screening and assessing movement patterns associated with ACL injury risk, relying solely on this test is insufficient for definitive risk prediction. Its results should therefore be interpreted alongside other assessment indicators to provide a more comprehensive evaluation.

Recommendations

Considering the physiological differences between men and women, it is recommended that future studies conduct similar research on female participants and compare the results with those of men. It is also suggested that the long-term retention effects be examined, as time limitations prevented such evaluation in the present study.

Future research is recommended to design more comprehensive training protocols that examine the effects of fatigue in other regions of the lower extremities and the core on the risk of anterior cruciate ligament injury. Studies with longer intervention periods and long-term follow-up are also suggested to provide more effective strategies for preventing ACL injuries.

Conclusion

The findings showed that TheraBand strength training and hopping exercises improved proprioception and time to stabilization under conditions of muscular fatigue. These results suggest that, due to improvements in proprioception and time to stabilization during fatigue, such exercises may help improve some of the risk factors associated with ACL injury. However, to draw direct conclusions regarding a reduction in the incidence of ACL injuries, longitudinal studies with long-term follow-up are required.

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Authors' Contribution

Zanyar Fallahi: Conception and design of the study; provision of administrative, technical, and scientific support; provision of study equipment and samples; data collection; analysis and interpretation of results; statistical expertise; drafting of the manuscript; critical revision of the manuscript for important intellectual content; approval of the final version of the manuscript for submission to the journal; and responsibility for maintaining the integrity of the research process from inception to publication, as well as responding to reviewers' comments.

Seyed Sadreddin Shojaedin: Conception and design of the study; acquisition of financial support; provision of administrative, technical, and scientific support; analysis and interpretation of results; drafting of the manuscript; critical revision of the manuscript for important intellectual content; approval of the final version of the manuscript for submission to the journal; and responsibility for maintaining the integrity of the research process from inception to publication, as well as responding to reviewers' comments.

Hamed Abbasi: Conception and design of the study; drafting of the manuscript; critical revision of the manuscript for important intellectual content; approval of the final version of the manuscript for submission to the journal; and responsibility for maintaining the integrity of the research process from inception to publication, as well as responding to reviewers' comments.

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Conflict of Interest

The authors did not have a conflict of interest.

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