Winner of the O'Donoghue Sports Injury Research Award

Risk of Revision and Reoperation After ACL Reconstruction: Comparison of Quadriceps Tendon, Patellar Tendon, and Hamstring Autografts Stratified by Patient Sex and Age

PODCAST 5-in-5

A Cohort Study of 27,715 Patients From 2012 to 2023

Christopher R. Lehman,*† MD, Heather A. Prentice,‡ PhD, Chelsea Reyes,‡
Colin Mansfield,§ MD, Justin S. Yang,|| MD, and Gregory B. Maletis,¶ MD
Investigation performed at Kaiser Permanente, San Diego, California, USA

Background: Many different graft choices exist for anterior cruciate ligament reconstruction (ACLR) with potential for variable outcomes based on graft type.

Purpose: To evaluate risk for subsequent surgical outcomes after primary ACLR according to autograft selection, stratified by patient sex and age.

Study Design: Cohort study; Level of evidence, 3.

Methods: Data from the Kaiser Permanente ACLR Registry was used to conduct a cohort study. A total of 27,715 patients with primary isolated autograft ACLR were identified (2012-2023). The exposure of interest was autograft type: quadriceps tendon (QT), patellar tendon (PT), or hamstring tendon (HT). Multivariable Cox proportional hazards regression models were used to evaluate the risk for revision and risk for ipsilateral reoperation according to autograft selection with adjustment for confounders.

Results: No differences were found in revision or reoperation risks across sex and age groups for QT versus PT ACLR. For QT compared to HT ACLR, QT was associated with a lower revision risk in females <22 years (hazard ratio [HR], 0.45; 95% CI, 0.22-0.92). A higher risk of reoperation for stiffness (HR, 3.12; 95% CI, 1.00-9.72) and cartilage (HR, 3.65; 95% CI, 1.28-10.44) was observed with QT versus HT ACLR in males <22 years, while a higher overall reoperation risk (HR, 1.59; 95% CI, 1.06-2.40) was observed in males ≥22 years. When comparing PT to HT ACLR, PT had a lower risk of revision (HR, 0.57; 95% CI, 0.43-0.75) but a higher stiffness reoperation risk (HR, 1.58; 95% CI, 1.11-2.25) in females <22 years. PT versus HT was associated with higher overall reoperation (HR, 1.39; 95% CI, 1.12-1.73) and stiffness reoperation (HR, 1.56; 95% CI, 1.10-2.21) risks in males ≥22 years.

Conclusion: In young female patients, HT ACLR was associated with a 2.3 and 1.8 times higher revision risk when compared to QT and PT ACLR, respectively. No differences in risk of revision were noted between QT and PT ACLR. The risk for ipsilateral reoperation varied across patient age and sex, with higher risks observed for specific reoperation reasons with QT and PT compared to HT ACLR. Surgeons should consider these data when discussing risks and benefits of the different graft options for ACLR, especially with their female patients.

Keywords: anterior cruciate ligament reconstruction; quadriceps tendon; hamstring autograft; patellar tendon autograft; revision; reoperation; male; female; age

Anterior cruciate ligament (ACL) tear is a common orthopaedic injury that can lead to knee pain and instability and has long-term consequences on knee function.[31,45,52] Arthroscopic ACL reconstruction (ACLR) is the most common form of surgical treatment for ACL tears, with the goal of restoring function and stability to the knee while minimizing revisions and reoperations. Outcomes of ACLR are generally favorable, but repeat ACL injury occurs in up to 30% of young active patients, with many requiring revision surgery.[6,7,38] Frequently cited revision ACLR rates are between 3% and 11%.[6,28,48] ACLR outcomes can be affected by both surgical and patient factors, with graft choice having potentially one of the biggest factors on the risk of revision.

The American Journal of Sports Medicine
2026;54(5):1011–1026
DOI: 10.1177/03635465261428123

Graft selection in ACLR has been controversial for many years, with debate surrounding the optimal autograft type.[18,21,31] There are numerous studies examining the 2 most commonly used autograft options, patellar tendon (PT) and hamstring tendon (HT), with a recent meta-analysis of randomized controlled trials of PT versus HT reporting no differences in graft rupture or revision rates.[16] However, this study only included 495 ACLRs, making subtle differences between graft types more difficult to determine. In contrast, large registry-based studies have found a higher revision risk with HT compared to PT.[15,22,30-32,41,44,45] Over the past decade, quadriceps tendon (QT) autograft utilization has increased for ACLR,[61] with studies reporting either improved or no differences in outcomes compared to PT and HT.[3,9,24,26,29,36,37,61] However, the overall numbers of QT ACLR represented in the orthopaedic literature are still smaller than the volume of PT and HT.

While risk for revision after ACLR is multifactorial, patient age and sex are 2 nonmodifiable factors that can potentially impact ACLR outcome. It is generally accepted that females have a higher incidence of ACL tears than males.[2,4,35] However, studies looking at outcomes after ACLR have reported conflicting results, with some studies finding a higher risk in females[20,54] and others reporting no differences in outcomes.[19,34,46,50] Several studies have reported younger age to be associated with a higher risk of revision.[8,30,39,51] This is likely due to a higher rate of return to sport in younger patients.[59] Using data from the Norwegian Knee Ligament Registry, Ekeland et al[12] found a 5 times higher risk of revision in patients <18 years compared to those >30 years of age. Maletis et al[30] reported a 9% overall revision rate in those <21 years and a 1.9% rate in those >40 years of age. When both younger age (<25 years) and return to sport were evaluated, approximately 23% of patients in this group may tear either their ipsilateral or contralateral ACL.[60] In an observational study of 1355 patients followed >10 years, Sanders et al[48] found that those <22 years of age had significantly higher failure rates than older patients. This highlights the importance of age when evaluating risks of revision.

Orthopaedic surgeons should strive to maximize outcomes after ACLR by choosing the best graft type for the appropriate patient. However, there remains a gap in the current literature regarding the relationship between graft selection and risk for outcomes after ACLR based on patient sex and age specifically. The purpose of this study was to determine whether autograft selection for primary ACLR and subsequent risk for surgical outcomes, including revision and reoperation, differ according to a patient's sex and age. The research hypothesis was that differences in risk for outcomes according to graft selection would vary depending on the patient's sex and age.

METHODS

Study Design, Setting, and Data Sources

Data from Kaiser Permanente's ACLR Registry (ACLRR) was used to conduct a retrospective cohort study. This US-based integrated health care system covers >12 million members in 8 geographical regions, including Colorado, Georgia, Hawaii, Mid-Atlantic states, Northern California, Northwest, Southern California, and Washington.[23] Health care plan membership is demographically representative of the regions covered.[10]

A detailed summary of data collection procedures, coverage, and participation rates for the ACLRR has been published previously.[32,40] The ACLRR was started in 2005 as a surveillance tool for all ACLR procedures performed within the health care system. Predefined patient, procedure, implant, surgeon, and hospital information is prospectively collected into the registry using intraoperative forms completed by the operating surgeon at the time of ACLR. Both these intraoperative forms and administrative data via procedure codes are used to identify and validate ACLR performed in the health care system. Additional information is also collected into the ACLRR using data from the integrated electronic health record (EHR), administrative claims data, health care membership data, other institutional registries, and mortality records. Subsequent surgical interventions after ACLR, including revisions and reoperations, are prospectively monitored using electronic screening algorithms in the EHR. The mean annual participation in the registry by surgeons was 85.7%.

Study Sample

Patients who underwent primary isolated ACLR using a single-bundle autograft were identified (2012-2023). Same-day bilateral ACLR (n = 20) and patients with a documented prior procedure in the same knee (n = 27) were excluded. Many of the patients were included in a similar analysis recently published; however, we desired to

*Address correspondence to Christopher R. Lehman, MD, Department of Orthopedic Surgery, The Permanente Medical Group, 1200 El Camino Real, 3rd Floor, South San Francisco, CA, 94080, USA (email: chris.lehman@kp.org).
†Department of Orthopedic Surgery, The Permanente Medical Group, South San Francisco, California, USA.
‡Medical Device Surveillance & Assessment, Southern California Permanente Medical Group, San Diego, California, USA.
§Department of Orthopedic Surgery, The Permanente Medical Group, Walnut Creek, California, USA.
||Department of Orthopedic Surgery, Southern California Permanente Medical Group, Los Angeles, California, USA.
¶Department of Orthopedic Surgery, Southern California Permanente Medical Group, Baldwin Park, California, USA.
Submitted October 7, 2025; accepted January 19, 2026.
Presented at the annual meeting of the AOSSM, Nashville, Tennessee, July 2025.
The authors declared that they have no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

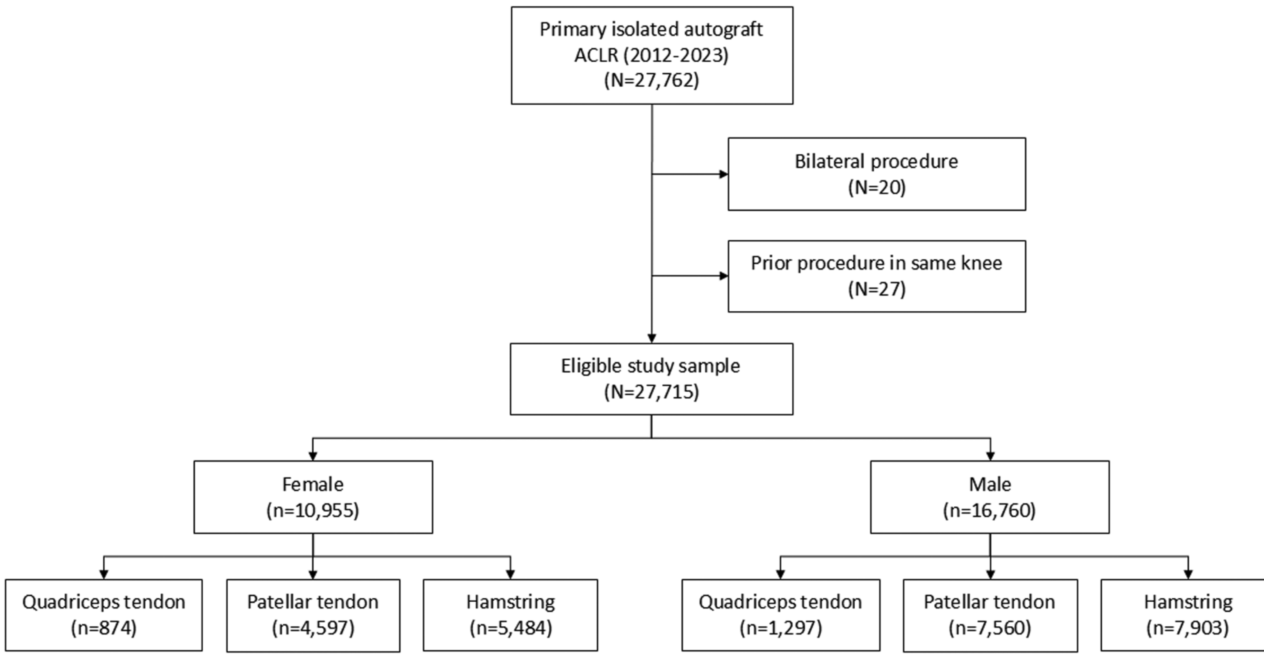

Figure 1. Flowchart for study sample. ACLR, anterior cruciate ligament reconstruction.

perform a new analysis with the increase in quadriceps grafts reflecting changes in practice patterns.[61] Procedures were performed by 319 surgeons at 58 health care centers in the organization (Figure 1).

Exposure of Interest

Autograft selection was the exposure of interest including QT, PT, and HT. Graft selection was determined by mutual agreement of the patient and surgeon. Autograft type used is reported by the operating surgeon on the intraoperative registry form, and this information is then collected into the ACLRR.

Outcome of Interest

The primary outcome was aseptic graft revision during follow-up. Revision was defined as surgery after the primary ACLR where the original graft was removed and replaced for noninfectious reasons. All patients are longitudinally monitored after their ACLR for revisions if they remain members. Identified events and reasons for the events are manually validated by trained research associates using the EHR. The median follow-up for the overall cohort was 4.7 years, with a maximum follow-up of 12 years. Loss to follow-up through health care membership termination was 19.1% (QT = 14.9%; PT = 17.4%; HT = 21.5%) at 5 years of follow-up.

Subsequent ipsilateral aseptic reoperation outside of revision surgery was evaluated as a secondary outcome. Reoperation was defined as any surgery for noninfectious reasons after the primary ACLR where the graft was left intact. Specific ipsilateral reoperation reasons were also considered and included stiffness (defined as arthrofibrosis or cyclops lesion), extensor disruption (defined as patellar fracture, QT rupture, or PT rupture), meniscal reasons (defined as surgery for meniscal tears or cysts), and cartilage reasons (defined as surgery for chondromalacia or cartilage defects). Reoperations and reoperation reasons were monitored longitudinally using the EHR and manually validated. For the present study, the specific reoperation reasons investigated were further manually chart reviewed by the clinical coauthors.

Covariates

Patient factors considered as covariates included age at the time of the ACLR, body mass index (BMI; in kg/m^2), self-reported race/ethnicity (Asian, Black, Hispanic, Other, or White), smoking status (current or former smoker or never smoker), American Society of Anesthesiologists (ASA) classification (1 or $\geq$2), activity at the time of injury (sports, trauma, or other reasons), and prior contralateral ACLR (yes or no). Procedure factors at the time of the ACLR considered included cartilage injury reported (yes or no), lateral meniscus injury reported (yes or no), medial meniscus injury reported (yes or no), tunnel drilling technique (lateral approach, medial portal, or transtibial), and operative time (in minutes). All patient and procedure factors are prospectively collected into the ACLRR.

Effect Modification

To tease out sex-specific risks for outcomes according to autograft selection, analyses were stratified by patient sex.

Statistical Analysis

Patient and procedure covariates are described for the cohort using means, standard deviations, frequencies, and proportions. Missing values for operative time (n = 3937; 14.2%) were handled through mean imputation and a missing value indicator; missing values for categorical variables were handled by creating a separate category for the covariate (smoking status = 236 [0.9%], ASA class = 3555 [12.8%], injury activity = 1575 [5.7%], and tunnel drilling technique = 1400 [5.1%]). The standardized mean difference (SMD), which is a measure to evaluate the distribution of a covariate between study groups, was calculated. An SMD <0.2 was used to indicate balance in the distribution of the covariate across study groups.

As patients in the study sample had variable follow-up, the cumulative incidence of revision and reoperation was calculated using 1 minus the Kaplan-Meier estimate. For revision, follow-up was defined as the time from the index ACLR to the date of revision surgery, health care membership termination, death, or study end date (December 31, 2023), whichever came first; patients without a revision were censored.

Follow-up for reoperation was defined as the time from the index ACLR to the date of reoperation, revision surgery, health care membership termination, death, or study end date, whichever came first; those without a reoperation were censored. Patients who underwent a reoperation continued to be followed for revision surgery for the assessment of the revision outcome. For more reliable estimates, follow-up for both outcomes was restricted to within 5 years for comparing QT ACLR to PT and HT ACLR as this was the last point where there were at least 50 QT ACLRs at risk. No restrictions in follow-up were made when comparing HT to PT ACLR.

Multivariable Cox proportional hazards regression was used to evaluate the association between graft selection and the outcomes of interest. Covariates were selected into the final multivariable model as confounders if they were imbalanced between the 2 comparison groups with an SMD >0.2 and associated with the outcome with a *P* value <.1 or if deemed clinically relevant. As there can be correlation between ACLRs performed by the same surgeon, regression models also included a cluster term at the surgeon level to address this. The proportional hazards assumption for the treatment variable was checked. When the assumption was not met, a flexible parametric model was used. Outcomes with <5 events in at least one of the study groups were not evaluated in regression analysis. Hazard ratios (HRs) and 95% confidence intervals are reported; a *P* value <.05 was the threshold for statistical significance and all tests were 2-sided. The number needed to treat (NNT) was also calculated from the regression analysis using the same covariates.[62] A positive value for the NNT was interpreted as the number of ACLRs needed with a QT graft to prevent the outcome compared to another autograft, while a negative value was interpreted as the number of ACLRs needed with a QT graft compared to another autograft to have the outcome; PT was the graft of interest for the PT versus HT comparison. Analyses were performed using R Version 3.3.0 (R Foundation for Statistical Computing).

Secondary Analyses

The above analysis was repeated after stratifying by patients aged <22 or ≥22 years at the time of their ACLR[61] as younger patients are typically more physically active.[59] There were 6446 (QT = 463; PT = 3247; HT = 2736) ACLRs performed in females <22 years and 6786 (QT = 486; PT = 3559; HT = 2741) ACLRs performed in males <22 years. There were 4509 (QT = 411; PT = 1350; HT = 2748) ACLRs in females and 9974 (QT = 811; PT = 4001; HT = 5162) ACLR in males included in the ≥22-year group.

RESULTS

The final study sample included 27,715 ACLRs. Of the 27,715 ACLRs, 10,955 (39.5%) were female and 16,760 (60.5%) were male. Of the 10,955 female patients with ACLR included, the mean age and BMI were 23 years and 25.7 kg/m^2, respectively. Most patients were White (51.4%), never smokers (90.9%), had an ASA class of 1 (53.3%), and tore their ACL through a sports injury (84.0%). Concomitant cartilage, lateral meniscus, and medial meniscus injuries were present in 17.1%, 36.1%, and 33.8% of female patients, respectively. The medial portal was the most frequent tunnel drilling technique (65.1%). In the female cohort, QT, PT, and HT autograft were used in 874 (8.0%), 4597 (42.0%), and 5484 (50.1%) ACLRs, respectively. Characteristics by graft selection are presented in Table 1.

Of the 16,760 male patients with ACLR, the mean age was 25.5 years, and the BMI was 27.2 kg/m^2. Similar to female patients, more patients were White (44.0%), never smokers (80.7%), had an ASA class of 1 (51.7%), and tore their ACL through a sports injury (82.2%), although frequencies varied. Concomitant cartilage, lateral meniscus, and medial meniscus injuries were more common in male patients than female patients, present in 23.8%, 47.8%, and 38.9% of male patients, respectively. The medial portal was the most frequent tunnel drilling technique (63.6%). There were 1297 (7.7%) QT, 7560 (45.1%) PT, and 7903 (47.2%) HT ACLRs performed in male patients. Characteristics by graft selection are presented in Table 2.

QT Versus PT

In adjusted models for female patients, no significant differences were observed in revision risk (HR, 0.76; 95% CI, 0.36-1.59; *P* = .465) or reoperation risk (HR, 0.83; 95% CI, 0.57-1.23; *P* = .355) when comparing QT to PT ACLR. No differences were observed for specific reoperation reasons. Crude event incidence is presented in Table 3. Figure 2 presents the cumulative incidence of revision

TABLE 1
Characteristics of 10,955 Female Patients Who Underwent Primary ACLR Within a US-Based Health Care System, by Graft Selection (2012-2023)[a]

				SMD[b]		
	QT	PT	HT	QT vs PT	QT vs PT	PT vs HT
Total No.	874	4597	5484			
Patient characteristics						
Age, y, mean (SD)	23.1 (8.8)	20.5 (7.3)	25.0 (10.7)	**0.324**	0.193	0.491
BMI, kg/m^2, mean (SD)	26.3 (5.9)	25.7 (5.4)	25.7 (5.2)	0.108	0.110	0.001
Race/ethnicity				**0.244**	**0.252**	**0.338**
Asian	159 (18.2)	568 (12.4)	624 (11.4)			
Black	69 (7.9)	467 (10.2)	446 (8.1)			
Hispanic	209 (23.9)	1430 (31.1)	1070 (19.5)			
Other	17 (1.9)	150 (3.3)	119 (2.2)			
White	420 (48.1)	1982 (43.1)	3225 (58.8)			
Smoking status				0.118	0.112	**0.217**
Current/former smoker	70 (8.0)	241 (5.2)	612 (11.2)			
Never smoker	800 (91.5)	4320 (94.0)	4834 (88.1)			
Missing	4 (0.5)	36 (0.8)	38 (0.7)			
ASA classification				**0.352**	**0.477**	**0.217**
1	461 (52.7)	2669 (58.1)	2710 (49.4)			
≥2	384 (43.9)	1447 (31.5)	1839 (33.5)			
Missing	29 (3.3)	481 (10.5)	935 (17.0)			
Activity at the time of injury				0.172	0.176	0.197
Sports	742 (84.9)	4035 (87.8)	4428 (80.7)			
Trauma	74 (8.5)	201 (4.4)	421 (7.7)			
Other	31 (3.5)	182 (4.0)	303 (5.5)			
Missing	27 (3.1)	179 (3.9)	332 (6.1)			
Contralateral ACLR	54 (6.2)	280 (6.1)	260 (4.7)	0.004	0.063	0.060
Surgical characteristics						
Cartilage injury reported	119 (13.6)	624 (13.6)	1128 (20.6)	0.001	0.186	0.187
Lateral meniscus injury reported	334 (38.2)	1709 (37.2)	1914 (34.9)	0.021	0.069	0.047
Medial meniscus injury reported	298 (34.1)	1509 (32.8)	1897 (34.6)	0.027	0.010	0.037
Tunnel drilling technique				**1.166**	**0.623**	**0.506**
Lateral approach	476 (54.5)	426 (9.3)	1558 (28.4)			
Medial portal	378 (43.2)	3482 (75.7)	3273 (59.7)			
Transtibial	6 (0.7)	447 (9.7)	393 (7.2)			
Missing	14 (1.6)	242 (5.3)	260 (4.7)			
Operative time, min, mean (SD)	107.4 (32.5)	106.9 (29.9)	100.8 (31.8)	0.014	0.193	0.183

[a]Data are presented as n (%) unless otherwise indicated. Missing data: BMI = 23 (0.2%), operative time = 1646 (15.0%). ACLR, anterior cruciate ligament reconstruction; ASA, American Society of Anesthesiologists; BMI, body mass index; HT, hamstring tendon; PT, patellar tendon; QT, quadriceps tendon; SMD, standardized mean difference.

[b]An SMD <0.2 indicated balance in the distribution of the covariate between the 2 study groups compared (covariates with an SMD ≥0.2 in bold).

(left) and reoperation (right) during 5 years of follow-up by graft type for females and males.

In male patients with ACLR, no differences in revision or reoperation risks were observed when comparing QT to PT (revision: HR, 0.94, 95% CI, 0.57-1.54, P = .801; reoperation: HR, 1.14, 95% CI, 0.72-1.81, P = .579) (Table 3).

QT Versus HT

QT ACLR in female patients was associated with a lower revision risk (HR, 0.44; 95% CI, 0.24-0.83; P = .011) compared to HT ACLR, but no differences were observed for reoperation (HR, 0.94; 95% CI, 0.63-1.38; P = .740). No other differences were observed between QT and HT ACLR for the additional reoperation reasons evaluated. Crude event incidence is presented in Table 4. Figure 3 presents the cumulative incidence of revision (left) and reoperation (right) during 5 years of follow-up by graft type for females and males.

In male patients with ACLR, no differences in revision or reoperation risks were observed when comparing QT to HT selection (revision: HR, 0.72, 95% CI, 0.49-1.07, P = .101; reoperation: HR, 1.31, 95% CI, 0.88-1.97, P = .187) (Table 4).

PT Versus HT

In female patients, PT ACLRs were noted to have a lower risk of revision (HR, 0.57; 95% CI, 0.44-0.73; P < .001)

TABLE 2
Characteristics of 16,760 Male Patients Who Underwent Primary ACLR Within a US-Based Health Care System, by Graft Selection (2012-2023)[a]

				SMD[b]		
	QT	PT	HT	QT vs PT	QT vs PT	PT vs HT
Total No.	1297	7560	7903			
Patient characteristics						
Age, y, mean (SD)	25.6 (8.6)	24.0 (7.7)	26.9 (9.6)	**0.200**	0.136	**0.329**
BMI, kg/m^2, mean (SD)	27.3 (5.3)	27.4 (5.2)	26.9 (4.7)	0.013	0.080	0.095
Race/ethnicity				0.112	**0.226**	**0.223**
Asian	230 (17.7)	1079 (14.3)	1013 (12.8)			
Black	121 (9.3)	731 (9.7)	670 (8.5)			
Hispanic	417 (32.2)	2603 (34.4)	2156 (27.3)			
Other	24 (1.9)	205 (2.7)	144 (1.8)			
White	505 (38.9)	2942 (38.9)	3920 (49.6)			
Smoking status				0.021	0.129	0.141
Current/former smoker	1075 (82.9)	6297 (83.3)	6147 (77.8)			
Never smoker	212 (16.3)	1194 (15.8)	1677 (21.2)			
Missing	10 (0.8)	69 (0.9)	79 (1.0)			
ASA classification				**0.224**	**0.347**	0.139
1	682 (52.6)	4040 (53.4)	3935 (49.8)			
≥2	547 (42.2)	2701 (35.7)	2745 (34.7)			
Missing	68 (5.2)	819 (10.8)	1223 (15.5)			
Activity at the time of injury				0.062	0.153	0.144
Sports	1090 (84.0)	6413 (84.8)	6282 (79.5)			
Trauma	95 (7.3)	469 (6.2)	612 (7.7)			
Other	38 (2.9)	277 (3.7)	447 (5.7)			
Missing	74 (5.7)	401 (5.3)	562 (7.1)			
Contralateral ACLR	65 (5.0)	317 (4.2)	293 (3.7)	0.039	0.064	0.025
Surgical characteristics						
Cartilage injury reported	276 (21.3)	1694 (22.4)	2013 (25.5)	0.027	0.099	0.072
Lateral meniscus injury reported	644 (49.7)	3724 (49.3)	3641 (46.1)	0.008	0.072	0.064
Medial meniscus injury reported	522 (40.2)	2805 (37.1)	3200 (40.5)	0.065	0.005	0.070
Tunnel drilling technique				**1.014**	**0.513**	**0.491**
Lateral approach	667 (51.4)	813 (10.8)	2359 (29.8)			
Medial portal	571 (44.0)	5586 (73.9)	4495 (56.9)			
Transtibial	20 (1.5)	735 (9.7)	630 (8.0)			
Missing	39 (3.0)	426 (5.6)	419 (5.3)			
Operative time, min, mean (SD)	107.6 (34.7)	111.0 (31.8)	104.0 (33.2)	0.093	0.100	**0.201**

[a]Data are presented as n (%) unless otherwise indicated. Missing data: BMI = 57 (0.3%), operative time = 2278 (13.6%). ACLR, anterior cruciate ligament reconstruction; ASA, American Society of Anesthesiologists; BMI, body mass index; HT, hamstring tendon; PT, patellar tendon; QT, quadriceps tendon; SMD, standardized mean difference.
[b]An SMD <0.2 indicated balance in the distribution of the covariate between the 2 study groups compared (covariates with an SMD ≥0.2 in bold).

compared to HT ACLRs and no difference in reoperation risk (HR, 1.09; 95% CI, 0.93-1.28; *P* = .282). A higher risk for reoperation due to stiffness was observed with PT ACLR (HR, 1.48; 95% CI, 1.11-1.98; *P* = .008). Crude event incidence is presented in Table 5. Figure 4 presents the cumulative incidence of revision (left) and reoperation (right) during 11 years after ACLR by graft type for females and males.

Similarly, in male patients, PT ACLR was associated with a lower revision risk compared to HT ACLR (HR, 0.79; 95% CI, 0.65-0.97; *P* = .027), no difference in reoperation risk (HR, 1.14; 95% CI, 0.96-1.35; *P* = .128), but a higher risk of reoperation for stiffness (HR, 1.59; 95% CI, 1.15-2.20; *P* = .005) (Table 5).

Secondary Analyses

Adjusted results when restricting to female patients who were <22 years at the time of ACLR were largely similar to those observed in the overall cohort (Tables 3-5). A lower revision risk for QT ACLR compared to HT ACLR was observed in younger patients (HR, 0.45; 95% CI, 0.22-0.92; *P* = .029). For PT ACLR compared to HT ACLR, a lower revision risk (HR, 0.57; 95% CI, 0.43-0.75; *P* < .001) but higher risk of reoperation for stiffness (HR, 1.58; 95% CI, 1.11-2.25; *P* = .012) was observed with PT ACLR in female patients. No differences in risk for subsequent surgical outcomes according to autograft selection were observed in female patients who were ≥22 years at the time of ACLR.

TABLE 3
Crude Cumulative Incidence and Adjusted Risk of 5-Year Revision and Ipsilateral Reoperation After QT ACLR Compared With PT ACLR Stratified by Female and Male Patients[a]

	Crude Incidence, n (%)[b]				
Surgical Intervention	QT	PT	Adjusted HR (95% CI)[c]	*P* Value	NNT[d]
Female patients					
Revision					
Overall cohort	9 (2.2)	107 (3.3)	0.76 (0.36-1.59)	.465	134.1
<22 y	8 (4.0)	97 (4.0)	0.77 (0.33-1.83)	.557	107.6
≥22 y	1 (0.3)	10 (1.2)	—	—	—
Ipsilateral reoperation					
Overall cohort	36 (8.4)	343 (9.4)	0.83 (0.57-1.23)	.355	67.8
<22 y	19 (8.5)	264 (9.9)	0.71 (0.46-1.10)	.121	36.2
≥22 y	17 (8.3)	79 (8.3)	1.14 (0.67-1.95)	.622	–93.7
Stiffness-related reoperation					
Overall cohort	18 (2.5)	145 (3.6)	0.83 (0.44-1.57)	.556	165.9
<22 y	10 (2.6)	105 (3.6)	0.81 (0.40-1.64)	.560	151.8
≥22 y	8 (2.4)	40 (3.6)	0.82 (0.33-2.07)	.679	169.3
Extensor disruption reoperation					
Overall cohort	0 (0.0)	6 (0.1)	—	—	—
<22 y	0 (0.0)	6 (0.2)	—	—	—
≥22 y	0 (0.0)	0 (0.0)	—	—	—
Meniscus-related reoperation					
Overall cohort	13 (4.8)	153 (4.9)	0.73 (0.37-1.45)	.372	80.3
<22 y	8 (5.7)	128 (5.5)	0.57 (0.26-1.23)	.148	41.9
≥22 y	5 (3.9)	25 (3.4)	1.34 (0.44-4.14)	.608	–91.7
Cartilage-related reoperation					
Overall cohort	8 (2.0)	49 (1.6)	1.66 (0.48-5.73)	.426	–98.0
<22 y	3 (0.8)	33 (1.5)	—	—	—
≥22 y	5 (3.5)	16 (2.3)	2.37 (0.47-11.20)	.296	–37.2
Male patients					
Revision					
Overall cohort	23 (3.7)	205 (3.7)	0.94 (0.57-1.54)	.801	449.4
<22 y	16 (7.0)	155 (5.6)	0.97 (0.55-1.72)	.924	649.9
≥22 y	7 (1.7)	50 (1.8)	0.76 (0.31-1.88)	.550	210.6
Ipsilateral reoperation					
Overall cohort	54 (7.7)	379 (6.6)	1.14 (0.72-1.81)	.579	–113.1
<22 y	19 (8.1)	161 (5.9)	1.34 (0.79-2.25)	.279	–53.4
≥22 y	35 (7.6)	218 (7.2)	1.04 (0.61-1.75)	.897	–407.7
Stiffness-related reoperation					
Overall cohort	17 (1.8)	116 (1.8)	1.13 (0.42-2.99)	.811	–450.5
<22 y	7 (2.0)	41 (1.3)	2.36 (0.87-6.44)	.093	–61.4
≥22 y	10 (1.6)	75 (2.3)	0.79 (0.25-2.55)	.696	214.5
Extensor disruption reoperation					
Overall cohort	1 (0.1)	15 (0.2)	—	—	—
<22 y	1 (0.2)	6 (0.2)	—	—	—
≥22 y	0 (0.0)	9 (0.2)	—	—	—
Meniscus-related reoperation					
Overall cohort	24 (4.2)	216 (4.2)	0.97 (0.60-1.59)	.908	853.4
<22 y	10 (5.9)	112 (4.4)	1.07 (0.53-2.17)	.847	–320.4
≥22 y	14 (3.4)	104 (4.0)	0.87 (0.43-1.75)	.688	191.3
Cartilage-related reoperation					
Overall cohort	10 (1.9)	55 (1.1)	1.65 (0.73-3.71)	.230	–143.0
<22 y	5 (2.2)	16 (0.7)	3.97 (0.99-15.97)	.053	–53.6
≥22 y	5 (1.6)	39 (1.5)	1.09 (0.43-2.73)	.857	–772.5

[a]There were 5471 female and 8857 male patients in this cohort: 3710 female and 4045 male patients <22 years of age, and 1761 female and 4812 male patients ≥22 years of age. ACLR, anterior cruciate ligament reconstruction; HR, hazard ratio; HT, hamstring tendon; NNT, number needed to treat; PT, patellar tendon; QT, quadriceps tendon. Dashes indicate there were too few events for regression analyses.

[b]Percentage calculated as 1 minus the Kaplan-Meier estimator at 5 years of follow-up.

[c]Regression models were adjusted for patient and surgical characteristics and included a cluster term for the operating surgeon.

[d]A positive NNT should be interpreted as the number of ACLRs needed with a QT graft to prevent a revision/reoperation, while a negative NNT should be interpreted as the number of ACLRs needed with a QT graft to have a revision/reoperation.

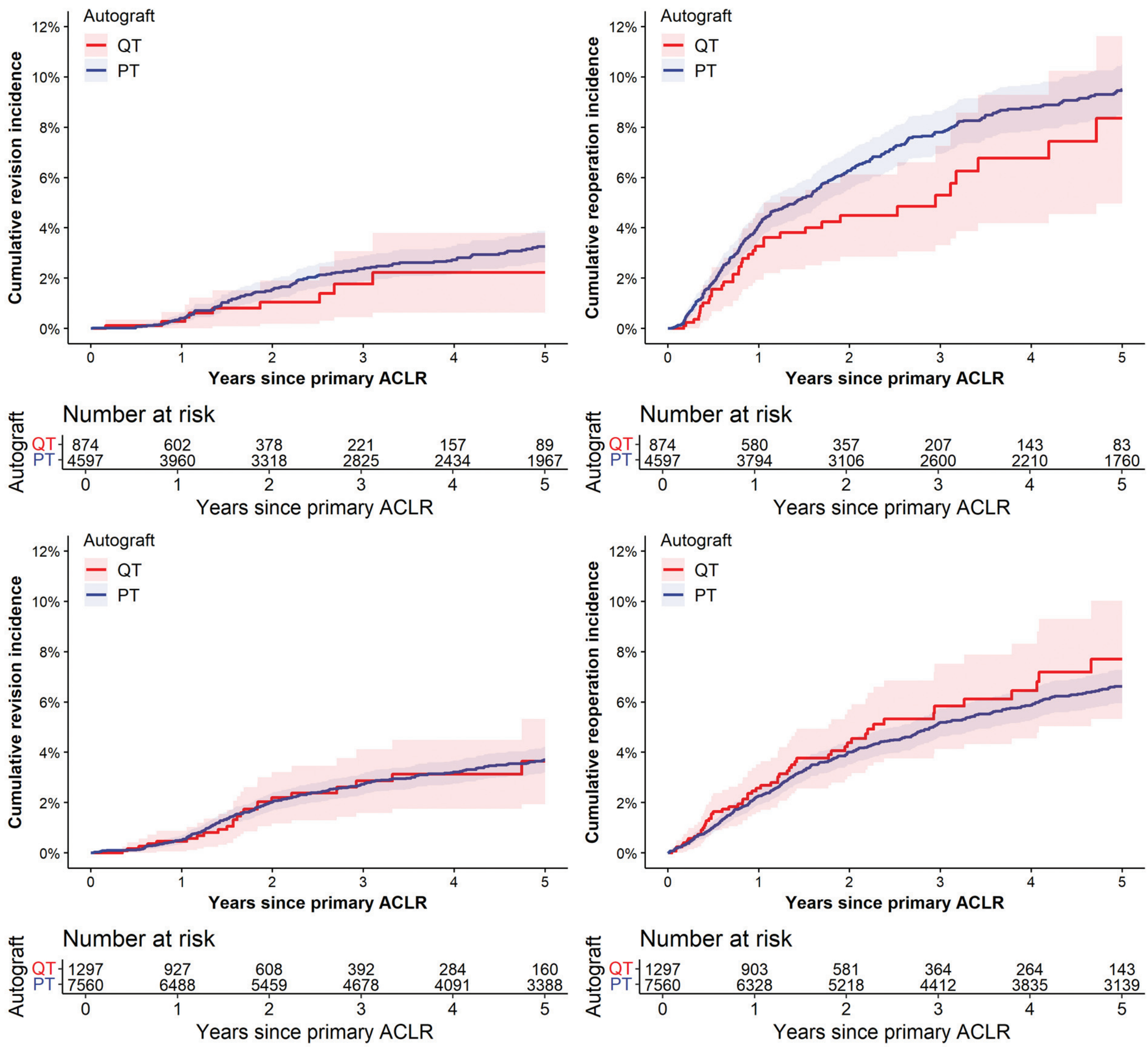

Figure 2. Cumulative incidence of revision (left) and ipsilateral reoperation (right) during follow-up for quadriceps tendon (QT) and patellar tendon (PT) anterior cruciate ligament reconstruction (ACLR) for female (top) and male (bottom) patients. The table under the x-axis presents the number of patients still at risk at each year of follow-up.

Results vary depending on age in male patients (Tables 3-5). In male patients who were <22 years, higher risks for reoperation due to stiffness (HR, 3.12; 95% CI, 1.00-9.72; P = .049) and cartilage reasons (HR, 3.65; 95% CI, 1.28-10.44; P = .016) were observed with QT versus HT ACLR. In those who were ≥22 years, QT ACLR was associated with a higher reoperation risk compared to HT ACLR (HR, 1.59; 95% CI, 1.06-2.40; P = .026). When comparing PT to HT ACLR, higher risks for reoperation overall (HR, 1.39; 95% CI, 1.12-1.73; P = .002) and for stiffness (HR, 1.56; 95% CI, 1.10-2.21; P = .012) were observed in patients who were ≥22 years at the time of ACLR.

DISCUSSION

The main finding in this large US-based multicenter cohort study is that HT autografts had a 2.3 times higher revision risk than QT autografts and a 1.8 times higher revision risk than PT autografts when used in female patients <22 years at the time of ACLR. No differences in the risk of revision or reoperation were observed when comparing QT to PT across sex or age. There was a higher risk of reoperation for stiffness with PT compared to HT for both males and females. There was a higher risk of reoperation for stiffness and cartilage reasons in males with QT.

TABLE 4
Crude Cumulative Incidence and Adjusted Risk of 5-Year Revision and Ipsilateral Reoperation After QT ACLR Compared With HT ACLR Stratified by Female and Male Patients[a]

Surgical Intervention	Crude Incidence, n (%)[b] QT	Crude Incidence, n (%)[b] HT	Adjusted HR (95% CI)[c]	*P* Value	NNT[d]
Female patients					
Revision					
Overall cohort	9 (2.2)	213 (4.9)	0.44 (0.24-0.83)	**.011**	38.6
<22 y	8 (4.0)	183 (7.8)	0.45 (0.22-0.92)	**.029**	23.9
≥22 y	1 (0.3)	30 (1.5)	—	—	—
Ipsilateral reoperation					
Overall cohort	36 (8.4)	368 (8.1)	0.94 (0.63-1.38)	.740	203.5
<22 y	19 (8.5)	217 (9.3)	0.84 (0.54-1.29)	.422	69.5
≥22 y	17 (8.3)	151 (6.8)	1.08 (0.65-1.79)	.766	–194.0
Stiffness-related reoperation					
Overall cohort	18 (2.5)	122 (2.5)	1.28 (0.71-2.31)	.420	–148.8
<22 y	10 (2.6)	57 (2.3)	1.47 (0.74-2.94)	.271	–95.8
≥22 y	8 (2.4)	65 (2.8)	1.06 (0.49-2.27)	.886	–652.0
Extensor disruption reoperation					
Overall cohort	0 (0.0)	0 (0.0)	—	—	—
<22 y	0 (0.0)	0 (0.0)	—	—	—
≥22 y	0 (0.0)	0 (0.0)	—	—	—
Meniscus-related reoperation					
Overall cohort	13 (4.8)	196 (4.7)	0.69 (0.38-1.24)	.211	71.0
<22 y	8 (5.7)	136 (6.2)	0.60 (0.30-1.21)	.152	42.0
≥22 y	5 (3.9)	60 (3.0)	0.94 (0.36-2.48)	.905	603.2
Cartilage-related reoperation					
Overall cohort	8 (2.0)	49 (1.2)	1.95 (0.65-5.83)	.235	–96.4
<22 y	3 (0.8)	22 (1.0)	—	—	—
≥22 y	5 (3.5)	27 (1.3)	2.14 (0.51-9.02)	.302	–71.5
Male patients					
Revision					
Overall cohort	23 (3.7)	301 (4.8)	0.72 (0.49-1.07)	.101	77.8
<22 y	16 (7.0)	202 (8.8)	0.72 (0.45-1.15)	.168	41.8
≥22 y	7 (1.7)	99 (2.6)	0.67 (0.36-1.26)	.216	119.7
Ipsilateral reoperation					
Overall cohort	54 (7.7)	367 (5.8)	1.31 (0.88-1.97)	.187	–56.9
<22 y	19 (8.1)	159 (7.2)	1.00 (0.59-1.70)	.989	3998.4
≥22 y	35 (7.6)	208 (5.0)	1.59 (1.06-2.40)	**.026**	–35.0
Stiffness-related reoperation					
Overall cohort	17 (1.8)	81 (1.2)	1.62 (0.68-3.82)	.274	–140.6
<22 y	7 (2.0)	17 (0.7)	3.12 (1.00-9.72)	**.049**	–71.4
≥22 y	10 (1.6)	64 (1.4)	1.24 (0.48-3.18)	.662	–301.5
Extensor disruption reoperation					
Overall cohort	1 (0.1)	0 (0.0)	—	—	—
<22 y	1 (0.2)	0 (0.0)	—	—	—
≥22 y	0 (0.0)	0 (0.0)	—	—	—
Meniscus-related reoperation					
Overall cohort	24 (4.2)	250 (4.2)	0.90 (0.59-1.39)	.646	253.4
<22 y	10 (5.9)	127 (6.0)	0.69 (0.37-1.31)	.259	55.0
≥22 y	14 (3.4)	123 (3.2)	1.17 (0.67-2.05)	.581	–188.6
Cartilage-related reoperation					
Overall cohort	10 (1.9)	55 (1.0)	1.99 (0.99-3.98)	.052	–108.4
<22 y	5 (2.2)	17 (0.9)	3.65 (1.28-10.44)	**.016**	–46.8
≥22 y	5 (1.6)	38 (1.0)	1.33 (0.56-3.18)	.519	–299.5

[a]There were 6358 female and 9200 male patients in this cohort: 3199 female and 3227 male patients <22 years of age, and 3159 female and 5973 male patients ≥22 years of age. ACLR, anterior cruciate ligament reconstruction; HR, hazard ratio; HT, hamstring tendon; NNT, number needed to treat; QT, quadriceps tendon. Dashes indicate there were too few events for regression analyses.

[b]Percentage calculated as 1 minus the Kaplan-Meier estimator at 5 years of follow-up.

[c]Regression models were adjusted for patient and surgical characteristics and included a cluster term for the operating surgeon. Bold indicates statistical significance ($P < .05$).

[d]A positive NNT should be interpreted as the number of ACLRs needed with a QT graft to prevent a revision/reoperation, while a negative NNT should be interpreted as the number of ACLRs needed with a QT graft to have a revision/reoperation.

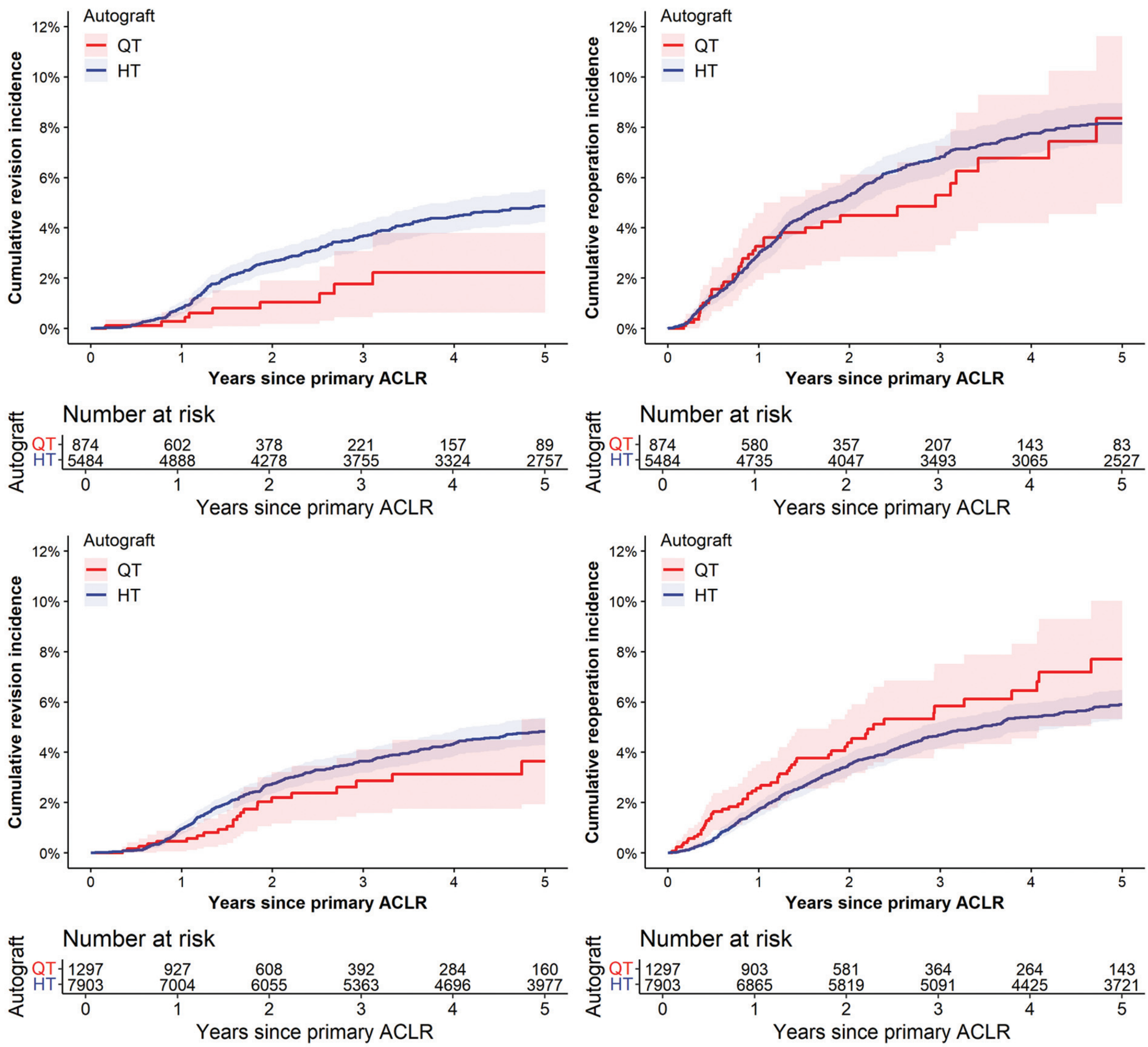

Figure 3. Cumulative incidence of revision (left) and ipsilateral reoperation (right) during follow-up for quadriceps tendon (QT) and hamstring tendon (HT) anterior cruciate ligament reconstruction (ACLR) for female (top) and male (bottom) patients. The table under the x-axis presents the number of patients still at risk at each year of follow-up.

These findings have important clinical implications based on the NNT. The NNT helps in translating the regression results into clinically meaningful values for surgeons and patients and is interpreted for the present study as the mean number of patients who must receive the treatment of interest to avoid a revision/reoperation. If performing ACLR in young females, a surgeon would have to perform only 24 ACLRs with QT and 23 ACLRs with PT to prevent 1 revision compared to the use of HT. In just the final year of our cohort, had only QT and PT been used in the 272 females instead of HT, the NNT analysis would suggest that nearly 12 fewer revisions would occur. This would save additional surgery and critical health care dollars,[1] but more importantly decrease the risk of subsequent osteoarthritis and eventual knee replacement, which have been shown to be increased after revision surgery.[11,42,58] Given the consequence of each revision ACLR, every effort should be made to individualize the graft type to the patient's risk profile.

Graft Selection and Revision Risk

As QT utilization has increased in more recent years, literature evaluating the association between this graft type and revision risk is increasing. Several studies have found no differences when comparing QT to PT[9,26,36,61] or to HT[3,9,36,47,61] ACLR. In a 2022 meta-analysis of 20 observational studies including 28,621 ACLRs, Tan et al[55] found similar graft failure rates, patient-reported outcomes, and functional outcomes between QT and HT autograft. The studies included overlap with other meta-analyses,[9,36]

TABLE 5
Crude Cumulative Incidence and Adjusted Risk of 11-Year Revision and Ipsilateral Reoperation After PT ACLR Compared With HT ACLR for Female and Male Patients[a]

Surgical Intervention	Crude Incidence, n (%)[b] PT	HT	Adjusted HR (95% CI)[c]	*P* Value	NNT[d]
Female patients					
Revision					
Overall cohort	107 (3.3)	213 (4.9)	0.57 (0.44-0.73)	**<.001**	32.5
<22 y	97 (4.0)	183 (7.8)	0.57 (0.43-0.75)	**<.001**	23.1
≥22 y	10 (1.2)	30 (1.5)	0.69 (0.31-1.52)	.356	143.8
Ipsilateral reoperation					
Overall cohort	343 (9.4)	368 (8.1)	1.09 (0.93-1.28)	.282	–110.8
<22 y	264 (9.9)	217 (9.3)	1.09 (0.89-1.33)	.397	–90.0
≥22 y	79 (8.3)	151 (6.8)	1.11 (0.82-1.49)	.507	–123.5
Stiffness-related reoperation					
Overall cohort	145 (3.6)	122 (2.5)	1.48 (1.11-1.98)	**.008**	–84.5
<22 y	105 (3.6)	57 (2.3)	1.58 (1.11-2.25)	**.012**	–76.3
≥22 y	40 (3.6)	65 (2.8)	1.33 (0.84-2.12)	.229	–111.7
Extensor disruption reoperation					
Overall cohort	6 (0.1)	0 (0.0)	—	—	—
<22 y	6 (0.2)	0 (0.0)	—	—	—
≥22 y	0 (0.0)	0 (0.0)	—	—	—
Meniscus-related reoperation					
Overall cohort	153 (4.9)	196 (4.7)	0.91 (0.74-1.12)	.356	161.9
<22 y	128 (5.5)	136 (6.2)	0.91 (0.71-1.17)	.450	130.1
≥22 y	25 (3.4)	60 (3.0)	0.93 (0.60-1.45)	.758	382.3
Cartilage-related reoperation					
Overall cohort	49 (1.6)	49 (1.2)	1.20 (0.79-1.83)	.385	–282.5
<22 y	33 (1.5)	22 (1.0)	1.29 (0.77-2.17)	.327	–201.8
≥22 y	16 (2.3)	27 (1.3)	1.08 (0.54-2.14)	.829	–724.0
Male patients					
Revision					
Overall cohort	205 (3.7)	301 (4.8)	0.79 (0.65-0.97)	**.027**	73.6
<22 y	155 (5.6)	202 (8.8)	0.83 (0.66-1.04)	.100	63.5
≥22 y	50 (1.8)	99 (2.6)	0.74 (0.1-1.06)	.096	88.2
Ipsilateral reoperation					
Overall cohort	379 (6.6)	367 (5.8)	1.14 (0.96-1.35)	.128	–95.9
<22 y	161 (5.9)	159 (7.2)	0.87 (0.69-1.11)	.278	93.2
≥22 y	218 (7.2)	208 (5.0)	1.39 (1.12-1.73)	**.002**	–38.0
Stiffness-related reoperation					
Overall cohort	116 (1.8)	81 (1.2)	1.59 (1.15-2.20)	**.005**	–137.3
<22 y	41 (1.3)	17 (0.7)	1.58 (0.88-2.82)	.122	–235.8
≥22 y	75 (2.3)	64 (1.4)	1.56 (1.10-2.21)	**.012**	–112.7
Extensor disruption reoperation					
Overall cohort	15 (0.2)	0 (0.0)	—	—	—
<22 y	6 (0.2)	0 (0.0)	—	—	—
≥22 y	9 (0.2)	0 (0.0)	—	—	—
Meniscus-related reoperation					
Overall cohort	216 (4.2)	250 (4.2)	0.95 (0.78-1.15)	.578	322.6
<22 y	112 (4.4)	127 (6.0)	0.81 (0.62-1.05)	.106	69.4
≥22 y	104 (4.0)	123 (3.2)	1.14 (0.86-1.52)	.372	–150.1
Cartilage-related reoperation					
Overall cohort	55 (1.1)	55 (1.0)	1.11 (0.76-1.60)	.597	–592.3
<22 y	16 (0.7)	17 (0.9)	0.75 (0.40-1.42)	.383	243.0
≥22 y	39 (1.5)	38 (1.0)	1.34 (0.89-2.02)	.159	–176.0

[a]There were 10,081 female and 15,463 male patients in this cohort: 5983 female and 6300 male patients <22 years of age, and 4098 female and 9163 male patients ≥22 years of age. ACLR, anterior cruciate ligament reconstruction; HR, hazard ratio; HT, hamstring tendon; NNT, number needed to treat; PT, patellar tendon. Dashes indicate there were too few events for regression analyses.

[b]Percentage calculated as 1 minus the Kaplan-Meier estimator at 11 years of follow-up.

[c]Regression models were adjusted for patient and surgical characteristics and included a cluster term for the operating surgeon. Bold indicates statistical significance ($P < .05$).

[d]A positive NNT should be interpreted as the number of ACLRs needed with a PT graft to prevent a revision/reoperation, while a negative NNT should be interpreted as the number of ACLRs needed with a PT graft to have a revision/reoperation.

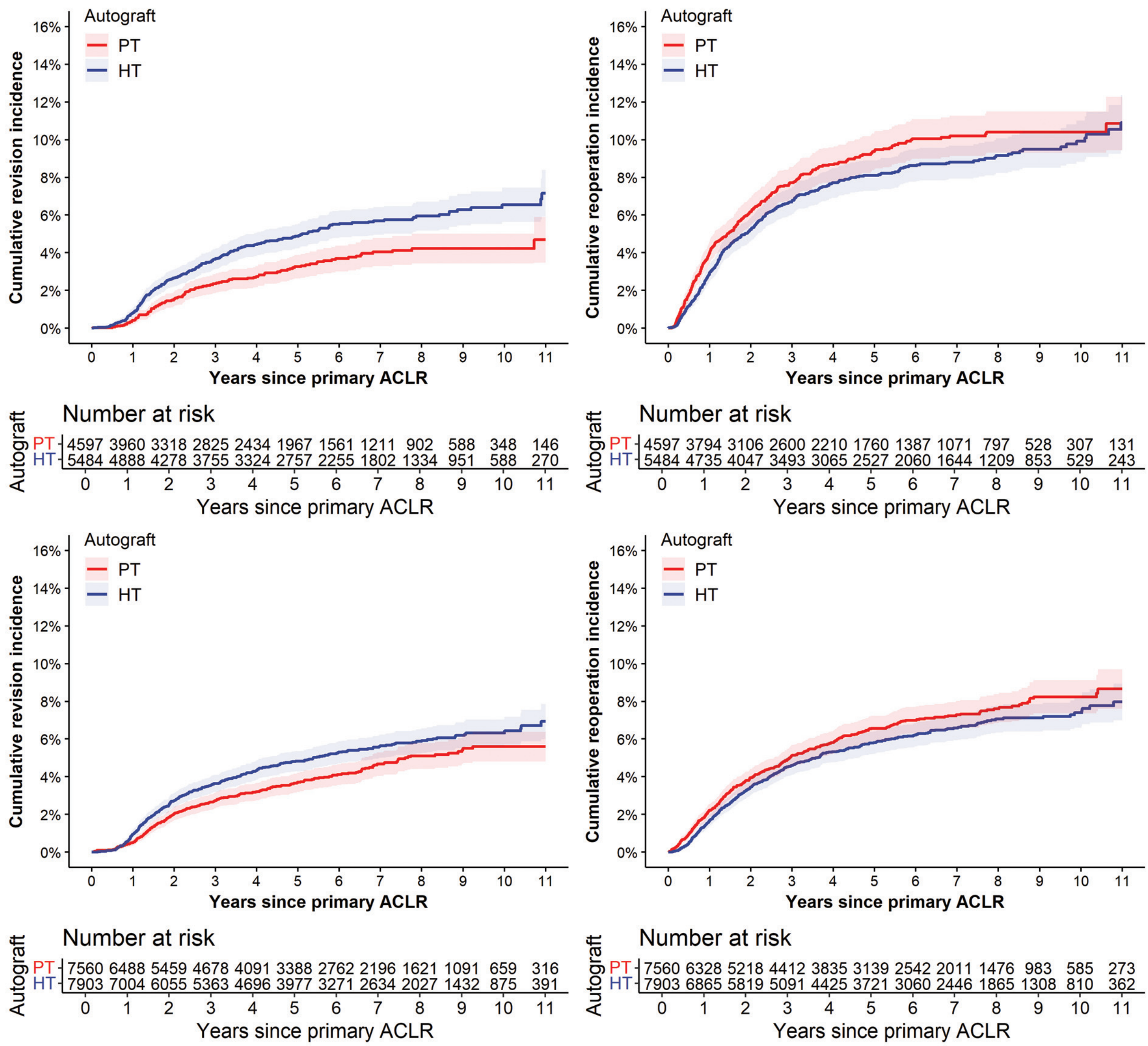

Figure 4. Cumulative incidence of revision (left) and ipsilateral reoperation (right) during follow-up for hamstring tendon (HT) and patellar tendon (PT) anterior cruciate ligament reconstruction (ACLR) for female (top) and male (bottom) patients. The table under the x-axis presents the number of patients still at risk at each year of follow-up.

and these studies did not always break down ACLR into relevant subgroups, such as sex and age, and may therefore have missed subtle outcome variability within these subgroups. The present study is an extension of that by Yang et al,[61] in which no differences were observed when comparing the entire cohort of QT to PT and HT ACLR. Using data from the same ACLRR, but with a larger cohort size and longer follow-up, young female patients were found to have a lower revision risk with QT compared to HT ACLR. This finding was similar to the lower risk observed with PT versus HT in young females. However, there was no difference in revision risk between QT and PT, nor any difference between QT and HT in men, regardless of age. Additional studies with larger sample sizes and longer follow-up of QT ACLR are needed to confirm the present findings regarding young female patients with ACLR, as well as investigate whether there are other patient or graft-specific subgroups with a lower revision risk. One hypothesis for younger females having the highest revision risk with HT, besides higher levels of sporting activity compared to older females, may be related to properties of the graft itself. Expansive discussion about the biomechanical properties of ACL grafts is beyond the scope of the study. However, studies on graft mechanics have reported variable findings, with some finding superior attributes with HT, while others have found inferior attributes.[5,13,56] Given this complicated relationship to mechanical properties, the higher failure rate in young females may come down to graft size. It is well known that graft size affects revision rate, with much higher rates of revision with smaller (<8.5 mm) HT grafts.[27,33,53] Although not the focus of this paper, an additional study looking at graft diameter within the subtypes of grafts is warranted.

Registry-based cohort studies comparing PT to HT have consistently reported a higher revision risk.[15,31,41,44,45,61] However, some studies have not shown differences.[6,17] When stratifying by sex, the current study still found a higher risk of revision with HT compared to PT ACLR across both females and males, although the strength of the association varied with a 1.8 times higher risk in females and a 1.3 times higher risk in males.

Reoperation Risk

Decisions about ACL graft choice are based on both revision rate and the side effects of specific graft harvest. In this study, sex- and age-stratified reoperation results across graft type were mixed. Manually reviewing charts of those patients with reoperations allowed us to determine the cause for reoperations. Causes of reoperation were categorized as stiffness, extensor disruption, meniscal reasons, or cartilage reasons specifically. Evaluating details of reoperation data within the subgroups of this large cohort of patients may help guide clinicians on graft choice. The strongest association observed was a 3.7 times higher risk of surgery for cartilage reasons with QT compared to HT in young male patients. While the crude incidence of surgery for stiffness was low at 1.7%, 2.1%, and 2.5% for HT, QT, and PT, respectively, a 1.5 times and 1.6 times higher risk of surgery for stiffness with PT compared to HT was observed in females and males, respectively. However, results varied when considering age, with the higher risk in young females and older males. For QT, there was a 3.1 times higher risk of surgery for stiffness compared to HT in young males but not in females. In 2021, the Danish Knee Ligament Reconstruction Registry reported a nonsignificant trend toward a higher risk of reoperation for cyclops lesions with the use of QT compared to HT (HR, 2.2; 95% CI, 0.8-5.8).[49] While the event count was low, one potential reason for the higher stiffness risk observed may be that PT and QT autografts can cause some early loss of extension, which may predispose to cyclops lesion formation. An additional reason may be that the volume of the graft is often larger in QT and PT compared to HT, which may predispose to stiffness. Clinically, there is a trend to decrease QT graft size to minimize the risk of stiffness.[17] Our study did not specifically assess graft size as a risk factor for stiffness, reoperation, or revision; further study is needed.

No significant differences in reoperation related to meniscal debridement or repair surgery were observed for any subgroup considered. Furthermore, the rate of extensor disruption was very low at <0.2%, and similar between QT and PT. Patellar fracture was the main mode of extensor disruption. Not surprisingly, there were no recorded extensor disruptions after HT ACLR. Because of the low event rate, subgroup analyses were not feasible for this reason.

Strengths and Limitations

The biggest study strength is the data source: our health care system's ACLRR. Data were prospectively collected into the registry in a standardized manner, and all identified outcomes were manually validated, minimizing information bias and increasing internal validity. The registry also allows for evaluation of rare outcomes that can occur over longer follow-up using a large cohort of 27,715 ACLRs, including 2171 QT ACLRs. The study used data since 2012, when the first QT was recorded in the ACLRR. Additionally, the ACLRs included in this study were performed by 319 community-based surgeons, increasing generalizability. The characteristics within the age and sex subgroups evaluated were similar based on the SMD. Finally, prior study has found patient characteristics and incidence of outcomes in our health care system's ACLRR to be comparable to those found in other national knee ligament registries.[43]

There are, however, limitations to this study. First, graft selection was left to the decision of the operating surgeon. This may introduce selection bias as surgeons may opt for different autografts based on patient characteristics. However, our regression models adjusted for patient characteristics and included a cluster term for the operating surgeon.

Second, the design is an observational study. Therefore, only associations are reported; causality cannot be stated. There is potential for residual confounding due to factors that could not be controlled for in the study design or statistical analysis due to data not being available in the ACLRR. For example, information on postoperative rehabilitation, return to play, patient compliance, and activity level is not collected by the registry. No clinical or functional outcomes are measured by the registry. Furthermore, lateral extra-articular procedures, which have been found to be associated with a lower risk of revision in HT ACLR,[14] were not evaluated.

Third, other nonsurgical outcomes that may be of clinical interest, such as graft failure without surgery, rates of anterior or kneeling-related knee pain, functional scores, and patient-reported outcome measures, were not evaluated as these are not collected by the registry. These factors could also affect a surgeon's graft choice. However, the registry does capture orthopaedically relevant hard endpoints (revision and reoperation) where both the surgeon and patient have deemed that the clinical condition requires surgical intervention. Additional study is needed to evaluate these other outcomes of interest.

Fourth, while our regression analyses accounted for correlation of ACLRs performed by the same surgeon, the present findings may reflect the early experience of a broad group of surgeons adopting QT ACLR. However, a study by Lind et al[25] found that low-volume surgeons had a higher revision risk with QT ACLR compared to higher-volume surgeons. The authors suggested that there might be a learning curve when transitioning to QT ACLR. It is generally accepted there is a learning curve with every surgical procedure. Although difficult to quantify, a review of multiple databases reported that higher surgical volume was associated with improved patient outcomes and a reduction in operative times.[57] Whether there are any differences in revision and reoperation risks based on surgeon experience, including early QT adoption, learning curve, and so forth, is outside the scope of the present study and an avenue for future investigation.

Fifth, the rate of patients lost to follow-up through leaving the health care system was 19.1% at 5 years of follow-up. There was variation in loss to follow-up observed across graft selection groups; however, our statistical analysis using survival analysis techniques sought to mitigate this loss to follow-up; patients contributed follow-up time in the analysis as long as they were members and were censored at the date of membership termination.

CONCLUSION

In young female patients, HT ACLR was associated with a 2.3 and 1.8 times higher revision risk when compared to QT and PT ACLR, respectively. In male patients, an HT ACLR was associated with a 1.3 times higher revision risk compared to PT. No differences in risk of revision were noted between QT and PT ACLR. Higher risks for reoperation due to stiffness were observed with PT compared to HT across sex and age. There was a higher risk of surgery for cartilage reasons with QT compared to HT and PT. Surgeons should consider these data when discussing risks and benefits of the different graft options for ACLR, especially with their young female patients. Specifically tailoring graft choice to individual patient characteristics such as sex and age may maximize outcomes and minimize risk of subsequent surgical interventions.

ACKNOWLEDGMENT

The authors acknowledge the Kaiser Permanente orthopaedic surgeons who contribute to the Kaiser Permanente Anterior Cruciate Ligament Reconstruction Registry as well as the staff of Medical Device Surveillance and Assessment, which coordinates registry operations.

ORCID iD

Heather A. Prentice https://orcid.org/0000-0002-2200-6564

REFERENCES

1. Bokshan SL, Mehta S, DeFroda SF, Owens BD. What are the primary cost drivers of anterior cruciate ligament reconstruction in the United States? A cost-minimization analysis of 14,713 patients. *Arthroscopy*. 2019;35(5):1576-1581.
2. Castellanos Dolk D, Hedevik H, et al. Nationwide incidence of anterior cruciate ligament reconstruction in higher-level athletes in Sweden: a cohort study from the Swedish National Knee Ligament Registry linked to six sports organisations. *Br J Sports Med*. 2025;59(7):470-479.
3. Cavaignac E, Coulin B, Tscholl P, Nik Mohd Fatmy N, Duthon V, Menetrey J. Is quadriceps tendon autograft a better choice than hamstring autograft for anterior cruciate ligament reconstruction? A comparative study with a mean follow-up of 3.6 years. *Am J Sports Med*. 2017;45(6):1326-1332.
4. Childers J, Eng E, Lack B, et al. Reported anterior cruciate ligament injury incidence in adolescent athletes is greatest in female soccer players and athletes participating in club sports: a systematic review and meta-analysis. *Arthroscopy*. 2025;41(3):774-784.e772.
5. Chivot M, Pioger C, Cognault J, et al. Every layer of quadriceps tendon's central and medial portion offers similar tensile properties than hamstrings or ilio-tibial band grafts. *J Exp Orthop*. 2020;7(1):50.
6. Connors JP, Cusano A, Saleet J, et al. Return to sport and graft failure rates after primary Anterior cruciate ligament reconstruction with a bone-patellar tendon-bone versus hamstring tendon autograft: a systematic review and meta-analysis. *Am J Sports Med*. 2025;53(8):1996-2006.
7. Crawford SN, Waterman BR, Lubowitz JH. Long-term failure of anterior cruciate ligament reconstruction. *Arthroscopy*. 2013;29(9):1566-1571.
8. Cristiani R, Forssblad M, Edman G, Eriksson K, Stålman A. Age, time from injury to surgery and quadriceps strength affect the risk of revision surgery after primary ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(12):4154-4162.
9. Dai W, Leng X, Wang J, Cheng J, Hu X, Ao Y. Quadriceps tendon autograft versus bone-patellar tendon-bone and hamstring tendon autografts for anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2022;50(12):3425-3439.
10. Davis AC, Voelkel JL, Remmers CL, Adams JL, McGlynn EA. Comparing Kaiser Permanente members to the general population: implications for generalizability of research. *Perm J*. 2023;27(2):87-98.
11. Ding DY, Prentice HA, Reyes C, Paxton EW, Chen F, Maletis GB. Patient and operative risk factors for subsequent knee arthroplasty after primary anterior cruciate ligament reconstruction: a cohort study of 52,222 patients. *Am J Sports Med*. 2025;53(10):2370-2378.
12. Ekeland A, Engebretsen L, Fenstad AM, Heir S. Similar risk of ACL graft revision for alpine skiers, football and handball players: the graft revision rate is influenced by age and graft choice. *Br J Sports Med*. 2020;54(1):33-37.
13. Garcia M, Momenzadah K, Shariyate MJ, et al. Plastic and elastic biomechanical properties of anterior cruciate ligament autografts. *BMC Musculoskelet Disord*. 2024;25(1):157.
14. Getgood AMJ, Bryant DM, Litchfield R, et al. Lateral extra-articular tenodesis reduces failure of hamstring tendon autograft anterior cruciate ligament reconstruction: 2-year outcomes from the STABILITY Study randomized clinical trial. *Am J Sports Med*. 2020;48(2):285-297.
15. Gifstad T, Foss OA, Engebretsen L, et al. Lower risk of revision with patellar tendon autografts compared with hamstring autografts: a registry study based on 45,998 primary ACL reconstructions in Scandinavia. *Am J Sports Med*. 2014;42(10):2319-2328.
16. Gopinatth V, Tartibi S, Smith MV, Matava MJ, Brophy RH, Knapik DM. Long-term results of bone-patellar tendon-bone versus hamstring tendon autograft for primary anterior cruciate ligament reconstruction: a meta-analysis of randomized controlled trials. *Orthop J Sports Med*. 2025;13(4):23259671251330307.
17. Haley RM, Lamplot JD, Myer GD, et al. Localized anterior arthrofibrosis after soft-tissue Quadriceps tendon anterior cruciate ligament reconstruction is more common in patients who are female, undergo meniscal repair, and have grafts of larger diameter. *Arthroscopy*. 2023;39(6):1472-1479.
18. Hulet C, Sonnery-Cottet B, Stevenson C, et al. The use of allograft tendons in primary ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(6):1754-1770.
19. Ireland ML. The female athlete: entitled to compete, predetermined to tear her anterior cruciate ligament? *Curr Sports Med Rep*. 2005;4(2):57-60.
20. Jackson GR, Lee J, Tuthill T, et al. Higher rates of residual postoperative instability after anterior cruciate ligament reconstruction in female patients: a systematic review of level II studies. *Arthrosc Sports Med Rehabil*. 2023;5(5):100772.
21. Kaeding CC, Aros B, Pedroza A, et al. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. *Sports Health*. 2011;3(1):73-81.
22. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Spindler KP. Risk factors and predictors of subsequent ACL injury in either knee after

ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. *Am J Sports Med*. 2015;43(7):1583-1590.
23. Kaiser Permanente. Fast Facts. Accessed January 8, 2025. https://about.kaiserpermanente.org/who-we-are/fast-facts
24. Lind M, Menhert F, Pedersen AB. Incidence and outcome after revision anterior cruciate ligament reconstruction: results from the Danish registry for knee ligament reconstructions. *Am J Sports Med*. 2012;40(7):1551-1557.
25. Lind M, Strauss MJ, Nielsen T, Engebretsen L. Low surgical routine increases revision rates after quadriceps tendon autograft for anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Registry. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(6):1880-1886.
26. Lund B, Nielsen T, Faunø P, Christiansen SE, Lind M. Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. *Arthroscopy*. 2014;30(5):593-598.
27. Magnussen RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE. Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. *Arthroscopy*. 2012;28(4):526-531.
28. Magnussen RA, Meschbach NT, Kaeding CC, Wright RW, Spindler KP. ACL graft and contralateral ACL tear risk within ten years following reconstruction: a systematic review. *JBJS Rev*. 2015;3(1):e3.
29. Magnussen RA, Trojani C, Granan LP, et al. Patient demographics and surgical characteristics in ACL revision: a comparison of French, Norwegian, and North American cohorts. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(8):2339-2348.
30. Maletis GB, Chen J, Inacio MC, Funahashi TT. Age-related risk factors for revision anterior cruciate ligament reconstruction: a cohort study of 21,304 patients from the Kaiser Permanente Anterior Cruciate Ligament Registry. *Am J Sports Med*. 2016;44(2):331-336.
31. Maletis GB, Inacio MC, Desmond JL, Funahashi TT. Reconstruction of the anterior cruciate ligament: association of graft choice with increased risk of early revision. *Bone Joint J*. 2013;95-B(5):623-628.
32. Maletis GB, Inacio MC, Funahashi TT. Analysis of 16,192 anterior cruciate ligament reconstructions from a community-based registry. *Am J Sports Med*. 2013;41(9):2090-2098.
33. Mariscalco MW, Flanigan DC, Mitchell J, et al. The influence of hamstring autograft size on patient-reported outcomes and risk of revision after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. *Arthroscopy*. 2013;29(12):1948-1953.
34. Mok AC, Fancher AJ, Vopat ML, et al. Sex-specific outcomes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Orthop J Sports Med*. 2022;10(2):23259671221076883.
35. Montalvo AM, Schneider DK, Webster KE, et al. Anterior cruciate ligament injury risk in sport: a systematic review and meta-analysis of injury incidence by sex and sport classification. *J Athl Train*. 2019;54(5):472-482.
36. Mouarbes D, Menetrey J, Marot V, Courtot L, Berard E, Cavaignac E. Anterior cruciate ligament reconstruction: a systematic review and meta-analysis of outcomes for quadriceps tendon autograft versus bone-patellar tendon-bone and hamstring-tendon autografts. *Am J Sports Med*. 2019;47(14):3531-3540.
37. Nyland J, Collis P, Huffstutler A, et al. Quadriceps tendon autograft ACL reconstruction has less pivot shift laxity and lower failure rates than hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(2):509-518.
38. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med*. 2014;42(7):1567-1573.
39. Paudel YR, Sommerfeldt M, Voaklander D. Incidence and risk factors for revision and contralateral anterior cruciate ligament reconstruction: a population-based retrospective cohort study. *Medicine (Baltimore)*. 2023;102(20):e33669.
40. Paxton EW, Kiley ML, Love R, Barber TC, Funahashi TT, Inacio MC. Kaiser Permanente implant registries benefit patient safety, quality improvement, cost-effectiveness. *Jt Comm J Qual Patient Saf*. 2013;39(6):246-252.
41. Persson A, Fjeldsgaard K, Gjertsen JE, et al. Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004-2012. *Am J Sports Med*. 2014;42(2):285-291.
42. Prentice HA, Chan PH, Paxton EW, Felson DT, Funahashi TT, Maletis GB. Patient and operative risk factors for osteoarthritis after primary anterior cruciate ligament reconstruction: a cohort study of 41,976 patients. *Am J Sports Med*. 2024;52(10):2482-2492.
43. Prentice HA, Lind M, Mouton C, et al. Patient demographic and surgical characteristics in anterior cruciate ligament reconstruction: a description of registries from six countries. *Br J Sports Med*. 2018;52(11):716-722.
44. Rahardja R, Zhu M, Love H, Clatworthy MG, Monk AP, Young SW. Effect of graft choice on revision and contralateral anterior cruciate ligament reconstruction: results from the New Zealand ACL Registry. *Am J Sports Med*. 2020;48(1):63-69.
45. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind M. Comparison of hamstring tendon and patellar tendon grafts in anterior cruciate ligament reconstruction in a nationwide population-based cohort study: results from the Danish registry of knee ligament reconstruction. *Am J Sports Med*. 2014;42(2):278-284.
46. Ruedl G, Webhofer M, Linortner I, et al. ACL injury mechanisms and related factors in male and female carving skiers: a retrospective study. *Int J Sports Med*. 2011;32(10):801-806.
47. Runer A, Wierer G, Herbst E, et al. There is no difference between quadriceps- and hamstring tendon autografts in primary anterior cruciate ligament reconstruction: a 2-year patient-reported outcome study. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):605-614.
48. Sanders TL, Pareek A, Hewett TE, et al. Long-term rate of graft failure after ACL reconstruction: a geographic population cohort analysis. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(1):222-228.
49. Schmücker M, Haraszuk J, Hölmich P, Barfod KW. Graft failure, revision ACLR, and reoperation rates after ACLR with quadriceps tendon versus hamstring tendon autografts: a registry study with review of 475 patients. *Am J Sports Med*. 2021;49(8):2136-2143.
50. Shultz SJ, Schmitz RJ, Nguyen AD. Research Retreat IV: ACL injuries—the gender bias: April 3-5, 2008 Greensboro, NC. *J Athl Train*. 2008;43(5):530-531.
51. Snaebjörnsson T, Svantesson E, Sundemo D, et al. Young age and high BMI are predictors of early revision surgery after primary anterior cruciate ligament reconstruction: a cohort study from the Swedish and Norwegian knee ligament registries based on 30,747 patients. *Knee Surg Sports Traumatol Arthrosc*. 2019;27(11):3583-3591.
52. Spindler KP, Huston LJ, Zajichek A, et al. Anterior cruciate ligament reconstruction in high school and college-aged athletes: does autograft choice influence anterior cruciate ligament revision rates? *Am J Sports Med*. 2020;48(2):298-309.
53. Spragg L, Chen J, Mirzayan R, Love R, Maletis G. The effect of autologous hamstring graft diameter on the likelihood for revision of anterior cruciate ligament reconstruction. *Am J Sports Med*. 2016;44(6):1475-1481.
54. Sutherland K, Clatworthy M, Chang K, Rahardja R, Young SW. Risk factors for revision anterior cruciate ligament reconstruction and frequency with which patients change surgeons. *Orthop J Sports Med*. 2019;7(11):2325967119880487.
55. Tan TK, Subramaniam AG, Ebert JR, Radic R. Quadriceps tendon versus hamstring tendon autografts for anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2022;50(14):3974-3986.
56. Urchek R, Karas S. Biomechanical comparison of quadriceps and 6-strand hamstring tendon grafts in anterior cruciate ligament reconstruction. *Orthop J Sports Med*. 2019;7(10):2325967119879113.
57. Vaishya R, Misra S, Singh LP, et al. Surgical training and learning curves in orthopedic surgery—a review. *J Orthop Rep*. 2025;4(2 suppl):100584.

58. Visnes H, Gifstad T, Persson A, et al. ACL reconstruction patients have increased risk of knee arthroplasty at 15 years of follow-up: data from the Norwegian Knee Ligament Register and the Norwegian Arthroplasty Register from 2004 to 2020. *JB JS Open Access*. 2022;7(2):e22.00023.
59. Webster KE, Feller JA. Return to level I sports after anterior cruciate ligament reconstruction: evaluation of age, sex, and readiness to return criteria. *Orthop J Sports Med*. 2018;6(8):2325967118788045.
60. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861-1876.
61. Yang JS, Prentice HA, Reyes CE, Lehman CR, Maletis GB. Risk of revision and reoperation after quadriceps tendon autograft ACL reconstruction compared with patellar tendon and hamstring autografts in a US cohort of 21,973 patients. *Am J Sports Med*. 2024;52(3):670-681.
62. Zhang Z, Ambrogi F, Bokov AF, Gu H, de Beurs E, Eskaf K. Estimate risk difference and number needed to treat in survival analysis. *Ann Transl Med*. 2018;6(7):120.