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Does proprioceptive training improve joint function and psychological readiness in patients after anterior cruciate ligament reconstruction? A randomized controlled trial

Qun-ya Zheng[1†], Jian-ning Sun[1†], Rui-song Wang[1], Yun-ru Ma[2] and Peng Chen[1*]

Abstract

Introduction A decrease in proprioceptive sensation occurs after anterior cruciate ligament reconstruction (ACLR). However, there is relatively little research on proprioceptive rehabilitation, compared with studies on muscle strength and range of motion (ROM). The purpose of this study was to assess the effect of supplementing a traditional rehabilitation program with proprioceptive training in ACLR patients to improve knee function, psychological readiness, pain and dynamic balance in the early postoperative period.

Methods This was a randomized, parallel-group, controlled trial in which 48 patients were enrolled in either proprioceptive group ($n = 24$) or control group ($n = 24$) from the first week up to 12 th weeks of the operation. Participants in the control group received a traditional ACLR rehabilitation program, while the proprioceptive group received additional proprioceptive training in addition to the traditional ACLR rehabilitation program. The outcome measures included the International Knee Documentation Committee (IKDC), the ACL Return to Sport After Injury scale (ACL-RSI), the visual analog scale (VAS), and the Y-Balance Test before and after surgery.

Results We found that, at 12 weeks post—surgery, patients in the proprioceptive group had significantly higher IKDC scores compared to those in the control group (74.8 ± 4.3 vs 71.6 ± 5.2, P = 0.04). At the 12 th week, the ACL-RSI score of patients in the proprioceptive group was greater than that of the control group (68.2 ± 9.2 vs 62.8 ± 8.2, P = 0.04). The Y balance comprehensive index (YBCI) in the proprioceptive group of patients was greater than that in the control group (94.5% ± 3.3% vs 91.5% ± 4.1%, $P = 0.01$) at 12 weeks after surgery. No statistically significant differences in the VAS score were found between the two groups.

Conclusions Proprioceptive training is superior to conventional training in terms of knee function, psychological readiness and dynamic balance 12 weeks after ACL reconstruction surgery, but has no statistically significant effect on pain.

Trial registration (Chinese Clinical Trial Registry (https://www.chictr.org.cn), No. ChiCTR2400087631, 7/31/2024).

Keywords Anterior cruciate ligament reconstruction, Proprioception, Rehabilitation, Return to sport

[†]Qun-ya Zheng and Jian-ning Sun contributed equally to this work.

*Correspondence:
Peng Chen
13506989645@163.com
Full list of author information is available at the end of the article

Introduction

Anterior cruciate ligament (ACL) injury is a prevalent type of sports injury [1]. ACL reconstruction surgery is considered the primary treatment. Sport recovery rates after ACL reconstruction (ACLR) are low with only 31% recovering at 1 year [2] 41% recovering after 2 years, [3] and 63% returning to pre-injury performance levels[4]. Experienced surgeons encounter difficulties in optimising patients'return to sport and performance through surgical techniques. In response to this obstacle, mainstream rehabilitation strategies primarily emphasise early functional and activity recovery aimed at muscle strength [5, 6] and joint mobility [7, 8]. However, research on proprioceptive rehabilitation remains limited compared to studies focusing on muscle strength and range of motion.

Proprioception is defined as the perception of the mechanical and spatial state of the body and its musculoskeletal parts [9] and plays a crucial role in joint stability, posture and motor control. [10] Studies have shown that despite the restoration of anatomical structure and dynamic balance after knee surgery, patients may have impaired proprioception around the joint. [10–12] Proprioception controls the sense of joint position and triggers reflexive contractions of the muscles around the knee joint, acting as a protective or stabilizing mechanism[13, 14]. A study mentioned that proprioception is related to the subjective function of the knee and that patients with symptomatic ACL deficits seem to have greater deficits than asymptomatic patients[15]. In addition, disturbances in knee mechanics occur both after non-surgical treatment of the ACL and after ACL reconstruction.

During movement, proprioception, in combination with vision and vestibular sensation, transmits body position and balance to the centre[15], where it is processed and acted upon by efferent nerves to regulate muscle tone and improve joint stability. Proprioception plays a crucial role in the kinesthetic and static functions of the motor system, including the perception of joint position, movement, and responsiveness to reflexes and efferent activity, which are essential components of dynamic balance[16]. With proprioceptive training, knee capsule tone and knee muscle groups can be increased, resulting in improved joint stability, mobility, and dynamic balance[17]. Lateral and backward walking [18] reduces the reliance on vision for balance and allows patients to make full use of proprioception to increase perception of joint position and motion, while reducing vestibular sensory intervention. This allows the central system to become more sensitive to proprioception, which in turn allows for better regulation of muscle tone and improved efferent activity in both reflex response circuits and muscle tone regulation circuits.

We assert that postoperative rehabilitation of proprioception is equally important for restoring muscle strength and ROM. Stable joints and improved control considerably increase patients'confidence during rehabilitation. Insufficient focus on proprioception in previous rehabilitation programs, particularly its impact on knee stability, can lead to knee dysfunction and hinder a patient's ability to return to sports postrehabilitation, which is especially unacceptable for individuals with high athletic demands.

We designed a randomised controlled trial with the purpose of assessing the effect of supplementing a traditional rehabilitation program with proprioceptive training in ACLR patients to improve knee function, psychological readiness, pain and dynamic balance in the early postoperative period. We hypothesized that adjunctive proprioceptive training could contribute to the improvement of knee function, psychological preparedness, pain level, and dynamic balance following ACLR.

Materials and methods

Trial design

This randomized, parallel-group, controlled trial was conducted from March to June 2024 at the Sports Medicine Department, with plans to enrol 48 patients.

Participants

Inclusion criteria

1. Age: ≥ 18 years old and < 50 years old.
2. Diagnosed with ACL injury and scheduled for reconstruction.
3. Voluntary signing of informed consent.

Exclusion criteria

1. Previous knee surgery.
2. Presence of significant comorbidities affecting limb control, such as Parkinson's.
3. Patients with concurrent injuries to the affected knee (including posterior cruciate ligament, collateral ligament and patellar dislocation).
4. Any deformity or lesion of the ankle, knee or hip joint.
5. Unwillingness or inability to complete study follow-up or incomplete follow-up information.

Intervention

The rehabilitation programs for ACLR in both groups are shown in Table 1.

Control group

The control group received the traditional rehabilitation program and were instructed to complete it at home. 0–2 weeks after surgery, patients were required

Table 1 Rehabilitation program for ACLR in both groups

Timing	control group	proprioceptive group
0–2 weeks:	• Toe-touch weight bearing with elbow crutches • Brace 0–90 degrees • Full extension (Avoid hyperextension for 12 weeks) • Passive and active flexion exercises • Ice and modalities to reduce pain and inflammation • Circulation exercises • Patella mobilisations • Static quads exercises (But not beyond 0 degrees)	Same as control group
3–5 weeks:	• Continue above • Continue Brace 0–90 degrees (From 3 weeks can remove brace with physio to do active-assisted flexion to 110 degrees) • Normalise Gait – wean off crutches as pain and quadriceps allow • Scar massage to prevent adherence • Full patella mobility • Hamstring management – soft tissue techniques/gentle stretching • Commence 'Wall push' Isometric quads and hams—in supine with legs at 90 degrees and feet against wall (gravity eliminates ant tibial translation from quads)	the addition of single-leg 4-way exercises, walking in a straight line with eyes closed, walking backwards with eyes open for at least 15 min/d
6–12 weeks:	• Wean out of brace • Gradual increase intensity glut/core work (Restore control and balance) • Active range of movement to 120 degrees • Gentle hamstrings strengthening exercises (prone knee curls) • Continue swelling control, scar management and patella mobility	the addition of toe drawing in the shape of an"8", horizontal and backward walking, and balance board exercises for at least 15 min/d

to wear braces strictly to protect the knee and actively complete rehabilitation activities, including patella mobilization, ankle pump training, and multidirectional straight leg raising. 3–5 weeks after surgery, patients were asked to continue brace at 0–90 degrees and increase knee motion by sitting in knee flexion. 6–12 weeks after surgery, patients begin to try to stop using braces and crutches and undergo gentle hamstring strengthening exercises (prone knee curls).

Proprioceptive group

In addition to the traditional rehabilitation, patients in the proprioceptive group also participated in proprioceptive rehabilitation. 0–2 weeks after surgery: no difference from traditional rehabilitation. 3–5 weeks after surgery: the addition of single-leg stance for half a minute, balance reach leg, balance reach arm exercises and bilateral squats 4 times a week, with 3 sets of 15 repetitions each time, and walking backward with one's eyes open for at least 15 min per day were performed. 6–12 weeks after surgery: Single-leg stance and single-leg pelvic bridge on the surgical side for more than half a minute, balance reach leg and balance reach arm exercises, single-leg squat and slide skip, 4 times a week, 3 sets each time, 15 repetitions per set, backward walking, and balance board exercises for at least 15 min per day were used.

Surgical procedures

Surgery was performed by experienced orthopedic surgeons who specialize in arthroscopic knee surgery. All surgeons used an arthroscopic single-bundle technique for primary ACLR. The hamstring tendon (HT) was harvested with a tendon harvester through an oblique incision over the pes anserinus and folded into a 4-strand graft via both the semitendinosus and the gracilis tendons. The femoral tunnel was placed anatomically in the center of the footprint through an anteromedial portal. The tibial tunnel was placed anatomically between the tibial spines at the level of the posterior border of the anterior horn of the lateral meniscus.

Outcome measures

All measurements were performed by a trained, independent researcher who was blinded to the group assignment. All participants were required to keep their grouping information confidential during follow-up.

Primary outcome measure

International knee documentation committee

To quantify knee function, participants completed a knee IKDC (International Knee Documentation Committee) score, which is used to determine symptoms, function, and motor activity, before and 12 weeks after surgery. The 12-week postoperative assessment was chosen as the time point for evaluation, as it allowed for early

detection, intervention, and treatment of postoperative complications such as joint stiffness and muscle atrophy. Scores range from zero (low function) to 100 (high function) [19, 20]. Previous studies have indicated that the IKDC has adequate validity and reliability for patients with knee injuries. Moreover, IKDC scores were the most frequently reported patient-reported outcome measures in RCTs after ACLR [21].

Secondary outcome measures

ACL Returns to sport after injury scale

The ACL-RSI scale is used to measure psychological readiness for return to sport (RTS) [22], and the questionnaire consists of 12 questions covering key aspects of RTS: emotions related to return (e.g., fear and frustration), confidence in athletic performance, and assessment of risk of serious injury.

Visual analog scale

The VAS score is widely used to evaluate the degree of postoperative pain. Patients were asked to select their own pain score on the horizontal axis of 0–100 mm, with each 10 mm representing 1 point and 0 indicating "no pain" to 10 points indicating "worst pain imaginable." Resting pain was measured after bed rest for at least 30 min. Pain during activity was measured immediately after a six-minute walk test.

Y-Balance Test

The Y-Balance Test (Y-BT) is used to assess dynamic balance in reconstructed and healthy knees. The Y-BT has been shown to be a reliable measure with the validity of a dynamic test for predicting the risk of lower limb injuries and identifying dynamic balance deficits in patients with a variety of lower limb disorders[23]. Subjects received verbal instructions and a visual demonstration of the Y-BT from the same physiotherapist. This test requires the subject to push the box as far as possible in the anterior, posteromedial, and posterolateral directions while maintaining a balanced stance on one foot, as shown in Fig. 1. The patients used Y-BT to conduct six Y-BT practice trials and three Y-BT measurement trials, and the average of the three measurements was used for data analysis. [24] To calculate the composite score, the sum of the maximum reaches in each of the three directions was divided by three times the leg length [25, 26].

Statistical analysis

Statistical analysis was conducted via IBM SPSS 27.0 software (Chicago, USA) and the threshold of significance wasp <0.05. The results are reported as the mean ± SD ($\bar{X} \pm S$). Demographic and clinical data were compared between the control group and proprioceptive group via Pearson's chi-square test. Intergroup differences were assessed for significance via independent t tests after confirming that the data followed a normal distribution. A power analysis based on IKDC was performed, and sample size calculations via G*Power 3.1 software (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) were performed on the basis of the results of the pre-experiment with an effect size of 1.1. Therefore, assuming a type 1 error of 5% and a statistical efficacy of 90%, 48 participants were required as the study population, accounting for a 20% dropout rate.

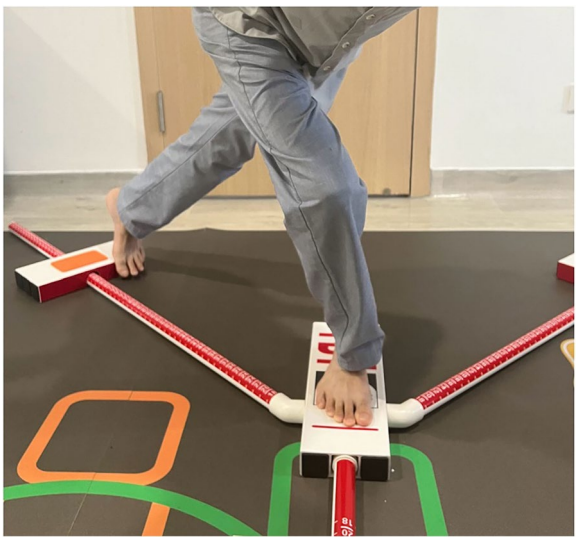

Fig. 1 Y-Balance Test

Randomization

After the patient met the inclusion and exclusion criteria of the study and agreed to participate, an independent statistician used a computer-generated random number sequence to randomly assign each patient to one of the two treatment options immediately, and the treatment options used blind codes. The statistician did not know the patient's identity or treatment plan throughout the process.

Ethical considerations

This study involved human participants, and all procedures performed in the study were in accordance with the Medical Institution Administration Regulation and conformed with the ethical standards of the National Research Council and Helsinki Declaration. This study was approved by the Ethics Committee of The First Affiliated Hospital of Fujian Medical University., registration number MRCTA, ECFAH of FMU| 2024 | 377. Informed consent to participate was obtained from all of the participants in the study.

Results

Participant flow

From March to June 2024, a total of 48 patients were included in this study, 24 in the control group and 24 in the proprioceptive group. During the follow-up period, 3 participants in the control group and 4 participants in the proprioceptive group withdrew from the trial. The final results included a total of 41 patients.

The study flowchart is shown in Fig. 2. The demographic characteristics are shown in Table 2. The two groups had similar in demographic characteristics.

Table 2 The demographic characteristics of the patients in both groups

	proprioceptive group($N=21$)	control group ($N=20$)	*P*
Age(year)	28.7 ± 8.6	29.2 ± 7.5	0.78
Gender(male/female)	12/9	9/11	0.44
BMI (kg/m^2)	24.8 ± 3.7	24.2 ± 2.7	0.44
Surgical side (left/right)	14/7	11/9	0.89
time between injury and surgery(month)	1.5 ± 3.1	1.7 ± 3.7	0.8

BMI Body Mass Index

Outcome measures

The outcomes preoperatively and postoperatively in both groups are shown in Table 3. We found that at week 12 after ACLR surgery, both groups of patients had improved IKDC scores compared with the preoperative values. Compared with the control group at 12 weeks after surgery, the proprioceptive group had higher IKDC scores (74.8 ± 4.3 vs 71.6 ± 5.1, p = 0.04). The difference between the two groups was statistically significant. Compared to preoperative, neither the proprioceptive group nor the control group improved IKDC by more than the MCID [27] at 3 months postoperatively, but we found that eight subjects in the proprioceptive group improved individual IKDC by more than the MCID at 3 months postoperatively, whereas the control group did not.

We found that the ACL-RSI score of patients in the proprioceptive group was greater than that of the control group at 12 weeks after surgery (68.2 ± 9.2 vs 62.8 ± 8.1, p = 0.04). Compared with the preoperative period, subjects in the proprioceptive group showed greater improvement in ACL-RSI than MCID [27]at 3 months postoperatively, whereas control subjects did not. Compared with the control group, the proprioceptive group

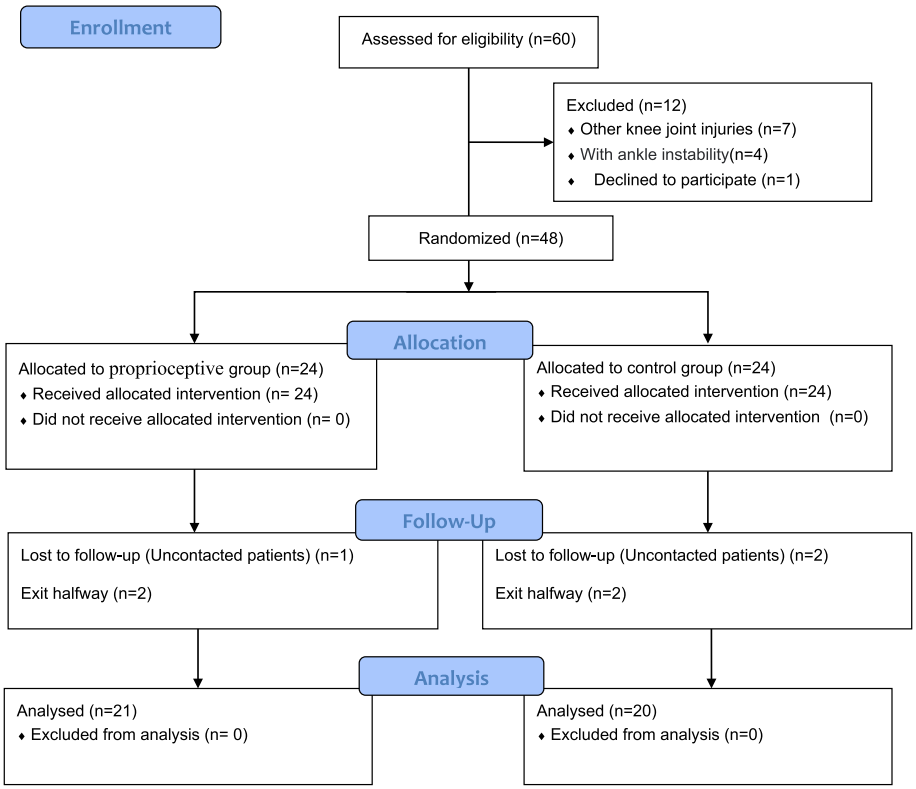

Fig. 2 The study flowchart

Table 3 Outcomes preoperatively and postoperatively in both groups

	Preoperative			Postoperative		
	proprioceptive group	control group	P	proprioceptive group	control group	P
IKDC	68.9 ± 7.2	69.8 ± 7.3	0.64	74.8 ± 4.3	71.6 ± 5.1	**0.04***
IKDC changes				5.9 ± 5.9	1.8 ± 5.2	**0.05***
ACL-RSI	57.1 ± 9.4	56.88 ± 8.2	0.90	68.2 ± 9.2	62.8 ± 8.1	**0.04***
VAS	0.5 ± 0.9	0.6 ± 0.7	0.71	0.3 ± 0.6	0.3 ± 0.5	0.93
YBCI on surgical leg	83.8% ± 4.9%	83.7% ± 3.0%	0.93	95.5% ± 3.5%	92.3% ± 3.8%	**0.02***
YBCI on health leg	99.8% ± 3.8%	98.6% ± 2.4%	0.19			

IKDC International Knee Documentation Committee, *ACL-RSI* The Anterior Cruciate Ligament-Return to Sport after Injury, *VAS* Visual Analogue Scale, *YBCI* Y-balance composite index = (anterior + posteromedial + posterolateral reach directions)/3* limb length (anterior superior iliac spine to medial malleolus) * 100%; *:$P < 0.05$

performed better in the Y balance test at 12 weeks postsurgery (95.5% ± 3.5% vs 92.3% ± 3.8%, $p = 0.02$).

There was no statistically significant difference in the VAS score between the two groups.

Discussion

The most significant finding of this study is that the postoperative knee function improvement was significantly greater in the proprioceptive group compared with the control group. We also found that at 12 weeks postsurgery, the proprioceptive-based training program was superior to the control program in improving patients'IKDC score and psychological readiness, and dynamic balance as measured by the Y-Balance Test.

The proprioceptive training in this study led to improvements in knee function, including increased dynamic balance, improved joint stability and mobility, and reduced deficits in knee control after ACL reconstruction. As a result, the improvement in the IKDC score at the 12-week postoperative test was significantly greater in the proprioceptive training group than in the control group. In addition, patients in the proprioceptive group subjectively reported improved knee control and demonstrated more confidence in the rehabilitation process than the control group. This positive cycle not only improves knee function and psychological readiness to return to sport, but also reduces the risk of falls during the early postoperative period after ACLR.

A previous study [28] confirmed that proprioceptive rehabilitation training led to improved functional performance of the knee compared with ordinary rehabilitation training. Similarly, our study revealed that proprioceptive training was beneficial for knee function. However, our study differed in the aspects that we initiated proprioceptive training at an earlier stage and evaluated patients earlier as well. This allows patients to improve their joint function and readiness to return to sports as early as possible after surgery, potentially reducing financial stress.

In this study, we observed a significant increase in the ACL-RSI score in the proprioceptive training group compared to with the control group. Previous studies have shown that athletes'psychological outlook can significantly improve during a training program, and those who experience improved psychological outlook during rehabilitation may also report an increase in function [29] This finding is consistent with the results of our study. Additional training programs can further enhance the patient's postural control and knee movement ability, allowing for a quicker return to daily activities and sports [30]. Proper training instruction [31], supervision, and improvements in knee function, such as increased perception of joint position and improved range of motion, can also help alleviate kinesiophobia.

Dynamic balance training, such as the proprioceptive exercises used in this study, enhances neuromuscular control, coordination, and proprioception, all of which are critical for improving balance. These improvements are directly reflected in Y-BT performance. Several studies have demonstrated that dynamic balance training significantly improves Y-BT scores. For example, Benis et al. found that a 8-week dynamic balance training program led to significant increases in all reach directions of the Y-BT among athletes[32]. Similarly, Wang et al. reported that improvements in neuromuscular control and balance, achieved through targeted training, were strongly associated with better Y-BT performance[33].

In our study, the proprioceptive training group showed significant improvements in Y-BT scores compared to the control group. This suggests that the proprioceptive exercises, which included single-leg stance, balance reach exercises, and backward walking, effectively enhanced dynamic balance by improving joint stability and neuromuscular control. These findings align with previous research and further support the use of dynamic balance training in rehabilitation programs for ACLR patients.

At the 12-week postoperative assessment, those with a Y-balance composite index greater than 95% (15/41)

showed improvement compared to before surgery. The proprioceptive training group (10/21) showed significant improvement compared with the control group (5/20) at 12 weeks postsurgery, possibly due to improved posterior control and knee movement ability from proprioceptive training.

Furthermore, it is important to consider the effects of fatigue during rehabilitation, as patients with ACL reconstruction typically experience a decrease of more than half in their peak quadriceps torque force [34]. Quadriceps strength is crucial for maintaining balance during lateral and backward walking [35], as is foot-pressing on balance boards, which were used in this experiment. Prolonged proprioceptive training can lead to fatigue, which may result in decreased joint stability or even reinjury from falling [34]. Therefore, in this study, we performed proprioceptive training before regular training in order to reduce the potential adverse consequences of postoperative rehabilitation.

This study is not without limitations which may have influenced our findings. The main results of this study depend on self-reported measurements. Using more objective measurements might yield slightly different results. In this study, the Y-BT was used as an assessment index for dynamic balance, which may also be affected by muscle strength and ankle ROM. We did not evaluate ankle range of motion in this study and are unable to comment on the potential influence of ankle motion in our sample. This may cause some interference to our results. Participants'physical activity levels were not included as a key consideration during the study design process. Physical activity levels may have a potential impact on study outcomes. Since the time required for the knee to return to sports is relatively long and the intervention in this study lasted only three months, it can only reflect the early stage after ACLR surgery.

Conclusions

In the early postoperative period after ACL reconstruction, the incorporation of proprioceptive training can improve knee function, psychological readiness and dynamic balance for patients.

Abbreviations

ACLR	Anterior cruciate ligament reconstruction
IKDC	International Knee Documentation Committee
ACL-RSI	ACL Return to Sport After Injury Scale
RTS	Return-to-Sport
VAS	Visual analog scale
YBCI	Y balance comprehensive index

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Authors' contributions

ZQY and SJN the study and drafted the manuscript. WRS were involved in the design, main contribution in literature search. CP and MYR were involved in the study design, and made further revision in this manuscript. All authors read and approved the final manuscript.

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All data collection and reporting underwent the necessary review and approval by the ethical committee of The First Affiliated Hospital of Fujian Medical University. (Approval No.: MRCTA,ECFAH of FMU| 2024 | 377).

Data availability

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

Declarations

Ethics approval and Consent to participate

This study was approved by the Ethics Committee of The First Affiliated Hospital of Fujian Medical University. (Approval No.: MRCTA,ECFAH of FMU| 2024 | 377). All methods were carried out in accordance with relevant guidelines and regulations. Informed consent to participate was obtained from all of the participants in the study.

Consent for publication

All written informed consent for publication of identifying images or other personal or clinical details was obtained from all of the participants.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Sports Medicine, The First Affiliated Hospital of Fujian Medical University, Fujian, China. [2]Fujian Medical University, Fujian, China.

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References

1. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: A 10-year study. Knee. 2006;13(3):184–8.
2. Ardern C, Taylor N, Feller J, Whitehead T, Webster K. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2013;41(7):1549–58.
3. Ardern C, Taylor N, Feller J, Whitehead T, Webster K. Sports participation 2 years after anterior cruciate ligament reconstruction in athletes who had not returned to sport at 1 year: a prospective follow-up of physical function and psychological factors in 122 athletes. Am J Sports Med. 2015;43(4):848–56.
4. Ardern C, Webster K, Taylor N, Feller J. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med. 2011;45(7):596–606.
5. Coulondre C, Souron R, Rambaud A, Dalmais É, Espeit L, Neri T, Pinaroli A, Estour G, Millet GY, Rupp T et al. Local vibration training improves the recovery of quadriceps strength in early rehabilitation after anterior cruciate ligament reconstruction: A feasibility randomised controlled trial. Ann Phys Rehabil Med. 2022;65(4):101441.
6. Ogrodzka-Ciechanowicz K, Głąb G, Ślusarski J, Gądek A. Quadriceps muscle strength recovery with the use of high tone power therapy after

anterior cruciate ligament reconstruction: a randomized controlled trial. BMC Musculoskelet Disord. 2021;22(1):975.
7. Song Y, Che X, Wang Z, Li M, Zhang R, Wang D, Shi Q. A randomized trial of treatment for anterior cruciate ligament reconstruction by radial extracorporeal shock wave therapy. BMC Musculoskelet Disord. 2024;25(1):57.
8. Culvenor AG, Girdwood MA, Juhl CB, Patterson BE, Haberfield MJ, Holm PM, Bricca A, Whittaker JL, Roos EM, Crossley KM. Rehabilitation after anterior cruciate ligament and meniscal injuries: a best-evidence synthesis of systematic reviews for the OPTIKNEE consensus. Br J Sports Med. 2022;56(24):1445–53.
9. Héroux ME, Butler AA, Robertson LS, Fisher G, Gandevia SC. Proprioception: a new look at an old concept. J Appl Physiol (1985). 2022;132(3):811–4.
10. Rossignol S, Dubuc R, Gossard JP. Dynamic sensorimotor interactions in locomotion. Physiol Rev. 2006;86(1):89–154.
11. Fremerey RW, Lobenhoffer P, Zeichen J, Skutek M, Bosch U, Tscherne H. Proprioception after rehabilitation and reconstruction in knees with deficiency of the anterior cruciate ligament: a prospective, longitudinal study. J Bone Joint Surg Br. 2000;82(6):801–6.
12. MacDonald PB, Hedden D, Pacin O, Sutherland K. Proprioception in anterior cruciate ligament-deficient and reconstructed knees. Am J Sports Med. 1996;24(6):774–8.
13. Barrack RL, Skinner HB, Buckley SL. Proprioception in the anterior cruciate deficient knee. Am J Sports Med. 1989;17(1):1–6.
14. Barrett DS, Cobb AG, Bentley G. Joint proprioception in normal, osteoarthritic and replaced knees. J Bone Joint Surg Br. 1991;73(1):53–6.
15. Lephart SM, Pincivero DM, Rozzi SL. Proprioception of the ankle and knee. Sports Med. 1998;25(3):149–55.
16. Proske U, Gandevia SC. The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. Physiol Rev. 2012;92(4):1651–97.
17. Ghai S, Driller M, Ghai I. Effects of joint stabilizers on proprioception and stability: A systematic review and meta-analysis. Phys Ther Sport. 2017;25:65–75.
18. Shen M, Che S, Ye D, Li Y, Lin F, Zhang Y. Effects of backward walking on knee proprioception after ACL reconstruction. Physiother Theory Pract. 2021;37(10):1109–16.
19. Collins N, Misra D, Felson D, Crossley K, Roos E: Measures of knee function: International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, Knee Injury and Osteoarthritis Outcome Score (KOOS), Knee Injury and Osteoarthritis Outcome Score Physical Function Short Form (KOOS-PS), Knee Outcome Survey Activities of Daily Living Scale (KOS-ADL), Lysholm Knee Scoring Scale, Oxford Knee Score (OKS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Activity Rating Scale (ARS), and Tegner Activity Score (TAS). Arthritis care & research 2011:S208–228.
20. Rossi MJ, Lubowitz JH, Guttmann D. Development and validation of the International Knee Documentation Committee Subjective Knee Form. Am J Sports Med. 2002;30(1):152.
21. Abed V, Kapp S, Nichols M, Castle JP, Landy DC, Conley C, Stone AV. Lysholm and KOOS QoL Demonstrate High Responsiveness in Patients Undergoing Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis of Randomized Clinical Trials. Am J Sports Med. 2024;52(12):3161–6.
22. Webster K, Feller J, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine. 2008;9(1):9–15.
23. Gribble PA, Hertel J, Plisky P. Using the Star Excursion Balance Test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. J Athl Train. 2012;47(3):339–57.
24. Takahashi H, Igawa T, Ito S, Urata R, Suzuki K, Ito R, Toda M, Matsumoto C, Ishizaka M. An examination of the intra-rater reliability of the Y Balance test for high school female athletes. J Phys Ther Sci. 2025;37(1):1–5.
25. Kinzey S, Armstrong C. The reliability of the star-excursion test in assessing dynamic balance. J Orthop Sports Phys Ther. 1998;27(5):356–60.
26. Maffiuletti N, Bizzini M, Schatt S, Munzinger U. A multi-joint lower-limb tracking-trajectory test for the assessment of motor coordination. Neurosci Lett. 2005;384:106–11.
27. Deviandri R, van der Veen HC, Lubis AM, Postma MJ, van den Akker-Scheek I. Responsiveness of the Indonesian Versions of the Anterior Cruciate Ligament-Return to Sport After Injury Score, the International Knee Documentation Committee Subjective Knee Form, and the Lysholm Score in Patients With ACL Injury. Orthop J Sports Med. 2023;11(8):23259671231191827.
28. Mustafa J, Nicola M, Filippo M, Ashokan A: Known-group validity of passive knee joint position sense: a comparison between individuals with unilateral anterior cruciate ligament reconstruction and healthy controls. J Orthop Surg Res 2023, 18(1).
29. Zarzycki R, Arhos E, Failla M, Capin J, Smith A, Snyder-Mackler L. Association of the Psychological Response to the ACL-SPORTS Training Program and Self-reported Function at 2 Years After Anterior Cruciate Ligament Reconstruction. Am J Sports Med. 2021;49(13):3495–501.
30. Webster KE, Nagelli CV, Hewett TE, Feller JA. Factors Associated With Psychological Readiness to Return to Sport After Anterior Cruciate Ligament Reconstruction Surgery. Am J Sports Med. 2018;46(7):1545–50.
31. Cronström A, Häger CK, Thorborg K, Ageberg E. Factors Associated With Sports Function and Psychological Readiness to Return to Sports at 12 Months After Anterior Cruciate Ligament Reconstruction: A Cross-sectional Study. Am J Sports Med. 2023;51(12):3112–20.
32. Benis R, Bonato M, La Torre A. Elite Female Basketball Players' Body-Weight Neuromuscular Training and Performance on the Y-Balance Test. J Athl Train. 2016;51(9):688–95.
33. Wang B, Wu B, Yang Y, Cai M, Li S, Peng H. Neuromuscular and balance adaptations following acute stretching exercise: a randomized control trial. Front Physiol. 2024;15:1486901.
34. Kim S, Glaviano NR, Park J. Exercise-induced fatigue affects knee proprioceptive acuity and quadriceps neuromuscular function more in patients with ACL reconstruction or meniscus surgery than in healthy individuals. Knee Surg Sports Traumatol Arthrosc. 2023;31(12):5428–37.
35. Alghadir AH, Anwer S, Sarkar B, Paul AK, Anwar D. Effect of 6-week retro or forward walking program on pain, functional disability, quadriceps muscle strength, and performance in individuals with knee osteoarthritis: a randomized controlled trial (retro-walking trial). BMC Musculoskelet Disord. 2019;20(1):159.

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