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Impact of a Prevent Injury and Enhance Performance (PEP) Training Program on Dynamic Balance and Center of Pressure in Soccer Players With and Without Anterior Cruciate Ligament Reconstruction

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ABSTRACT

Background: Anterior cruciate ligament (ACL) injuries are common in soccer and can substantially impair postural stability and athletic performance. The Prevent Injury and Enhance Performance (PEP) program has been developed to reduce the risk of ACL injury. This study aimed to examine the effects of an 8-week PEP training program on time to stability (TTS) and center of pressure (COP) parameters in soccer players with and without ACL reconstruction (ACLR).

Methods: This semi-experimental study employed a pre-test–post-test design. Twenty-one male soccer players (mean age: 25.43 years) at an average of 15.12 months post-ACLR and 21 healthy male soccer players (mean age: 22.79 years) participated. Participants performed a jump-landing task, and COP variables and TTS were measured before and after the 8-week PEP training program. Within-group comparisons were conducted using paired t-tests, while between-group differences were analyzed using one-way ANOVA. Statistical significance was set at $p \leq 0.05$.

Results: Within-group analyses demonstrated significant reductions in mediolateral (M-L) COP fluctuations ($p = 0.018$) and M-L TTS ($p = 0.001$) in the healthy group. In the ACLR group, significant improvements were observed in M-L COP fluctuations ($p = 0.001$), M-L COP variability ($p = 0.034$), total TTS ($p = 0.015$), and M-L TTS ($p = 0.001$) following the intervention. Pre-test between-group comparisons revealed significantly greater M-L COP fluctuations ($p = 0.001$), M-L COP variability ($p = 0.044$), and total TTS ($p = 0.021$) in the ACLR group. However, no significant between-group differences were observed post-intervention ($p > 0.05$), suggesting that the PEP program effectively reduced postural control deficits in the ACLR group to levels comparable with healthy players.

Conclusion: The 8-week PEP training program produced significant improvements in postural control in both healthy and ACLR soccer players. These findings support the potential effectiveness of structured neuromuscular training programs in reducing postural instability and possibly lowering the risk of ACL injury or re-injury.

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Introduction

Today, participation in sports is increasing, and health and movement specialists can gain valuable insights into the identification of movement dysfunctions across stages by analyzing an athlete's movement patterns before the season, during the season, or upon returning to training and competition after an injury [1]. In particular, soccer is one of the most popular sports worldwide, with approximately 270 million participants. Due to the high speed of movements, sudden directional changes, and frequent collisions, the risk of injury in soccer is significantly high [2].

Injuries to the lower limbs are the most prevalent in this sport, among which damage or rupture of the anterior cruciate ligament (ACL) is highly frequent [3]. ACL injuries can occur during tasks such as jumping and landing, as well as cutting and pivoting movements. Furthermore, ACL injuries are associated with complications such as osteoarthritis, financial burden, proprioceptive deficits, postural control impairments, and knee joint instability [4].

Most soccer players opt for surgical treatment to return to their previous level of performance. In clinical practice, ACL reconstruction (ACLR) is the gold standard surgical intervention for active patients with an ACL rupture, providing reliable restoration of functional stability [5]. The rate of return to pre-injury competition levels following ACLR has been widely investigated in the literature [6]. Robert et al. [7] reported that only 36% of soccer players returned to their previous competitive level after ACLR.

Several factors contribute to the failure to return to the previous level of competition after ACLR, with postural control deficits being among the most critical. Although reconstruction can restore knee mechanical stability, functional deficits, including impaired proprioception and compromised postural control, may persist for years [8, 9]. In this context, Culvenor et al. [10] demonstrated that postural control deficits, including alterations in center of pressure (COP) and time to stability (TTS), may persist for up to two years following ACLR. These findings underscore the importance of implementing structured injury-prevention programs.

In this regard, one prominent injury-mitigation initiative is the Prevent Injury and Enhance Performance (PEP) program, developed in 1999 by the Santa Monica Orthopaedic and Sports Medicine Research Foundation [11]. This program includes warm-up, plyometric, strength, agility, and stretching exercises. Additionally, the PEP training program emphasizes instruction in proper movement mechanics through verbal feedback [12].

Previous research has demonstrated that the PEP training program can effectively improve performance and reduce ACL injury rates. For example, Lim et al. [13] reported that the PEP training program enhances speed, strength, and agility. Similarly, Jolie et al. [14] demonstrated that the PEP training program can reduce ACL re-injury rates by up to 70%.

Nevertheless, the mechanisms underlying the effects of such exercises in reducing ACL injury rates remain incompletely understood. It remains unclear whether improvements in functional variables, such as muscle strength and other performance-related factors, account for the reduction in ACL injuries, or whether biomechanical factors also contribute to the decrease in injury rates [12]. Consequently, the primary objective of this study was to conduct a comparative analysis of the effects of the PEP training program on postural stability metrics, specifically time to stability (TTS) and center of pressure (COP), between two distinct groups: soccer players post-ACLR and those with no history of ACL injury.

Method

The research employed a semi-experimental pretest–posttest design. The participants were recruited from a population of professional soccer players representing 15 teams in the nation's premier first and second soccer divisions. Sample size calculation was performed using G*Power, which indicated that 21 participants per group were required to detect a statistically significant difference, assuming an effect size, power = 0.80, and $\alpha = 0.05$ [15]. For all analyses, a p-value of less than 0.05 was considered statistically significant.

A total of 42 soccer players were ultimately included in the study and divided into two groups: 21 healthy participants and 21 participants with ACLR. The ACLR group consisted of 21 male soccer players, of whom 17 had undergone reconstruction on the dominant leg and four on the non-dominant leg.

The time elapsed since surgery in the ACLR group ranged from 6 to 18 months, and participants' ages ranged from 20 to 30 years. Additionally, all participants had at least three years of soccer-playing experience. The exclusion criteria were as follows: (1) a history of knee injury or surgery (excluding ACL injury), (2) re-injury or reoperation of the ACLR knee, (3) injury or surgery in the contralateral knee, (4) any condition affecting daily functioning (e.g., visual or vestibular disorders that could influence balance), (5) knee pain within the past three months, and (6) absence from more than three sessions or from two consecutive sessions of the PEP training program.

This investigation was conducted in accordance with ethical standards and received official approval (approval code: SSRI.REC-2312-2560; date: February 29, 2024) from the Ethics Committee of the Iranian Research Institute of Physical Education and Sport Sciences. All participants provided written informed consent before enrollment in the study.

Procedures

All tests were conducted under the supervision of an expert from a sports biomechanics laboratory. Demographic variables, including age, weight, height, body mass index (BMI), and Tegner Activity Scale (TAS) level, were recorded for all participants. Following the collection of demographic data, participants performed a jump and, after completing a soccer-specific heading task, landed on the force plate on a single leg (Figure I).

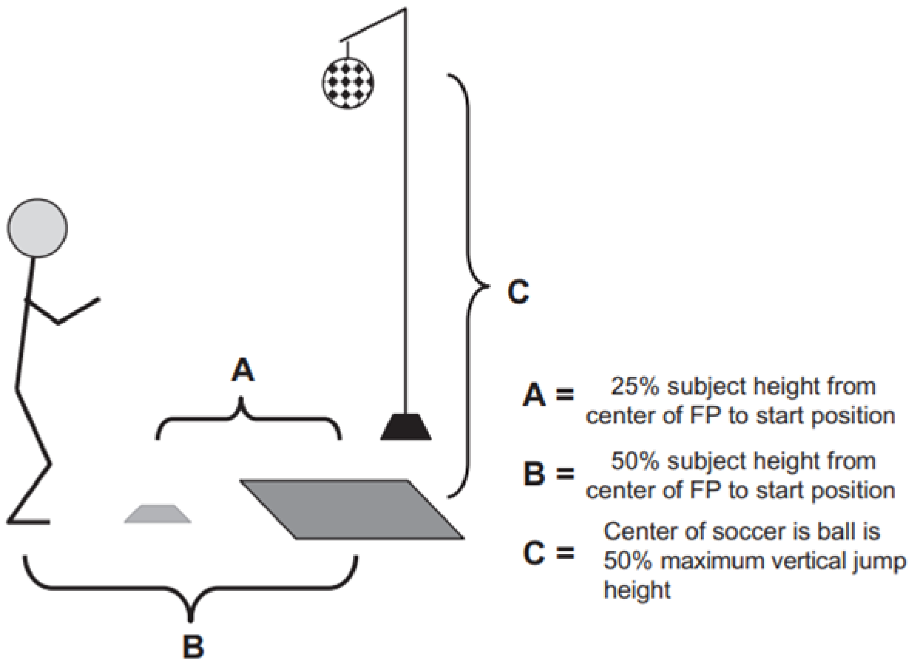

Figure 1: Diagram of Subject Testing Set-Up (FP = Force Plate).

Kinetic data were acquired using a Kistler force plate at a sampling frequency of 1000 Hz. Measurements included time to stabilization (TTS) and center of pressure (COP) displacements along both the mediolateral (ML) and anteroposterior (AP) axes.

Jumping and Landing Task

Participants were positioned at a distance equivalent to half of their body height from the center of the force plate (Figure 1). The task required participants to clear a low hurdle (a 7.5-cm cone) placed at the midpoint of the approach. Upon landing, they were instructed to immediately perform a vertical jump to simulate heading a stationary ball. The ball was suspended at a height equivalent to 50% of each participant's predetermined maximum vertical jump. The maneuver was completed with a deliberate single-leg landing on the force plate [16].

Participants were also instructed to maintain their balance for 5 to 10 seconds after landing [17]. If the contralateral leg touched either the floor or the tested leg, the trial was terminated. No additional landing instructions were provided, as the study aimed to assess the participants' natural postural strategies [18].

Data Processing

Kinetic data were processed and analyzed using Nexus 1.8.5 and Visual3D software. The data were smoothed using a fourth-order Butterworth filter with a 20 Hz cutoff frequency and subsequently normalized to each subject's body weight [19]. Additionally, CoP changes (fluctuations and variability) in the mediolateral (ML) and anteroposterior (AP) directions were analyzed. ICC values for the key variables ranged from 0.73 to 0.87, indicating good to excellent reliability [20].

The sequential averaging method was employed to calculate TTS in the AP, ML, and vertical directions. For standardization, balance maintenance was assessed over a 10-second window beginning with the first contact with the force plate [21]. This period was chosen because all participants had reached a stable state, and the force plate signals had stabilized. In this method, the overall mean of the ground reaction force data was first calculated. Subsequently, the time to stability was determined instantaneously using the sequential averaging method according to formulas 1, 2, and 3 [22].

1. Seqavgx (n) = $\frac{\sum_1^n fx}{n}$
2. Seqavgy (n) = $\frac{\sum_1^n fy}{n}$
3. Seqavgz (n) = $\frac{\sum_1^n fz}{n}$
4. TTS total = $\sqrt{TTSx^2 + TTSy^2} + TTSz^2$

PEP Training Program

The PEP training program consists of warm-up, strength training, plyometric exercises, agility drills, and stretching (Table 1). Both the healthy and ACLR groups participated in an 8-week PEP training program during the preseason, before the start of competition. Each training session lasted 15–20 minutes [11]. Additionally, the PEP training program incorporates verbal feedback to correct and enhance movement patterns [23]. Coaches emphasized proper landing technique and instructed players to perform soft landings. To ensure correct execution, a one-hour session was dedicated to teaching the proper exercise techniques.

Table 1: PEP* Training Program

Phase	Activity (Duration of Time To Complete Activity)	Time at Which Activity Occurs During Workout	Purpose
1.Warm–up (purpose: preparation)	Jog line-to-line (30 sec)	0 to 0.5 min	Prepare for training session
	Shuttle run (side-to side)(30 sec)	0.5 to 1 min	Engage hip abductors and adductors; promote speed; avoid inward caving of knee joint
	Backward run (30 sec)	1 to 1.5 min	Engage hip extensors and hamstrings
2. Strengthening (purpose: leg strength)	Walking lunges (1 min)	1.5 to 2.5 min	Strengthen quadriceps
	Russian hamstring (1 min)	2.5 to 3.5 min	Strengthen hamstrings
	Single toe raises (1 min)	3.5 to 4.5 min	Strengthen calf; improve balance
3. Plyometrics (purpose: power, strength, speed)	Lateral hops over cone (30 sec)	4.5 to 5 min	Increase power and strength; emphasize neuromuscular control
	Forward and backward hops over cone (30 sec)	5 to 5.5 min	Increase power and strength; emphasize neuromuscular control
	Single leg hops over cone (30 sec)	5.5 to 6 min	Increase power and strength; emphasize neuromuscular control
	Vertical jumps with headers (30 sec)	6 to 6.5 min	Increase vertical jump
	Scissor jump (30 sec)	6.5 to 7 min	Increase vertical jump
4. Agilities	Forward run with 3-step deceleration	7 to 8 min	Increase dynamic stability of ankle-knee-hip complex
	Lateral diagonal runs	8 to 9 min	Encourage technique and stabilization of hip and knee; avoids ‘‘knock-knee’’ position
	Bounding run (44 yd)	9 to 10 min	Increase hip-flexion strength, power, and speed
5.Stretching (can be performed after warm-up)	Calf stretch (30 sec · 2 repetitions)	10 to 11 min	Stretch calf; focus on lengthening muscle
	Quadriceps stretch (30 sec · 2 repetitions)	11 to 12 min	Stretch quadriceps; focus on lengthening muscle
	Figure four hamstring stretch (30 sec · 2 repetitions)	12 to 13 min	Stretch hamstrings; focus on lengthening muscle
	Inner thigh stretch (20 sec · 3 repetitions)	13 to 14 min	Stretch adductors; focus on lengthening muscle
	Hip flexor stretch (30 sec · 2 repetitions)	14 to 15 min	Stretch hip flexors; focus on lengthening muscle

PEP* = Prevent injury and Enhance Performance

Statistical Analyses

All measured variables were tested for normality using the Shapiro–Wilk method. For intra-group comparisons, a paired t-test was applied. At the same time, a one-way Analysis of Variance (ANOVA) was used to examine pre-test and post-test differences between the healthy and ACLR groups. All statistical analyses were conducted using IBM SPSS (Version 26.0), with a significance level set at $p \leq 0.05$.

Results

Table 2 presents the demographic characteristics of the participants.

Tables 3 and 4 present the within-group comparisons (pre-test vs. post-test) for the healthy control and ACLR groups, respectively, based on dependent t-tests. In the healthy group (Table 3), significant improvements from pre- to post-test were observed only in the mediolateral (ML) direction, specifically in COP fluctuations ($p = 0.018$) and time to stabilization (TTS, $p = 0.001$). The remaining COP and TTS components did not show statistically significant changes (all $p \geq 0.05$). In contrast, the ACLR group (Table 4) demonstrated more pronounced improvements following the intervention. Significant pre-post differences were identified in multiple metrics, including COP fluctuations in the ML direction ($p = 0.001$), COP variability in the ML direction ($p = 0.034$), total TTS ($p = 0.015$), and TTS in the ML direction ($p = 0.001$).

As shown in Table 5, pre-test comparisons revealed significant between-group differences. Specifically, the ACLR group exhibited greater postural sway than the healthy controls in the mediolateral (ML) direction, reflected by higher COP fluctuations (p = 0.001) and increased COP variability (p = 0.044). Furthermore, the ACLR group demonstrated longer stabilization times in both the ML direction (TTS-ML, p = 0.015) and overall (Total TTS, p = 0.021). Following the 8-week PEP intervention, these disparities were no longer observed. Post-test comparisons (Table 6) indicated no significant differences between the groups for any COP or TTS measure (all $p \geq 0.05$).

Table 2: Demographic Characteristics

Variable	healthy (n=21) Mean ± SD	ACLR (n=21) Mean ± SD
Age (y)	22.79±2.09	25.43 ± 2.20
Height (cm)	182.29±24.14	180.54±20.31
Weight (kg)	74.66±7.29	74.32±6.93
BMI (kg/m2)	22.08±3.27	23.19±4.0
Time since surgery (mo)	N/A	15.12±3.86
TAS	8.43±2.81	7.59±3.33
Injured limb (Dominant Limb)	N/A	17

BMI: body mass index, TAS: Tegner activity scale, ACLR: Anterior cruciate ligament reconstruction.

Table 3: Results of the Dependent t-test for the Healthy Group

	Pre-test Mean ± SD	Post-test Mean ± SD	t	p
COP fluctuations (A-P)	61.73 ± 17.09	54.10 ± 10.22	2.03	0.314
COP fluctuations (M-L)	74.72 ± 21.58	61.18 ± 23.43	2.62	0.018*
COP variability (A-P)	182.33 ± 42.01	159.90 ± 39.17	1.14	0.267
COP variability (M-L)	288.67 ± 63.24	265.71 ± 52.01	1.91	0.069
TTS total	4.67 ± 0.16	4.11 ± 0.13	1.27	0.214
TTS vertical	2.86 ± 0.07	2.82 ± 0.10	0.38	0.711
TTS (A-P)	3.03 ± 0.12	2.84 ± 0.18	1.72	0.101
TTS (M-L)	3.31 ± 0.20	2.82 ± 0.11	3.89	0.001*

A-P: antero–posterior direction, M-L: medio-lateral direction, COP (Center of Pressure) Values (mm), TTS (Time to stability) values (S).

Table 4: Results of the Dependent t-Test for the ACLR Group

	Pre-test Mean ± SD	Post-test Mean ± SD	t	p
COP fluctuations (A-P)	89.12 ± 24.37	66.31 ± 17.72	3.02	0.099
COP fluctuations (M-L)	102.56 ± 19.20	72.43 ± 20.08	5.12	0.001*
COP variability (A-P)	189.19 ± 39.25	153.74 ± 46.40	2.71	0.112
COP variability (M-L)	312.80 ± 59.42	281.90 ± 61.13	2.31	0.034*
TTS total	5.13 ± 0.21	4.27 ± 0.15	3.89	0.015*
TTS vertical	3.07 ± 0.09	2.90 ± 0.17	0.76	0.461
TTS (A-P)	3.44 ± 0.20	3.01 ± 0.14	1.75	0.098
TTS (M-L)	3.61 ± 0.19	2.99 ± 0.10	4.92	0.001*

ACLR: Anterior cruciate ligament reconstruction, A-P: antero–posterior direction, M-L: medio-lateral direction, COP (Center of Pressure) Values (mm), TTS (Time to stability) values (S).

Table 5: The Between-Group Differences in the pre-test.

	Healthy Mean ± SD	ACLR Mean ± SD	p	f	Effect Size (η²)
COP fluctuations (A-P)	61.73 ± 17.09	89.12 ± 24.37	0.057	2.12	0.18
COP fluctuations (M-L)	74.72 ± 21.58	102.56 ± 19.20	0.٠01*	4.56	0.51
COP variability (A-P)	182.33 ± 42.01	189.19 ± 39.25	0.462	0.56	0.03
COP variability (M-L)	288.67 ± 63.24	312.80 ± 59.42	0.044*	2.18	0.19
TTS total	4.67 ± 0.16	5.13 ± 0.21	0.021*	2.89	0.29
TTS vertical	2.86 ± 0.07	3.07 ± 0.09	0.207	1.34	0.09
TTS (A-P)	3.03 ± 0.12	3.44 ± 0.20	0.600	0.28	0.02
TTS (M-L)	3.31 ± 0.20	3.61 ± 0.19	0.15*	1.52	0.12

ACLR: Anterior cruciate ligament reconstruction, A-P: antero–posterior direction, M-L: medio-lateral direction, COP (Center of Pressure) Values (mm), TTS (Time to stability) values (S).

Table 6: The between-group Differences in the post-test.

	Healthy Mean ± SD	ACLR Mean ± SD	p	f	Effect Size (η²)
COP fluctuations (A-P)	54.10 ± 10.22	66.31 ± 17.72	0.367	0.85	0.07
COP fluctuations (M-L)	61.18 ± 23.43	72.43 ± 20.08	0.711	0.14	0.01
COP variability (A-P)	159.90 ± 39.17	153.74 ± 46.40	0.222	1.56	0.13
COP variability (M-L)	265.71 ± 52.01	281.90 ± 61.13	0.113	2.68	0.22
TTS total	4.11 ± 0.13	4.27 ± 0.15	0.316	1.05	0.09
TTS vertical	2.82 ± 0.10	2.90 ± 0.17	0.470	0.54	0.05
TTS (A-P)	2.84 ± 0.18	3.01 ± 0.14	0.502	0.46	0.04
TTS (M-L)	2.82 ± 0.11	2.99 ± 0.10	0.089	3.12	0.26

ACLR: Anterior cruciate ligament reconstruction, A-P: antero–posterior direction, M-L: medio-lateral direction, COP (Center of Pressure) Values (mm), TTS (Time to stability) values (S).

Discussion

This study aimed to investigate the effects of an 8-week PEP training program on postural control in soccer players with and without ACL reconstruction. The results demonstrated that the PEP program improved postural control deficits in both the healthy and ACLR groups. Although pre-test comparisons revealed significant differences in certain COP and TTS components between the healthy and ACLR groups, these differences were not observed at the post-test, highlighting the positive impact of the PEP training program.

It is well established that static postural control is impaired following ACLR compared to healthy controls [24]. The findings of the present study indicate that performing a dynamic task can further exacerbate postural control deficits in the ACLR limb. In this context, Sugimoto et al. [25] reported significantly impaired single-leg postural stability in the ACLR limb compared to healthy controls, whereas no deficits were observed during bipedal standing. Similarly, two other studies demonstrated that postural control deficits were significantly worse in the injured limb compared to the contralateral limb. This suggests that when both feet are on the ground, the base of support is increased, and postural control deficits in the double-leg stance may not reflect a history of ACL injury [9, 10].

Given the nature of soccer, which involves repeated single-leg jumps and landings, cutting movements, and frequent reliance on one leg, the ability to maintain postural control and rapidly regain balance after these tasks is recognized as a critical factor in injury prevention [26].

Maintaining balance during landing after a jump requires simultaneous postural control in both the anteroposterior (AP) and mediolateral (ML) directions. Greater deviations in either direction are generally indicative of increased postural instability [27]. In the present study, postural control deficits were more pronounced in the ML direction than in the AP direction. Previous research suggests that these ML-direction deficits following ACLR likely reflect the heightened demands for mediolateral knee motion control during single-leg landing. Although knee valgus was not directly assessed in this study, prior investigations have shown that knee valgus is greater during landing in individuals post-ACLR than in healthy controls [28, 29].

The role of neuromuscular training (NMT) in enhancing postural stability and balance has attracted considerable attention from researchers in recent years [30, 31]. Traditionally, NMT was primarily regarded as a form of balance training; however, it is now recognized as encompassing multi-component exercises that involve movements across multiple planes.

In this context, studies by Kowalczyk et al. [32], Bieć et al. [33], Lee et al. [34], and Borghuis et al. [35] align with the findings of the present study, demonstrating that NMT can improve time to stabilization (TTS) and center of pressure (COP) components in soccer players. Conversely, some studies have reported limited effects of NMT on postural control. For example, research by Patrick et al. [36] and Everett et al. [37] found that six weeks of NMT did not yield significant improvements in postural stability. These discrepancies suggest that the effectiveness of NMT may vary with specific training conditions, population characteristics, or the duration and intensity of the intervention.

In the present study, the 8-week PEP training program effectively improved COP and TTS deficits in the ACLR group. However, this improvement was not significant in the anteroposterior (AP) direction. This effect can be attributed to the nature of the PEP program, which encompasses exercises across multiple movement planes. Indeed, intervention programs targeting multiple planes of motion are necessary for effectively reducing the risk of ACL injury. While conventional muscle strength training often emphasizes movements in the sagittal or frontal planes, the PEP program also engages the coronal plane, where ACL injuries frequently occur [38].

Consistent with the present findings, studies by Paterno et al. [39], Myer et al. [40], and Malgorzata et al. [32] demonstrated that six weeks of NMT could significantly reduce COP fluctuations in the mediolateral (ML) direction. In the current study, the PEP program was implemented over eight weeks, suggesting that a 6- to 8-week NMT intervention is sufficient to enhance motor recruitment. However, it may not provide the duration necessary for muscle hypertrophy or improvements in muscular endurance [41].

Kamath et al. [42] reported that participants in training programs incorporating agility and balance components showed faster improvements in TTS than those following traditional rehabilitation protocols. The improvement in TTS observed in the ACLR group following the PEP program may also be linked to neuroplastic changes in the brain. For example, one study found that the ACLR group showed enhanced visual cognition following NMT, with visual memory associated with neural activity in the cerebral cortex—a correlation not observed in healthy controls. These findings suggest that the PEP program may induce distinct neuroplastic adaptations in ACLR patients, contributing to improved proprioception and postural stability to a degree not observed in healthy players [8].

The studies by Seok et al. [43], Choi et al. [44], and Tanpowpong et al. [45] are also consistent with the present findings. These studies demonstrated that multi-component rehabilitation training could significantly reduce TTS after ACLR. The rapid recovery of balance following NMT is likely linked to improvements in proprioception. NMT enhances proprioception by promoting balance, stability, and neuromuscular coordination. Such exercises stimulate proprioceptive receptors in the joints and muscles, enabling the body to more accurately perceive its position and movement [46].

Our findings suggest that, irrespective of the underlying mechanism for improvements in balance after training, changes in movement patterns and postural control may be a key factor in the success of injury-prevention programs in reducing the risk of

ACL tears.

Several limitations of the current study should be acknowledged. First, participants' lifestyle factors, including sleep patterns, dietary habits, and exercise-induced fatigue, were not controlled, which may have influenced the outcomes. Additionally, the study focused exclusively on soccer players, which limits the generalizability of the findings. To obtain a more comprehensive understanding, future research should include athletes from diverse sports disciplines, such as volleyball and basketball.

Conclusions

The analysis demonstrated that the PEP training program led to significant improvements in postural control measures in both the ACLR and healthy control groups. These findings suggest that the program enhances motor performance and may reduce the risk of ACL injury. Accordingly, the PEP training program can be considered an effective strategy for preventing ACL injury or re-injury in soccer players.

Author Contributions

A SH M: design. M M: data collection. M GH: writing – original draft. H D: results analysis. M GH: writing – review & editing, results analysis.

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Google Scholar profile: https://scholar.google.com/citations?user=if1jLtMAAAAJ&hl=en

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