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# Four-year comparative analysis of return to sport and psychological recovery following ACL revision: Artificial ligament vs. anterior tibial tendon allograft

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ABSTRACT

*Background:* Research on return to sport and psychological recovery in anterior cruciate ligament (ACL) revision remains scarce. The clinical efficacy of artificial ligament in ACL revision requires further exploration. Our objectives were (1) to compare the midterm clinical outcomes of artificial ligament versus allogenic tendon graft in ACL revision and (2) to analyze the effects of employing artificial ligament on return to sport and psychological recovery in ACL revision.

*Methods:* This cohort study included the cases receiving ACL revision from 2014 to 2021 in Sports Medicine Department of Huashan Hospital. The grafts used were Ligament Advanced Reinforcement System (LARS) and ATT allograft. We recorded patients' baseline data. The final follow-up assessment included subjective scales, physical examination, and return to sport status. We recorded the rates and timings of return to sport. Subjective scales included the 2000 International Knee Documentation Committee (IKDC) subjective score, Lysholm Knee Scaling Score (LKSS), Knee injury and Osteoarthritis Outcome Score (KOOS), Tegner activity score, Marx activity rating score, and Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI). Anterior knee stability was assessed using the KT-1000 arthrometer.

*Results:* Fifty cases (LARS group: 27; ATT group: 23) enrolled and 45 (LARS group: 23; ATT group: 22) completed evaluations with a median follow-up period of 49 months. At recent follow-up, LARS group outperformed in knee stability (1.0 $\pm$ 1.9 mm vs. 2.6 $\pm$ 3.0 mm, $P = 0.039$), confidence (86.7 $\pm$ 12.4 vs. 69.4 $\pm$ 18.6, $P < 0.001$), emotion (82.7 $\pm$ 11.3 vs. 70.7 $\pm$ 16.2, $P < 0.001$), KOOS knee function (78.7 $\pm$ 8.8 vs. 69.5 $\pm$ 11.0, $P = 0.003$), quality of life (79.1 $\pm$ 16.1 vs. 66.4 $\pm$ 19.5, $P = 0.014$), Tegner score (6.3 $\pm$ 1.9 vs. 5.2 $\pm$ 2.1, $P < 0.001$), and Marx activity score (10.7 $\pm$ 3.7 vs. 7.9 $\pm$ 4.0, $P = 0.012$). The LARS group had significantly higher return rates: recreational (91.3 % vs. 63.6 %, $P = 0.026$), knee cutting and pivoting (87.0 % vs. 59.1 %, $P = 0.035$), competitive (78.3 % vs. 45.5 %, $P = 0.023$), and pre-injury (56.5 % vs. 27.3 %, $P = 0.047$). For return timings, the LARS group was earlier at recreational (11.2 $\pm$ 3.9 vs. 27.8 $\pm$ 9.0 weeks, $P < 0.001$), knee cutting and pivoting (17.2 $\pm$ 5.8 vs. 35.6 $\pm$ 13.8 weeks, $P < 0.001$), competitive (24.8 $\pm$ 16.2 vs. 53.2 $\pm$ 22.0 weeks, $P < 0.001$), and pre-injury levels (32.8 $\pm$ 11.0 vs. 72.8 $\pm$ 16.9 weeks, $P < 0.001$).

*Conclusion:* In ACL revision, using LARS demonstrated improved joint stability and functionality compared to using allogenic ATT four years postoperative. Patients accepting the LARS procedure exhibited higher rates and earlier timings of return to various levels of sport, indicating enhanced confidence and emotional resilience.

*The translational potential of this article:* In ACL revision, the choice of artificial ligament to shorten recovery time, thereby enabling patients to return to sport more quickly and effectively, is thought-provoking. The research value extends beyond mere graft selection, guiding future clinical trials and studies. This research enhances our understanding of the application value of artificial ligament in ACL revision, emphasizing the importance of psychological recovery and updating our perceptions of return to sport levels post-revision. It stimulates exploration into personalized rehabilitation programs and treatment strategies, aiming to optimize clinical outcomes and meet the real-world needs of patients with failed ACL reconstruction.

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## 1. Introduction

The anterior cruciate ligament (ACL) is pivotal in maintaining knee joint stability, especially during cutting and pivoting movements [1]. An injury to the ACL, whether caused by direct or indirect trauma, can lead to knee instability, hindering daily and athletic activities. Delayed treatment can precipitate further complications, such as damage to the meniscus or other ligaments, and even heighten the risk of osteoarthritis [2]. ACL reconstruction (ACLR) has emerged and is widely accepted as a practical and effective therapeutic approach. Its primary goal is to restore joint stability and prevent further joint damage. When successful, patients can resume daily and athletic activities and reduce the risk of long-term knee issues [3]. However, the success rate of a primary ACLR isn't always guaranteed, with reported failure rates varying between 10 % and 25 % across various studies [4]. Such failures may lead to persistent knee instability and an increased risk of osteoarthritis [5]. For athletes, this could mean an inability to return to their pre-injury competitive level. Consequently, revision surgery becomes a pivotal secondary treatment strategy for cases where the primary ACLR is unsuccessful, aiming to replace the damaged ACL graft for re-established knee stability [6].

Revision surgeries often face distinct challenges, mainly when dealing with pre-existing scars and the aftermath of prior surgeries, which can complicate the procedure，particularly in cases where bone tunnels are misaligned [7,8]. In this scenario, the importance of selecting the right graft cannot be overstated, as it plays a crucial role in determining the surgery's success and significantly affects the patient's recovery [9]. Recent research on ACL revision has predominantly concentrated on the surgical application of autograft and allograft, primarily focusing on joint stability and patient-reported outcomes [9–12]. These studies, while significant, often overlook three critical aspects. Firstly, although efficacy assessments should focus on knee stability, symptom management, and patient satisfaction, the objective of an ACL revision should be to enable patients to confidently and safely resume athletic activities [13,14]. For sports enthusiasts, the ability to return to the field should be a core measure of revision surgery's success. Secondly, the traditional grafts like autografts and allografts in these revisions present inherent limitations, such as self-tissue sacrifice and a propensity for slower healing, resulting in extended recovery time, consequently impeding patients' timely return to athletic endeavors [15,16]. Thirdly, most studies neglected the evaluation of patients' psychological states postsurgery. The utilization of artificial ligaments in primary ACLR is now a well-established consensus among medical professionals in China, offering advantages such as ensuring immediate mechanical strength, faster postoperative recovery, and an earlier return to sports activities [17–19]. However, comprehensive studies and evidence supporting its application in ACL revision remain limited.

In summary, our center conducted a prospective study spanning from June 2014 to June 2021, focusing on patients who underwent ACL revision. This study was primarily designed to evaluate mid-term recovery, encompassing clinical outcomes, psychological recovery, and return to sport in patients treated with either Ligament Advanced Reinforcement System (LARS) artificial ligaments or anterior tibialis tendon (ATT) allograft. This research aims to establish a robust, data-driven foundation to assist in clinical decision-making regarding the selection of optimal grafts, seeking to maximize therapeutic and rehabilitation outcomes following ACL revision.

## 2. Methods

### 2.1. Case selection

From June 2014 to June 2021, we enrolled the ACL revisions in our department according to the inclusion and exclusion criteria in this non-randomized prospective cohort study (Table 1). We informed patients about the characteristics, advantages, and disadvantages of different grafts in clinical applications, ultimately leaving the choice of graft to the patients themselves. The Ethics Committee of Huashan Hospital (Huashan Institutional Review Board, HIRB) approved this study protocol (KY2011337), and all procedures were conducted following the principles outlined in the Declaration of Helsinki.

### 2.2. Sample size calculation

The primary outcome was the return to sport rate, comparing the LARS and ATT groups. Preliminary results showed that one year after surgery, 10 % of the LARS group and 50 % of the ATT group did not return to sport, with an RR of 20 % for the LARS group compared to the ATT group. Setting $\alpha = 0.05$ (two-sided) and $\beta = 0.20$, the sample size for both the test and control groups was N1═N2=17. Considering the study's 15 % dropout rate, the total sample size was N═N2=17/85 % = 20, meaning each group needed at least 20 patients. The sample size was calculated using Power Analysis and Sample Size Software 15 (NCSS, LLC. Kaysville, Utah, USA).

### 2.3. Surgical technique

All revision were performed by one senior sports medicine doctor (Shiyi Chen). Treatment was concurrently administered for meniscus and cartilage injuries, involving debridement of inflamed synovial tissue within the joint and loosening of scar tissue. For patients undergoing revision using the LARS (AC120, France), we confirmed the locations of the tibial and femoral tunnels based on previously reported isometric point positioning methods [20]. After drilling the tibial tunnel, we prepared the tunnel using the tibial method with a diameter of 7.5 mm. After placing the guidewire and fixing the pin, we introduced the graft and carefully adjusted the ligament tunnel segment to avoid cutting effects. Both the tibial and femoral ends were fixed using titanium screws. For the gamma-irradiated ATT allograft (OSTEOLINK, Hubei, China), its minimal length was 26 mm, trimmed 4 mm from both ends and was fixed with #4843 wire weaving, used for tibial end fixation. The graft diameter was 8 mm. After introducing the graft, the femoral end is

**Table 1**
Inclusion and exclusion criteria for this study.

| Inclusion criteria | Exclusion criteria |
|---|---|
| Age between 18 and 65 years | Pregnant women or women planning to become pregnant |
| Male or female | Severe complications, such as joint adhesions, infections |
| Recurrent joint laxity after primary ACLR[a] | Already participating in other clinical trials |
| Underwent ACL revision surgery at our center | Cases involving work-related injuries or traffic accident compensations |
| Graft is either the LARS or ATT allograft | Multiple ligament injuries (MCL injuries treated conservatively excluded) |
| Providing informed consent for the study | Concomitant use of autograft |
| Without cognitive or communication barriers | Second-stage revision (bone grafting)[b] |
| | Combined lateral extraarticular tenodesis[c] or osteotomy[d] |
| | Refusal to participate in the study |

[a] According to the 2000 IKDC standard, joint stability is graded as C or D.
[b] Indications for second-stage revision (bone grafting) include a maximum bone tunnel diameter greater than 14 mm; preoperative joint passive motion deficits, with an extension greater than 5° and a flexion greater than 25°; the primary surgery tunnel interferes with the revision tunnel position.
[c] Indications for osteotomy correction include abnormalities in the lower limb force line, such as a tibial plateau posterior tilt angle greater than 12° and a coronal deformity greater than 10°.
[d] Indications for lateral extraarticular tenodesis: high positive of pivot-shift test (II-III) under anesthesia and persistent positive pivot-shift test after the completion of the intraarticular revision.

suspended and fixed with a titanium plate, while the tibial end is doubly secured using an interference screw and a spike washer.

## 3. Rehabilitation program

Rehabilitation was carried out in four phases, respectively 1) initial rehabilitation phase, 2) functional enhancement phase, 3) functional consolidation phase; 4) pre-return to sport phase. For a detailed rehabilitation program, see Appendix 1.

Evaluation and follow-up:

We recorded information on concurrent injuries (meniscus, cartilage), treatment methods, and operation time during surgery. Regular postoperative follow-ups were conducted. Last follow-ups were done four to five years after surgery (an average of four years). Subjective scoring tools included the 2000 International Knee Documentation Committee (IKDC) subjective score, Lysholm Knee Scaling Score (LKSS), Knee injury and Osteoarthritis Outcome Score (KOOS), Tegner activity score, Marx activity rating score, and Chinese version of Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI). Objective assessments followed the 2000 IKDC standard, including swelling, range of motion, and stability. The KT-1000 arthrometer (MEDmetric, USA) was used to quantitatively assess anterior knee joint stability. Regarding returning to sport, we noted if patients could return, their best level achieved (recreational, cutting and pivoting, competitive, preinjury levels), and the time of return.

### *3.1. Statistical analysis*

For categorical data (e.g., gender, return to sports level, knee joint objective examination results), we calculated frequencies and percentages. For continuous data (e.g., age, anterior knee displacement, patient subjective scores), central tendencies were represented by means and medians, while dispersion was measured using standard deviation and quartiles. For data analysis, we used chi-square tests and Fisher's exact tests for categorical data and t-tests or Mann–Whitney U tests for continuous data after evaluating data distribution. Statistical analyses were conducted utilizing SPSS software version 19.0 (IBM Corporation, Armonk, NY, USA).

## 4. Results

The study included a total of 50 patients. Among them, 27 underwent ACL revisions using the LARS. At the last follow-up (median follow-up time was 49 months, ranging from 36 to 68 months), 23 patients were reached, with a follow-up rate of 85.2 %. Of 23 patients who used ATT allograft, 22 were reached at the last follow-up, with a follow-up rate of 95.7 %. For a detailed inclusion process, see Fig. 1.

There were no significant differences in age, gender, and the time from the first surgery to the revision between the two groups. More information is in Table 2.

The combined injuries (meniscus and cartilage damage) and the corresponding treatment methods showed no significant difference between the two groups. For details, see Table 3.

The two groups had no significant difference in the preoperative subjective scores and objective evaluation. For detailed content, see Table 4.

During the average 4-year postoperative follow-up, the two groups exhibited significant differences in terms of ACL-RSI, Tegner activity score, Marx activity rating score, 2000 IKDC objective examination

**Table 2**
Demographics and other basic information of patients in the two groups.

| Variable | LARS group (n = 23) | ATT group (n = 22) | P-value |
|---|---|---|---|
| Age，y | 28.1 ± 4.3 | 27.5 ± 5.6 | 0.580 |
| Gender，male/female，n | 21/2 | 16/6 | 0.103 |
| BMI | 24.8 ± 4.0 | 23.9 ± 5.1 | 0.503 |
| Time from injury to revision, mo | 28.6 ± 18.3 | 25.7 ± 25.2 | 0.666 |
| Index surgery at our center, n | 4 | 5 | n/a |
| Graft choice in index surgery, n | | | |
| HT autograft | 14 | 10 | 0.225 |
| ATT/PTT allograft | 5 | 10 | |
| LARS | 4 | 2 | |
| Return to sports, n | | | |
| Competitive sports | 16 | 10 | 0.260 |
| Recreational sports | 6 | 10 | |
| Sedentary life | 1 | 2 | |
| Reinjury, yes/no, n | 14/9 | 15/7 | 0.608 |
| Preinjury Tegner score | 7.7 ± 1.7 | 8.0 ± 1.6 | 0.486 |

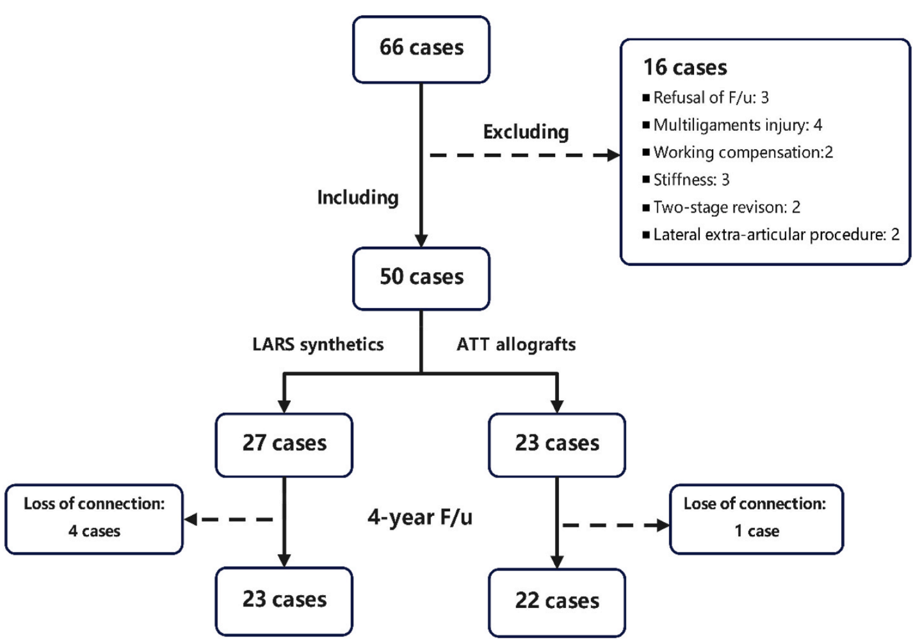


**Figure 1.** The flowchart of enrollment, allocation, and follow-up.

**Table 3**
Surgery-related information of patients in the two groups.

| Variable | LARS group (n = 23) | ATT group (n = 22) | P-value |
|---|---|---|---|
| Meniscus injury, n | | | |
| Medial | 6 | 4 | 0.849 |
| Lateral | 3 | 2 | |
| Medial and Lateral | 6 | 6 | |
| None | 8 | 10 | |
| Medial meniscus treatment , n | | | |
| Suture | 5 | 3 | 0.495 |
| Meniscectomy | 7 | 6 | |
| Posterior root reconstruction | 0 | 1 | |
| Lateral meniscus treatment, n | | | |
| Suture | 2 | 4 | 0.365 |
| Meniscectomy | 6 | 4 | |
| Posterior root reconstruction | 1 | 0 | |
| Cartilage injury (Outerbridge) | | | |
| None | 4 | 3 | 0.573 |
| i ~ ii | 6 | 9 | |
| Iii ~ iv | 13 | 10 | |
| Cartilage injury treatment | | | |
| Microfracture | 2 | 3 | 0.631 |
| Chondralplasty | 17 | 16 | |

**Table 4**
Preoperative assessment results of patients in the two groups.

| Variable | LARS group (n = 23) | ATT group (n = 22) | P-value |
|---|---|---|---|
| ACL-RSI | | | |
| Confidence | 40.6 ± 21.9 | 45.5 ± 22.2 | 0.433 |
| Emotion | 32.7 ± 13.9 | 36.1 ± 17.8 | 0.547 |
| Fear of Reinjury | 12.8 ± 19.1 | 19.1 ± 27.0 | 0.546 |
| IKCD Subjective score | 61.7 ± 14.2 | 58.0 ± 13.8 | 0.394 |
| Lysholm knee scaling score | 68.2 ± 14.7 | 64.7 ± 13.6 | 0.191 |
| Tegner Activity Score | 3.8 ± 2.5 | 4.4 ± 2.1 | 0.395 |
| KOOS | | | |
| Pain | 81.8 ± 12.9 | 79.8 ± 13.3 | 0.640 |
| Symptom | 69.9 ± 14.4 | 63.3 ± 14.7 | 0.138 |
| Daily Life Activity | 95.6 ± 4.6 | 94.6 ± 6.3 | 0.679 |
| Function | 46.5 ± 18.6 | 50.5 ± 16.6 | 0.437 |
| Quality of Life | 39.4 ± 21.4 | 34.7 ± 18.8 | 0.524 |
| IKDC Objective Score (AB/CD) | | | |
| Swelling | 12/11 | 14/8 | 0.436 |
| Flexion deficit | 14/9 | 12/10 | 0.668 |
| Extension deficit | 15/8 | 13/9 | 0.672 |
| Joint instability | 0/23 | 0/22 | n/a |

(Lachman test, anterior drawer test), and anterior joint stability (KT-1000). No significant statistical differences were observed in the other indices. For more details, refer to Table 5.

In terms of return to sport rate, the LARS group significantly outperformed the ATT group at various levels: 1 ) Recreational level: LARS: 91.3 % vs. ATT: 63.6 % (P = 0.026); 2 ) Level involving cutting and pivoting: LARS: 87.0 % vs. ATT: 59.1 % (P = 0.035); 3 ) Competitive level: LARS: 78.3 % vs. ATT: 45.5 % (P = 0.023); 4 ) Pre-injury level: LARS: 56.5 % vs. ATT: 27.3 % (P = 0.047). Regarding the timing of return to sports, the LARS group significantly surpassed the ATT group at various levels: 1 ) Recreational level: LARS: 11.2 ± 3.9 weeks vs. ATT: 27.8 ± 9.0 weeks (P < 0.001); 2 ) Level involving cutting and pivoting: LARS: 17.2 ± 5.8 weeks vs. ATT: 35.6 ± 13.8 weeks (P < 0.001); 3 ) Competitive level: LARS: 24.8 ± 16.2 weeks vs. ATT: 53.2 ± 22.0 weeks (P < 0.001); 4 ) Pre-injury level: LARS: 32.8 ± 11.0 weeks vs. ATT: 72.8 ± 16.9 weeks (P < 0.001). For more details, see Fig. 2.

The two groups had no significant statistical differences regarding reinjury and reoperation. See Table 6 for details.

**Table 5**
Average 4-year postoperative assessment results of patients in the two groups.

| Variable | LARS group (n = 23) | ATT group (n = 22) | P-value |
|---|---|---|---|
| ACL-RSI | | | |
| Confidence | 86.7 ± 12.4 | 69.4 ± 18.6 | <0.001 |
| Emotion | 82.7 ± 11.3 | 70.7 ± 16.2 | <0.001 |
| Fear of Reinjury | 48.5 ± 18.3 | 51.0 ± 14.8 | 0.578 |
| IKCD Subjective score | 92.4 ± 9.0 | 88.2 ± 10.0 | 0.092 |
| Lysholm knee scaling score | 93.0 ± 8.5 | 94.3 ± 6.3 | 0.837 |
| Tegner Activity Score | 6.3 ± 1.9 | 5.2 ± 2.1 | <0.001 |
| Marx activity rating score | 10.7 ± 3.7 | 7.9 ± 4.0 | 0.012 |
| KOOS | | | |
| Pain | 93.3 ± 4.1 | 91.7 ± 4.7 | 0.202 |
| Symptom | 87.6 ± 6.6 | 84.2 ± 7.8 | 0.145 |
| Activity of Daily Life | 97.2 ± 5.4 | 96.7 ± 5.9 | 0.934 |
| Function | 78.7 ± 8.8 | 69.5 ± 11.0 | 0.003 |
| Quality of Life | 79.1 ± 16.1 | 66.4 ± 19.5 | 0.014 |
| IKDC Objective Score (AB/CD) | | | |
| Swelling | 20/3 | 21/1 | 0.317 |
| Flexion deficit | 21/2 | 22/0 | 0.157 |
| Extension deficit | 23/0 | 21/1 | 0.301 |
| Lachman | 22/1 | 19/3 | 0.140 |
| Pivot-shift | 23/0 | 21/1 | 0.301 |
| ADT | 22/1 | 19/3 | 0.070 |
| KT-1000, mm (Mean ± SD) | 1.0 ± 1.9 | 2.6 ± 3.0 | 0.039 |

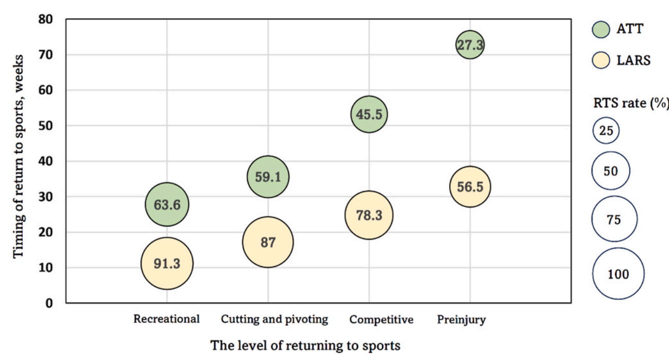


**Figure 2.** Bubble chart of the rate and timing for patients returning to various levels of sport postsurgery.

**Table 6**
Postoperative Reinjury and reoperation status of patients in the two groups.

| Variable | LARS group (n = 23) | ATT group (n = 22) | P value |
|---|---|---|---|
| Reoperation (yes/no) | | | |
| Second revision | 0/23 | 1/21 | 0.301 |
| Meniscectomy | 2/21 | 1/21 | 0.577 |
| Debridement (Cyclops) | 0/23 | 1/21 | 0.301 |
| Contralateral Knee Injury (yes/no) | | | |
| ACL/MCL* | 2/21 | 3/19 | 0.598 |
| Meniscus | 1/22 | 1/21 | 0.974 |
| Cartilage | 3/20 | 2/20 | 0.673 |

## 5. Discussion

The results of this study indicate that in the ACL revision, the LARS group generally outperformed the ATT group after an average of 4 years post-operation. The LARS group surpassed the ATT group significantly in joint stability, return to sport rate, timing of return to sport, Tegner activity scores, Marx activity rating scores, psychological scores, and KOOS-function and QoL scores, suggesting that utilizing LARS for ACL revision offers superior functional recovery, enabling patients to return to higher-intensity sport and maintain a more consistent athletic performance.

In ACL revision, joint stability and lower limb functional recovery have always been considered vital evaluation indicators of postoperative efficacy [21]. Although various grafts have been utilized in surgeries, there remains a lack of consensus in the academic community regarding which graft promotes joint stability and lower limb function more effectively. This gap challenges clinical decision-making and limits our understanding of the best treatment methods, leading to uncertainty when choosing an appropriate graft. This study provides compelling data support for graft choice in revision by comparing the joint stability and lower limb functional recovery of the LARS and ATT ACL revision after an average of four years postoperative. Based on our findings, we believe that the advantages of LARS in maintaining joint stability and function may be attributed to several reasons. Firstly, the mechanical strength of LARS is remarkable, with a rupture strength reaching up to 5000N, almost three times that of the natural human ACL [17]. Secondly, its fixation method is reliable. The compression screw provides an immediate and sturdy fixation for the graft, effectively reducing the graft's slippage in the bone tunnel. This is especially crucial in revision, where bone tunnel widening is common. The compression fixation technique also grants surgeons more operative flexibility when facing primary fixation materials or remnants, catering to complex anatomical situations [3]. Finally, the LARS allows patients to embark on rapid postoperative recovery, which should not be overlooked [22–25]. Since lower limb functional recovery not only depends on the physical stability of the joint but also involves neuromuscular regulation, muscle strength, and flexibility restoration, early postoperative recovery and functional training facilitate the coordination and integration of these physiological processes [26,27]. In evaluating ACL revision surgery efficacy, accounting for patient demographics, surgical methods, rehabilitation status, comorbidities, and pre-surgery activity levels is essential for outcome assessment. Key factors like age, gender, BMI, concurrent injuries, and return-to-sport post-initial surgery significantly influence surgical outcomes. Our study revealed no significant differences in these critical demographics between patient groups, ensuring a balanced comparison and validating our findings' reliability.

Although previous studies have delved into ACL revision, literature on how to revise for patients, particularly professional athletes or high-intensity athletes aiming to return to the competitive arena is scarce. A significant question arises: Among the many graft options available, which is the most suitable for rapidly and safely facilitating the return of these specific individuals to high-intensity sports? The lack of a theoretical basis causes uncertainty in clinical decision-making and limits our understanding of the best treatment strategy for a particular population after the failed primary ACLR. In this study, we observed that during the 4-year postoperative follow-up, the LARS group showed significant advantages regarding the rate and timing of returning to sport. This indicates that LARS restores joint stability and benefits patients returning to sport. For professional athletes and high-intensity sports enthusiasts, returning to sports after rehabilitation is undoubtedly a crucial indicator [28,29]. The LARS provides an ideal option for these groups. The notable advantages exhibited by LARS in ACL revision can be elucidated as follows. The primary reason is the immediate joint stability it offers. As a high-strength artificial graft, LARS immediately provides reliable joint stability [30]. For those who are physically active, this means they can benefit from more robust joint support in intense sporting situations, such as jumping, sprinting, or changing direction. Another reason is the shortened recovery period. Since the LARS doesn't require a vascular regeneration and remodeling phase typical of grafts, patients can commence functional training relatively early postoperative, allowing for a rapid recovery of strength and joint function, and an earlier return to the sport field [17]. Additionally, psychological factors play a pivotal role. Undoubtedly, ACLR failures and subsequent revision surgeries can negatively impact a patient's mental state. Relative to traditional grafts, the LARS is associated with enhanced postoperative recovery speed and earlier restoration of function, which may positively impact patient confidence. A positive mindset facilitates a more efficient functional rehabilitation, enabling patients to transition back to the competitive arena after ACL revision.

In the literature on ACL revision, researchers primarily focus on the recovery of knee function, surgical strategies, and relevant techniques [31–35]. Regrettably, the assessment of patients' psychological recovery is often overshadowed [14]. This oversight restricts our comprehensive understanding of patients' holistic recovery, thereby affecting our advisories on their return to sport. Indeed, if we omit considering the psychological aspect, it becomes challenging to decipher why some patients, despite exhibiting good clinical and functional recovery, still refrain from resuming sports. Historically, such behavior was broadly attributed to "fear of movement"; however, this conclusion appears overly simplistic without a systematic psychological assessment [36,37]. Further investigation suggests that post-ACLR patients' reluctance towards returning to sport stems from three psychological dimensions: confidence, emotional state, and fear of reinjury [38]. This study indicates that patients treated with LARS exhibit a significant advantage in psychological recovery, particularly in confidence and emotional well-being, compared to those treated with ATT. Intriguingly, there was no notable difference in the fear of reinjury between the two groups. We posit that the LARS helps patients regain confidence in the early postoperative phase, subsequently uplifting their emotional state due to its capacity to swiftly restore joint stability and functionality. Conversely, those treated with ATT endured a prolonged recovery phase, potentially delaying their recuperation of confidence and emotional well-being. Additionally, opting for LARS as the graft for revision, coupled with the associated positive rehabilitation expectations, could intrinsically offer psychological benefits to patients. Regarding the fear of reinjury, we recognize it as a universal psychological response, unrelated to the choice of graft or surgical technique [39,40]. This apprehension likely finds its roots in past injury experiences, painful memories, the level and type of sport, and the cognizance of the ramifications of reinjury. To ensure a holistic recovery of patients' psychological states, relying solely on advancements in surgical techniques, selecting the appropriate graft, or adopting proactive physical rehabilitation strategies seems insufficient. We should emphasize psychological interventions, assisting patients in overcoming their fear.

This study features the following significant innovations. Firstly, this study initiated a more extended comparative follow-up than the existing literature. While some previous research only assessed the short-term results of ACLR revision, a direct comparison of the medium-term outcomes of LARS and ATT postoperatively remains a research gap [41]. We delve deeper into the midterm results of joint stability and function by conducting a more extended follow-up. Secondly, this study emphasizes a detailed analysis centered on returning to sport. Previous studies predominantly focused on the general aspect of patients' return to sport; our research explored deeper, offering a layered analysis. We intricately examine various dimensions of this return, including the restoration to pre-injury athletic performance level, re-engagement in competitive sports, and participation in recreational or knee-cutting and pivoting activities [42–44]. Moreover, few studies have delved deep into the psychological impacts of post-ACL reconstruction. This study not only evaluated the overall psychological status of patients but also explored the relationship between confidence, emotion, fear of reinjury, and the choice of graft explicitly. Lastly, our study initiated a systematic comparison, offering the first comprehensive effects evaluation of using ATT allograft and the LARS in ACL revision.

The generalizability of our research findings hinges on several critical factors. Foremost is subject selection; our data predominantly derives from a young athlete demographic, potentially limiting relevance for older individuals, the non-athletics, or those with differing physiological conditions. Surgical technique, particularly the accurate placement of the bone tunnel, is another critical factor affecting the success of ACL revision. In scenarios lacking technical sophistication or complex bone tunnel situations, the positioning for the LARS artificial ligament may be suboptimal, affecting the study's broader applicability.

Furthermore, our research scope excluded patients with secondary revision or multiple ligament injuries, narrowing the conclusions' applicability to these specific cases. Consequently, these limitations should be carefully considered when applying our findings to varied clinical contexts.

In the discourse on graft selection for ACL revision, it is imperative to recognize a prevailing reality: traditional grafts, such as the contralateral hamstring tendon, bone-patellar tendon-bone, and quadriceps tendon, continue to be the mainstream choices [45,46]. Notably, artificial ligaments are not preferred in certain regions, especially in North America and parts of Europe. The international disparities in using artificial ligaments for ACL revisions introduce complex ramifications for our research. Positively, these disparities amplify the study's global pertinence and provide a basis for fostering medical innovation and facilitating comparative analysis of distinct treatment modalities. Conversely, they unveil significant challenges stemming from variances in medical practices and resource allocations across different regions. Such disparities can constrain the generalizability of our findings and influence the heterogeneity of treatment options. Despite the regional limitations on artificial ligaments, our research offers invaluable insights into their potential global application and clinical efficacy. It underscores the critical need for a better understanding of graft selection in ACL revision within the international orthopedic community.

The significance of this research is multifaceted. Firstly, it offers crucial insights for graft selection in ACL revision by providing a comparative analysis of the therapeutic effects of LARS artificial ligaments and allograft tendon (ATT), thus aiding clinicians and patients in informed decision-making. Secondly, the study underscores the importance of returning to sport, a relatively underexplored area in previous research. By examining joint stability and patient subjective scores, it provides a comprehensive assessment of revision success in terms of sports re-engagement. Additionally, the study delves into the psychological impact after ACL revision, shedding light on various psychological changes during recovery and offering strategies to enhance rehabilitation outcomes. It also contributes empirical evidence regarding using artificial ligaments in ACL injuries, particularly addressing the effectiveness of LARS in revision. Finally, the study proposes a novel criterion for successful revision—safe and confident return to sport, presenting an innovative perspective for future research and clinical applications.

The study has several limitations. First, its single-center design and exclusive focus on ACL revision patients may limit the findings' generalizability, as recovery and return-to-sport outcomes can vary across different medical settings due to distinct surgical and rehabilitation approaches. Second, the lack of a randomized control group introduces potential selection biases, potentially affecting the results' reliability. Furthermore, while the study tracks postoperative recovery for an average of four years, a longer follow-up period could provide deeper insights into the long-term effectiveness of the grafts and patients' sustained health. Additionally, the comparison is limited to LARS and ATT allograft, excluding other common graft types like autograft tendons, thus restricting the results' broader applicability. It's also crucial to note that return to sports depends on graft choice, postoperative rehabilitation, physical therapy, and patient adherence. Observed differences in rehabilitation approaches between the two groups could have impacted the findings. Beisdes, with an average follow-up of four years, the study did not include osteoarthritis progression in its final analysis, with plans to conduct radiological assessments at the 5-year mark, indicating a need for future research in this area. Finally, it is crucial to emphasize that differences in fixation techniques represent a key confounding factor. Due to the inherent characteristics of the fixation methods associated with different surgical techniques, it is challenging to avoid variations in fixation approaches when using different grafts for revision surgeries. However, the findings of our study provide valuable insights into the significant role of fixation methods in joint stability. Notably, the use of a dual fixation method (screw and dowel) in the allograft group (ATT group) actually showed a statistically significant disadvantage in anterior stability compared to the artificial ligament group that used a single fixation method (screw). This suggests that graft characteristics may have a more decisive impact on ensuring joint stability than the method of fixation.

Future research directions encompass the following avenues. Subsequent investigations should consider extended follow-up of the current cohort to ascertain the long-term efficacy of the two graft types. Multicenter collaborations should be contemplated to augment the sample size, enhancing the universality and robustness of the findings. Upcoming research should also consider alternative graft types and techniques to discern their respective efficacies in ACL revision. While the current study broached psychological evaluations, subsequent studies must delve more profoundly into this realm. Explored questions might include: Why do certain patients fear reinjury? What strategies can ameliorate these concerns? The feasibility of psychological interventions, such as cognitive behavioral therapy, could be further explored to aid patients in surmounting these psychological impediments. The allografts used at our center are ATT, which do not include bone block tissues such as the quadriceps tendon and bone-patellar tendon-bone. In the future, multi-center collaborations should be initiated to comprehensively evaluate the efficacy of different allografts, especially those with bone blocks, in revision surgeries.

## 6. Conclusion

In ACL revision, the adoption of the LARS artificial ligaments showed superior joint stability and knee function at the four-year follow-up when contrasted with using ATT allograft. Notably, recipients of the LARS artificial ligaments demonstrated a significant advantage in both the rate and timing of return to sport. Although a prevalent apprehension of reinjury persisted among all patients, those treated with LARS artificial ligaments exhibited better postoperative performance in terms of confidence and emotional stability, indicating a more favorable psychological recovery.

## Declaration of AI and AI-assisted technologies in the writing process

No AI or AI-assisted technologies were adopted in this work.

## Declaration of competing interest

All authors wish to declare that there are no conflicts of interest regarding the publication of this paper, particularly in relation to the use of Ligament Advanced Reinforcement System (LARS) and allograft tendons.

None of the authors have any financial or personal relationships with the companies or organizations that manufacture or distribute these materials that could inappropriately influence or bias the content and findings of this manuscript.

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## Appendix 1

**Table 1**

| Initial Rehabilitation Phase (First Stage) | | | |
|---|---|---|---|
| **LARS-ACL** | | **异体肌腱** | |
| **Time** | **Postoperative 0–2 weeks** | **Time** | **Postoperative 0–4 weeks** |
| **Goal** | Alleviate swelling and pain.<br>Restore patellar mobility.<br>Restore full extension of the knee joint and gradually promote flexion angle (at least to 90°).<br>Minimize quadriceps muscle inhibition around the knee joint, rebuild quadriceps control, and achieve active full-range knee extension. | **Goal** | Alleviate swelling and pain.<br>Restore patellar mobility.<br>Restore full extension of the knee joint and gradually promote flexion angle (at least to 90°).<br>Minimize quadriceps muscle inhibition around the knee joint, rebuild quadriceps control, and achieve active full-range knee extension.<br>Protecting graft. |
| **Education** | Keep the knee extended and elevated while sitting and lying down; do not place anything under the knee.<br>Avoid using the operated leg for any pivoting movements.<br>Ensure good support on the operated side when transferring positions (e.g., from sitting to lying down).<br>How to use crutches and other aids for daily functions. | **Education** | Keep the knee extended and elevated while sitting and lying down; do not place anything under the knee.<br>Avoid using the operated leg for any pivoting movements.<br>Ensure good support on the operated side when transferring positions (e.g., from sitting to lying down).<br>How to use crutches and other aids for daily functions. |
| **Weight-bearing** | Begin walking<br>Start with double crutches and tolerate weight-bearing as much as possible.<br>If there is no pain or swelling during training and good quadriceps activation is achieved with proper gait, consider discarding the crutches.<br>Stairs management: Ascend with the healthy side first and descend with the crutches and operated side first. | **Weight-bearing** | Begin walking<br>Start with double crutches and tolerate weight-bearing as much as possible.<br>If there is no pain or swelling during training and good quadriceps activation is achieved with proper gait, consider discarding the crutches.<br>Stairs management: Ascend with the healthy side first and descend with the crutches and operated side first. |
| **Intervention** | Swelling Management<br>Cold compress, compression, elevation.<br>Venous return techniques.<br>Ankle pumps.<br>Mobility/Flexibility<br>Patellar mobility: superior/inferior and medial/lateral.<br>Knee flexion promotion: seated assisted knee flexion-extension and towel slide under foot.<br>Knee extension promotion: low intensity, prolonged knee stretching with heel support.<br>Standing gastrocnemius and soleus muscle stretching.<br>Supine active and passive hamstring stretching.<br>Strength Training<br>Heel raises.<br>Quadriceps isometric contractions.<br>Quadriceps short arc contractions.<br>Seated knee extensions at 90° and 60° for isometric contractions as allowed by knee joint angle.<br>Hip strength maintenance: lateral hip abduction in side-lying position, hip extension in prone position, internal hip rotation in side-lying position.<br>Physiotherapy<br>Neuromuscular electrical stimulation of the quadriceps, ideally performed daily to aid muscle activation.<br>Symptomatic treatment for swelling and pain relief. | **Intervention** | Swelling Management<br>Cold compress, compression, elevation.<br>Venous return techniques.<br>Ankle pumps.<br>Mobility/Flexibility<br>Patellar mobility: superior/inferior and medial/lateral.<br>Knee flexion promotion: seated assisted knee flexion-extension and towel slide under foot.<br>Knee extension promotion: low intensity, prolonged knee stretching with heel support.<br>Standing gastrocnemius and soleus muscle stretching.<br>Supine active and passive hamstring stretching.<br>Strength Training<br>Heel raises.<br>Quadriceps isometric contractions.<br>Quadriceps short arc contractions.<br>Seated knee extensions at 90° and 60° for isometric contractions as allowed by knee joint angle.<br>Hip strength maintenance: lateral hip abduction in side-lying position, hip extension in prone position, internal hip rotation in side-lying position.<br>Physiotherapy<br>Neuromuscular electrical stimulation of the quadriceps, ideally performed daily to aid muscle activation.<br>Symptomatic treatment for swelling and pain relief. |
| **Progression Criteria** | Quadriceps contraction with superior patellar glide, active full-range knee extension.<br>Ability to perform a straight leg raise without quadriceps lag. | **Progression Criteria** | Quadriceps contraction with superior patellar glide, active full-range knee extension.<br>Ability to perform a straight leg raise without quadriceps lag. |

**Table 2**

| Functional Enhancement Phase (Second Stage) | | | |
|---|---|---|---|
| **LARS-ACL** | | **ATT-Allograft** | |
| **Time** | Postoperative 3–4 weeks | **Time** | Postoperative 5–12 weeks |
| **Goal** | Maintain knee extension range and strive for active hyperextension.<br>Knee flexion should reach at least 120°.<br>Enhance endurance of muscles around the joint, introduce balance and proprioception training, and strengthen joint function. | **Goal** | Maintain knee extension range and strive for active hyperextension.<br>Knee flexion should reach at least 120°.<br>Enhance endurance of muscles around the joint, introduce balance and proprioception training, and strengthen joint function.<br>Continuing protecting graft. |
| **Education** | Inform patients about the characteristics of returning to sports after ACL reconstruction using artificial ligaments.<br><br>Continue interventions from the first phase and enhance the following aspects: | **Education** | Inform patients about the healing process after ACL reconstruction using allograft tendons and advise them to avoid early physical activities.<br>Emphasize the importance of muscle strength training, including the necessity of quadriceps and hamstring strength exercises. |
| **Intervention** | **Continue with the interventions from the first phase, and enhance the following aspects:** | **Intervention** | **Continue with the interventions from the first phase, and enhance the following aspects:** |

(*continued on next page*)

**Table 2** (*continued*)

| **Functional Enhancement Phase (Second Stage)** | | | |
|---|---|---|---|
| **LARS-ACL** | | **ATT-Allograft** | |
| **Time** | Postoperative 3–4 weeks | **Time** | Postoperative 5–12 weeks |
| | **Mobility/Flexibility**<br>Gentle stretching of all muscle groups: prone quadriceps stretching, supine hip flexor stretching at the edge of the bed.<br>**Strength Training (All exercises should be pain-free, focusing on muscle endurance at this stage, adjust the load to 12–15 repetitions per set, 3 sets per exercise)**<br>Quadriceps long arc contraction.<br>Prone hamstring curl training, start with seated knee flexion isometric contraction.<br>Squat exercises: start with mini squats for both legs, progress to mini squat with weight shift, then to half squats, and progress to half squat with weight shift.<br>Step-ups and step drive-ups.<br>Lumbar-pelvic-hip strength enhancement: progress from a glute bridge to a single-leg glute bridge, then to a Swiss ball glute bridge, and finally to a Swiss ball glute bridge with alternating single-leg support. Side-lying hip external rotation clamshell (starting from 10 to 15 pounds resistance band to 20–25 pounds resistance band), standing hip lifts.<br>**Balance/Proprioception**<br>Tandem stance balance from static to dynamic, stable to unstable surface.<br>Single-leg stance balance (with slightly bent knee) from static to dynamic, stable to unstable surface.<br>Joint position sense retraining. | | **Mobility/Flexibility**<br>Gentle stretching of all muscle groups: prone quadriceps stretching, supine hip flexor stretching at the edge of the bed.<br>**Strength Training (All exercises should be pain-free, focusing on muscle endurance at this stage, adjust the load to 12–15 repetitions per set, 3 sets per exercise)**<br>Quadriceps long arc contraction.<br>Prone hamstring curl training, start with seated knee flexion isometric contraction.<br>Squat exercises: start with mini squats for both legs, progress to mini squat with weight shift, then to half squats, and progress to half squat with weight shift.<br>Step-ups and step drive-ups.<br>Lumbar-pelvic-hip strength enhancement: progress from a glute bridge to a single-leg glute bridge, then to a Swiss ball glute bridge, and finally to a Swiss ball glute bridge with alternating single-leg support. Side-lying hip external rotation clamshell (starting from 10 to 15 pounds resistance band to 20–25 pounds resistance band), standing hip lifts.<br>**Balance/Proprioception**<br>Tandem stance balance from static to dynamic, stable to unstable surface.<br>Single-leg stance balance (with slightly bent knee) from static to dynamic, stable to unstable surface.<br>Joint position sense retraining. |
| **Progression Criteria** | Exercises in this phase should not cause knee pain or swelling.<br>Swelling compared to the first phase should gradually improve and not exceed 1+ (using Modified Stroke Test).<br>Knee can hyperextend, with a difference of about 5° compared to the healthy side.<br>Knee flexion >120°. | **Progression Criteria** | Exercises in this phase should not cause knee pain or swelling.<br>Swelling compared to the first phase should gradually improve and not exceed 1+ (using Modified Stroke Test).<br>Knee can hyperextend, with a difference of about 5° compared to the healthy side.<br>Knee flexion >120°. |

**Table 3**

| **Functional Consolidation Phase (Third Stage)** | | | |
|---|---|---|---|
| **LARS-ACL** | | **ATT-Allograft** | |
| **Time** | Postoperative 5–8 weeks | **Time** | Postoperative 13–20 weeks |
| **Goal** | Avoid post-exercise pain/swelling.<br>Continue to advance knee joint mobility.<br>Safely begin advanced strength training.<br>Train correct movement patterns. | **Goal** | Avoid post-exercise pain/swelling.<br>Continue to advance knee joint mobility.<br>Safely begin advanced strength training.<br>Train correct movement patterns.<br>Continuing protecting graft. |
| **Education** | Inform patients about the significance and requirements of functional consolidation.<br>Advise patients to avoid blindly optimistic views about treatment efficacy and continue functional training. | **Education** | Continue to emphasize the healing characteristics post-ACL reconstruction using allograft tendons, advising patients to remain patient.<br>Encourage patients to actively engage in rehabilitation training, overcome laxity and laziness, and avoid prematurely undertaking activities involving joint rotation. |
| **Intervention** | **Implement the following content (as needed, continue interventions from Phases 1 and 2 based on patient condition):**<br>**Mobility/Flexibility**<br>If the patient has limited mobility or pain at the end of the range of motion, use joint mobilization or dynamic joint loosening techniques specifically, adjusting accessory movements of the tibiofemoral joint (such as gentle rotation of the tibia).<br>**Aerobic Exercise**<br>Begin with preferred and feasible aerobic exercises like elliptical machines, stair climbing, cycling, alternating leg water slapping, pool jogging, etc.<br>**Strength Training (All exercises should be pain-free, focusing on muscle endurance at this stage, adjust/enhance training intensity as needed, ensuring intervention quality)**<br>If the patient can go to the gym, provide a fixed equipment training plan: leg press machine (single and double leg), seated hamstring curl machine, hip abductor and adductor machine, hip extension machine, Roman chair, seated calf machine, etc., for comprehensive lower limb and core exercises. Progress training intensity (strength) and duration (endurance). | **Intervention** | **Implement the following content (as needed, continue interventions from Phases 1 and 2 based on patient condition):**<br>**Mobility/Flexibility**<br>If the patient has limited mobility or pain at the end of the range of motion, use joint mobilization or dynamic joint loosening techniques specifically, adjusting accessory movements of the tibiofemoral joint (such as gentle rotation of the tibia).<br>**Aerobic Exercise**<br>Begin with preferred and feasible aerobic exercises like elliptical machines, stair climbing, cycling, alternating leg water slapping, pool jogging, etc.<br>**Strength Training (All exercises should be pain-free, focusing on muscle endurance at this stage, adjust/enhance training intensity as needed, ensuring intervention quality)**<br>If the patient can go to the gym, provide a fixed equipment training plan: leg press machine (single and double leg), seated hamstring curl machine, hip abductor and adductor machine, hip extension machine, Roman chair, seated calf machine, etc., for comprehensive lower limb and core exercises. Progress training intensity (strength) and duration (endurance). |

(*continued on next page*)

**Table 3** (*continued*)

| Functional Consolidation Phase (Third Stage) | | | |
|---|---|---|---|
| **LARS-ACL** | | **ATT-Allograft** | |
| **Time** | Postoperative 5–8 weeks | **Time** | Postoperative 13–20 weeks |
| | The following exercises focus on correct control and emphasize good proximal stability:<br>Double-leg squat, chair height. If self-weight feels easy for the patient, progress to weighted squats, maintaining strength training intensity at 10-12RM.<br>Side lunges.<br>Deadlift.<br>Single-leg progression: lunge, slide board lunge: backward and lateral, step training and step-up drive, lateral step training, single-leg mini squat, wall-supported single-leg squat.<br>**Balance/Proprioception**<br>Advanced single-leg balance exercises, with added disturbances. | | The following exercises focus on correct control and emphasize good proximal stability:<br>Double-leg squat, chair height. If self-weight feels easy for the patient, progress to weighted squats, maintaining strength training intensity at 10-12RM.<br>Side lunges.<br>Deadlift.<br>Single-leg progression: lunge, slide board lunge: backward and lateral, step training and step-up drive, lateral step training, single-leg mini squat, wall-supported single-leg squat.<br>**Balance/Proprioception**<br>Advanced single-leg balance exercises, with added disturbances. |
| **Progression Criteria** | No swelling/pain post-training.<br>Joint mobility almost identical to the opposite side, flexion may have a 5–10° difference.<br>Joint position sense symmetrical (error <5°).<br>Bilateral quadriceps muscle strength symmetry ≥80 %.<br>Completely symmetrical gait, able to ascend and descend stairs normally. | **Progression Criteria** | No swelling/pain post-training.<br>Joint mobility almost identical to the opposite side, flexion may have a 5–10° difference.<br>Joint position sense symmetrical (error <5°).<br>Bilateral quadriceps muscle strength symmetry ≥80 %.<br>Completely symmetrical gait, able to ascend and descend stairs normally. |

**Table 5**

| Pre-Return to Sport Phase ( Fourth Stage ) | | | |
|---|---|---|---|
| | | **ATT-Allograft** | |
| **Time** | Postoperative 9–10 weeks | **Time** | Postoperative 21–24 weeks |
| **Goal** | Achieve full joint range of motion.<br>Continue to enhance strength training to meet symmetry requirements.<br>Complete various single-leg jump training exercises.<br>Ensure correct movement patterns during complex actions.<br>Begin low-intensity physical activities and specialized training, such as jogging<br>In preparation for returning to sport. | **Goal** | Achieve full joint range of motion.<br>Continue to enhance strength training to meet symmetry requirements.<br>Complete various single-leg jump training exercises.<br>Ensure correct movement patterns during complex actions.<br>Begin low-intensity physical activities and specialized training, such as jogging<br>Continuing protecting graft.<br>In preparation for returning to sport. |
| **Education** | Inform patients about the training content and specific significance of this phase.<br>Ensure patients understand joint care to prevent re-injury and improve intervention effectiveness. | **Education** | Inform patients about the training content and specific significance of this phase.<br>Ensure that patients understand the joint care needed to prevent re-injury, thereby enhancing the effectiveness of interventions.<br>Educate patients about the healing characteristics of allografts to increase awareness of self-diagnosis for injuries. |
| **Intervention** | **Implement the following content (as needed, continue interventions from Phases 1–3):**<br>Training movements can maintain methods from Phases 2 and 3, but increase the load intensity to 8-12RM.<br>Begin jump preparation movements; start with double-leg jump progressions when movement patterns are good.<br>Single-leg squat (at least 60° knee flexion): the operated side should complete 8–10 with good force line control before starting single-leg jump exercises.<br>Continue joint balance and stability training.<br>Gradually return to running and specific sports.<br>Advanced isometric and agility training (recommend knee functional braces for patients). | **Intervention** | **Implement the following content (as needed, continue interventions from Phases 1–3):**<br>Training movements can maintain methods from Phases 2 and 3, but increase the load intensity to 8-12RM.<br>Begin jump preparation movements; start with double-leg jump progressions when movement patterns are good.<br>Single-leg squat (at least 60° knee flexion): the operated side should complete 8–10 with good force line control before starting single-leg jump exercises.<br>Continue joint balance and stability training.<br>Gradually return to running and specific sports.<br>Advanced isometric and agility training (recommend knee functional braces for patients). |
| **Return to sport criteria** | Ligament stability checks (KT1000, MRI, and other ACL integrity tests).<br>Full ROM (Range of Motion) recovery.<br>No swelling and pain during movement.<br>Thigh circumference difference ≤1 cm.<br>Strength: quadriceps/hamstring/gluteal muscle strength ≥90 %.<br>H:Q ratio (hamstring/quadriceps ratio) ≥70 %.<br>Single-leg jump series test ≥90 % compared to the opposite side (using single-leg vertical jump, single-leg triple hop, single-leg crossover hop, timed 6m hop, single-leg lateral hop).<br>Lower limb dynamic stability: Y-balance.<br>Movement pattern and quality: LESS. | **Return to sport criteria** | Ligament stability checks (KT1000, MRI, and other ACL integrity tests).<br>Full ROM (Range of Motion) recovery.<br>No swelling and pain during movement.<br>Thigh circumference difference ≤1 cm.<br>Strength: quadriceps/hamstring/gluteal muscle strength ≥90 %.<br>H:Q ratio (hamstring/quadriceps ratio) ≥70 %.<br>Single-leg jump series test ≥90 % compared to the opposite side (using single-leg vertical jump, single-leg triple hop, single-leg crossover hop, timed 6m hop, single-leg lateral hop).<br>Lower limb dynamic stability: Y-balance.<br>Movement pattern and quality: LESS. |

Note: For safety reasons, patients should be informed:(1) Larger amplitude cutting, changing direction, and turning movements may be initiated based on the patient's actual training situation, starting with non-contact training and progressing from slow to fast.(2) The return to sport should be gradual, transitioning from non-contact training to full participation training and eventually to full competitive play. It takes time, and even after ending the interventions, it is still necessary to continue maintaining strength, balance, agility, and other sport-related training.

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