

Effects of an 8-Week PEP Training Program on Lower-Extremity Kinematics and Injury Incidence During a 90° Cutting Maneuver in Soccer Players With and Without ACL Reconstruction

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Abstract

Background

Anterior cruciate ligament reconstruction (ACLR) restores knee stability, but biomechanical deficits during cutting often persist after return to sport, potentially increasing the risk of subsequent injury. This study investigated the effects of an 8-week Prevent Injury and Enhance Performance (PEP) training program on three-dimensional lower-extremity kinematics during a 90° cutting maneuver and subsequent 6-month injury incidence in soccer players with ACLR and healthy controls.

Methods

Forty-two male competitive soccer players (ACLR, $n = 21$; control, $n = 21$) participated in this quasi-experimental pre-test/post-test study. Participants completed three-dimensional biomechanical assessments before and after an 8-week PEP training program (three sessions/week, 15–20 min/session). Lower-extremity kinematics during a 90° cutting maneuver were recorded using a Vicon motion analysis system. Injury surveillance was conducted prospectively for six months after the intervention, and injury incidence rates were calculated based on soccer training and match exposure. Changes in kinematic variables were analyzed using two-way mixed-design ANOVA.

Results

Significant improvements over time were observed in several ankle, knee, and hip kinematic variables, with the largest effects found for knee flexion ($\eta^2 = 0.589$), hip flexion ($\eta^2 = 0.463$), and ankle abduction ($\eta^2 = 0.401$). Significant Group $\times$ Time interactions were identified for ankle eversion ($p = 0.009$), knee flexion ($p = 0.031$), and hip flexion ($p = 0.007$), indicating greater improvements in the ACLR group. During the 6-month follow-up, injury incidence rates were comparable between groups (11.43 vs. 13.03 injuries per 1000 exposure hours), and no ACL graft ruptures or contralateral ACL injuries were recorded.

Conclusion

The 8-week PEP training program improved lower-extremity movement patterns during a sport-specific cutting task in both groups, with greater biomechanical adaptations observed in athletes following ACL reconstruction. Although injury incidence was similar between groups during follow-up, the study was not powered to evaluate injury prevention outcomes. These findings support incorporating structured neuromuscular training into late-stage rehabilitation to address persistent movement deficits after ACL reconstruction.

Key Points

- An 8-week PEP program improved lower-extremity biomechanics during a 90° cutting maneuver.
- Biomechanical adaptations were greater in soccer players following ACL reconstruction than in healthy controls.
- The findings support the clinical use of the PEP program to improve cutting mechanics and potentially reduce injury risk after ACL reconstruction.

Background

Anterior cruciate ligament (ACL) rupture is one of the most serious injuries in soccer, with more than 250,000 new cases reported annually in the United States alone [1]. Beyond the immediate physical consequences, ACL injury also places a substantial economic burden on healthcare systems, with annual costs exceeding \$3 billion, and may prematurely end the careers of competitive athletes [2, 3]. Although surgical techniques and postoperative rehabilitation have advanced considerably, the risk of a second ACL injury after reconstruction remains substantial. Approximately 20–25% of athletes who return to sport following ACL reconstruction (ACLR) sustain a subsequent ACL injury, particularly younger athletes participating in high-demand sports [4–6]. A recent meta-analysis reported a comparable second ACL injury incidence of 21.6% among soccer players, further emphasizing the magnitude of this problem [7]. This is particularly important because revision ACL reconstruction is associated with poorer functional outcomes and lower rates of successful return to sport than primary reconstruction [8, 9].

Persistent neuromuscular and biomechanical impairments are believed to contribute substantially to the risk of secondary injury after ACLR. Even after meeting return-to-sport criteria, many athletes continue to demonstrate abnormal movement patterns during dynamic tasks [10–12]. These deficits include reduced knee flexion, greater knee valgus, and higher ground reaction forces, all of which have been associated with increased ACL loading [13, 14]. Similar abnormalities have also been reported during cutting tasks. Pediatric soccer players who returned to sport after ACLR demonstrated greater peak hip flexion, greater knee valgus, and reduced knee flexion during unplanned cutting compared with healthy players [15].

Among sport-specific movements, cutting is one of the most frequent mechanisms of non-contact ACL injury and accounts for nearly half of all cases [16]. A 90° cutting maneuver places substantial mechanical demands on the lower extremity because it combines rapid deceleration, multiplanar loading, and frontal-plane knee control within a very short ground-contact period [17, 18]. Athletes following ACLR commonly perform this task with reduced knee flexion and lower knee extensor moments during stance [19, 20]. These movement patterns likely reflect a protective stiffening strategy that may compensate for quadriceps weakness or perceived knee instability [21]. Although this strategy may increase confidence during movement, it also reduces shock absorption and may increase loading

on passive knee structures, potentially maintaining injury risk [22, 23]. Given these biomechanical demands, interventions that improve movement control during cutting may help reduce injury risk and support safer return to sport.

Supporting this rationale, a recent systematic review reported that neuromuscular and sensorimotor training improves joint position sense, balance, muscle strength, and movement biomechanics following ACLR [24]. Among the available neuromuscular interventions, the Prevent Injury and Enhance Performance (PEP) program, developed by the Santa Monica Orthopaedic and Sports Medicine Research Foundation, is one of the most widely studied neuromuscular injury prevention programs in sports medicine [25, 26]. The program consists of a 15–20-minute warm-up that incorporates stretching, strengthening, plyometric, agility, and running exercises to improve lower-extremity neuromuscular control [27]. Consistent use of the PEP program has been associated with reductions in ACL injury incidence of up to 70% [25]. Evidence also suggests that combining the program with external focus instructions may further improve hip and knee biomechanics during dynamic tasks, including in athletes following ACL reconstruction [28].

Despite increasing evidence supporting neuromuscular training, several important questions remain unanswered. Most previous studies have focused on primary ACL injury prevention or landing biomechanics rather than cutting mechanics after ACL reconstruction [29]. Direct comparisons between athletes with ACLR and healthy soccer players undergoing the same intervention are also limited, making it unclear whether movement deficits can be restored to levels comparable with those of uninjured athletes [30]. Few studies have combined biomechanical assessment with prospective injury surveillance, making it difficult to determine whether improvements in movement quality translate into more favorable injury outcomes after return to sport. Therefore, the present study investigated the effects of an 8-week Prevent Injury and Enhance Performance training program on three-dimensional lower-extremity kinematics during a 90° cutting maneuver in soccer players with and without ACL reconstruction, followed by a 6-month injury surveillance period. We hypothesized that the PEP program would improve lower-extremity kinematics in both groups, with greater kinematic adaptations in athletes following ACL reconstruction. We also hypothesized that injury incidence during follow-up would be comparable between groups after completion of the training program.

Methods

Study Design

This quasi-experimental investigation employed a two-group pre-test/post-test design with a 6-month prospective injury surveillance period. Participants completed baseline biomechanical testing, underwent an 8-week PEP training program, and repeated the same assessments under identical laboratory conditions following the intervention. Participants were subsequently followed for 6 months to document lower-extremity injuries. The primary outcome was three-dimensional lower-extremity kinematics during a 90° cutting maneuver. Secondary outcomes included injury incidence, injury type,

injury mechanism, and exposure hours. The study was approved by the Ethics Committee of the Iranian Research Institute of Physical Education and Sport Sciences (approval code: SSRI.REC-2312-2560; February 29, 2024) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to study enrollment.

Participants

A total of 42 male competitive soccer players participated in this study. Sample size was calculated a priori using G*Power (version 3.1.9.7) based on effect size estimates from previous studies examining lower-extremity kinematics and neuromuscular adaptations following ACL reconstruction and neuromuscular training [27]. Based on a significance level of $\alpha = 0.05$, a statistical power of 80%, and an expected moderate-to-large effect size (Cohen's $d = 0.60$), the required sample size was 17 participants per group [31].

Eligible participants were male soccer players aged 18–25 years with at least three years of competitive playing experience and regular participation in a minimum of three training sessions per week. Participants in the ACLR group had undergone unilateral primary ACL reconstruction 6–14 months before baseline testing, had returned to unrestricted soccer participation, and had received medical clearance for return to sport. ACL reconstruction had been performed using either a hamstring tendon autograft ($n = 15$) or a bone–patellar tendon–bone autograft ($n = 6$). Control participants had no history of ACL injury or reconstruction.

Participants were excluded if they had a history of lower-extremity surgery other than unilateral ACL reconstruction, current knee symptoms or self-reported knee osteoarthritis, balance or neuromuscular disorders, any lower-limb injury within the previous six months, structural lower-limb malalignment, systemic or inflammatory joint disease, or any medical condition that contraindicated high-intensity physical activity.

Procedures

After eligibility was confirmed, participants received standardized verbal instructions regarding all study procedures. They then completed a questionnaire that collected demographic characteristics, injury history, and Tegner Activity Scale scores. Participants subsequently attended the biomechanics laboratory for baseline testing. Data collection was completed over five consecutive days between 13:00 and 18:00 to ensure consistent testing conditions. Before testing, the principal investigator demonstrated the 90° cutting maneuver and provided standardized instructions to ensure consistent task performance. Participants then performed the cutting task while three-dimensional kinematic data were recorded using a Vicon motion capture system. A one-minute rest period was provided between trials to minimize fatigue. Following baseline testing, participants completed the 8-week PEP training program. Training sessions were conducted between 15:00 and 16:00 under the supervision of the

principal investigator and a certified soccer coach. Upon completion of the intervention, post-training biomechanical assessments were conducted under identical laboratory conditions using the same protocol as baseline testing.

Kinematic Measures

Three-dimensional lower-extremity kinematics were recorded using a four-camera Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, UK) sampling at 200 Hz [32]. The primary outcomes were hip, knee, and ankle joint angular excursions during the 90° cutting maneuver. Angular excursion was defined as the difference between the joint angle at initial ground contact and the peak angle reached during the stance phase [33]. Initial ground contact was identified using the event detection algorithm implemented in Visual3D (C-Motion Inc., Germantown, MD, USA), based on the kinematic trajectories of the foot markers.

A modified Plug-in Gait marker set with cluster tracking was used for motion capture. Fourteen-millimeter reflective markers were placed bilaterally on the acromion processes, anterior and posterior superior iliac spines, medial and lateral femoral epicondyles, medial and lateral malleoli, the posterior aspect of the calcaneus, and the dorsum of the foot between the first and second metatarsal heads. Rigid four-marker clusters were secured to the mid-thigh and mid-shank segments to improve tracking accuracy [34]. Before dynamic testing, participants completed a static calibration trial while standing in a neutral anatomical position. This trial was used to define segment coordinate systems, estimate joint centers, and generate an individualized biomechanical model [35]. Participants then performed the cutting task, and four successful trials were collected for each participant and averaged for analysis. Trials were repeated if balance was lost, marker trajectories were incomplete, or the cutting maneuver was performed incorrectly. Marker trajectories were processed using Nexus software and subsequently analyzed in Visual3D.

90° Cutting Maneuver Procedure

Participants began each trial from a starting position located 5 m before the change-of-direction point. They were instructed to accelerate at a near-maximal speed from the starting position, plant the test limb, perform a 90° cut toward the contralateral side, and continue running for at least 3 m [36]. In the ACLR group, the reconstructed limb was tested, whereas the dominant limb, defined as the preferred leg for kicking a ball, was assessed in the control group [37]. Participants received no instructions regarding cutting technique to preserve their natural movement strategy [38]. Four successful trials were collected from each participant for analysis.

Intervention

Participants completed an 8-week Prevent Injury and Enhance Performance (PEP) training program three times per week. Each session lasted approximately 15–20 minutes and was supervised by the principal

investigator and an experienced soccer coach [26, 39]. The program consisted of five components: warm-up (jogging, shuttle runs, and backward running), stretching (calf, quadriceps, hamstrings, hip flexors, and adductors), strengthening (walking lunges, Russian hamstring exercise, and single-leg toe raises), plyometric exercises (lateral, forward/backward, and single-leg hops, vertical jumps, and scissors jumps), and agility drills (shuttle, diagonal, and bounding runs). Participants received standardized verbal instructions using an external focus of attention (e.g., "land softly" and "push off quickly") and were consistently encouraged to maintain neutral lower-limb alignment, minimize excessive frontal-plane knee motion, and land with greater hip and knee flexion [40, 41]. Before the intervention began, all participants attended a familiarization session during which all exercises were demonstrated and practiced under supervision.

Injury Surveillance

Following completion of the intervention, participants were prospectively monitored for 6 months to record lower-extremity injuries sustained during soccer participation. Injury surveillance followed the international recommendations for soccer injury reporting [42, 43]. All injuries occurring during training sessions or competitive matches were recorded by the principal investigator in collaboration with the team medical staff. A reportable injury was defined as any lower-extremity musculoskeletal complaint that resulted in the inability to fully participate in at least one subsequent training session or match [44]. Injury severity was classified according to time lost from sport as minimal (1–3 days), mild (4–7 days), moderate (8–28 days), or severe (> 28 days) [45]. Injuries were further categorized according to mechanism (contact or non-contact), setting (training or match), and anatomical location (knee or other lower-extremity regions). Individual training and match exposure time was recorded for each participant throughout the follow-up period and used to calculate injury incidence per 1000 hours of exposure [42]. Rehabilitation sessions completed by participants in the ACLR group were excluded from exposure calculations, as only soccer-specific training and match participation were considered.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean $\pm$ standard deviation (SD). Data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Baseline differences between groups were examined using independent-samples t-tests. Changes in lower-extremity kinematics were analyzed using a two-way mixed-design analysis of variance (ANOVA) to evaluate the main effects of group and time, as well as the Group $\times$ Time interaction [46]. When significant main or interaction effects were identified, Bonferroni-adjusted pairwise comparisons were performed. Effect sizes were reported as partial eta squared (η^2), and statistical significance was set at $p < 0.05$ [47]. All participants completed the study; therefore, no missing data imputation was required. Injury incidence was calculated as the number of injuries per 1000 hours of soccer exposure.

Results

Participant Characteristics

Participant characteristics are summarized in Table 1. The ACLR and control groups did not differ significantly in age, height, body mass, body mass index, or Tegner Activity Scale score (all $p > 0.05$). The mean time since ACL reconstruction was 9.12 ± 3.86 months.

Table 1
Participant characteristics (mean $\pm$ SD)

Variable	ACLR (n = 21)	Control (n = 21)	p
Age (years)	23.43 $\pm$ 2.20	22.79 $\pm$ 2.09	0.32
Height (cm)	180.54 $\pm$ 10.31	182.29 $\pm$ 9.14	0.71
Body mass (kg)	74.32 $\pm$ 6.93	74.66 $\pm$ 7.29	0.48
Body mass index (kg/m ²)	23.19 $\pm$ 4.00	22.08 $\pm$ 3.27	0.25
Time since ACL reconstruction (months)	9.12 $\pm$ 3.86	—	—
Tegner Activity Scale score	7.59 $\pm$ 2.33	8.43 $\pm$ 2.81	0.18

ACLR, anterior cruciate ligament reconstruction; SD, standard deviation.

Kinematic Outcomes

Table 2 summarizes the changes in lower-extremity kinematics following the 8-week PEP training program. Significant main effects of time were observed for ankle plantarflexion, eversion, and abduction; knee flexion, abduction, and internal rotation; and hip flexion and internal rotation (all $p \leq 0.005$), indicating significant changes in these variables following the intervention. Significant main effects of group were identified for ankle eversion, knee flexion, knee abduction, hip flexion, and hip internal rotation (all $p < 0.05$). Overall, the control group demonstrated greater knee and hip flexion together with lower frontal-plane angular values than the ACLR group across the assessment period. Significant Group $\times$ Time interactions were observed for ankle eversion ($p = 0.009$, $\eta p^2 = 0.159$), knee flexion ($p = 0.031$, $\eta p^2 = 0.111$), and hip flexion ($p = 0.007$, $\eta p^2 = 0.169$). Post hoc analyses showed that the ACLR group exhibited greater changes in these variables following the intervention than the control group. No significant Group $\times$ Time interactions were observed for the remaining kinematic variables (Table 2).

Table 2
Kinematic variables (degrees) and ANOVA results (mean $\pm$ SD)

Joint	Variable	Group	Pre-test	Post-test	Main Effect Group	Main Effect Time	Interaction
Ankle							
	Dorsiflexion	ACLR	11.43 $\pm$ 2.51	11.89 $\pm$ 2.67	F = 1.09, p = 0.299, $\eta p^2=0.027$	F = 0.13, p = 0.721, $\eta p^2=0.003$	F = 0.09, p = 0.765, $\eta p^2=0.002$
		CON	12.67 $\pm$ 2.38	12.81 $\pm$ 2.94			
	Plantarflexion	ACLR	34.21 $\pm$ 2.18	37.46 $\pm$ 2.81	F = 3.18, p = 0.082, $\eta p^2=0.074$	F = 10.77, p = 0.002, $\eta p^2=0.212$	F = 0.68, p = 0.414, $\eta p^2=0.017$
		CON	36.54 $\pm$ 3.11	39.28 $\pm$ 2.34			
	Eversion	ACLR	16.89 $\pm$ 2.47	13.67 $\pm$ 2.31	F = 4.80, p = 0.034, $\eta p^2=0.107$	F = 15.30, p < 0.001, $\eta p^2=0.277$	F = 7.56, p = 0.009, $\eta p^2=0.159$
		CON	14.56 $\pm$ 2.12	14.12 $\pm$ 3.08			
	Adduction	ACLR	19.12 $\pm$ 2.78	17.05 $\pm$ 2.92	F = 1.82, p = 0.182, $\eta p^2=0.044$	F = 2.41, p = 0.128, $\eta p^2=0.057$	F = 0.04, p = 0.842, $\eta p^2=0.001$
		CON	17.89 $\pm$ 2.41	17.76 $\pm$ 2.45			
	Abduction	ACLR	15.87 $\pm$ 1.92	12.18 $\pm$ 2.27	F = 3.68, p = 0.062, $\eta p^2=0.084$	F = 26.76, p < 0.001, $\eta p^2=0.401$	F = 2.89, p = 0.097, $\eta p^2=0.067$
		CON	13.05 $\pm$ 2.11	11.02 $\pm$ 2.09			
Knee							
	Flexion	ACLR	52.67 $\pm$ 7.23	63.52 $\pm$ 7.31	F = 6.78, p = 0.012, $\eta p^2=0.145$	F = 57.35, p < 0.001, $\eta p^2=0.589$	F = 5.01, p = 0.031, $\eta p^2=0.111$
		CON	58.34 $\pm$ 5.12	64.62 $\pm$ 8.41			
ACLR, anterior cruciate ligament reconstruction; CON, healthy control group; SD, standard deviation; ηp^2 , partial eta squared. Values are presented as mean $\pm$ SD. Bold values indicate statistically significant effects (p < 0.05).							

Joint	Variable	Group	Pre-test	Post-test	Main Effect Group	Main Effect Time	Interaction
Knee	Abduction	ACLR	10.89 ± 3.91	7.25 ± 2.19	F = 8.90, p = 0.005, $\eta^2=0.182$	F = 8.85, p = 0.005, $\eta^2=0.181$	F = 2.48, p = 0.123, $\eta^2=0.058$
		CON	7.98 ± 3.05	6.99 ± 2.08			
	Internal Rotation	ACLR	21.45 ± 6.12	15.89 ± 4.23	F = 0.67, p = 0.419, $\eta^2=0.016$	F = 27.32, p < 0.001, $\eta^2=0.406$	F = 0.81, p = 0.373, $\eta^2=0.020$
		CON	20.12 ± 5.01	16.05 ± 3.62			
	External Rotation	ACLR	6.89 ± 0.85	4.45 ± 0.86	F = 0.92, p = 0.342, $\eta^2=0.022$	F = 0.10, p = 0.750, $\eta^2=0.003$	F = 0.63, p = 0.432, $\eta^2=0.016$
		CON	6.34 ± 0.72	5.45 ± 0.85			
Hip							
Hip	Flexion	ACLR	51.89 ± 4.98	60.12 ± 5.23	F = 6.25, p = 0.017, $\eta^2=0.135$	F = 34.49, p < 0.001, $\eta^2=0.463$	F = 8.15, p = 0.007, $\eta^2=0.169$
		CON	59.23 ± 5.67	61.34 ± 6.12			
	Adduction	ACLR	17.12 ± 2.92	13.45 ± 2.08	F = 3.43, p = 0.069, $\eta^2=0.079$	F = 3.80, p = 0.058, $\eta^2=0.087$	F = 1.20, p = 0.280, $\eta^2=0.029$
		CON	13.67 ± 2.45	11.56 ± 2.61			
	Internal Rotation	ACLR	12.89 ± 3.45	9.67 ± 2.01	F = 4.23, p = 0.046, $\eta^2=0.096$	F = 12.82, p = 0.001, $\eta^2=0.243$	F = 0.78, p = 0.383, $\eta^2=0.019$
		CON	9.89 ± 3.11	8.56 ± 1.87			
	External Rotation	ACLR	5.78 ± 0.87	5.45 ± 0.84	F = 1.48, p = 0.229, $\eta^2=0.036$	F = 0.11, p = 0.742, $\eta^2=0.003$	F = 0.52, p = 0.474, $\eta^2=0.013$
		CON	7.34 ± 1.05	6.78 ± 1.08			
	ACLR, anterior cruciate ligament reconstruction; CON, healthy control group; SD, standard deviation; η^2 , partial eta squared. Values are presented as mean ± SD. Bold values indicate statistically significant effects ($p < 0.05$).						

[Insert Table 2 here]

Bonferroni-adjusted pairwise comparisons were performed for variables demonstrating significant Group × Time interactions. In the ACLR group, ankle eversion decreased significantly (mean difference = -3.22° , 95% CI: -4.98 to -1.46 , padjusted = 0.002), whereas knee flexion (mean difference = 10.85° , 95% CI: 7.56 – 14.14 , padjusted < 0.001) and hip flexion (mean difference = 8.23° , 95% CI: 5.12 – 11.34 , padjusted < 0.001) increased significantly following the intervention. In the control group, significant but smaller improvements were observed in knee flexion (mean difference = 6.28° , 95% CI: 2.89 – 9.67 , padjusted = 0.001) and hip flexion (mean difference = 2.11° , 95% CI: 0.45 – 3.77 , padjusted = 0.028), whereas no significant change was observed in ankle eversion. Between-group differences in ankle eversion, knee flexion, and hip flexion were smaller at post-test compared with pre-test.

Injury Surveillance

During the 6-month follow-up, all 42 participants completed injury surveillance (Tables 3 and 4). The ACLR group accumulated 349.78 ± 41.09 hours of soccer exposure, whereas the control group accumulated 383.61 ± 32.12 hours.

Table 3
Injury incidence during the 6-month follow-up

Variable	ACLR Group (n = 21)	Control Group (n = 21)
Exposure hours (mean ± SD)	349.78 ± 41.09	383.61 ± 32.12
Total lower-extremity injuries, n (%)	4 (19.04%)	5 (23.80%)
Match injuries, n (%)	2 (9.52%)	4 (19.04%)
Training injuries, n (%)	2 (9.52%)	1 (4.76%)
Non-contact injuries, n (%)	2 (9.52%)	3 (14.28%)
Contact injuries, n (%)	2 (9.52%)	2 (9.52%)
Injury incidence rate (per 1000 exposure hours)	11.43	13.03

Exposure hours represent soccer training and match participation only.

Table 4
Injury characteristics during the 6-month follow-up

Variable	ACLR Group (n = 21)	Control Group (n = 21)
Type of injury		
Muscle injury (stiffness, tenderness, pain), n (%)	1 (4.76%)	2 (9.52%)
Muscle strain, n (%)	2 (9.52%)	2 (9.52%)
Meniscus injury, n (%)	1 (4.76%)	0 (0%)
Other ligament injury, n (%)	0 (0%)	1 (4.76%)
Complete ACL graft rupture, n (%)	0 (0%)	0 (0%)
Contralateral ACL rupture, n (%)	0 (0%)	0 (0%)
Injury mechanism		
Cutting maneuver, n (%)	1 (4.76%)	2 (9.52%)
Rapid start/acceleration, n (%)	1 (4.76%)	1 (4.76%)
Hyperextension, n (%)	2 (9.52%)	1 (4.76%)
Jumping/landing, n (%)	0 (0%)	1 (4.76%)

A total of four lower-extremity injuries were recorded in the ACLR group and five in the control group, corresponding to injury incidence rates of 11.43 and 13.03 injuries per 1000 exposure hours, respectively. Match injuries were more frequent than training injuries in the control group, whereas injuries were evenly distributed between matches and training in the ACLR group. Non-contact injuries accounted for 50% of injuries in the ACLR group and 60% in the control group. Muscle-related injuries were the most common injury type in both groups. One meniscal injury occurred in the ACLR group, whereas one injury involving other knee ligaments was observed in the control group. No ACL graft ruptures or contralateral ACL injuries were recorded during the follow-up period. Hyperextension was the most frequent injury mechanism in the ACLR group, whereas cutting maneuvers accounted for the largest proportion of injuries in the control group. Only one jumping/landing injury was observed, and it occurred in the control group.

Discussion

Kinematic Adaptations to Training

This study investigated the effects of an 8-week PEP training program on lower-extremity kinematics during a 90° cutting maneuver and subsequent 6-month injury incidence in soccer players with and without ACLR. The 8-week PEP program improved lower-extremity kinematics during the 90° cutting maneuver in both groups, with the greatest changes observed in athletes following ACL reconstruction.

Knee flexion increased by 10.85° in the ACLR group compared with 6.28° in the control group, while hip flexion improved by 8.23° and 2.11°, respectively. Athletes with ACLR also demonstrated a significant reduction in ankle eversion, resulting in a smaller biomechanical difference between groups after training. These findings support our hypothesis that athletes with ACL reconstruction may have a greater capacity for neuromuscular adaptation, likely because their larger baseline movement deficits provide greater potential for improvement following targeted training.

At baseline, athletes with ACL reconstruction demonstrated lower knee and hip flexion than healthy controls, consistent with the stiffer movement strategy commonly reported following ACL reconstruction during demanding tasks such as cutting and landing [19, 20]. This strategy is generally considered a protective adaptation that limits motion of the reconstructed knee during high-load activities [21]. However, restricting sagittal-plane motion may reduce the lower extremity's ability to absorb impact forces efficiently. As a result, ACL loading may increase because of reduced shock absorption and altered lower-limb loading mechanics during rapid changes of direction [48, 49]. The improvements observed after the intervention suggest that the PEP program may have reduced this movement strategy by encouraging greater hip and knee flexion during cutting, leading to more effective dynamic knee control.

Previous studies have shown that some biomechanical deficits may persist after ACL reconstruction, even after athletes meet return-to-sport criteria [1, 15, 50]. Reduced knee flexion and greater frontal-plane knee motion during cutting appear to be among the most persistent alterations, suggesting that conventional rehabilitation may not fully restore movement quality during high-demand sport-specific tasks [15, 51]. Encouragingly, accumulating evidence indicates that these deficits can be substantially improved through targeted neuromuscular training. Neuromuscular training programs, including those incorporating external-focus instructions, have been shown to increase knee and hip flexion while reducing frontal-plane knee motion [4, 8]. The current findings extend these observations by showing that an 8-week PEP program was associated with similar biomechanical adaptations during a 90° cutting maneuver, with larger improvements observed in athletes with ACL reconstruction. Although the intervention substantially reduced the biomechanical differences between groups, complete normalization of movement patterns was not achieved. The present findings indicate that neuromuscular training can improve movement mechanics after ACL reconstruction; however, longer interventions may be needed to achieve more complete recovery of cutting mechanics.

The biomechanical improvements observed after the intervention were likely driven by several interacting neuromuscular adaptations rather than by gains in muscle strength alone. The strengthening, plyometric, and agility components of the PEP program may have challenged athletes under sport-specific conditions that required both force production and dynamic movement control [26, 39, 52]. Because persistent quadriceps weakness after ACL reconstruction has been linked to reduced knee flexion, altered landing mechanics, and movement asymmetries [53, 54], the marked increase in knee flexion observed in the ACLR group may reflect improved eccentric quadriceps control during the weight-acceptance phase of cutting. Enhanced stretch-shortening cycle efficiency and intermuscular

coordination may also have contributed by enabling athletes to adopt a less rigid and more efficient movement strategy. Previous studies have reported similar improvements in quadriceps function, limb symmetry, and dynamic movement mechanics following neuromuscular training after ACL reconstruction [55, 56].

The reductions in ankle eversion and knee abduction observed after training suggest improved frontal-plane movement control during cutting. Similar neuromuscular training programs have been shown to enhance proprioception, muscle activation, lower-limb coordination, and hip abductor function, all of which contribute to frontal-plane stability during dynamic tasks [57, 58]. By directing attention toward movement outcomes rather than individual body segments, such instructions are thought to promote more automatic movement control and have been associated with superior landing biomechanics than internally focused cues [59, 60]. Although these mechanisms were not directly assessed, they provide a plausible explanation for the coordinated improvements observed across multiple joints following the PEP program [26, 39].

Ankle eversion was the only variable that demonstrated a significant Group $\times$ Time interaction, with a meaningful reduction observed exclusively in the ACLR group. Excessive ankle eversion may reflect altered distal lower-extremity control and contribute to unfavorable lower-limb alignment and increased knee loading during cutting maneuvers [61, 62]. The greater reduction observed in the ACLR group may be related to the larger baseline movement deficits present before training, providing greater opportunity for improvement following the PEP program. Although knee abduction did not show a significant Group $\times$ Time interaction, its reduction after training may have been partly related to improved distal control. Previous studies suggest that ankle mechanics can influence knee movement during dynamic tasks [14, 63]. Thus, better ankle control may contribute to improved lower-extremity alignment during cutting.

Despite these improvements, residual biomechanical deficits remained after the intervention. Athletes with ACL reconstruction continued to demonstrate greater knee abduction together with lower knee and hip flexion than healthy controls, although these between-group differences were considerably smaller than those observed at baseline. This pattern is consistent with previous laboratory- and field-based studies showing that altered lower-extremity biomechanics may persist for months or even years after ACL reconstruction despite successful rehabilitation and return-to-sport clearance [7]. These remaining differences indicate that, although the PEP program improved cutting biomechanics after ACL reconstruction, longer or more targeted rehabilitation may be needed to fully restore movement patterns.

From a biomechanical perspective, persistent frontal-plane knee motion may remain an important concern despite the overall improvements observed after training. Excessive knee abduction has consistently been associated with increased ACL loading and a greater risk of ACL injury during cutting and landing tasks [64]. Greater cutting angles have also been shown to increase knee loading while reducing knee flexion, and athletes who later sustained ACL injuries have demonstrated larger knee valgus angles and moments than uninjured athletes [5, 65]. Although knee abduction improved following the intervention, the remaining between-group difference suggests that an 8-week PEP program alone

may not be sufficient to fully restore frontal-plane knee control after ACL reconstruction. Dynamic frontal-plane stability depends on several interacting factors, including quadriceps-hamstring co-contraction, hip muscle function, sensorimotor integration, and neuromuscular coordination [66–68]. Although these variables were not directly assessed in the present study, previous research has shown that persistent weakness of the hip abductors and stabilizers after ACL reconstruction may contribute to excessive knee abduction during dynamic tasks [69, 70]. Therefore, incomplete restoration of these underlying mechanisms may partly explain the residual frontal-plane deficits observed after training. Future rehabilitation strategies incorporating more targeted neuromuscular and hip-focused interventions may therefore be required to optimize frontal-plane control. This explanation is also supported by recent systematic review evidence showing that neuromuscular and sensorimotor interventions can further reduce dynamic knee valgus and other biomechanical risk factors associated with ACL injury [24].

Injury Incidence and Clinical Implications

After the 8-week PEP program, injury incidence was similar in both groups during the 6-month follow-up. Together with the observed biomechanical improvements, these findings suggest that the PEP program may provide additional benefits when incorporated into rehabilitation after ACL reconstruction. Although athletes returning to pivoting sports after ACL reconstruction are generally considered to be at elevated risk of subsequent ACL and lower-extremity injuries [7, 71], injury rates in the present study were comparable between groups. The ACLR group sustained four lower-extremity injuries (11.43 injuries per 1000 exposure hours), whereas the control group sustained five injuries (13.03 injuries per 1000 exposure hours). Notably, no ACL graft ruptures or contralateral ACL injuries were recorded during follow-up. While the present study was not powered to detect differences in injury incidence, these findings are consistent with previous evidence suggesting that neuromuscular injury-prevention programs, including the PEP program, may reduce ACL injury risk in soccer players, particularly those with a history of ACL reconstruction [25, 26]. Nevertheless, the relatively small sample size and short follow-up period warrant cautious interpretation, and the injury surveillance findings should be viewed as supportive rather than conclusive evidence of injury prevention.

No secondary ACL injuries occurred despite the high biomechanical demands of cutting maneuvers, a common movement pattern in soccer that accounts for approximately half of all non-contact ACL injuries [16]. The present study was not designed to determine whether these biomechanical improvements affected injury outcomes. However, the changes in cutting mechanics observed after training are in line with movement patterns associated with lower ACL loading during high-risk tasks. Increased knee flexion, together with reduced knee abduction and ankle eversion, suggests that participants adopted movement patterns associated with more effective impact attenuation and improved dynamic knee control. Previous biomechanical studies have shown that greater knee flexion enhances shock absorption, reduces quadriceps-induced anterior tibial shear forces, and increases hamstring contribution during dynamic activities, thereby decreasing ACL loading [72]. Movement strategies characterized by lower multiplanar knee loading during change-of-direction tasks have also

been associated with reduced ACL loading while maintaining athletic performance [11]. These mechanisms were not directly assessed in the present study. However, the observed kinematic changes are consistent with evidence showing that neuromuscular training may promote safer movement strategies and reduce ACL loading during sport-specific tasks [9, 10].

Previous studies evaluating structured neuromuscular warm-up programs have reported similar findings. Large prospective trials have consistently shown that programs such as the PEP protocol, FIFA 11+, and Sportsmetrics can reduce ACL and lower-extremity injury rates in soccer players. For example, Mandelbaum et al. [25] reported a marked reduction in serious knee injuries among female soccer players following implementation of the PEP program, whereas Soligard et al. [73] demonstrated that the FIFA 11 + significantly reduced overall and severe injuries in young female football players during an entire competitive season. Similarly, Hewett et al. [74] observed a lower incidence of serious knee injuries after implementation of the Sportsmetrics program in female athletes. However, they differ substantially from the present investigation. Most involved considerably larger cohorts and monitored athletes over an entire competitive season or longer, providing greater statistical power to detect differences in injury incidence. In addition, they primarily focused on injury surveillance without examining the biomechanical adaptations that may underlie any protective effect. In contrast, the present study combined three-dimensional biomechanical analysis with prospective injury surveillance in athletes following ACL reconstruction. Although injury prevention was not the primary outcome of this study, the biomechanical findings provide useful context for interpreting the injury results observed during follow-up.

Muscle-related injuries were the most common injury type in both groups, accounting for three injuries (14.3%) in the ACLR group and four injuries (19.0%) in the control group. This finding is of interest because athletes returning to sport after ACL reconstruction are generally considered to remain vulnerable to secondary muscle injuries despite successful rehabilitation. Consistent with this, the UEFA Elite Club Injury Study reported a 60% higher incidence of thigh muscle injuries during the first two years after return to play among professional soccer players with previous ACL reconstruction compared with players without a history of ACL injury [75]. Similarly, a retrospective matched-cohort study found that 32.5% of professional soccer players following ACL reconstruction sustained at least one secondary muscle injury within the first year after return to play, compared with 12.5% of matched controls [76]. In the present study, however, muscle injury rates were similar between groups. Although the number of injuries was too small to draw firm conclusions, the combined neuromuscular, strengthening, and plyometric exercises included in the PEP program may have contributed to this finding.

The pattern of injury mechanisms also deserves attention, although the small number of injuries precludes firm conclusions. Cutting-related injuries were relatively uncommon (one in the ACLR group and two in the control group), which is in line with the improvements in cutting biomechanics observed after training. In contrast, hyperextension injuries occurred only in the ACLR group, suggesting that some movement deficits may have persisted despite the overall biomechanical improvements. From a clinical perspective, these results support incorporating structured neuromuscular training, such as the PEP

program, into the later stages of rehabilitation after ACL reconstruction to address movement deficits that often remain after conventional rehabilitation. They also highlight the importance of assessing movement quality alongside traditional strength- and time-based return-to-sport criteria. However, the persistence of deficits in knee abduction and sagittal-plane mechanics suggests that some athletes may benefit from longer or more individualized rehabilitation, particularly interventions targeting frontal-plane control. Objective biomechanical assessment during cutting may therefore help identify athletes who require additional rehabilitation before return to sport. Continued neuromuscular training after return to sport, together with periodic biomechanical assessment during sport-specific tasks, may help preserve these biomechanical adaptations over time. Given the limited statistical power to detect differences in injury incidence, the injury surveillance findings should be interpreted cautiously and considered preliminary evidence of potential clinical value rather than direct evidence of injury prevention.

Limitations and Future Directions

Several limitations of this study should be acknowledged. First, the quasi-experimental design without a non-training control group limits the ability to attribute the observed improvements exclusively to the PEP program rather than to natural recovery or repeated testing effects. Nevertheless, the pre-test/post-test design, together with the inclusion of both ACLR and healthy control participants receiving the same intervention, provides useful evidence regarding changes over time. Second, the sample consisted exclusively of male soccer players, which limits the generalizability of the findings to female athletes or participants from other sports. Given the known sex-related differences in ACL injury mechanisms and neuromuscular characteristics, future studies should examine whether similar adaptations occur in female athletes [77, 78]. Third, the relatively small sample size and the 6-month follow-up period limited the ability to detect differences in injury incidence, particularly for relatively uncommon outcomes such as ACL graft rupture or contralateral ACL injury. Fourth, psychological factors that may influence movement quality and return-to-sport outcomes, such as kinesiophobia, self-confidence, and psychological readiness, were not assessed [79, 80]. Fifth, the ACLR group included athletes with different graft types and varying time since surgery. Although all participants had been medically cleared to return to sport, these clinical differences may have influenced neuromuscular adaptations and responsiveness to training. Sixth, only kinematic variables were evaluated in the present study. Kinetic variables, such as joint moments and ground reaction forces, as well as neuromuscular measures including muscle strength and electromyographic activity, were not assessed. Incorporating these outcomes in future studies would provide a more comprehensive understanding of the mechanisms underlying the observed biomechanical adaptations.

Future research should determine whether the biomechanical improvements observed after neuromuscular training translate into sustained reductions in injury risk following ACL reconstruction. Including female athletes and participants from different sports would improve the generalizability of future findings. Comparative studies evaluating different neuromuscular training protocols may also help identify the optimal program duration, training frequency, and exercise components. In addition, integrating kinetic analyses, muscle strength assessments, electromyography, and musculoskeletal

modeling could provide further insight into the mechanisms underlying biomechanical adaptations. Finally, randomized controlled trials with adequate statistical power are needed to establish the long-term effectiveness of neuromuscular training in reducing secondary ACL injuries and optimizing return-to-sport outcomes.

Conclusion

This study demonstrated that an 8-week PEP training program was associated with significant improvements in lower-extremity kinematics during a 90° cutting maneuver in both soccer players following ACL reconstruction and healthy controls. Athletes in the ACLR group exhibited greater improvements in knee flexion, hip flexion, and ankle eversion, substantially reducing the initial biomechanical differences between groups. During the 6-month follow-up, injury incidence was comparable between groups, and no ACL graft ruptures or contralateral ACL injuries were observed. Although the present study was not powered to evaluate injury prevention outcomes, the observed biomechanical improvements are consistent with movement patterns associated with lower ACL loading during high-risk sport-specific tasks. These findings support the incorporation of structured neuromuscular training, such as the PEP program, into late-stage rehabilitation and return-to-sport preparation following ACL reconstruction. However, persistent frontal-plane movement deficits suggest that longer rehabilitation programs incorporating targeted neuromuscular interventions for frontal-plane control may be necessary to further optimize biomechanical recovery.

Abbreviations

ACL: Anterior Cruciate Ligament; ACLR: Anterior Cruciate Ligament Reconstruction; PEP: Prevent Injury and Enhance Performance; CON: Control; SPSS: Statistical Package for the Social Sciences; 3D: Three-Dimensional; CI: Confidence Interval; ANOVA: Analysis of Variance; η^2 : Partial Eta Squared.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Ethics Committee of the Iranian Research Institute of Physical Education and Sport Sciences (Approval No. SSRI.REC-2312-2560). All procedures were conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to participation.

Consent for publication

Not applicable.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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The authors received no specific funding for this work.

Authors' contributions

MG contributed to the study conception and design, data collection, data analysis, interpretation of the results, and manuscript drafting. HD contributed to the study design, supervision, interpretation of the findings, and critical revision of the manuscript. ASM contributed to the study design, supervision, and critical revision of the manuscript. MM contributed to data interpretation and critical revision of the manuscript. All authors read and approved the final manuscript.

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