Original Article
http://mjiri.iums.ac.ir
Medical Journal of the Islamic Republic of Iran (MJIRI)

Med J Islam Repub Iran. 2024 (10 Jul);38.79. https://doi.org/10.47176/mjiri.38.79

Comparison of Clinical Results Using Hamstring Versus Quadriceps Tendon Graft Versus Bone Patella Tendon in Anterior Cruciate Ligament Reconstruction Surgery: A Randomized Clinical Trial

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Received: 8 Feb 2024 Published: 10 Jul 2024

Abstract

Background: Anterior cruciate ligament (ACL) reconstruction is pivotal for restoring knee stability and function in individuals with ACL injuries. While bone-patellar tendon-bone (PT), hamstring tendon (HT), and quadriceps tendon (QT) autografts are commonly employed, their comparative effectiveness remains a subject of ongoing research. This study aims to comprehensively compare the functional outcomes, knee stability, revision rates, and incidence of anterior knee pain associated with these autografts.

Methods: In this randomized clinical trial, adult male participants undergoing primary single-bundle ACL reconstruction were randomized into three groups (PT, HT, QT) using a computer-generated sequence with allocation concealment. Blinded assessments were conducted at 2-, 6-, and 12-months post-surgery to evaluate knee function, stability, and patient satisfaction. The rehabilitation protocol was standardized across groups, including specific exercises and cryotherapy, to minimize postoperative swelling and pain.

Results: A total of 75 participants were followed for 12 months post-surgery. While significant improvements in knee function and stability were observed across all groups, there were no statistically significant differences between the autograft types in terms of revision rates or the incidence of anterior knee pain. Detailed statistical analysis revealed effect sizes and confidence intervals, substantiating the clinical relevance of the findings.

Conclusion: PT, HT, and QT autografts each provide favorable outcomes for ACL reconstruction without significant differences in efficacy up to one year postoperatively.

Level of Evidence: Level 2 (Randomized Clinical Trial)

Keywords: Anterior Cruciate Ligament, Quadriceps Tendon, Hamstring Tendon, Tendon Graft, Patella Tendon Graft

Conflicts of Interest: *None declared*
Funding: *None*

Cite this article as: Fallah E, Naghshbandi M, Ghafoury R, Hosseini Zare N. Comparison of Clinical Results Using Hamstring Versus Quadriceps Tendon Graft Versus Bone Patella Tendon in Anterior Cruciate Ligament Reconstruction Surgery: A Randomized Clinical Trial. *Med J Islam Repub Iran.* 2024 (10 Jul);38:79. https://doi.org/10.47176/mjiri.38.79

Introduction

Anterior cruciate ligament (ACL) damage is a prevalent knee pathology, with an estimated rate of 38- 75 per 100,000 individual-years in the United States (1, 2). ACL injuries can profoundly impact patients' quality of life, often causing pain, instability, and limitations in mobility. These injuries can impede individuals from engaging in

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↑What is "already known" in this topic:
Anterior cruciate ligament (ACL) reconstruction is crucial for restoring knee stability and function in individuals with ACL injuries. Different types of autografts, such as bone-patellar tendon-bone (PT), hamstring tendon (HT), and quadriceps tendon (QT), are commonly used for ACL reconstruction, but their comparative effectiveness has been a topic of ongoing research.

→What this article adds:
This study fills a crucial gap in the literature by comparing the efficacy of PT, HT, and QT autografts in ACL reconstruction. The findings show that all three types offer similar favorable outcomes over a one-year postoperative period, informing clinical decisions in this field.

physical activities they enjoy, affect their ability to perform daily tasks and diminish overall well-being. Moreover, ACL tears may lead to long-term complications such as recurrent laxity, meniscal lesions, osteoarthritis, and degenerative joint disease, further exacerbating the burden on patients' quality of life (3). When it comes to ACL damage, reconstruction surgery is considered the golden standard intervention to reduce instability and avert further meniscal and articular cartilage deterioration in physically active individuals. Successful ACL reconstruction plays a pivotal role in restoring knee function and mitigating the risk of long-term complications. By restoring stability to the knee joint, reconstruction surgery aims to enable patients to resume activities and sports participation while minimizing the likelihood of future injuries. Additionally, ACL reconstruction can help prevent the progression of degenerative changes in the knee, thereby preserving joint health and reducing the incidence of osteoarthritis in the long run (4). An approximate annual tally of 130,000 anterior cruciate ligament reconstruction (ACLR) practices is carried out in the United States (5). A plethora of graft types have been utilized for ACLR to reinstate knee stability, yet the ideal graft origin remains a subject of contention (6).

The choice of graft type in ACL reconstruction is of paramount importance in achieving optimal outcomes. ACLR is predominantly executed utilizing either bone-patellar tendon-bone (PT) autograft or hamstring tendon (HT) autograft; nevertheless, implementation of quadriceps tendon (QT) autograft has amplified throughout the previous ten years (7). Different graft options, including HT, QT, and PT, each have unique characteristics and considerations. Selecting the most appropriate graft type involves careful evaluation of factors such as patient age, activity level, preinjury knee function, and surgeon preference. The chosen graft should possess adequate strength, stability, and biocompatibility to facilitate successful ligament reconstruction and promote long-term knee function. Furthermore, the selection of an appropriate graft type can influence postoperative recovery, rehabilitation protocols, and ultimately, patient satisfaction and outcomes. Surgeons must weigh the benefits and drawbacks of each graft option and tailor their choice to the individual patient's needs and goals. By selecting the optimal graft type, surgeons can enhance the likelihood of successful ACL reconstruction, thereby improving patients' quality of life and long-term knee health (8, 9). Donor-site morbidity is prevalent in both PT and HT autografts (10). Pain in the anterior regions of the knee is the most frequent complication in PT autograft harvesting which occurs in about 40% of patients (11). Furthermore, PT grafts are contraindicated as autografts for skeletally immature patients due to potential injury to open physes (12). The primary complications of HT autograft harvesting involve sensory deficits resulting from damage to the saphenous nerve branches in the infrapatellar region, which can also elicit anterior knee pain (13). Other possible complications include reduction of medial knee stability in patients with medial collateral ligament deficiency (14), and impaired knee internal rotation and flexion strength (15). Moreover, a meta-analysis demonstrated that PT autografts yield less residual anterior knee laxity compared to HT autografts (16). Although studies on quadriceps tendon (QT) autografts have shown promise, there remains insufficient and unconvincing evidence to supplant other autograft types (16). Currently, it is feasible to utilize QT autografts concomitantly with other autograft varieties.

Given the significance of graft selection in ACL reconstruction and its implications for patient outcomes, our study aims to provide a comprehensive comparison of PT, HT, and QT autografts. In contrast to existing studies and meta-analyses that typically compare two graft types at a time, our study stands out by conducting a direct comparison of all three primary graft choices for ACL reconstruction within the same cohort and timeframe. This distinctive approach offers unparalleled insights into the relative merits of HT, QT, and PT grafts, facilitating informed decision-making for orthopedic surgeons, optimizing surgical outcomes, and enhancing patient satisfaction and quality of life post-ACL reconstruction. Through a detailed examination of functional outcomes, knee stability, revision rates, and the incidence of anterior knee pain associated with each graft type, we strive to contribute valuable insights to the ongoing discourse on the optimal approach to ACL reconstruction.

Methods

Study Strata & Patient Selection

This study is a randomized, double-blinded Clinical Trial conducted on 75 individuals who underwent unilateral ACLR between January 2021 and August 2023 at our institution. All patients had previously been diagnosed either through arthroscopy or magnetic resonance imaging (MRI). Only patients that had been diagnosed with an MRI imaging went on through our study and the other groups were eliminated (Figure 1). A power analysis confirmed the number tested was adequate to detect significant differences.

The subsequent eligibility criteria employed in this investigation comprised of the following: age > 18 years, primary single-bundle ACLR, (3) isolated unilateral ACL lesion devoid of concomitant ligamentous, chondral or meniscal impairments, BMI ≤ 35, absence of contraindications for imaging modalities (computed tomography [CT] scan or MRI), no uncontrolled psychiatric or progressive neurological disorders or substance dependence, no lower extremity axis deviation <5 mm, no prior surgical intervention on the affected knee joint and minimum follow-up duration of 12 months.

The sample size calculation for our study was predicated on detecting a clinically significant disparity in the primary outcome measure of knee stability post-surgery, with an alpha level of 0.05 and a power of 90%. Factoring in an anticipated dropout rate of 10%, we arrived at the conclusion that 25 participants per group would be requisite for our investigation. These calculations were meticulously conducted using G*Power software, taking into consideration an effect size gleaned from preliminary studies comparing various graft types in ACL reconstruction.

The outcomes of our Power analysis revealed a robust

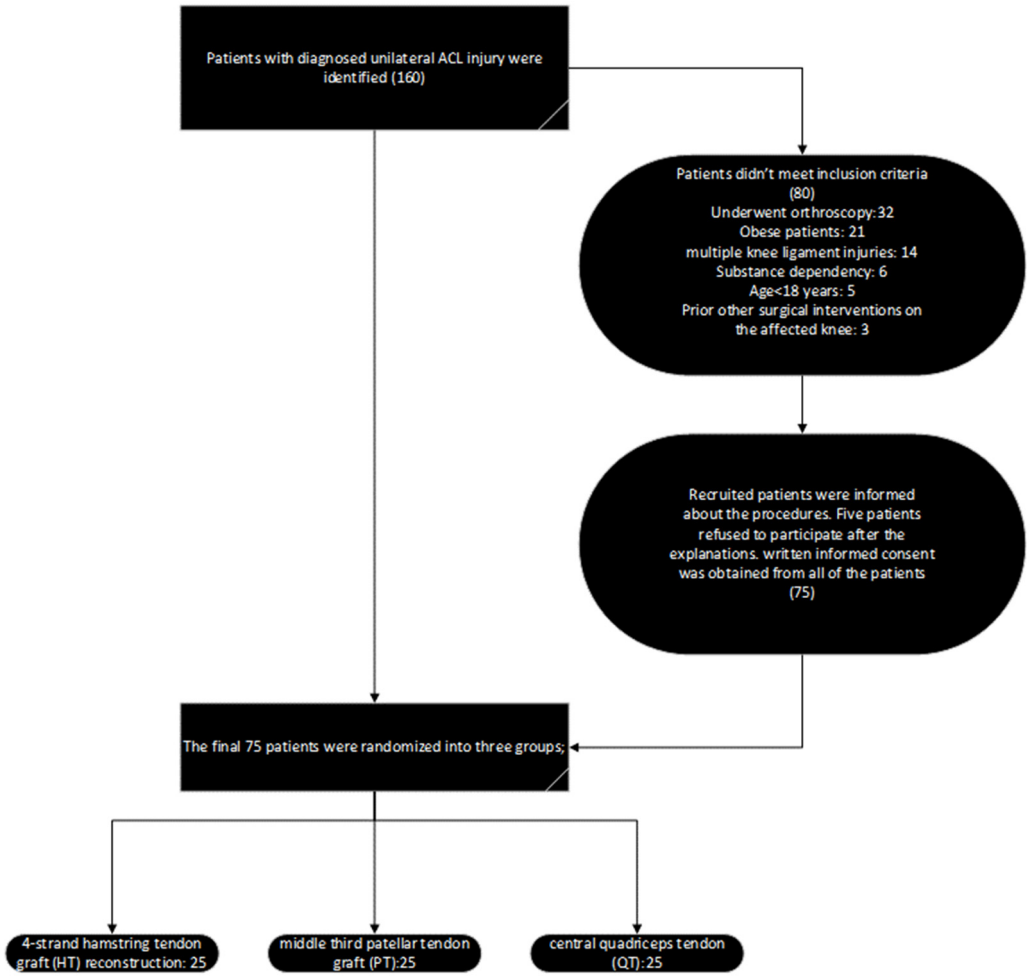

Figure 1. The flowchart of the patient's recruitment

statistical power of 0.91 for our specified sample size, affirming the adequacy of our study design to detect meaningful differences in knee stability among the different graft groups.

Patients were interviewed and consented before their surgery, subsequently being categorized based on age, duration post-injury, and degree of joint instability. The IRCT code of our clinical trial is IRCT20230716058805N1. The clinical trial was registered on 31/7/2023. The patients were randomly divided into one of three groups: (1) those undergoing reconstruction with a 4-strand HT, (2) those receiving treatment via middle third PT, or (3) individuals subject to reconstruction employing a central QT. Due to variances in incision locations for each procedure, patient blinding to graft type remained unfeasible. Institutional review board approval was acquired from the hospital research ethics committee.

Randomization

The foundation of our approach was the implementation of a computer-generated sequence to assign participants randomly to one of the three study groups, ensuring an unbiased distribution. A computer-generated list, crafted by an independent statistician with no involvement in participant recruitment or assessment, was utilized for this purpose. Employing a block randomization method with a block size of 4, we ensured that the allocation sequence remained undisclosed to the clinical team, thereby preserving concealment.

To conceal allocation to the hamstring tendon, quadriceps tendon, or bone-patellar tendon graft groups, sequentially numbered, opaque, sealed envelopes were prepared by the independent statistician. These envelopes, containing the group assignments, were prepared in advance by the same independent statistician and were only opened after the enrolled participants had completed their baseline assessments. This method guaranteed that neither the surgeon nor any members of the clinical team were aware of the group allocation until the moment of surgery, thereby upholding allocation concealment throughout the study.

Blinding

The study adopted a double-blind design, ensuring that both participants and outcome assessors remained unaware of the group assignments. However, due to the nature of the surgical intervention, the surgeon could not be blinded to the type of graft used. Nevertheless, to uphold the integrity

of the double-blind design, all postoperative assessments were performed by independent assessors who were kept uninformed about the participants' group allocations.

Additionally, to minimize the risk of unblinding, patients received postoperative care instructions that were identical across all groups. This measure aimed to maintain consistency and prevent any inadvertent disclosure of group assignments to participants during the recovery period.

Procedure & variables

Patients underwent preoperative consultation and evaluation before their surgical procedure. The subsequent parameters were documented: Lysholm score, pivot shift test, anterior drawer test (ADT), and range of motion (ROM). The ROM (°) was calculated through a physical exam using a goniometer. Arthrometry was consistently utilized for the assessment of the contralateral limb. The arithmetic means of three reproducible arthrometric readings were computed. All operations were carried out by the same surgeon as two more orthopedic surgeons helped with the readings.

Graft selection and surgical techniques

All procedures underwent arthroscopic execution. Graft selection adhered to specific criteria: The PT group received a central third patellar tendon graft, harvested utilizing a modified Jones technique necessitating dual minor longitudinal incisions (17). The HT group received a four-strand hamstring graft, which was acquired from the semitendinosus and gracillis tendons employing the single-incision technique explained by Pinczewski (18). The QT group acquired a central quadriceps tendon graft measuring 10 mm in width, 6 to 7 mm in thickness, and 55 mm in length (19). A 9 mm-diameter EndoPearl apparatus was affixed to the tendon's extremity. We drilled tunnels to place the graft anatomically. All of the procedures utilized an interference screw modality for fixation, employing 7*25-mm screws for the femur and 9*25-mm for the tibia.

All surgical procedures were performed exclusively by a highly experienced orthopedic surgeon. This deliberate decision aimed to mitigate variability in surgical technique, thereby minimizing potential confounding factors that could influence the outcomes of anterior cruciate ligament reconstruction using different graft types. By ensuring consistency in the surgical approach across all cases, our objective was to bolster the reliability of the comparisons between outcomes associated with HT, QT, and PT grafts.

Postoperative rehabilitation

The standard postoperative protocol, rate, and modality of progression were homogenized for all cohorts, adhering to Shelbourne's methodology (20). The post-operational physical exam was carried out by the surgeon. Prompt encouragement of full extension was implemented post-surgery, accompanied by cryotherapy application (21-23). Participants were notified of the permit to bear their full weight immediately. A gradual rehabilitation program focusing on muscle strength regain was introduced to patients that included gait instruction, closed-chain lower body exercises, and proprioceptive and coordination drills. To reach complex multiplane accomplishments like leaping and side-step cutting, each patient is rehabilitated on a separate basis. Subsequently, they were discharged from the rehabilitation program after receiving additional counseling on knee care management. The study population comprised young males with relatively similar weight and body size; thus, the grafts used for ACL reconstruction for these patients were of the same size.

The initial phase of rehabilitation commenced within the first 24 hours post-surgery, focusing on pain management and reduction of swelling using cryotherapy and elevation. Patients were also encouraged to engage in passive range of motion (ROM) exercises to prevent joint stiffness. Weight-bearing was allowed as tolerated, with the aid of crutches, progressing towards full weight-bearing as pain and swelling decreased. From the second week, the frequency of rehabilitation sessions was set at three times per week, with each session lasting approximately 60 minutes. This phase emphasized achieving full knee extension, improving knee flexion up to 120 degrees, and beginning isometric strengthening exercises. The use of a continuous passive motion (CPM) machine was recommended for patients struggling to regain ROM. By the sixth week, the rehabilitation protocol advanced to include closed kinetic chain exercises, proprioceptive training, and gradual strengthening exercises to enhance muscle tone and joint stability. The intensity of the exercises was carefully monitored and adjusted based on the individual's pain threshold and functional progress.

The final phase, starting from the twelfth-week post-surgery, introduced sport-specific drills and plyometric exercises to prepare patients for a return to sports and daily activities. This phase was tailored to each patient’s specific sport or activity level, focusing on agility, endurance, and high-intensity strength training. The duration of the entire rehabilitation process was approximately six months, with the goal of returning to pre-injury levels of activity. Regular follow-up assessments were conducted to monitor the recovery progress and adjust the rehabilitation protocol as necessary, ensuring a personalized approach to each patient’s rehabilitation.

The first post-operational physical examination was carried out on the second day post-operation. Follow-up appointments were handed out to all of the patients for 2, 6, and 12 months after the day of surgery. Each follow-up appointment comprised a standardized series of evaluations designed to gauge recovery progress and functional outcomes. These assessments were thorough and conducted consistently during every visit, ensuring a comprehensive understanding of each patient's recovery trajectory. In case of an absence in a follow-up appointment, a reminder letter was sent to the patients. All participants successfully completed all scheduled follow-up sessions, ensuring robust data collection and minimizing potential dropout bias in the study.

Statistical Analysis

All statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA), with a predetermined significance level of $\alpha = 0.05$ for all tests. Continuous variables were presented as mean ± standard deviation

(SD), while categorical variables were expressed as frequencies (percentages). The normality of distribution for continuous variables was assessed using the Shapiro-Wilk test. For normal distributions, the independent t-test and chi-square test were used, and for non-normal distributions, the Mann-Whitney test and Fischer test were utilized.

Primary Outcome Analysis

The primary outcome measure, knee stability, was assessed through the Lachman Test and Pivot Shift Test scores. These ordinal outcomes were analyzed using the Kruskal-Wallis H test due to their non-parametric nature. Post-hoc Mann-Whitney U tests were employed for pairwise comparisons between groups, with adjustments made for multiple comparisons using the Bonferroni correction. Continuous outcomes, such as the Lysholm Knee Scoring Scale, were subjected to one-way ANOVA to compare mean scores across the three groups at baseline and each follow-up point. In instances where significant group differences were detected, post-hoc analyses with Tukey's HSD test were conducted to ascertain which groups exhibited significant disparities.

Secondary Outcome Analysis

Secondary outcomes, encompassing patient-reported pain levels (measured on a Visual Analog Scale) and functional recovery, were analyzed using mixed-model ANOVA to accommodate repeated measures over time. This approach facilitated the assessment of the interaction between time (preoperative vs. postoperative) and group (HT, PT, QT) while considering within-subject correlations.

Adjustment for Baseline Imbalances

ANCOVA was employed to correct for any baseline imbalances in demographic and clinical characteristics among the groups. Preoperative scores of the primary and secondary outcomes served as covariates in these models to mitigate potential confounding effects.

Results

we enrolled a total of 75 participants, with 25 patients allocated to each group. The demographic characteristics of these participants are summarized in Table 1.

Upon analysis, no statistically significant differences were observed between the groups in terms of demographic and preoperative data ($P > 0.05$). This suggests that, prior to any interventions or treatments, the groups were comparable in terms of their baseline characteristics. The lack of statistical significance indicates that any observed variations in age, gender, or other demographic factors are likely due to random variability rather than meaningful differences between the groups.

These findings underscore the comparability of the study groups at baseline, minimizing the potential for confounding effects and enhancing the validity of subsequent analyses regarding the study outcomes (Table 1).

Table 2 presents the preoperative data, encompassing medical examinations such as ADT (Anterior Drawer Test), Pivot Shift, Lachman test, Lysholm test, extension, and flexion, as well as the patient-reported pain score measured

Table 1. Demographic characteristics of the patients (hamstring tendon (HT), quadriceps tendon (QT), bone-patellar tendon-bone (PT))

Baseline variable	Total	HT	QT	PT	*P*-value
Patients, n	75	25	25	25	
Age (Mean±SD), year	25.79 ± 3.95	25.80 ± 3.89	25.24 ± 3.95	26.32 ± 4.11	0.625^{ns}
Gender, n (%)					1.000^{ns}
Male	75 (100.00)	25 (100.00)	25 (100.00)	25 (100.00)	
BMI (Mean±SD), Kg/m^2	25.34 ± 4.25	24.94 ± 3.32	25.72 ± 4.51	25.37 ± 4.89	0.812^{ns}

Data are means (SD) or numbers (%),; ns: not significant.

Table 2. Pre-operative data of the three study groups (hamstring tendon (HT), quadriceps tendon (QT), bone-patellar tendon-bone (PT))

Preoperative	Total	HT	QT	PT	*P*-value
ADT (Mean±SD), (mm)					0.966^{ns}
Grade 0	5 (6.66)	2 (8.00)	2 (8.00)	1 (4.00)	
Grade I	44 (58.66)	13 (52.00)	16 (64.00)	15 (60.00)	
Grade II	21 (28.00)	8 (32.00)	6 (24.00)	7 (28.00)	
Grade III	5 (6.66)	2 (8.00)	1 (4.00)	2 (8.00)	
Pivot shift (Mean±SD), (points)					0.872^{ns}
Grade 0	9 (12.00)	3 (12.00)	3 (12.00)	3 (12.00)	
Grade I	31 (41.33)	13 (52.00)	8(32.00)	10 (40.00)	
Grade II	25 (33.33)	6 (24.00)	10(40.00)	9 (36.00)	
Grade III	10 (13.33)	3 (12.00)	4 (16.00)	3 (12.00)	
Lachman (Mean±SD), (mm)					0.938^{ns}
Grade 0	9 (12.00)	4 (16.00)	3 (12.00)	2 (8.00)	
Grade I	35 (46.66)	10 (40.00)	12 (48.00)	13 (52.00)	
Grade II	27 (36.00)	10 (40.00)	9 (36.00)	8 (32.00)	
Grade III	4 (5.33)	1 (4.00)	1 (4.00)	2 (8.00)	
Lysholm (Mean±SD), (points)	66.56 ± 3.93	66.44 ± 3.91	66.92 ± 3.70	66.32 ± 4.28	0.738^{ns}
VAS (SD), (Mean±SD), (mm)	4.97 ± 1.40	4.40 ± 1.35	5.40 ± 1.25	5.12 ± 1.50	0.052^{ns}
Extension (Mean±SD), (°)	0.00	0.00	0.00	0.00	1.000^{ns}
Flexion (Mean±SD), (°)	125.76 ± 1.51	125.56 ± 1.35	126.16 ± 1.74	125.56 ± 1.38	0.448^{ns}

Mann-Whitney & t-test analysis, Data are means (SD); ns: not significant; mm: millimeter; °: degrees.

Table 3. Postoperative data of the three groups (hamstring tendon (HT), quadriceps tendon (QT), bone-patellar tendon-bone (PT))

Postoperative	Total	HT	QT	PT	*P*-value
ADT (Mean±SD), (mm)					0.979[ns]
Grade 0	54 (72.00)	19 (76.00)	18 (72.00)	17 (68.00)	
Grade I	18 (24.00)	5 (20.00)	6 (24.00)	7 (28.00)	
Grade II	3 (4.00)	1 (4.00)	1 (4.00)	1 (4.00)	
Grade III	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	
Pivot shift (Mean±SD), (points)					0.939[ns]
Grade 0	52 (69.33)	18 (72.00)	17 (68.00)	17 (68.00)	
Grade I	23 (30.66)	7 (28.00)	8 (32.00)	8 (32.00)	
Grade II	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	
Grade III	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	
Lachman (Mean±SD), (mm)					0.857[ns]
Grade 0	52 (69.33)	18 (72.00)	17 (68.00)	17 (68.00)	
Grade I	21 (28.00)	6 (24.00)	8 (32.00)	7 (28.00)	
Grade II	2 (2.66)	1 (4.00)	0 (0.00)	1 (4.00)	
Grade III	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	
Lysholm (Mean±SD), (points)	93.04 ± 2.05	93.28 ± 1.90	93.52 ± 1.26	92.32 ± 2.62	0.119[ns]
VAS 0 (Mean±SD), (mm)	2.75 ± 2.15	2.80 ± 2.29	2.16 ± 1.86	3.28 ± 2.22	0.202[ns]
VAS 1 (Mean±SD), (mm)	0.77 ± 1.16	0.72 ± 1.10	0.79 ± 1.09	0.88 ± 1.33	0.995[ns]
VAS 3 (Mean±SD), (mm)	0.62 ± 0.65	0.32 ± 0.62	0.37 ± 0.57	0.24 ± 0.72	0.558[ns]
VAS 6 (Mean±SD), (mm)	0.37 ± 0.35	0.16 ± 0.37	0.17 ± 0.47	0.12 ± 0.33	0.900[ns]
VAS 12 (Mean±SD), (mm)	0.08 ± 0.27	0.08 ± 0.27	0.10 ± 0.25	0.06 ± 0.29	0.997[ns]
Extension (Mean±SD), (°)	-1.96 ± 0.87	-1.80 ± 0.76	-2.00 ± 0.95	-2.08 ± 0.90	0.463[ns]
Flexion (Mean±SD), (°)	127.76 ± 2.53	128.48 ± 1.91	127.56 ± 3.09	127.24 ± 2.36	0.448[ns]

Mann-Whitney & t-test analysis, Data are means (SD); ; ns: not significant; mm: millimeter; °: degrees.

Table 4. Comparison of the three groups regarding knee pain, revision surgery, and satisfaction level (hamstring tendon (HT), quadriceps tendon (QT), bone-patellar tendon-bone (PT))

	Total	HT	QT	PT	*P*-value
Anterior Knee pain, n (%)	6 (8.00)	3 (12.00)	1 (4.00)	2 (8.00)	0.581[ns]
Revision, n (%)	5 (6.66)	2 (8.00)	2 (8.00)	1 (4.00)	0.807[ns]
Satisfaction, n (%)					0.984[ns]
Very satisfied	27 (36.00)	8 (32.00)	10 (40.00)	9 (36.00)	
Somewhat satisfied	25 (33.33)	8 (32.00)	8 (32.00)	9 (36.00)	
Neither satisfied nor dissatisfied	18 (24.00)	7 (28.00)	5 (20.00)	6 (24.00)	
Somewhat dissatisfied	5 (6.66)	2 (8.00)	2 (8.00)	1 (4.00)	

Mann-Whitney & t-test analysis, ns: not significant.

by the Visual Analog Scale (VAS).

Analysis of the data revealed that there were no statistically significant differences among the three groups for any of the aforementioned parameters ($P > 0.05$). This indicates that, prior to undergoing any surgical intervention or treatment, patients across all three groups exhibited comparable results in terms of medical examination outcomes and reported pain levels.

These findings suggest a uniform baseline status across the groups, signifying a balanced distribution of preoperative characteristics. Consequently, any subsequent disparities in postoperative outcomes can be more confidently attributed to the interventions administered rather than baseline differences among the groups.

Following the surgical interventions, postoperative variables were assessed across the three groups. Our analysis revealed that there were no statistically significant differences in these variables one year post-surgery ($P > 0.05$) (Table 3).

This indicates that, after the intervention, patients in all three groups demonstrated similar outcomes across the variables examined. These findings suggest that the surgical procedures administered did not lead to discernible differences in the postoperative outcomes among the groups.

The lack of statistical significance underscores the consistency of outcomes across the groups, further supporting the notion that any observed disparities in postoperative variables are likely not attributable to the surgical interventions themselves but rather to other factors.

The comparison between the three groups focused on anterior knee pain, revision rates, and satisfaction levels. Analysis of these factors, as presented in Table 4, revealed no statistically significant differences among the groups ($P > 0.05$).

This indicates that, in terms of anterior knee pain, rates of revision surgeries, and patient satisfaction levels, there were no substantial variations observed between the three groups. The lack of statistical significance suggests that the interventions or treatments administered to each group did not result in significantly different outcomes in these respects.

These findings support the notion of comparable effectiveness across the interventions or treatments evaluated in the study, highlighting consistency in outcomes related to anterior knee pain, revision rates, and patient satisfaction levels among the three groups.

Figure 2 illustrates the comparison of pre- and post- operative variables among the patients. The analysis, conducted using the Wilcoxon Signed Ranks Test, revealed statistically significant differences in these variables ($P < 0.05$).

This indicates that there were significant changes in the measured variables from the preoperative to the postoperative period within the patient cohort. The significance level

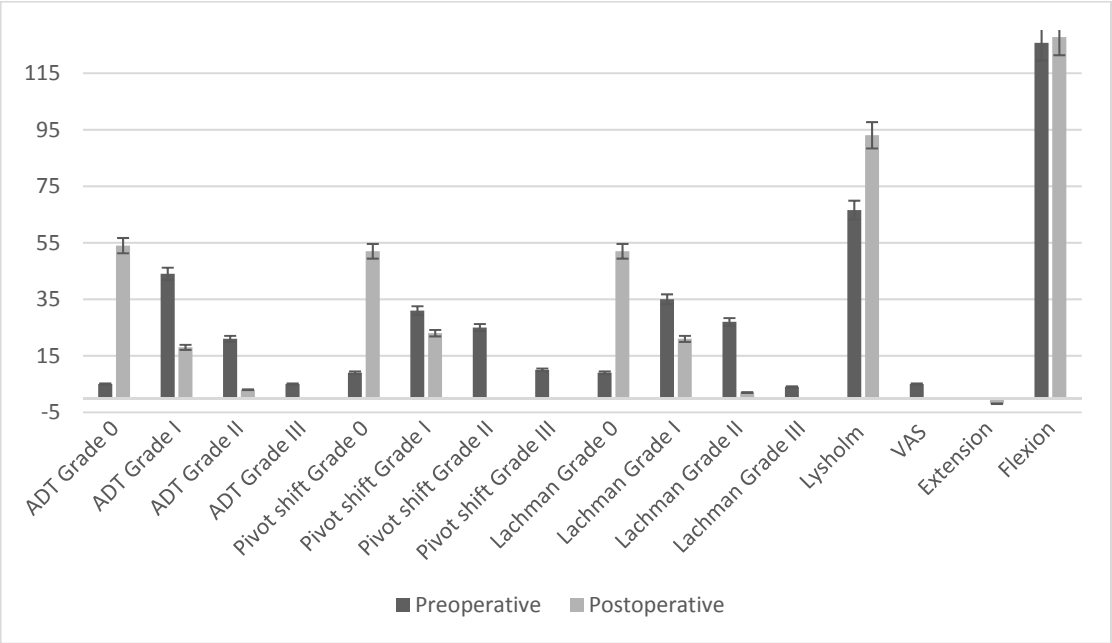

Figure 2. Pre- and post-operative variables of the patients based on Wilcoxon Signed Ranks Test

of $P < 0.05$ suggests that these changes are unlikely to have occurred due to random variation and are more likely attributed to the surgical interventions or treatments administered.

The figure visually depicts the magnitude and direction of these changes, further emphasizing the significance of the observed differences in pre- and post-operative variables among the patients.

Discussion

This study prospectively investigated the suitability of three autograft types: bone-patellar tendon-bone (PT), hamstring tendon (HT), and quadriceps tendon (QT). The results demonstrated that all three autograft types were suitable for ACL reconstruction, with statistically significant improvements in postoperative knee function and stability. However, no statistically significant differences were observed between the three autograft types regarding postoperative physical examination, pain, ROM, patient satisfaction, or revision rate ($P > 0.05$).

Prior to the initiation of the trial, our study protocol distinctly delineated both primary and secondary outcome measures. Primary outcomes were focused on assessing knee stability, as determined by the Lachman Test and Pivot Shift Test, conducted at baseline, 6 months, and 12 months postoperatively. Secondary outcomes encompassed patient-reported pain levels, functional recovery gauged through the Lysholm Knee Scoring Scale, and the occurrence of adverse events. These secondary measures were also evaluated at the same time intervals as the primary outcomes, ensuring comprehensive assessment throughout the study duration.

Our study rigorously considered several key confounders that could potentially influence surgical outcomes, such as patient age, preoperative activity level, and the presence of concomitant knee injuries. These variables are well-documented in the literature for their potential impact on ACL reconstruction efficacy and patient recovery trajectories. Patient age, for instance, is a critical factor in the healing process and rehabilitation outcomes post-ACL reconstruction. Younger patients may exhibit more robust healing capabilities and resilience, potentially skewing outcomes when compared to older populations (24, 25). To mitigate this, we stratified our analysis by age groups, allowing for a more nuanced understanding of graft performance across different age demographics. Preoperative activity levels were also taken into consideration, given their significance in determining patients' postoperative recovery and return to pre-injury activity levels (24, 25). Recognizing the varied baseline functional statuses among our study population, we included preoperative activity levels as a covariate in our statistical models. This adjustment aimed to ensure that comparisons between graft types were not confounded by differences in patients' baseline functional capacities. Additionally, the presence of concomitant knee injuries could significantly affect surgical outcomes and rehabilitation progress (26, 27). To account for this, patients with known concomitant injuries were either excluded from the study or their data were analyzed separately to ascertain the isolated impact of the ACL reconstruction technique. This approach allowed for a clearer assessment of graft efficacy, uninfluenced by the complexities introduced by additional knee pathologies. Beyond these strategies, our statistical analysis incorporated several techniques designed to minimize the potential impact of these confounders. Multiple regression analysis was employed to adjust for these variables, ensuring that the observed differences in outcomes could be attributed with greater confidence to the graft type

rather than extraneous factors.

Most studies are limited to comparing two techniques at a time. Due to the paucity of information on all three autograft types, existing meta-analyses have failed to provide adequate data on pairwise comparisons. A key strength of this study is its concurrent examination of all three autograft types. However, comparing our findings with those of other studies revealed that patients in all three groups had no statistically significant differences in postoperative pain (VAS score) or anterior knee pain, consistent with other studies (28-31). Some studies, such as that by Biau et al. (32), have found better outcomes with HT autograft than with BP autograft. However, many studies have used other terms, such as local complications and donor site morbidity, to describe these outcomes. Studies show no statistically significant differences between autografts in these terms (33-35), although some studies have found different results, with QT autografts associated with fewer donor site morbidity (26-38). Further investigation is required in future studies.

One intriguing observation from other studies was the use of alternative pain measurement scales. For example, Buescu et al. (33) used rescue analgesic consumption as a pain metric and reported superior outcomes with QT autograft (50% of patients did not require rescue analgesia). However, given the different variables investigated in this study, divergent results were not unexpected. No significant differences between autograft types were found in the Belk et al. (39) study, which used patient-reported outcomes.

One of the investigated variables in this study was revision rate. Our study found no statistically significant difference between the three groups, and examination of other studies in terms of this variable revealed that autograft types differed in most studies. Still, this difference was not statistically significant (34, 35, 38-42). These findings are consistent with the results of our study. However, some studies have reported different results. For example, Hurley et al. (36)found that QT autograft had better results, while Lind et al. (43) found that QT autograft had weaker results in terms of revision rates. Given the controversy, additional studies on this variable are warranted.

One of the most important findings of this study was the assessment of functional outcomes and knee stability after ACLR surgery. Previous studies have investigated this topic using various tools but generally agree that no statistically significant difference exists between autografts regarding outcomes and stability. Additionally, comparing the operated knee to the contralateral knee after surgery has shown no significant difference, with both knees scoring well (28, 31, 36, 40-46). While some studies have reported increased objective knee laxity with QT autograft, this increase was not statistically significant (43). Similar findings were observed for isokinetic strength (44, 45).

Further investigations of functional outcomes and knee stability focused on ADT after surgery. In the current study, no statistically significant differences were observed between the three groups, consistent with other studies (31, 47, 48). The following variable examined was the pivot shift test, which showed no statistically significant differences between the autografts. Examination of other studies revealed that most studies confirmed the findings of our research (30, 31, 34, 38, 47-49). However, some studies have reported different results. For example, Hurley et al. (46) and Lind et al. (43) reported a more positive pivot shift test with QT autografts than with HT and PT autografts.

The Lachman test was the following variable used to assess stability in our study. Our findings showed no statistically significant difference between the three autograft groups in this variable, consistent with other studies (30, 31, 34, 36, 38, 47-49). However, some studies have reported different findings. For example, Biau et al. (32) found a lower rate of positive Lachman tests in the HT group than in the BP group, while Cavaignac et al. (44) found a higher rate of positive Lachman tests in the HT group than in the QT group. These findings were not replicated in other studies and were rejected in studies that examined all three autografts together (31).

Our study found no statistically significant difference between the three autograft groups regarding the Lysholm score, consistent with the findings of other studies (17, 28-31, 35, 36, 38, 48, 50). Nevertheless, some studies have reported different results. For example, Gorschewsky et al. (37) found that QT autograft was associated with better Lysholm scores. However, given that this finding was not replicated in other studies, this outcome appears to be accidental.

One of the most essential aspects of ACL tear treatment is achieving normal or near-normal range of motion (ROM) in patients after surgery (51). Our study found that surgery had a statistically significant effect on correcting extension and flexion in patients, but there was no significant difference between autograft types. A review of other studies also showed that most reported no statistically significant differences in postoperative ROM (47, 49). Full ROM is typically achieved after surgery in most patients (41). Other studies have confirmed these findings by examining specific extension and flexion angles (30, 45, 50). The initial physical examination conducted on the second-day post-surgery was specifically crafted to evaluate the immediate postoperative condition of the patients. Emphasizing safety checks and early recovery indicators, this examination prioritized patient well-being over comprehensive functional assessments. Recognizing that patients commonly experience pain and swelling during this stage of recovery, the examination was conducted with gentleness and primarily relied on observational cues to ascertain the absence of immediate postoperative complications. Moreover, all patients received appropriate pain management in accordance with standardized protocols, ensuring the feasibility of this early assessment. To prevent any misinterpretation, we will explicitly clarify these aspects in the manuscript.

Our study's assessment of patient satisfaction after surgery revealed high patient satisfaction. Additionally, our study found no statistically significant difference in patient satisfaction between the three autograft types, consistent with other studies' findings (29-31, 35, 39).

It is important to note that no single "optimal" variable for evaluating ACLR surgery exists. The most appropriate

variables will depend on the individual patient's goals and the specific aspects of their ACLR surgery being assessed. A review of the literature revealed that other variables might help evaluate ACLR surgery, such as kneeling test (32), KT-1000, KT-2000 (28, 30), knee walking, single-leg hop test (47), Tegner activity score (17, 29), IKDC (28, 40, 50), PROMIS Mobility T-Score (40), Shelbourne-Trumper score (44), varus-valgus angles, electromyography, vastus medialis obliquus activity (46), Radiologic Findings (30, 39) and Autograft size and patient's ACL size (52).

A review of other studies also revealed some intriguing findings. For example, Anderson et al. (51) reported that muscle strength also depends on surgery, with 90% of muscle strength restored (compared to the contralateral side) one year after surgery. Autograft types did not differ significantly in terms of this variable. Baker et al. (53) raised an interesting point about the severe complications of autograft harvesting sites, which have been investigated in a few studies. They reported an all-cause complication rate of approximately 2% and suggested that further investigation in subsequent studies would be beneficial. Finally, Kim et al. (48) demonstrated that smoking negatively impacts all outcomes and reduces the quality of the final result.

In this study, we compared the clinical outcomes of ACL reconstruction surgery using HT, QT, and PT autografts at one year post-surgery. While the one-year results are critical for evaluating early rehabilitation and functional recovery, considering the long-term durability and efficacy of these autografts is essential for comprehensive clinical recommendations. Our one-year follow-up data indicate that all three autograft types offer satisfactory outcomes with no significant differences in knee stability, range of motion, or patient-reported outcome measures. However, long-term performance varies: HT grafts generally maintain good stability but may experience graft elongation and increased laxity over time (54, 55), QT grafts, though less studied, show promising long-term results with potentially lower anterior knee pain (54, 56), and PT grafts provide excellent long-term stability but have higher donor site morbidity (54, 55, 57). Clinicians should consider both short-term and long-term outcomes when selecting an autograft, taking into account the potential for donor site morbidity with PT grafts, graft elongation with HT grafts, and the less documented long-term performance of QT grafts. Future research should focus on long-term randomized controlled trials to better understand the durability, functional outcomes, and patient satisfaction of these grafts, along with studies investigating their biological and biomechanical properties over time to improve ACL reconstruction techniques.

Our trial maintained its integrity with no significant protocol violations affecting the outcome validity. Minor deviations, observed in a limited number of instances, primarily consisted of delays in scheduled follow-up assessments due to unforeseen circumstances. These deviations were evenly distributed across all study groups and were appropriately managed in accordance with predefined protocol amendment procedures.

Strengths and limitations

Our study boasts several strengths. We included 75 male participants, with 25 in each group, leading to higher statistical power than similar studies. Participants had similar physical measurements, reducing bias from graft size differences, particularly for HT grafts. All three surgical techniques were performed by one surgeon, minimizing performance bias. We rigorously controlled key variables such as graft type, surgical technique, and rehabilitation protocols. Patient compliance was monitored through regular follow-ups and detailed postoperative instructions. Despite acknowledging potential confounding factors, we believe our design and analytical approach effectively mitigated their impact. The robust randomization process minimized the influence of potential confounding variables. Additionally, stringent selection criteria helped control and standardize the primary variables affecting ACL reconstruction outcomes. This thorough and methodologically sound approach enhanced the reliability of our findings.

We recognize limitations in our study, including the challenge of achieving double-blinding and the focus on a single demographic, limiting applicability to females. Our singleinstitution study may not represent broader populations or different surgical settings. The study's one-year follow-up might not capture long-term outcomes, highlighting the need for extended research. Future studies should include diverse participant pools and long-term follow-ups, spanning five years or more, to assess the durability and success rates of PT, HT, and QT autografts comprehensively. This approach will provide a more nuanced understanding of patient satisfaction, quality of life, and potential late-stage complications. Despite these limitations, our study provides valuable insights into the effectiveness of different graft types in ACL reconstruction. We advocate for further research to explore these findings across a broader and more diverse participant pool. Such studies will enhance the generalizability and applicability of ACL reconstruction outcomes. This comprehensive understanding will foster better treatment strategies across different demographic groups.

Conclusion

In conclusion, the results of this study demonstrate that PT, HT, and QT autografts offer similar favorable outcomes for ACL reconstruction up to one year postoperatively. Our findings suggest that there are no significant differences in functional outcomes, knee stability, revision rates, or the incidence of anterior knee pain among these three autograft types. These results support the notion that all three autograft options can be considered effective choices for individuals undergoing ACL reconstruction surgery.

Authors' Contributions

M. N, R. Gh: substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work, or preparation of tables and figures. E. F, NH. Z: agreement to be accountable for all aspects of the work in ensuring that questions related to the

accuracy or integrity of any part of the work are appropriately investigated and resolved. E. F, NH. Z M. N, R. Gh: drafting the work or revising it critically for important intellectual content. E. F, NH. Z: approval of the final version to be published. All authors reviewed the manuscript.

Ethical Considerations

This study was approved by the ethics committee of AJA University of Medical Sciences. The ethical Code of the current study is as follows: IR.AJAUMS.REC. 1901.075, Additionally, the IRCT code of our clinical trial is: IRCT20230716058805N1.

Acknowledgment

This study was carried out with the support of AJA University of Medical Sciences and the sincere cooperation of the respected director and colleagues of 501 Artesh Hospital, to whom we hereby express our gratitude and appreciation.

Conflict of Interests

The authors declare that they have no competing interests.

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