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RESEARCH

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The effects of contralateral limb cross-education training on post-surgical rehabilitation outcomes in patients with anterior cruciate ligament reconstruction: a randomized controlled trial

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Abstract

Objective This study examines whether cross-education training of the healthy limb promotes cross-transfer through central nervous system stimulation, enhancing the function, kinematic parameters, dynamic balance, and plantar pressure of the affected knee joint in patients recovering from postoperative anterior cruciate ligament reconstruction (ACLR).

Methods Forty anterior cruciate ligament reconstruction (ACLR) patients, 5–6 weeks postoperatively, were included and randomly assigned to either an experimental group ($n=20$) or a control group ($n=20$). The experimental group participated in six weeks of cross-education (CE) training in addition to conventional rehabilitation, while the control group received only conventional rehabilitation. Assessment outcomes included knee function (Lysholm score, joint mobility, and surface electromyographic characteristics of the rectus femoris muscle), kinematic parameters (stride length, stride speed, and stride width), dynamic balance (gait line length, single-support line length, and medial-lateral displacements), and plantar pressure (forefoot, midfoot, and hindfoot pressures). The effect of CE training on postoperative ACLR rehabilitation was comprehensively assessed by comparing the pre- and post-intervention changes within each group and the differences between the groups.

Results Before the intervention, no statistically significant differences were observed between the two groups across all measured parameters ($P>0.05$). Following the intervention, significant improvements in knee function, kinematic parameters, balance function, and plantar pressure were observed in both groups, with the experimental group showing significantly more significant improvements ($P<0.05$). The Lysholm score, range of motion (ROM), and surface electromyographic activity of the rectus femoris muscle were significantly higher in the experimental group compared to the control group ($P<0.01$). Among kinematic parameters, the experimental group demonstrated a

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significant increase in stride length and reduced stride width, whereas differences in stride speed were not statistically significant ($P > 0.05$). Regarding balance function, the experimental group exhibited significantly longer gait and single-support line lengths, significantly reducing medial-lateral displacement ($P < 0.05$). Analysis of plantar pressure revealed significant improvements in forefoot and hindfoot pressures in the experimental group, with a particularly notable increase in hindfoot pressure ($P < 0.05$). However, changes in midfoot pressure were not statistically significant ($P > 0.05$).

Conclusion CE training markedly enhanced knee function, kinematic metrics, dynamic stability, and plantar pressure in postoperative ACLR patients providing initial evidence for the prospective utilization of CE theory in rehabilitation. Nonetheless, the fundamental mechanics of its effects remain ambiguous, and variables such as individual differences and neuromuscular adaptation processes may affect training results. Future studies should examine its long-term impacts and uncover potential neuromuscular pathways to establish a solid scientific basis for improving postoperative rehabilitation procedures.

Keywords Anterior cruciate ligament graft surgery, Cross-transfer, Knee function, Kinematic metrics, Dynamic stability, Plantar pressure

Introduction

Anterior cruciate ligament reconstruction (ACLR) is widely recognized as the gold standard for restoring the knee's anatomy, stability, and function [1–3]. However, postoperative dysfunction remains a common issue, significantly impairing patients' mobility and quality of life [4, 5]. In the early postoperative phase, high-intensity training is often hindered by joint pain, effusion, and the need to protect the graft, resulting in a pronounced reduction in quadriceps strength. This reduction adversely impacts knee functional recovery and challenges subsequent rehabilitation processes [6, 7]. Moreover, ACL injuries are frequently accompanied by a loss of proprioception and extensive tissue damage, leading to diminished joint position sense and impaired motor control [8–10]. These factors further exacerbate neuromuscular control deficits, resulting in knee instability, reduced dynamic balance, and impaired motor coordination [11–16]. Additionally, mechanoreceptor damage contributes to reduced quadriceps activation, compounding functional deficits [17]. Evidence also suggests that ACLR induces significant neurological adaptations, characterized by increased spinal reflex pathway excitability and reduced corticospinal pathway excitability, strongly associated with bilateral quadriceps strength deficits and reduced capacity for random muscle activation [18–20]. Consequently, rehabilitation interventions targeting central nervous mechanisms, particularly strategies to restore neural pathway excitability, are crucial for enhancing postoperative functional outcomes [21].

Cross Education (CE) refers to the phenomenon where unilateral limb training transfers strength or skill to the contralateral untrained limb [22]. Although the specific mechanisms underlying CE remain unclear, it is widely believed to be associated with interhemispheric impulse propagation, which enhances central motor drive [23, 24]. The CE effect has been extensively validated in strength training and conditioned reflexes studies [25, 26]. Its potential application in ACLR rehabilitation is gaining recognition. Evidence suggests that CE can effectively mitigate postoperative quadriceps strength loss, facilitate recovery, and improve quadriceps reaction time at 90° knee flexion [24, 27, 28]. However, research on the impact of balance training for the healthy limb in rehabilitating the affected limb remains limited. For example, a study by Karimijashni et al. [29] demonstrated that an 8-week CE training program significantly improved dynamic and static balance and pain in the affected knee during the early postoperative period following ACLR. Nevertheless, the objectivity and generalizability of these findings require further verification through more extensive and standardized experiments, as the assessment methods relied heavily on subjective patient feedback.

In this study, CE training was conducted in patients 5–6 weeks post-ACLR, using the Zebris plantar pressure balance analysis system and wireless surface electromyography (SEMG) technology based on the principle of CE. The objective was to systematically evaluate the specific effects of CE training on knee function, kinematic parameters, dynamic balance, and plantar pressure during the early postoperative phase. Additionally, the study aimed to provide a scientific basis for optimizing early rehabilitation strategies in patients following ACLR. It was hypothesized that patients undergoing CE training would demonstrate significant improvements in knee function, kinematic parameters, dynamic balance, and plantar pressure compared to those receiving conventional rehabilitation alone.

Methods

Experimental design

This study was conducted as a single-masked, randomized controlled trial, designed and reported in adherence to the CONSORT statement guidelines—all postoperative ACLR patients who met the inclusion criteria provided written informed consent before participating. An independent researcher, who was not involved in the intervention or data collection, used a computer-generated randomization sequence to allocate patients to the trial and control groups in a 1:1 ratio. The trial group underwent CE training for the healthy limb in addition to regular rehabilitation, while the control group received only standard rehabilitation. Both groups participated in their respective interventions for six weeks, three times per week. Due to the nature of the intervention, the physiotherapist could not be blinded to the subgroups but did not participate in preoperative or postoperative assessments. All assessments, including knee function, kinematic parameters, dynamic balance, and plantar pressure, were conducted independently by a study physiotherapist who was blinded to the intervention. Statistical analyses were performed under fully blinded conditions to ensure the validity and reliability of the results.

Sample size estimation

Referring to the study by Karimijashni et al. [29], dynamic balance (SEBT Anterior) was selected as the primary outcome measure, and the sample size estimation was based on the mean improvement in medial balance values observed in the intervention group ($\Delta = 5.04$, $SD = 14.79$). Assuming a medium effect size (Cohen's $d = 0.5$), a significance level of $\alpha = 0.05$, and a test power of $1-\beta = 0.8$, the required sample size was calculated using G*Power software, indicating the need for 15 patients per group. Considering a 10% dropout rate, the adjusted sample size was increased to 17 patients per group. Ultimately, 20 patients were included in each group to ensure statistical validity, resulting in a total sample size of 40 participants.

Subjects

This study was conducted from July to November 2024 at the Sports Rehabilitation Center of Binzhou Medical University Hospital, where 50 patients were screened. Patients were recruited from the outpatient and inpatient departments of the Affiliated Hospital of Binzhou Medical University. The supervising physician initially screened them based on postoperative time, baseline function, and age criteria. Eligible patients were referred to the Sports Rehabilitation Center for further evaluation, where they were screened in detail based on inclusion and exclusion criteria. After obtaining informed consent, 40 patients were included in the study. They were randomly assigned to the experimental group (20 patients) or the control group (20 patients). Inclusion criteria included age 18–45 years, unilateral ACL injury, undergoing arthroscopic ACL reconstruction (using hamstring tendon grafts), walking without crutches within 5–6 weeks postoperatively, normal contralateral knee function, and no previous history of specialized rehabilitation. Exclusion criteria included a prior ACL injury, severe postoperative complications, inability to attend follow-ups, severe cardiopulmonary disease, cognitive impairment, or abnormal function of the contralateral lower extremity. No participants withdrew from the study, and all completed the intervention and follow-up.

The study was approved by the Ethics Committee of Binzhou Medical University Hospital (approval number: 2024-L004; KYLL-239) and was registered in the China Clinical Trial Registry (ChiCTR2400087325) (Fig. 1).

Programme implementation

The control group underwent a 6-week conventional rehabilitation program, while the experimental group received additional CE training for the healthy limb alongside the conventional rehabilitation program. Professional physiotherapists supervised and tailored all training sessions to each patient's condition.

Conventional rehabilitation training

Joint mobility training The patient sits on the edge of a bed while the therapist applies light pressure above the ankle joint to assist the patient in slowly flexing the knee until a slight stretch is felt, holding for 1 min. Once the knee flexion angle exceeds 90°, prone knee flexion training is introduced, lasting 10 min per session to gradually restore knee mobility while avoiding excessive pressure on the reconstructed ligament.

Plyometrics Begin with straight leg raises, gradually incorporating non-weight-bearing or light resistance training to strengthen the quadriceps muscles. After the third week, static wall squats and lunge exercises are introduced, each lasting only at most 20 min. Intensity is gradually increased while avoiding overloading.

Core training Begin with a supine hip bridge exercise. The patient flexes their legs, tightens the core, and raises the hips until the body forms a straight line. Perform 30 repetitions per set, repeating for three sets. As rehabilitation progresses, alternating leg lifts and leg flexion curls are added to strengthen the core muscles further and reduce strain on the knee joints and ligaments.

Balance and proprioception training Weight transfer exercises are initially performed to restore proprioception and dynamic stability in the knee joint. Subsequently, balance ball training is introduced. The patient stands on a balance ball with both feet and slightly flexed knees, maintaining balance for 1 min per session. Training duration is limited to 5 min to enhance knee stability.

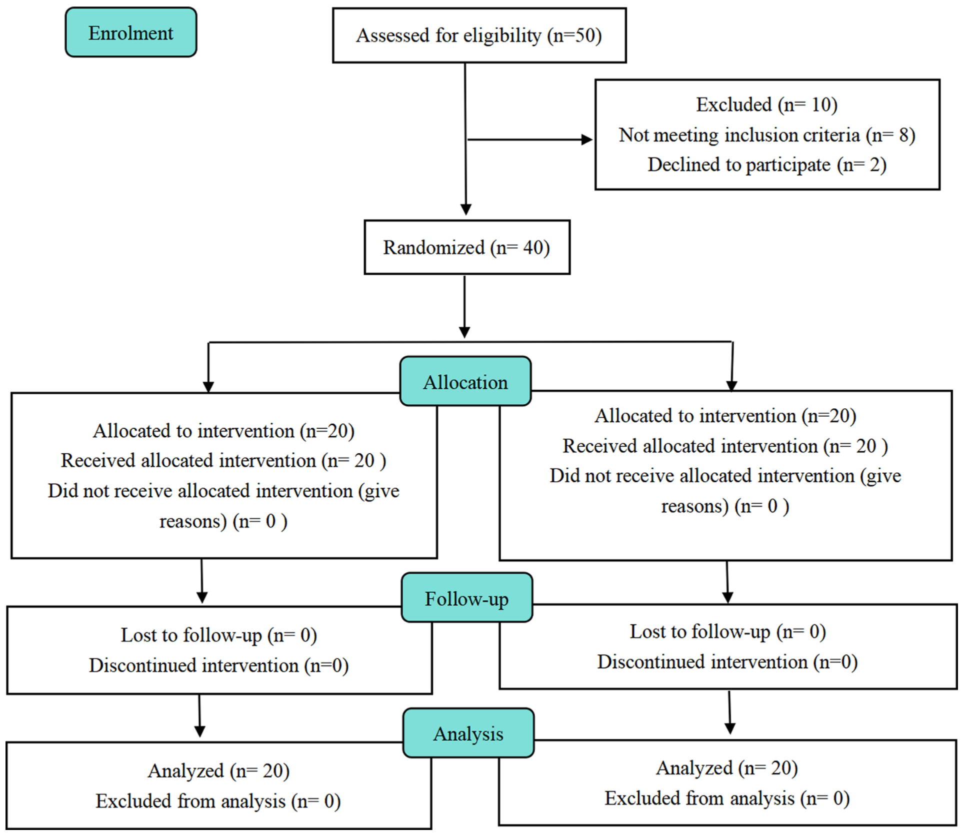

Fig. 1 Flow chart of subject recruitment enrollment

Stretching and relaxation training Post-training stretching focuses on the quadriceps, hamstrings, and calf muscle groups. Stretches are held for 20–30 s each and repeated 2–3 times to relieve muscle tension, improve joint mobility, promote circulation, and prevent postoperative discomfort.

Cross-education training
Based on the findings of Karimijashni et al. [29], this study developed a step-by-step training program to improve dynamic balance and knee function in ACL reconstruction patients. The program, which progressively increased support surface difficulty while integrating upper limb movements, was designed to enhance rehabilitation. The experimental group performed CE training for the healthy limb alongside conventional rehabilitation. Over six weeks, the program was divided into three stages, with gradual progression tailored to each patient's recovery. It involved progressively increasing the difficulty of the support surface, reducing the support base area, and intensifying exercises.

Stage 1:

(1) The patient stands with their back against a wall on one leg on a stable surface, raising the affected leg. The patient maintains balance with eyes open for 30 s, followed by 30 s with eyes closed. The movement is repeated with the healthy leg slightly flexed for five repetitions per set, completing 10 sets, with a 1-minute rest between sets (Figure 2a).
(2) The complexity increases when the patient stands on the healthy leg and points the affected leg sequentially to the left front, left back, right, right, and right front. Balance exercises are performed alternately with eyes open and closed, repeating each set of movements five times for 10 sets, with a 1-minute rest between sets (Figure 2b).

Stage 2:

(1) The patient stands on the healthy leg with a slight flexion while raising the affected leg forward. Balance is maintained with eyes open for 30 s, followed by 30 s with eyes closed. The movement is repeated five times per set, for 10 sets, with a 1-minute rest between sets (Figure 2c).
(2) All movements from Stage 1 are repeated on a step to introduce instability, thereby increasing the difficulty of the training (Figure 2)d.

Stage 3:

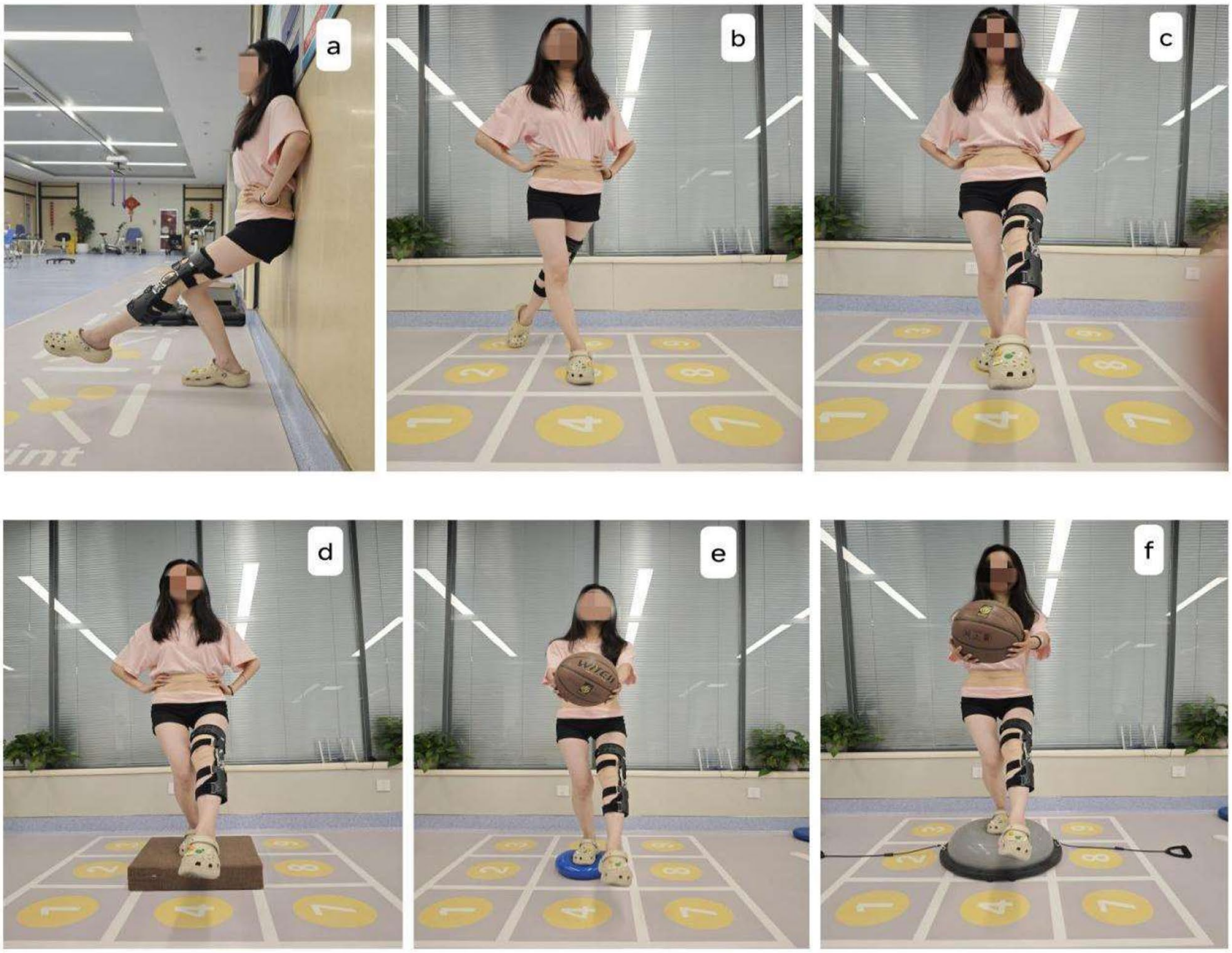

Fig. 2 a-f Cross-Education Training

(1) The patient stands on a balance ball while lifting the affected leg forward. Holding a ball with both hands, the patient throws and catches in different directions for 30 s. The exercise is then repeated with the healthy leg slightly flexed. Each set of movements is repeated five times for 10 sets, with a 1-minute rest between sets (Figure 2e).
(2) All movements from Stage 2 are repeated with increased difficulty and intensity. Modifications include increasing the frequency of ball throws and catches, adjusting the flexion angle of the healthy leg, and varying the size of the balance ball (Figure 2f).

Indicators of outcome

Functional evaluation of knee joints

(1) Lysholm knee score The validated Chinese version of the Lysholm Knee Rating Scale was used to assess knee function in ACLR patients comprehensively. The scale underwent rigorous translation, cultural adaptation, and validation to ensure reliability and validity among Chinese-speaking populations [30]. With its demonstrated high reliability, validity, and responsiveness, the Lysholm Scale is widely used to evaluate knee function following knee injuries and has shown excellent applicability in ACLR patients. The Lysholm Scale evaluates eight dimensions: lameness, bracing, locking, instability, pain, swelling, stair climbing, and squatting. It has a total score of 100, with higher scores indicating better recovery of knee function [31].

(2) Assessment of joint mobility This study used a standardized goniometer to assess the knee joint's range of motion (ROM). During the assessment, patients were supine, with the knee joint naturally flexed and muscles fully relaxed to minimize interference from muscle tension or discomfort. Using anatomical landmarks, the researchers marked fixed measurement points above and below the knee joint, strictly following standardized measurement procedures to ensure consistency and accuracy.

Fig. 3 Data collection process

Fig. 4 Electrode placement for rectus femoris SEMG

(3) Surface electromyographic characterization of the rectus femoris muscle SEMG characteristics were recorded using the Noraxon Ultium SEMG system with a sampling frequency of 2000 Hz and a 16-channel wireless connection. Before testing, the target muscle area was cleaned with 75% alcohol wipes and was allowed to dry. During the assessment, the patient was seated with the knee flexed at 90 degrees and the foot suspended freely to ensure maximum tension and stability of the quadriceps muscle. The examiner applied resistance above the ankle joint and instructed the patient to perform a maximal knee extension, activating the rectus femoris muscle. The electrode was then attached to the most prominent area of the rectus femoris muscle belly (Fig. 3). The maximum isometric contraction of the rectus femoris muscle was measured during a 7- to 8-second knee extension, with a 1-minute rest interval between tests, for a total of three repetitions. SEMG signals were processed using MR3 software to obtain normalized data. Root mean square (RMS) values of the signals during maximal isometric contraction were analyzed 2.5 s before and after the signal peak, both pre-and post-training, to assess changes in the activation strength of the rectus femoris muscle.

Kinematic parameters, dynamic balance, and plantar pressure evaluation

The FDM2 plantar pressure plate (212.2 cm × 60.5 cm × 2.5 cm, equipped with 115,360 sensors and a sampling frequency of 60 Hz) from ZEBRIS MEDICAL was used for data acquisition. Before the test, patients walked barefoot on a 6-meter runway to familiarize themselves with the testing environment. During the formal measurement, patients walked naturally for 60 s, with the system automatically recording their walking data (Fig. 4).

(1) Evaluation of kinematic parameters Kinematic parameters play a critical role in gait analysis. These parameters involve stride length, speed, and width, providing a comprehensive overview of an individual's athletic ability and gait characteristics [32]. Stride length primarily reflects forward propulsion and gait coordination; more significant and symmetrical values indicate better lower limb function [33]. Stride speed reflects gait efficiency, with faster speeds suggesting better dynamic movement ability. Stride width is related to lateral stability; an appropriate width reflects a stable gait, while excessively wide or narrow strides suggest balance control abnormalities [32, 34].

(2) Dynamic balance function assessment Key indicators for assessing dynamic balance function include gait line length, single-support line length, and medial-lateral displacement (Fig. 5). Gait line length reflects the path of the Center of Pressure (COP) during walking and is used to evaluate dynamic stability [35]. Single-support line length reflects the COP's path from heel to toe during the single-leg support phase, assessing balance control during a single-leg stance [36]. These two metrics primarily reflect dynamic balance in the anterior-posterior direction. For ACLR patients, longer values for these two measurements signify enhanced stability, whereas shorter values indicate reduced stability. Medial-lateral displacement reflects the distance the COP moves laterally and is used to evaluate balance control in the left-right direction. Larger medial-lateral displacements indicate poorer left-right balance control, while smaller displacements indicate better control [37, 38].

(3) Plantar pressure assessment The plantar pressure assessment comprehensively evaluates gait stability and the weight-bearing capacity of the foot by measuring key indicators such as forefoot pressure, midfoot pressure, and hindfoot pressure [39]. Forefoot pressure primarily assesses the force generated during the propulsion phase of gait, with uniform and stable pressure distribution indicating better propulsion ability and forward stability [40]. Midfoot pressure reflects the support and cushioning function of the foot arch; a normal distribution suggests good dynamic balance and efficient impact absorption [41]. Hindfoot pressure evaluates stability during the initial landing phase of gait and the buffering ability of ground reaction forces, with uniform pressure distribution indicating strong landing stability [42].

Statistical analysis

Data analysis was performed using SPSS 25.0 software. All measured variables were tested for normality before analysis, and data conforming to a normal distribution were expressed as mean ± standard deviation (Mean ± SD). Critical demographic parameters (e.g., age, height, weight) were analyzed using the independent samples t-test to confirm the validity of randomization between groups. Pre- and post-intervention data were analyzed using repeated measures of two-way ANOVA with Greenhouse-Geisser correction. When the interaction was statistically significant, further simple effects analyses were conducted. If the interaction was insignificant but the main effect significant, multiple comparisons between time points within groups were performed using the Bonferroni method. The significance level of $P < 0.05$ was applied for all statistical tests.

Results

General information

No statistically significant differences were observed in the demographic characteristics between the two groups ($P > 0.05$), indicating that they were comparable in terms of essential features (Table 1).

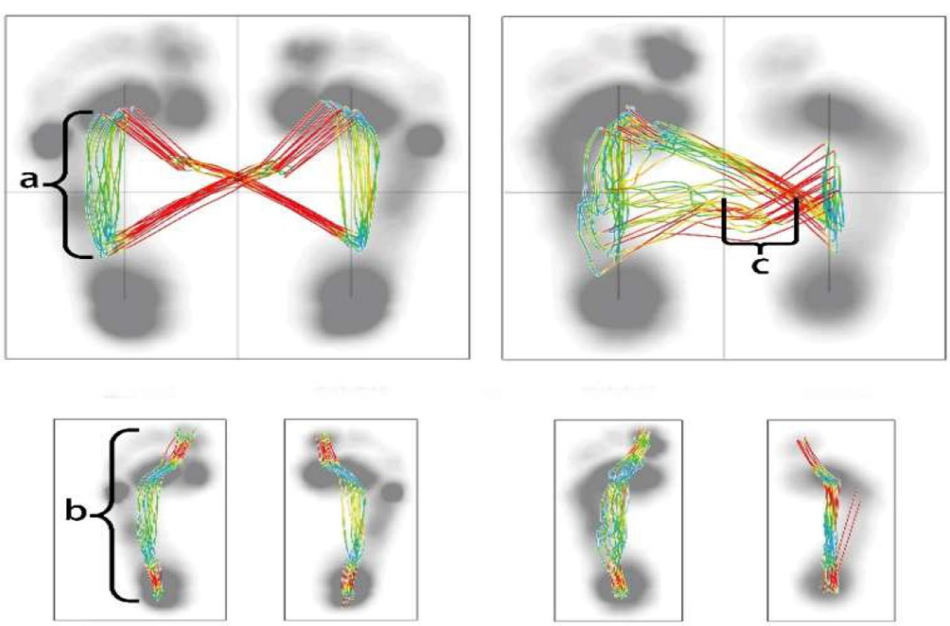

Fig. 5 Butterfly diagram of COP and gait line in patients with ACL reconstruction. Note: a denotes gait line length; b denotes single support line length; c denotes medial-lateral displacement

Table 1 Comparison of general information between the two groups($\bar{X}$±S)

Group	Age (years)	Duration of illness (days)	Weight (kg)	Height (cm)	Gender		Injured side (cases)	
					Male	Female	Left	Right
Test Group	33.20 ± 4.93	38.30 ± 2.64	70.05 ± 8.76	167.45 ± 7.72	14	6	14	6
Control Group	34.25 ± 6.21	38.15 ± 2.23	71.50 ± 9.95	168.25 ± 7.71	8	12	13	7
t-value	0.593	-0.194	0.847	0.328	2.525		0.00	
P-value	0.560	0.847	0.628	0.745	0.11		1.00	

Knee function

Comparison of lysholm knee function score

The Lysholm knee function scores improved significantly in the experimental and control groups before and after the intervention. The score changes were statistically significant in both groups ($P<0.01$, η^2 = 0.89; $P<0.01$, η^2 = 0.77). Between-group comparisons revealed that the experimental group improved significantly more than the control group ($P<0.01$, η^2 = 0.25). The time effect, group effect, and the interaction effect between time and group were all statistically significant ($P<0.01$, η^2 = 0.92; $P=0.04$, η^2 = 0.10; $P<0.01$, η^2 = 0.34) (Table 2).

ROM comparison

Range of motion (ROM) significantly improved in both the test and control groups before and after the intervention. The changes in ROM were statistically significant in both groups ($P<0.01$, η^2 = 0.90; $P<0.01$, η^2 = 0.84). Between-group comparisons revealed that the test group showed significantly greater improvement in ROM than the control group ($P<0.01$, η^2 = 0.78). Both the time effect and the interaction effect between time and group were statistically significant ($P<0.01$, η^2 = 0.94; $P<0.01$, η^2 = 0.21), while the group effect approached statistical significance but did not reach it ($P=0.07$, η^2 = 0.08) (Table 2).

Comparison of SEMG characteristics of the rectus femoris muscle

The sEMG characteristics of the rectus femoris muscle improved significantly in both the test and control groups before and after the intervention. The changes in EMG characteristics were statistically significant in both groups ($P<0.01$, η^2 = 0.85; $P<0.01$, η^2 = 0.35). Between-group comparisons revealed that the test group improved significantly more than the control group ($P<0.01$, η^2 = 0.63). The time effect, group effect, and their interaction were all statistically significant ($P<0.01$, η^2 = 0.83; $P<0.01$, η^2 = 0.49; $P<0.01$, η^2 = 0.58) (Table 2).

Kinematic parameters

Comparison of stride length

Stride length improved significantly in both the test and control groups before and after the intervention. The changes in stride length were statistically significant in both groups ($P<0.01$, η^2 = 0.62; $P<0.01$, η^2 = 0.49). Between-group comparisons revealed that the improvement in stride length after the intervention was significantly greater in the test group than in the control group ($P=0.02$, η^2 = 0.13). The time effect was statistically significant ($P<0.01$, η^2 = 0.72); however, neither the group effect nor the interaction between time and group was statistically significant ($P=0.09$, η^2 = 0.07; $P=0.21$, η^2 = 0.04) (Table 2).

Comparison of step width

Step width improved significantly in both the test and control groups before and after the intervention. The changes in step width were statistically significant in both groups ($P<0.01$, η^2 = 0.32; $P=0.01$, η^2 = 0.15). However, between-group comparisons revealed that the difference in step width between the two groups after the intervention did not reach statistical significance ($P=0.60$, η^2 < 0.01). A significant time effect was observed ($P<0.01$, η^2 = 0.38), but neither the group effect nor the time-group interaction effect reached statistical significance ($P=0.84$, η^2 < 0.01; $P=0.24$, η^2 = 0.04) (Table 2).

Comparison of stride speed

Stride speed improved significantly in both the test and control groups before and after the intervention. The changes in stride speed were statistically significant in both groups ($P<0.01$, η^2 = 0.54; $P<0.01$, η^2 = 0.46). However, between-group comparisons revealed that the difference in stride speed between the two groups did not reach statistical significance after the intervention ($P=0.22$, η^2 = 0.04). The time effect was statistically significant ($P<0.01$, η^2 = 0.67), but neither the group effect nor the interaction effect between time and group reached statistical significance ($P=0.30$, η^2 = 0.03; $P=0.51$, η^2 = 0.01) (Table 2).

Balance functions

Gait line length

Gait line length improved significantly in both the test and control groups before and after the intervention. The changes in gait line length were statistically significant in both groups ($P<0.01$, η^2 = 0.65; $P<0.01$, η^2 = 0.33). Between-group comparisons revealed significantly greater improvement in the test group than in the control

Table 2 Statistical comparison of indicators in the experimental and control groups before and after intervention

Indicators	Experimental group				Control group				Time effect		Subgroup effect		Subgroup*time effect	
	Pre-intervention	Post-intervention	*P*-value	η^2	Pre-intervention	Post-intervention	*P*-value	η^2	*P*-value	η^2	*P*-value	η^2	*P*-value	η^2
Lysholm score	68.95 ± 2.09	81.30 ± 3.15[a]	<0.01	0.89	69.50 ± 2.54	77.45 ± 3.71	<0.01	0.77	0.01	0.92	0.04	0.10	0.01	0.34
Stride length	69.35 ± 20.86	106.40 ± 13.41[a]	<0.01	0.62	66.10 ± 17.17	94.80 ± 16.80	<0.01	0.49	<0.01	0.72	0.09	0.07	0.21	0.04
Step width	16.15 ± 3.15	12.25 ± 3.57	<0.01	0.32	15.20 ± 3.37	12.85 ± 3.66	0.01	0.15	<0.01	0.38	0.84	<0.01	0.24	0.04
Stride Speed	1.76 ± 0.69	2.98 ± 0.54	<0.01	0.54	1.68 ± 0.61	2.73 ± 0.72	<0.01	0.46	<0.01	0.67	0.30	0.03	0.51	0.01
ROM	127.05 ± 4.12	144.20 ± 0.95[a]	<0.01	0.90	127.85 ± 4.08	140.85 ± 0.88	<0.01	0.84	<0.01	0.94	0.07	0.08	<0.01	0.21
SEMG Characteristics	67.09 ± 34.34	257.75 ± 65.03[a]	<0.01	0.85	70.79 ± 34.49	129.91 ± 30.36	<0.01	0.35	<0.01	0.83	<0.01	0.49	<0.01	0.58
Gait Line Length	172.03 ± 30.06	221.79 ± 17.60[a]	<0.01	0.65	173.48 ± 25.44	199.09 ± 18.08	<0.01	0.33	<0.01	0.68	0.09	0.07	<0.01	0.18
Single-Support Line Length	33.66 ± 19.67	95.90 ± 18.56[a]	<0.01	0.84	31.39 ± 19.77	73.66 ± 13.68	<0.01	0.71	<0.01	0.88	0.02	0.15	<0.01	0.22
Medial-Lateral Displacement	34.44 ± 8.63	8.68 ± 3.77[a]	<0.01	0.86	34.90 ± 8.40	13.21 ± 4.83	<0.01	0.82	0.01	0.91	0.17	0.05	0.09	0.07
Forefoot Pressure	389.67 ± 147.44	654.52 ± 129.83[a]	<0.01	0.57	359.98 ± 139.18	526.99 ± 89.64	<0.01	0.34	0.01	0.64	0.01	0.15	0.07	0.08
Midfoot Pressure	140.16 ± 56.91	175.86 ± 81.85	0.08	0.08	138.98 ± 62.78	137.05 ± 62.54	0.92	<0.01	0.23	0.04	0.21	0.04	0.18	0.05
Hindfoot Pressure	270.03 ± 85.71	390.47 ± 85.72[a]	<0.01	0.41	250.95 ± 75.55	302.05 ± 51.28	0.04	0.11	0.01	0.41	0.01	0.20	0.04	0.10

Note: a indicates a statistically significant difference between the test group and the control group after the intervention, $p < 0.05$

group ($P < 0.01$, η^2 = 0.30). Both the time effect and the interaction effect between time and group were statistically significant ($P < 0.01$, η^2 = 0.68; $P < 0.01$, η^2 = 0.18), while the group effect approached significance ($P = 0.09$, η^2 = 0.07) (Table 2).

Single-support line length

Single-support line length improved significantly in both the test and control groups before and after the intervention. The changes in single-support line length were statistically significant in both groups ($P < 0.01$, η^2 = 0.84; $P < 0.01$, η^2 = 0.71). Between-group comparisons revealed significantly greater improvement in the test group than in the control group ($P < 0.01$, η^2 = 0.33). The time effect, group effect, and interaction effect between time and group were all statistically significant ($P < 0.01$, η^2 = 0.88; $P = 0.02$, η^2 = 0.15; $P < 0.01$, η^2 = 0.22) (Table 2).

Medial-lateral displacement

Medial-lateral displacement improved significantly in both the test and control groups before and after the intervention. The changes in medial-lateral displacement were statistically significant in both groups ($P < 0.01$, η^2 = 0.86; $P < 0.01$, η^2 = 0.82). Between-group comparisons revealed significantly greater improvement in the test group than in the control group ($P < 0.01$, η^2 = 0.22). The time effect was statistically significant ($P < 0.01$, η^2 = 0.91), but neither the group effect nor the interaction effect between time and group reached statistical significance ($P = 0.17$, η^2 = 0.05; $P = 0.09$, η^2 = 0.07) (Table 2).

Plantar pressure

Forefoot pressure

Forefoot pressure improved significantly in both the test and control groups before and after the intervention. The changes in forefoot pressure were statistically significant in both groups ($P < 0.01$, η^2 = 0.57; $P < 0.01$, η^2 = 0.34). Between-group comparisons revealed significantly greater improvement in the test group than in the control group ($P < 0.01$, η^2 = 0.26). Both the time effect and the group effect were statistically significant ($P < 0.01$, η^2 = 0.64; $P = 0.01$, η^2 = 0.15), whereas the interaction effect between time and group approached statistical significance ($P = 0.07$, η^2 = 0.08) (Table 2).

Midfoot pressure

The change in midfoot pressure did not reach statistical significance in either group before or after the intervention ($P = 0.08$, η^2 = 0.08; $P = 0.92$, η^2 < 0.01). Similarly, the time effect, group effect, and time-group interaction effect did not reach statistical significance ($P = 0.23$, η^2 = 0.04; $P = 0.21$, η^2 = 0.04; $P = 0.18$, η^2 = 0.05) (Table 2).

Hindfoot pressure

Hindfoot pressure improved significantly in both the test and control groups before and after the intervention. The changes in hindfoot pressure were statistically significant in both groups ($P < 0.01$, $\eta^2 = 0.41$; $P = 0.04$, $\eta^2 = 0.11$). Between-group comparisons revealed significantly greater improvement in the test group than in the control group ($P < 0.01$, $\eta^2 = 0.29$). Both the time effect, group effect, and interaction effect between time and group were statistically significant ($P < 0.01$, $\eta^2 = 0.41$; $P < 0.01$, $\eta^2 = 0.20$; $P = 0.04$, $\eta^2 = 0.10$) (Table 2).

In summary, the findings of this study demonstrate that CE training significantly improves knee function, kinematic parameters, balance function, and plantar pressure distribution. Compared to the control group, the experimental group exhibited significantly more significant improvements in key indicators, including the Lysholm knee score, joint mobility, surface electromyographic characteristics of the rectus femoris muscle, stride width, balance control, forefoot, and rearfoot pressures ($P < 0.05$). While no significant group differences were observed for step width, step speed, and midfoot pressure, the time effects for most indicators reached statistical significance ($P < 0.05$), highlighting the overall efficacy of the intervention in promoting functional recovery.

Discussion

This study applied CE theory as a framework to evaluate the effects of six weeks of CE training on the healthy limb during postoperative rehabilitation in patients after ACL reconstruction. The results showed that the experimental group outperformed the control group in knee joint functionality, kinematic metrics, dynamic balance, and plantar pressure distribution. These findings confirm the efficacy of CE training in postoperative rehabilitation, providing a solid theoretical foundation for improving rehabilitation techniques and emphasizing its significant therapeutic value.

Effect of CE training on knee function after ACLR

CE training significantly improved the Lysholm knee score, joint mobility, and surface electromyographic (sEMG) characteristics of the rectus femoris muscle on the affected side. The experimental group demonstrated significantly more significant improvements across various indices than the control group, with statistical analysis confirming the effects of time, group, and their interaction. These results further support the effectiveness of CE training in postoperative rehabilitation. Training the healthy limb improved Lysholm scores on the affected side, particularly in joint stability and directional control, effectively reducing functional instability and lowering the risk of postoperative complications and secondary injuries [29, 43]. Improved joint mobility facilitated the recovery of daily functional activities and provided a foundation for gradually resuming high-intensity exercise [44]. CE training enhanced control and load-bearing capacity of the affected knee by stimulating the rectus femoris and improving muscle coordination, optimizing overall knee joint function [45]. Furthermore, CE training alleviated strain on the injured knee, improved joint stability, expedited functional recovery, and reduced the likelihood of postoperative instability [29, 46].

Effect of CE training on postoperative kinematic parameters of ACLR

CE training demonstrated significant clinical efficacy in enhancing essential kinematic measures, including stride length, width, and speed. The experimental group showed considerably more significant improvements in stride width than the control group, and the significant time effect further supports the effectiveness of CE training in boosting gait propulsion and dynamic knee stability. These improvements were linked to increased knee range of motion, enhanced muscular strength, and improved motor coordination [47, 48]. Although there were no statistically significant differences in stride speed between the groups, the significant time effect suggests that CE training positively influenced overall motor function recovery by modifying gait rhythm and improving dynamic knee control. The reduction in stride width signifies enhanced lateral gait stability, and the decrease in lateral swing amplitude could help lower the risk of secondary injuries caused by knee instability [49, 50]. CE training showed considerable potential for enhancing postoperative gait performance by notably increasing stride length, speed, and width.

Effect of CE training on dynamic balance after ACLR

CE training significantly improved key kinematic indices, including gait line length, single-support line length, and medial-lateral displacement, with the experimental group showing substantially more significant improvements than the control group. Statistical analyses revealed significant time, group, and interaction effects, affirming the effectiveness of CE training in restoring dynamic balance. The increased gait line length indicated enhanced stability and improved coordination of the center of plantar pressure (COP) trajectory [51, 52]. In contrast, the extended single-support line length reflected better knee control and balance support [53]. Additionally, the substantial reduction in medial-lateral displacement underscored CE training's role in minimizing lateral sway and enhancing lateral gait stability, critical for reducing knee joint load and mitigating the risk of secondary postoperative injuries [37, 54, 55]. These improvements are likely due to neuromuscular adaptive adjustments and central nervous system remodeling facilitated by CE training, which strengthened neuromuscular control mechanisms and improved dynamic postural stability [43, 56, 57]. Overall, CE training provides compelling evidence for its integration into postoperative rehabilitation following ACL reconstruction, effectively optimizing gait patterns, enhancing dynamic balance, and reducing the risk of complications.

Effect of CE training on plantar pressure after ACLR surgery

CE training significantly improved forefoot and hindfoot pressure distribution, proving its clinical effectiveness in postoperative rehabilitation. The experimental group exhibited notably more significant pressure distribution improvements than the control group, with statistical analysis confirming significant time, group, and interaction effects. These results demonstrate that CE training enhances dynamic knee stability and increases the loading capacity of gait. The increased forefoot pressure indicates restored knee function and improved gait symmetry, contributing to better stability and reduced knee joint stress [40, 58]. Likewise, the rise in hindfoot pressure reflects the more effective center of gravity shifting, promoting smoother and more coordinated gait patterns, which enhance knee control and dynamic balance [42, 59]. While changes in midfoot pressure were not statistically significant, the optimization trend in the experimental group suggests improved muscle coordination and better transmission of gait force. In conclusion, CE training significantly optimized gait patterns, increased overall loading capacity, reducing the negative impact of gait abnormalities on the knee joint, and supported functional recovery.

In conclusion, CE training improved knee function, kinematic metrics, dynamic balance, and plantar pressure distribution during ACLR rehabilitation. Enhancing gait symmetry and knee stability reduced the risk of secondary injuries and optimized gait control. The simplicity and ease of implementation make it an ideal option for home-based training, offering patients greater convenience and autonomy in their rehabilitation process. Promoting CE training can significantly boost patient engagement and improve rehabilitation outcomes, supporting integration into standard and personalized rehabilitation programs. Expanding its use in community settings would increase accessibility, reduce healthcare burdens, and provide a sustainable solution for long-term rehabilitation.

Limitations

This study has several limitations. First, the small sample size restricts the generalizability of the findings. Future research involving more significant and diverse populations is needed to enhance external validity. Second, while CE training demonstrated effectiveness in postoperative ACLR rehabilitation, the underlying neuromuscular mechanisms remain unclear. Future studies should investigate its effects on neuromuscular adaptation, motor control, and gait coordination using more advanced experimental designs. Lastly, the short follow-up period limited the evaluation of long-term outcomes. More extended follow-up studies are necessary to confirm whether improvements in knee function, motor ability, and quality of life are sustained over time.

Conclusion

CE training of the healthy limb has shown significant efficacy in postoperative ACLR rehabilitation, leading to improvements in knee function, dynamic balance, and kinematic parameters. However, the exact neuromuscular adaptation mechanisms remain insufficiently understood, and individual variability may influence the outcomes of the intervention. Future research should prioritize investigating the specific neuromuscular mechanisms underlying CE training, particularly its effects on motor control and gait coordination. Furthermore, developing personalized intervention strategies and evaluating the long-term efficacy of CE training is crucial for refining rehabilitation protocols and enhancing their applicability in clinical practice.

Author contributions

Chao Liu, Guqiang Li, and Xiangzhan Jiang designed the experiment. Chao Liu, Shijia Li, Jianping Li, and Honghao Zhang performed the experiments. Chao Liu was responsible for data analysis and manuscript preparation. Chao Liu and Shijia Li made equal contributions to this work and are recognized as co-first authors.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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