Graft failure rates in bone-patellar tendon-bone, hamstring, and quadriceps tendon autografts in patients younger than 25 years-old: A systematic review and meta-analysis

TITLE: Graft failure rates in bone-patellar tendon-bone, hamstring, and quadriceps tendon autografts in patients younger than 25 years-old: A systematic review and meta-analysis

ABSTRACT

Background: Anterior cruciate ligament reconstruction (ACLR) is being increasingly performed due in part to higher injury rates among young athletes (≤ 25 years old). High allograft failure rates support the use of autograft for ACLR in young patients. However, reported data examining the failure rates of the different autografts used in this population are lacking.

Purpose: The purpose of this study was to compare graft failure rates among bone-patellar tendon-bone (BPTB), hamstring tendon (HT), and quadriceps tendon (QT) autografts in patients ≤ 25 years old. The secondary aim was to stratify graft failure by potential modifiers, including sex, mean follow-up (FU), time to graft rupture, and concomitant meniscus surgery.

Study Design: Systematic review and Meta-analysis

Methods: Studies that reported ACL graft (BPTB, HT, QT) reinjury rates in patients ≤ 25 years old with a minimum 24 months of follow-up were included. Studies examining revision ACLR, allograft ACLR, allograft augmentation ACLR, concomitant lateral extraarticular tenodesis, and studies without graft reinjury rates reported by both graft type and young age (≤ 25) were excluded.

Results: 46 studies comprising 10,624 patients (HT: n = 6,090, 47.0% female, 54.5-month mean FU; BPTB: n = 3,990, 63.0% female, 63.6-month mean FU; QT: n = 544, 40.3% female, 41.6-month mean FU) were included. HT exhibited the highest failure rate at 11.1% (95% CI, 8.8%-13.9%). Failure rates for BPTB and QT were 5.1% (95% CI, 3.5%-7.2%) and 2.5% (95% CI, 0.5%-11.2%), respectively. HT had a significantly higher failure rate than BPTB ($Q = 13.1$; $p < 0.001$). There were no significant differences in failure rate between HT and QT ($Q = 3.7$; $p =$

0.06) or between BPTB and QT (Q = 0.8, p = 0.4). Males and females had similar risk of graft failure regardless of graft type.

Conclusion: The results of this meta-analysis suggest that HT grafts are not the optimal choice for young patients undergoing ACLR. Instead, these patients should consider BPTB to reduce the risk of graft failure. Further research including RCTs with larger sample sizes are required to determine how QT grafts compare with BPTB grafts in this population.

Clinical Relevance: These findings can guide autograft selection in patients ≤25 years undergoing ACLR who wish to minimize the risk of graft failure.

Key Terms: ACL, autograft, young, athlete, graft failure

What is known about the subject: Patients 25 years and younger have an increased risk of ACL graft failure. Autografts are used more frequently in young patients due to higher failure rates of allografts. Autograft type, age, and sex are known risk factors for ACL graft failure.

What this study adds to existing knowledge: This study provides a meta-analysis of graft failure rates in young patients aged 25 years and younger who underwent HT, BPTB, or QT ACLR. This study reports graft-specific pooled failure rates for this high-risk young age group. Despite increasing popularity, there is a lack of sufficient data regarding QT ACLR failure rates in young patients.

Level of evidence: 4

Conflicts of interest: The authors report no conflicts of interest relevant to the study of interest.

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INTRODUCTION

Anterior cruciate ligament (ACL) ruptures continue to occur in high numbers in patients under the age of 25.[21,41] Although there has been a modest decrease in the incidence of ACL tears from 90.11 tears per 100,000 person-years in 2010 to 53.32 tears per 100,000 person-years in 2020, the relative use of ACLR has increased in incidence over the last decade.[9] Following ACL injury, young patients are at risk of knee instability, meniscal injuries, osteochondral defects, and early degenerative joint disease.[1,12,39] ACL reconstruction (ACLR) is the standard of care for ACL ruptures and has shown long-lasting, favorable subjective outcomes and objective stability.[81] Despite this, graft failure remains a challenging problem in young athletic populations due to high levels of physical activity resulting in increased stress on the graft over longer periods of time,[88] with greatest risk of failure within the first two years following return to sport.[55,88]

While there is debate as to which graft type minimizes the risk of graft failure, [18,36] ACLR with autograft has been consistently reported as superior to allograft in patients ≤ 25 years of age due to lower graft failure rates.[4,6,20,22,38] The most commonly used autografts include ipsilateral bone-patellar tendon-bone (BPTB), hamstring tendon (HT), and quadriceps tendon (QT) with or without a patellar bone block and have all demonstrated positive patient outcomes.[23,81] Previously, BPTB was the most frequent primary ACLR choice, but in recent years HT and QT grafts have increased in popularity as an alternative to avoid the anterior knee pain and kneeling discomfort of BPTB.[3,87] However, observed differences in graft strength and stiffnesses, donor site morbidity, graft incorporation, and healing properties result in unequal failure rates.[27,50,90,94] Hamstring tendon has demonstrated high failure rates,[29] which has lead to increased interest in the quadriceps tendon for patients wishing to avoid anterior knee pain and reduce failure rates.

Previous studies examining autograft reinjury rates often fail to stratify between older adults and younger patients despite higher rates of failure in younger cohorts.[2,93] Furthermore, many studies fail to separate adolescents (≤18 yrs) and young adults (19-25 yrs), notwithstanding a higher risk of graft failure in adolescents.[77,82] The higher risk observed may be due in part to the mixed demographic of skeletally immature (open physes) and mature (closed physes) patients within the adolescent population.[82]

Aggregated failure rates and the effects of risk factors across studies in young patients have not been well described; therefore, surgical guidelines are unclear. The purpose of this study was to compare graft failure rates between BPTB, HT, and QT autografts in patients younger than 25 years old at a minimum follow-up of 24 months. The secondary aim of this review was to stratify graft failure by potential modifiers, including sex, mean follow-up, mean time to graft rupture, and concomitant meniscus surgery. The hypothesis was that HT would have a significantly higher failure rate compared to BPTB and QT.

METHODS

Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement was used to guide this review. An information specialist/librarian (MSW) searched PubMed/MEDLINE (National Library of Medicine: 1946-), Embase (Elsevier: 1966-), Cochrane CENTRAL (Cochrane Library 1996-)*, and Web of Science Core Collection (Clarivate: 1900-) from origin of database to March 3, 2022. A combination of controlled vocabulary and text words related to autografts were combined with the Boolean operator "AND" with controlled vocabulary and text words associated with ligaments, tendons, and bone grafts related to the patella (**Appendix**

1). Language was limited to English, and we excluded case reports, comments, commentaries, editorials, reviews, or letters. Age filters were not added to the searches to avoid inadvertent exclusion of relevant studies.

On January 16, 2024, the original searches were rerun from the previous date of search: March 2022 to January 2024, and 3480 new studies were retrieved. Precise date searching is not available in some of the databases. The 3480 studies were compared to the original search results from January 16, 2024, and overlapping duplicates were removed using EndNote 20©. Next, 1501 new studies were uploaded to Covidence© and an additional 104 duplicates were removed by Covidence©. Following this, 1397 studies remained to be reviewed in the title/abstract screening. On August 28, 2024, 318 studies were retrieved. Using EndNote 21© and via visual screening, 105 duplicate studies were removed. The 213 studies were compared to the results from January 16th and overlapping duplicate studies were removed. Subsequently, 201 studies were uploaded to Covidence© where one additional duplicate study was removed, leaving 200 studies to be screened.

Data Extraction

A total of 6,220 studies were retrieved and imported into the citation manager EndNote 20©. Using EndNote's "Find duplicates" feature, 2,110 duplicates were removed, and 5,812 studies were uploaded to Covidence©, a Systematic Review platform. A total of 737 duplicates were removed, and 5,075 studies were advanced for the initial title/abstract screening. Of the 5,075 studies reviewed, 4,726 studies were deemed irrelevant or out of scope for this study. Team members (CBP, ZBH) reviewed the studies and additional team members (JDL, AM, GDM) served as the conflict resolvers of studies. Three-hundred forty-nine (349) studies were determined to be eligible for full text review, and ultimately 46 papers were included for this study. The PRISMA figure summarizing the data extraction can be seen in **Figure 1.**

Selection Criteria

Studies on autograft ACLR using hamstring tendon [HT], quadriceps tendon [QT] (comprising a combination of quadriceps tendon–bone [QTB] and all–soft tissue quadriceps tendon [ASTQT]),or bone-patellar tendon-bone [BPTB] autograft in patients ≤ 25 years old with a minimum follow-up of 24 months years were included. Studies had to report ACL graft reinjury rates in patients ≤ 25 years to be included in the review. Those on revision, allograft, and/or allograft augmentation ACLR, ACLR with concomitant lateral extraarticular tenodesis, and studies without graft reinjury rates reported by both graft type and young age (≤ 25) were excluded. If more than one study reported outcomes on the same patient population, only the most appropriate study (complete outcomes dataset) was included in the meta-analysis. The inclusion and exclusion criteria are also detailed in **Table 1**.

Table 1: Inclusion/Exclusion Criteria

Inclusion	Exclusion
Proportions of graft used and graft failures by graft type and age	No proportion of grafts and graft failures for younger population (≤ 25 years)
All ages permitted in study, but study must include the proportion of grafts and graft failures for younger population (≤ 25 years)	Revision ACLR
Patient underwent ACL reconstruction (ACLR) using autograft (hamstring, quadriceps tendon-bone [QTB], all-soft tissue quadriceps tendon [ASTQT], or bone-patellar tendon-bone [BPTB])	ACLR using allograft
Rates of clinical failure (grade 2+ or worse Lachman, grade 2+ or worse pivot shift, overall IKDC grade C or D, instrumented laxity with side-to-side difference of greater than 5 mm)	ACLR with concomitant lateral extraarticular tenodesis
Observational study	Multiligament knee injury (MCL, LCL, PLC, and/or PCL repaired or reconstructed)
Therapeutic intervention	Concomitant cartilage repair or restoration surgery

Human study	Minimum follow-up < 24 months
Peer-reviewed literature, articles published in scientific journals	Laboratory or animal study
Origin of database – date search is performed	Reviews without original data
English	Non-peer reviewed study
	General/systematic reviews, meta-analyses, case reports, editorials, conference abstracts, book chapters
	Non-English
	Data already reported in a separate, included manuscript

Methodological Quality Assessment

The Risk of Bias in Non-Randomized Studies of Interventions (ROBINS-I) tool was utilized.[79] The 7 criteria of the ROBINS-I tool were assessed by two independent reviewers (CBP, ZBH): (1) bias due to confounding, (2) bias in selection of participants into the study, (3) bias in classification of interventions, (4) bias due to deviations from intended interventions, (5) bias due to missing data, (6) bias in measurement of outcomes, and (7) bias in selection of the reported result. Each criterion was rated as low risk, moderate risk, serious risk, critical risk, or no information in accordance with the ROBINS-I tool.[79]

Statistical Analysis

A meta-analysis of proportions was conducted using the metaprop function from the meta R package[71], applying a generalized linear mixed-effects model (GLMM) with a logit transformation (PLOGIT) to account for sparse binary outcome data and study-level variability. Subgroup analyses were performed by graft type, with pooled estimates back-transformed for interpretability, and differences evaluated using the standard Wald-type Q test for categorical moderators. A pairwise meta-analysis of binary outcomes was also performed using the metabin function in the meta package[71], comparing re-rupture rates between BTB and HT grafts using the inverse variance method to estimate pooled odds ratios (ORs) with corresponding confidence intervals. Due to the limited number of studies, QT was not included in the odds ratio comparison/estimation. Moderator analysis was conducted using the metareg function from the meta R package[71] with between-study variance estimated using restricted maximum likelihood. Sensitivity analysis was conducted to assess if the rate estimates were similar utilizing only two-arm studies. Statistical significance was set at $p<.05$.

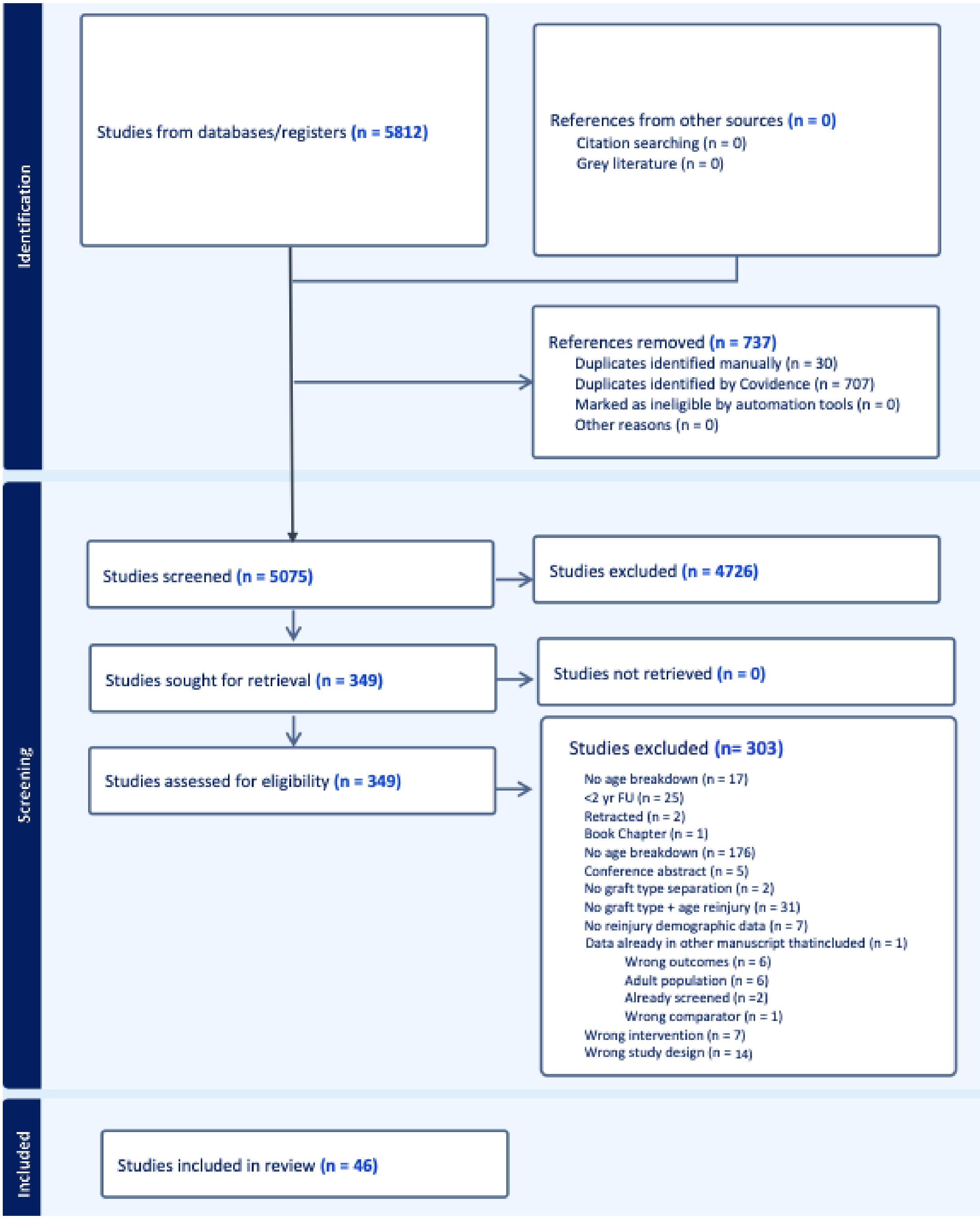

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart for inclusion and exclusion of articles.

RESULTS

Demographic Characteristics

Across all 46 included studies, there were 6,090 HT (33 studies), 3,990 bone-patellar tendon-bone (19 studies), and 544 quadriceps tendon (6 studies total; 109 QTB [3 studies][23,65,86], 435 ASTQT [3 studies]) patients included. The mean age of patients who underwent hamstring tendon, bone-patellar tendon-bone, and quadriceps tendon autograft ACLR was 15.5 yrs (SD, 11.0-25.0), 16.8 yrs (SD, 11.5-25.0), and 15.3 yrs (SD, 10.0-22.9), respectively. The mean follow-up duration was 54.5 months (SD, 24.0-246.0) for patients who underwent hamstring tendon autograft ACLR, 63.6 months (SD, 24.0-246.0) for bone-patellar tendon-bone autograft ACLR, and 41.6 months (SD, 24.0-139.0) for quadriceps tendon autograft ACLR. On average, the follow-up completion was 86.6% for patients who underwent hamstring tendon autograft ACLR, 77.3% for patients who underwent bone-patellar tendon-bone autograft ACLR, and 84.1% for patients who underwent quadriceps tendon autograft ACLR. There were 47% females who underwent hamstring tendon autograft ACLR, 63% females who underwent bone-patellar tendon-bone autograft ACLR, and 40.3% females who underwent quadriceps tendon autograft ACLR **(Table 2)**. Forty-three studies included follow up range data, 34 included sex data, 9 included mean time to graft rupture, and 12 included concomitant injury data.

Table 2: Study Demographics

Author	Patients, n	Mean age, yrs (range)	Sex (% female)	Mean follow-up (FU), months (range)	FU completion (%)
Bone-Patellar Tendon-Bone Autograft					
Barber et al 2014[4]	53	18.6 (13-25)	51	31 (24-132)	100.0
Britt et al 2020[10]	41	15.4 (NR-18)	100	37.4 (24-NR)	78.9
Cordasco et al 2019[16]	209	16.2 (12-20)	NR	38.9 (24-84)	97.6
Ellis et al 2012[21]	59	16 (14-18)	NR	50.4 (24-135.6)	84.3

Hurt et al 2017[32]	377	17.62 (NR-25)	46.7	24 (24-NR)	41.0
Kane et al 2016[38]	101	19.8 (NR-25)	48.5	24 (24-NR)	59.4
McCarroll et al 1994[45]	60	14.2 (13-17)	51.7	50.4 (24-84)	NR
Morgan et al 2016[49]	48	16 (13-18)	NR	198 (180-246)	84.0
Nelson et al 2016[52]	55	15.2 (11.5-16.9)	54.5	34.8 (24-NR)	NR
Rauck et al 2021[63]	53	16.6 (14.2-18.7)	71.7	45.36 (31.2-59.3)	37.0
Salem et al 2019[66]	175	18.56 (15-25)	100	45.12 (31.2-63.6)	71.4
Salmon et al 2006[67]	13	NR (NR-21)	NR	156 (156-NR)	NR
Sanada et al 2021[69]	27	16.3 (13-20)	100	34.2 (24-60)	100.0
Schilaty et al 2017[70]	310	NR (NR-25)	NR	163.2 (24-NR)	66.0
Shelbourne et al 2009[74]	878	NR (14-25)	47.1	60 (60-NR)	78.0
Smith et al 2020[75]	32	17.8 (13-24)	53	24 (24-NR)	92.0
Spindler et al 2020[78]	492	17 (14-22)	47	72 (72-NR)	92.0
Persson et al 2014[59]	936	NR (15-19)	33	48 (24-NR)	86.0
Tomihara et al 2024[83]	71	16.9 (NR-NR)	4	33.6 (24-NR)	NR
Hamstring Tendon Autograft					
Berdis et al 2019[8]	143	16 (8-21)	55.2	52 (25-94)	73.7
Britt et al 2020[10]	30	15.4 (NR-18)	100	46.1 (24-NR)	78.9
Calvo et al 2015[11]	27	13 (12-16)	40.7	127.2 (120-156)	100.0
Cohen et al 2009[14]	26	13.3 (11-15)	57.7	45 (24-84)	NR
Cordasco et al 2019 B[16]	66	14.3 (12-17)	NR	36.6 (24-84)	97.6
Cordasco et al 2019 C[16]	49	12 (8-16)	NR	41.4 (24-84)	97.6
Courvoisier et al 2011[17]	37	14 (11-15)	54.1	36 (24-48)	100.0
Engelman et al 2014[22]	35	15.6 (12.7-18.6)	34.3	50.9 (24-NR)	65.0
Getgood et al 2020[24]	298	18.8 (14-25)	52	24 (24-NR)	95.0
Jacobs et al 2017[33]	46	14.6 (NR-18)	56.5	46.7 (24-NR)	NR
Jeffers et al 2022[34]	34	NR (17-23)	0	102 (24-NR)	NR
Kamien et al 2013[37]	48	16.99 (12-25)	NR	24 (24-NR)	NR
Larson et al 2016[42]	22	14.4 (12.3-16)	59.1	48 (24-84)	NR
Mariscalco et al 2013[43]	85	NR (13-18)	NR	24 (24-NR)	82.2
Matava et al 1997[44]	8	14.4 (11.8-15.6)	25	32 (27-44)	100.0
McIntosh et al 2006[46]	16	13.6 (11.2-14.9)	31	41.1 (24-112)	NR
Monaco et al 2022[48]	40	16.3 (13.9-17.6)	6	43.8 (24-89)	81.4
Morgan et al 2016[49]	194	16 (13-18)	NR	198 (180-246)	84.0
Nelson et al 2016[52]	388	14.8 (11.5-16.9)	31.7	34.8 (24-NR)	NR
Nikolaou et al 2011[53]	94	13.7 (11.6-15.9)	40	38 (24-60)	NR
Pennock et al 2019[57]	56	14.8 (NR-18)	31	34.8 (24-NR)	92.0

Persson et al 2014[59]	2783	NR (15-19)	264	48 (24-NR)	86.0
Rao et al 2021[62]	42	NR (NR-24)	NR	50.64 (24-NR)	NR
Redler et al 2012[64]	18	14.2 (NR-18)	33.3	43.4 (24-86.6)	94.7
Runer et al 2020[65]	51	NR (NR-15)	NR	24 (24-NR)	NR
Salem et al 2019[66]	81	18.46 (15-25)	100	45.12 (32.4-64.8)	60.5
Sanada et al 2021[69]	29	16.5 (12-20)	100	33.8 (24-60)	100.0
Schilaty et al 2017[70]	56	NR (NR-25)	NR	163.2 (24-NR)	66.0
Smith et al 2020[76]	27	17.6 (13-24)	59	24 (24-NR)	92.0
Spindler et al 2020[78]	278	17 (14-22)	50	72 (72-NR)	91.8
Takazawa et al 2017[80]	58	17 (14-19)	0	56.5 (24-175)	78.0
Thorolfsson et al 2021[82]	569	17.1 (9-19)	17	NR (24-NR)	NR
Tomihara et al 2024[83]	86	17.2 (NR-NR)	19	44.5 (24-NR)	NR
Webster et al 2016[87]	316	17.2 (11-19)	37	60 (36-120)	89.0
Quadriceps tendon autograft					
Gagliardi et al 2020[23]	81	15.9 (10-18)	48.1	37.2 (24-36)	84.0
Kohl et al 2014[40]	13	12.8 (6.2-15.8)	20	49.2 (22.8-116.4)	NR
Pennock et al 2019[58]	27	14.8 (NR-18)	32	28.8 (24-NR)	92.0
Petit et al 2024[60]	395	17.8 (14.0-22.9)	44	73 (24-139)	60.2
Runer et al 2020[65]	6	NR (NR-15)	NR	24 (24-NR)	NR
Vaughn et al 2021[86]	22	15 (12-17)	50	33.6 (24-60)	100.0

Key: NR, not reported

Methodological Quality Assessment

Using the ROBINS-I tool[79], 37 (80.5%) studies were rated with an overall "serious" risk of bias. Six (13%) studies were rated with an overall "moderate" risk of bias and three (6.5%) studies were rated with an overall "low" risk of bias (**Figure 2**).[25]

Risk of bias domains

Study	D1	D2	D3	D4	D5	D6	D7
Barber 2014	X	-	+	+	+	-	-
Berdis 2019	X	X	+	+	X	+	-
Britt 2020	X	-	+	+	X	-	+
Calvo 2015	X	-	+	+	-	-	-
Cohen 2009	X	-	+	+	-	-	-
Cordasco 2019	-	-	+	+	-	-	-
Courvoisier 2011	X	-	+	-	X	-	X
Ellis 2012	X	-	+	+	-	-	-
Engelman 2014	-	X	+	+	X	-	-
Gagliardi 2020	X	X	+	+	X	-	X
Getgood 2020	-	+	+	-	-	-	-
Hurt 2017	X	X	+	-	-	-	-
Jacobs 2017	X	X	-	-	-	-	-
Jeffers 2022	X	X	-	-	X	X	-
Kamien 2013	X	-	+	+	X	-	-
Kane 2016	X	-	+	+	X	-	-
Kohl 2014	X	-	+	+	-	-	-
Larson 2016	X	-	+	+	-	-	X
Lind 2020	-	-	+	+	X	-	-
Mariscalco 2013	X	-	+	-	-	X	X
Matava 1997	X	X	+	+	-	-	-
McCarroll 1994	X	-	-	-	-	-	-
McIntosh 2006	X	-	+	+	-	X	-
Monaco 2022	-	+	-	+	X	-	-
Morgan 2016	X	X	+	-	X	-	X
Nelson 2016	X	X	-	-	-	X	-
Nikolaou 2011	X	-	+	-	X	-	X
Pennock 2019	X	-	+	-	-	-	-
Persson 2024	+	+	+	+	+	+	+
Petit 2024	+	+	+	+	+	+	+
Rao 2021	X	X	+	-	X	-	-
Rauck 2021	X	X	+	-	X	-	-
Redler 2012	X	-	+	+	X	-	X
Runer 2020	-	-	+	+	-	-	-
Salem 2019	X	-	+	-	X	-	-
Salmon 2006	X	X	+	+	X	-	X
Sanada 2021	X	X	+	+	X	-	-
Schilaty 2017	X	-	+	-	X	X	-
Shelbourne 2009	X	-	+	+	-	-	-
Smith 2020	-	+	+	+	-	-	-
Spindler 2020	X	-	+	-	-	-	-
Takazawa 2017	-	X	+	-	-	-	-
Thorolfsson 2021	+	+	+	+	X	+	+
Tomihara 2024	-	+	+	+	-	-	+
Vaughn 2022	X	-	+	-	-	-	X
Webster 2016	X	-	+	-	-	-	-

Domains:
D1: Bias due to confounding.
D2: Bias due to selection of participants.
D3: Bias in classification of interventions.
D4: Bias due to deviations from intended interventions.
D5: Bias due to missing data.
D6: Bias in measurement of outcomes.
D7: Bias in selection of the reported result.

Judgement
X Serious
- Moderate
+ Low

Figure 2. Risk-of-bias assessments for included studies using the Risk of Bias in Non-Randomized Studies of Interventions tool.

Meta-analysis

Overall graft failure rates

The pooled autograft graft failure rate was 11.1% (95% CI 8.8-13.9) for hamstring tendon, 5.1% (95% CI 3.5-7.2) for bone-patellar tendon-bone, and 2.5% (95% CI 0.5-11.2) for quadriceps tendon. There was a significant difference among failure rates by ACLR graft type ($\chi2= 15.7$, $p<0.01$) (**Figure 3**). Hamstring tendon had significantly higher failure rates compared to bone-patellar tendon-bone (Q=13.1, $p<0.001$). There were no differences in failure rate between hamstring tendon and quadriceps tendon (Q=3.7, p=0.06) or bone-patellar tendon-bone and quadriceps tendon (Q=0.8, p=0.4).

Study or Subgroup	Events	Total	GLMM, Random, 95% CI
Graft Type = BTB			
Barber et al 2014	5	53	0.0943 [0.0313; 0.2066]
Britt et al 2020 A	4	41	0.0976 [0.0272; 0.2313]
Cordasco et al 2019 A	12	209	0.0574 [0.0300; 0.0981]
Ellis et al 2012	2	59	0.0339 [0.0041; 0.1171]
Hurt et al 2017	38	377	0.1008 [0.0723; 0.1357]
Kane et al 2016	1	101	0.0099 [0.0003; 0.0539]
McCarroll et al 1994	3	60	0.0500 [0.0104; 0.1392]
Morgan et al 2016 A	4	48	0.0833 [0.0232; 0.1998]
Nelson et al 2016 A	3	55	0.0545 [0.0114; 0.1512]
Rauck et al 2021	4	53	0.0755 [0.0209; 0.1821]
Salem et al 2019 A	12	175	0.0686 [0.0359; 0.1167]
Salmon et al 2006	4	13	0.3077 [0.0909; 0.6143]
Sanada et al 2021 A	0	27	0.0000 [0.0000; 0.1277]
Schlaty et al 2017 A	1	310	0.0032 [0.0001; 0.0178]
Shelbourne et al 2009	55	878	0.0626 [0.0475; 0.0808]
Smith et al 2020 A	0	32	0.0000 [0.0000; 0.1089]
Spindler et al 2020 A	35	492	0.0711 [0.0500; 0.0975]
Persson et al 2024	33	936	0.0353 [0.0244; 0.0492]
Tomihara et al 2024	4	71	0.0563 [0.0156; 0.1380]
Total (95% CI)		3990	0.0506 [0.0351; 0.0723]
Heterogeneity: $Tau^2 = 0.4377$; $Chi^2 = 47.31$, df = 18 ($P < 0.01$); $I^2 = 62\%$			
Graft Type = HT			
Berdis et al 2019	7	143	0.0490 [0.0199; 0.0983]
Britt et al 2020 B	4	30	0.1333 [0.0376; 0.3072]
Calvo et al 2015	4	27	0.1481 [0.0419; 0.3373]
Cohen et al 2009	3	26	0.1154 [0.0245; 0.3015]
Cordasco et al 2019 B	13	66	0.1970 [0.1093; 0.3132]
Cordasco et al 2019 C	3	49	0.0612 [0.0128; 0.1687]
Courvoisier et al 2011	5	37	0.1351 [0.0454; 0.2877]
Engelman et al 2014	4	35	0.1143 [0.0320; 0.2674]
Getgood et al 2020	34	298	0.1141 [0.0803; 0.1558]
Jeffers et al 2022	2	34	0.0588 [0.0072; 0.1968]
Kamien et al 2013	12	48	0.2500 [0.1364; 0.3960]
Larson et al 2016	2	22	0.0909 [0.0112; 0.2916]
Mariscalco et al 2013	13	85	0.1529 [0.0840; 0.2473]
Matava et al 1997	1	8	0.1250 [0.0032; 0.5265]
McIntosh et al 2006	2	16	0.1250 [0.0155; 0.3835]
Morgan et al 2016 B	38	194	0.1959 [0.1425; 0.2588]
Nelson et al 2016 B	29	388	0.0747 [0.0506; 0.1056]
Nikolaou et al 2011	4	94	0.0426 [0.0117; 0.1054]
Pennock et al 2019 B	12	56	0.2143 [0.1159; 0.3444]
Rao et al 2021	13	42	0.3095 [0.1762; 0.4709]
Redler et al 2012	0	18	0.0000 [0.0000; 0.1853]
Runer et al 2020 A	3	51	0.0588 [0.0123; 0.1624]
Salem et al 2019 B	11	81	0.1358 [0.0698; 0.2300]
Sanada et al 2021 B	3	29	0.1034 [0.0219; 0.2735]
Schlaty et al 2017 B	0	56	0.0000 [0.0000; 0.0638]
Smith et al 2020 B	2	27	0.0741 [0.0091; 0.2429]
Spindler et al 2020 B	36	278	0.1295 [0.0924; 0.1747]
Takazawa et al 2017	12	58	0.2069 [0.1117; 0.3335]
Webster et al 2016	57	316	0.1804 [0.1396; 0.2273]
Thorolfsson et al 2021	17	569	0.0299 [0.0175; 0.0474]
Monaco et al 2022	6	40	0.1500 [0.0571; 0.2984]
Persson et al 2024	264	2783	0.0949 [0.0842; 0.1064]
Tomihara et al 2024	19	86	0.2209 [0.1386; 0.3233]
Total (95% CI)		6090	0.1108 [0.0878; 0.1389]
Heterogeneity: $Tau^2 = 0.3891$; $Chi^2 = 138.81$, df = 32 ($P < 0.01$); $I^2 = 77\%$			
Graft Type = QT			
Gagliardi et al 2020	1	81	0.0123 [0.0003; 0.0669]
Kohl et al 2014	0	13	0.0000 [0.0000; 0.2471]
Pennock et al 2019 A	1	27	0.0370 [0.0009; 0.1897]
Runer et al 2020 B	0	6	0.0000 [0.0000; 0.4593]
Vaughn et al 2021	0	22	0.0000 [0.0000; 0.1544]
Petit et al 2024	44	395	0.1114 [0.0821; 0.1466]
Total (95% CI)		544	0.0248 [0.0051; 0.1123]
Heterogeneity: $Tau^2 = 1.1418$; $Chi^2 = 6.31$, df = 5 ($P = 0.28$); $I^2 = 21\%$			
Total (95% CI)		**10624**	**0.0775 [0.0617; 0.0970]**
Heterogeneity: $Tau^2 = 0.6057$; $Chi^2 = 253.89$, df = 57 ($P < 0.01$); $I^2 = 78\%$			
Test for subgroup differences: $Chi^2 = 15.69$, df = 2 ($P < 0.01$)			

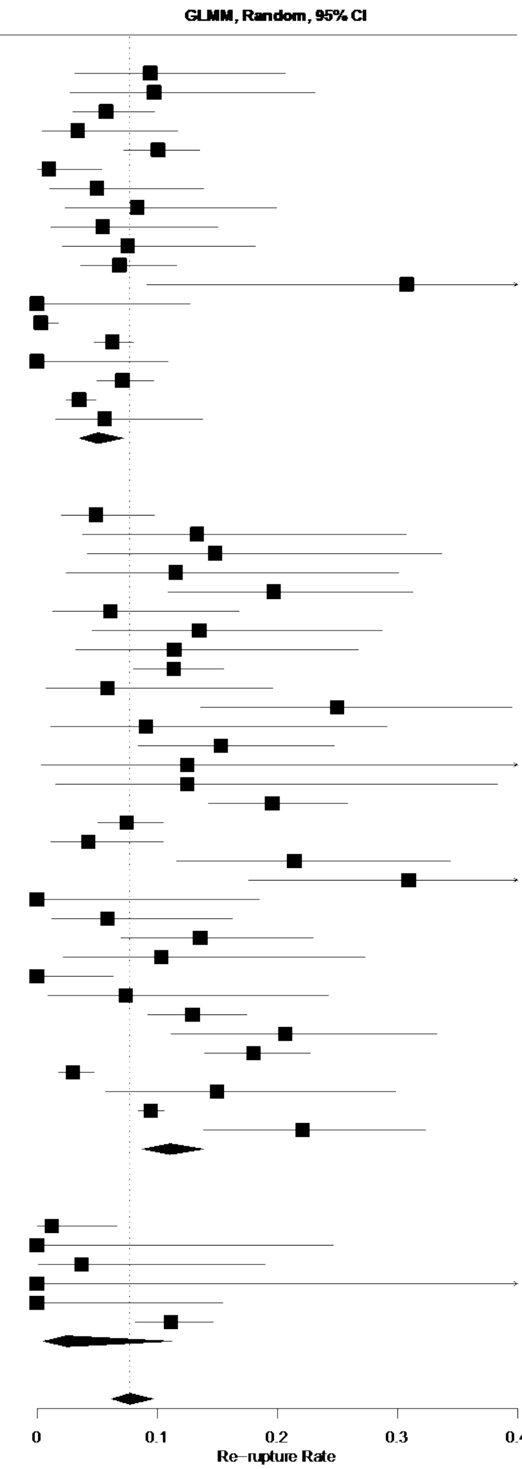

Figure 3. Forest plot for graft failure rates by graft type. A/B/C designations were added to author groups that included more than one autograft type in their study in order to distinguish between graft type groups when performing statistical analysis

Sensitivity Analyses

There were 13 two-arm studies included in the analysis. The pooled autograft failure rate was 11.4% (95% CI 8.4-15.3) for hamstring tendon, 4.2% (95% CI 2.9-6.1) for bone-patellar tendon-bone, and 3.0% (95% CI 0.4-18.6) for quadriceps tendon (**Figure 4**). There was a significant difference among graft failure rates ($\chi2= 17.7$, $p<0.01$). The odds of failure were significantly lower for bone-patellar tendon-bone ACLR compared to hamstring tendon (OR=0.4, 95% CI 0.3-0.5; **Figure 5**). There were too few two-arm studies directly comparing QT with hamstring tendon (HT) or bone–patellar tendon–bone (BTB) grafts to permit a pooled comparison.

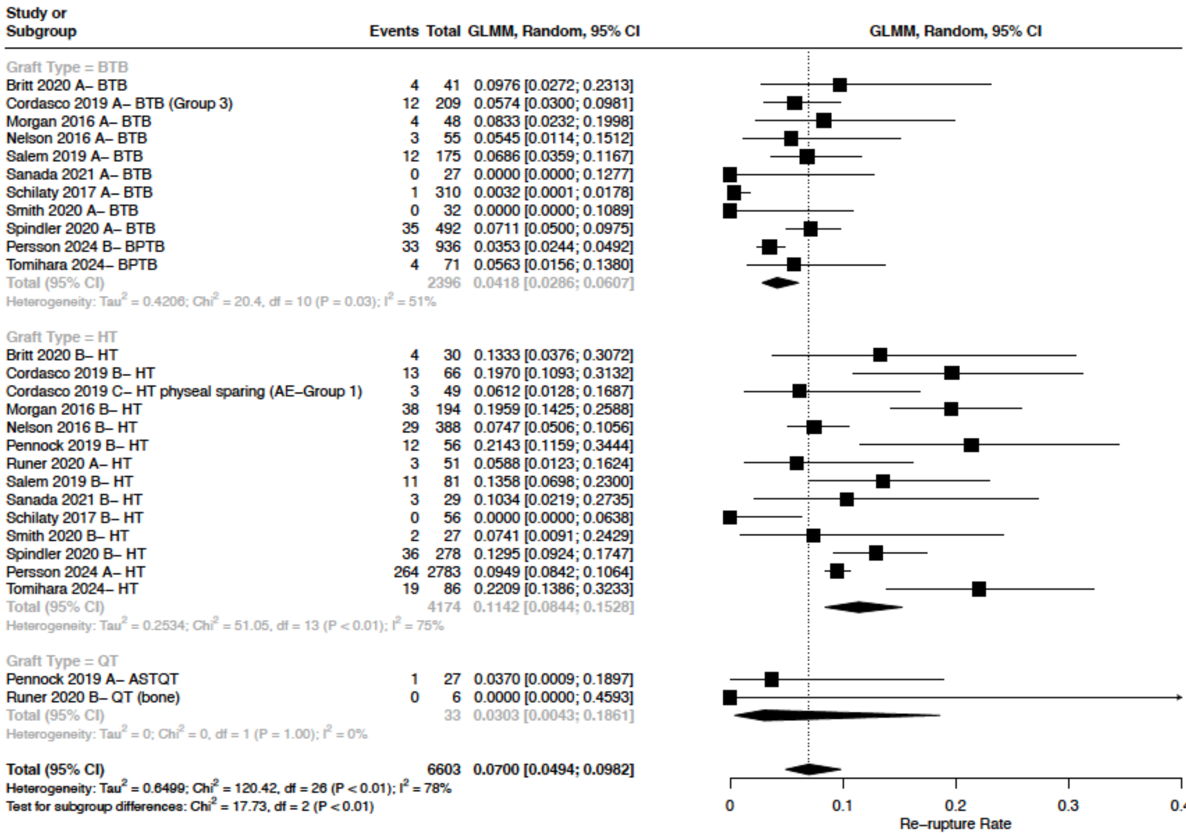

Figure 4. Risk of graft rupture among studies that included comparisons by graft type. A/B/C designations were added to author groups that included more than one autograft type in their study in order to distinguish between graft type groups when performing statistical analysis

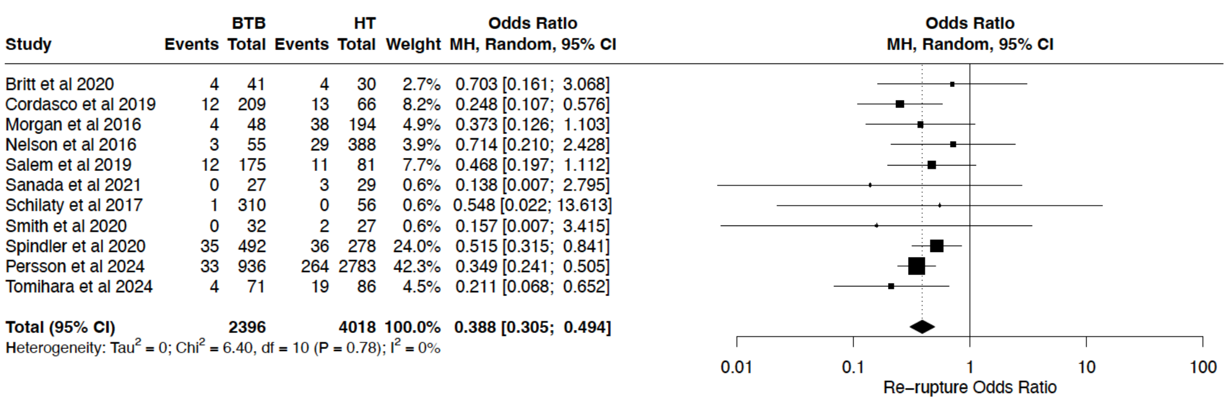

Figure 5. Odds of graft failure in two-arm studies for hamstring tendon ACLR relative to bone-patellar tendon-bone ACLR. Odds Ratio < 1 indicates lower re-rupture rate in BPTB

Follow-up, time to graft rupture, concomitant meniscus surgery, age and sex

There were no differences between graft types regarding mean follow up (Q=0.03, p=0.9), time to graft failure (Q=1.0, p=0.3), overall concomitant meniscus surgery (Q=0.8, p=0.4)**,** age (Q=0.02, p=0.9) or proportion of females (Q=0.6, p=0.5). Odds of failure by sex among graft types indicated no differences (OR=1.0, 95% CI 0.7-1.5, $\chi 2$= 0.8, p=0.7; **Figure 6**). Males and females had similar risk of graft failure regardless of graft type.

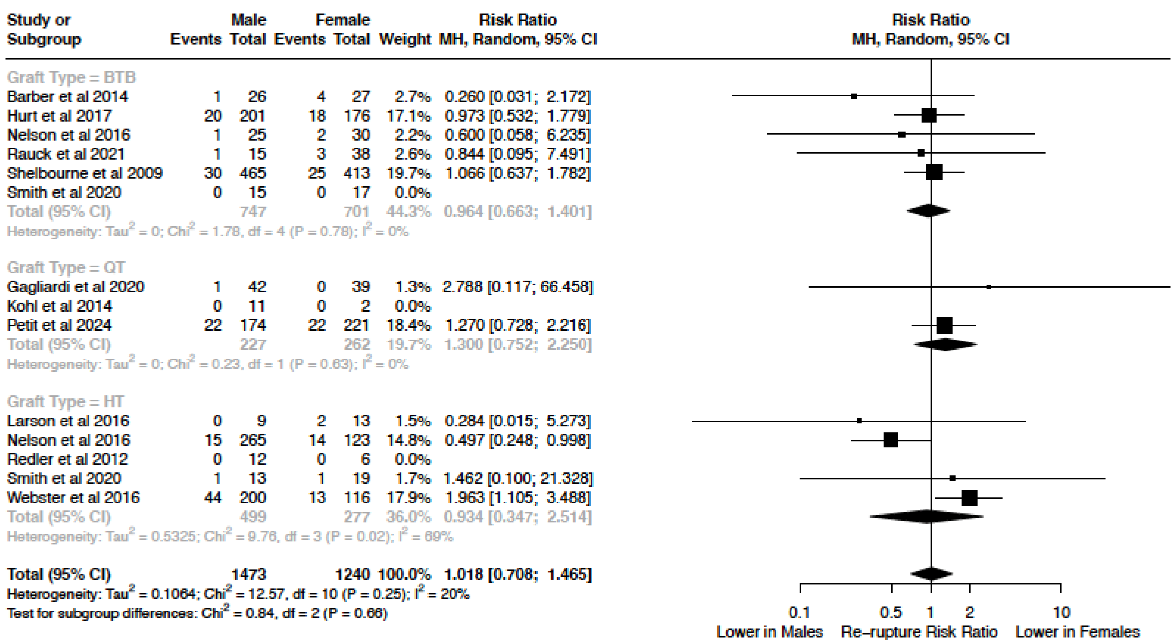

Figure 6. Odds of graft failure in females relative to males by graft type.

DISCUSSION

The purpose of this study was to compare graft failure rates among bone-patellar tendon-bone (BPTB), hamstring tendon (HT), and quadriceps tendon (QT) autografts in patients ≤ 25 years old. The secondary aim was to stratify graft failure by potential modifiers, including sex, mean follow-up (FU), time to graft rupture, and concomitant meniscus surgery. We found that BPTB autografts resulted in significantly lower rates of rupture than HT autograft. There were no differences between BPTB and QT. In aggregate, sensitivity and moderator analyses did not demonstrate differences, indicating that the main finding that lower BPTB and QT graft failure rates holds true regardless of sex, age, length of follow-up, time to graft failure, concomitant meniscal surgery, or study type.

The main finding of our meta-analysis indicates that ACL reconstruction using BPTB autografts resulted in significantly lower rates of graft rupture than HT autograft in patients ≤ 25 years. This is consistent with previous research suggesting BPTB graft has a lower failure rate[29,89]; whereas the outcomes from other related studies in the literature are less clear.[19,47,50,68,92] However, the data from previous meta-analyses included mainly adults and there was no separation based on chronological age or skeletal maturity. Barrett et al.[6] reported significantly lower rates of re-rupture in allograft and BPTB grafts vs. HT in patients < 25 years. Dai et al.[19] also reported similar graft failure rates between QT and BPTB in accordance with previous research[5,30] and the findings of the current study. Cumulatively, these data suggest QT autograft is a viable option, especially in younger patients and further research is encouraged.

Mechanical differences may in part explain divergence in graft failure rates. For instance, the HT graft has reportedly greater variability in harvested graft diameter than BPTB and QT grafts.[54,84] Additionally, HT ACLR can lead to long lasting hamstring weakness resulting in an increased quadriceps/hamstring ratio that can increase the risk of graft failure.[35,61] The BPTB displays biomechanical similarity to a native ACL. In younger patients, the maximum load to failure of a BPTB autograft has been shown to exceed that of a native ACL by ~800 N.[15] However, it should be considered that the load to failure rate reduces with age.[73,91] QT autografts also have comparable, and potentially superior, load to failure rates, and elastic modulus to the BPTB graft and a native ACL.[73] For the QT graft, the mean ultimate load to failure was 2,185.9 ± 758.8 N compared with 1,580.6 ± 479.4 N for the BPTB graft (P = 0.045), although this biomechanical work does not take into account fixation options in patient surgery, as well as healing of different graft tissues. Moreover, the QT graft mean stiffness was 466.2 ± 133 N/mm while the BPTB mean stiffness was 278.0 ± 75 N/mm (P = 0.005).[73] Previous studies have shown that autografts such as a QT with similar characteristics to the native ACL are beneficial for graft integration, reducing failure rates and allowing the knee to function optimally.[73,85,91] More recent research has investigated the biomechanics of HT, BPTB and QT grafts in cadaveric specimens.[28] The QT displayed greater cross-sectional area than the other graft types, and increased stiffness than the HT. Cumulatively, it appears the biomechanical properties of the QT graft display characteristics which may be favorable including greater cross-sectional area and an elastic modulus that closely approximates a native ACL.[13]

The subgroup tests (Q) on our data indicated no statistically significant difference in rupture rates between BPTB and QT autografts following ACLR. However, it should be noted the QT sample size was substantially lower, with a wide confidence interval that overlapped with BPTB. Despite no statistically significant difference, we believe including the QT data is important due to the increased interest in the graft utilization for ACLR and therefore the increased need for data outlining its outcomes. In a recent systematic review by Hurley et al.[31] comparing QT, BPTB and HT autografts, there were no differences in autograft rupture rates. Nonetheless, the authors observed that QT displayed a lower prevalence of anterior knee pain than with BPTB, and improved stability compared to HT, further supporting the use of QT as an optimal choice for ACLR. A potential disadvantage of the BPTB autograft is the presence of donor site morbidity including anterior knee pain, kneeling discomfort, and short-term reductions in extensor torque.[87] However, recent data[72] indicate no differences in quadriceps peak torque at 6- and 9 months post-surgery. It should also be considered that ACLR autograft donor site morbidity following ACLR with BPTB has been shown to reduce over time.[87]

When interpreting the findings from the current study, several factors which have the potential to affect graft rupture rates should be considered. Firstly, the number of studies and respective patients included was lower for the QT graft. The rehabilitation protocols were also not typically well described which makes standardization across studies difficult. Similarly, physical performance metrics at the time of return to sports were not measured. Deficits in quadriceps strength[26] and landing biomechanics[56] have been associated with an increased risk of re-injury after ACLR. Reporting these functional characteristics in athletes with different graft types would appear to be an important factor in understanding the risk of graft failure. Similarly, the time of return to sport can affect graft rupture rates.[7] There is not a universal agreement on when an athlete is safe to return to sport, with some surgeons employing functional tests to determine readiness to RTS while others determine RTS based on length of time since surgery. Younger athletes with less donor site morbidity and increased quadricep strength may pass RTS tests and begin competitive sport activities earlier, potentially increasing their risk of graft failure. The mean age of HT patients was also higher (17 vs. 15.4, and 14.6 years on BTP and QT respectively), and the follow up for

QT was shorter. Finally, there was also a large range across studies in follow up completion rate and, in several studies, this was not reported. Cumulatively, while the data from our literature synthesis indicate that BTP and QT are preferable choices in patients ≤ 25 years, further research is warranted, including RCTs, with longer follow up, and controls in place for the range of confounding factors stated above.

Limitations

There are several limitations to this study. Between the update on January 16, 2024, and August 28, 2024, the original search strategy for Cochrane CENTRAL could not be located. In addition, CINAHL was inadvertently searched instead of Cochrane Central for the update from January 16, 2024 to August 28, 2024. When the error was recognized, the Cochrane Central search strategy was recreated as close to the original search as possible to run the search update on August 28, 2024. We believe that with the overlap of coverage among the databases, the key articles related to this meta-analysis were retrieved and included in this project. Additionally, there was not enough data on type of quadriceps tendon graft used (ASTQT vs QTB) to stratify the data for this analysis which could be a confounding factor. Furthermore, graft failure rate is multifactorial and could be dependent on other factors not reviewed in this analysis, such as sport played, return to sport, and rehabilitation protocol. There were insufficient studies that stratified meniscus surgery types or that outlined rehabilitation protocols to stratify in data analysis. Moreover, due to the nature of non-randomized studies, there is a significant risk of bias attached to many of the the studies included in this analysis.

Conclusion

The results of this meta-analysis suggest that HT grafts are not the optimal choice for young patients undergoing ACLR. Instead, these patients should consider BPTB to reduce the risk of graft failure.

References

1. Aichroth PM, Patel DV, Zorrilla P. The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. A prospective review. *J Bone Joint Surg Br.* 2002;84(1):38-41.
2. Andernord D, Desai N, Björnsson H, et al. Patient predictors of early revision surgery after anterior cruciate ligament reconstruction: a cohort study of 16,930 patients with 2-year follow-up. *Am J Sports Med.* 2015;43(1):121-127.
3. Arnold MP, Calcei JG, Vogel N, et al. ACL Study Group survey reveals the evolution of anterior cruciate ligament reconstruction graft choice over the past three decades. *Knee Surgery, Sports Traumatology, Arthroscopy.* 2021;29(11):3871-3876.
4. Barber FA, Cowden CH, Sanders EJ. Revision rates after anterior cruciate ligament reconstruction using bone-patellar tendon-bone allograft or autograft in a population 25 years old and younger. *Arthroscopy.* 2014;30(4):483-491.
5. Barié A, Sprinckstub T, Huber J, Jaber A. Quadriceps tendon vs. patellar tendon autograft for ACL reconstruction using a hardware-free press-fit fixation technique: comparable stability, function and return-to-sport level but less donor site morbidity in athletes after 10 years. *Arch Orthop Trauma Surg.* 2020;140(10):1465-1474.
6. Barrett AM, Craft JA, Replogle WH, Hydrick JM, Barrett GR. Anterior Cruciate Ligament Graft Failure:A Comparison of Graft Type Based on Age and Tegner Activity Level. *The American Journal of Sports Medicine.* 2011;39(10):2194-2198.
7. Beischer S, Gustavsson L, Senorski EH, et al. Young Athletes Who Return to Sport Before 9 Months After Anterior Cruciate Ligament Reconstruction Have a Rate of New Injury 7 Times That of Those Who Delay Return. *J Orthop Sports Phys Ther.* 2020;50(2):83-90.
8. Berdis AS, Veale K, Fleissner PR. Outcomes of Anterior Cruciate Ligament Reconstruction Using Biologic Augmentation in Patients 21 Years of Age and Younger. *Arthroscopy.* 2019;35(11):3107-3113.
9. Bergstein VE, Ahiarakwe U, Haft M, Fox H, Best MJ. Decreasing Incidence of Anterior Cruciate Ligament Tears and Increasing Utilization of Anterior Cruciate Ligament Reconstruction in the United States From 2010 to 2020. *Arthroscopy.* 2025;41(6):1912-1918.e1911.
10. Britt E, Ouillette R, Edmonds E, et al. The Challenges of Treating Female Soccer Players With ACL Injuries: Hamstring Versus Bone-Patellar Tendon-Bone Autograft. *Orthop J Sports Med.* 2020;8(11):2325967120964884.
11. Calvo R, Figueroa D, Gili F, et al. Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. *Am J Sports Med.* 2015;43(2):289-294.
12. Church S, Keating JF. Reconstruction of the anterior cruciate ligament: timing of surgery and the incidence of meniscal tears and degenerative change. *J Bone Joint Surg Br.* 2005;87(12):1639-1642.
13. Clinger B, Xerogeanes J, Feller J, et al. Quadriceps tendon autograft for anterior cruciate ligament reconstruction: state of the art. *J ISAKOS.* 2022;7(6):162-172.
14. Cohen M, Ferretti M, Quarteiro M, et al. Transphyseal anterior cruciate ligament reconstruction in patients with open physes. *Arthroscopy.* 2009;25(8):831-838.

15. Cooper DE. Biomechanical properties of the central third patellar tendon graft: effect of rotation. *Knee Surg Sports Traumatol Arthrosc.* 1998;6 Suppl 1:S16-19.
16. Cordasco FA, Black SR, Price M, et al. Return to Sport and Reoperation Rates in Patients Under the Age of 20 After Primary Anterior Cruciate Ligament Reconstruction: Risk Profile Comparing 3 Patient Groups Predicated Upon Skeletal Age. *Am J Sports Med.* 2019;47(3):628-639.
17. Courvoisier A, Grimaldi M, Plaweski S. Good surgical outcome of transphyseal ACL reconstruction in skeletally immature patients using four-strand hamstring graft. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(4):588-591.
18. Cruz AI, Beck JJ, Ellington MD, et al. Failure Rates of Autograft and Allograft ACL Reconstruction in Patients 19 Years of Age and Younger: A Systematic Review and Meta-Analysis. *JB JS Open Access.* 2020;5(4).
19. Dai W, Leng X, Wang J, et al. 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.
20. Duchman KR, Lynch TS, Spindler KP. Graft Selection in Anterior Cruciate Ligament Surgery: Who gets What and Why? *Clin Sports Med.* 2017;36(1):25-33.
21. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. *Arthroscopy.* 2012;28(12):1819-1825.
22. Engelman GH, Carry PM, Hitt KG, Polousky JD, Vidal AF. Comparison of allograft versus autograft anterior cruciate ligament reconstruction graft survival in an active adolescent cohort. *Am J Sports Med.* 2014;42(10):2311-2318.
23. Gagliardi AG, Carry PM, Parikh HB, Albright JC. Outcomes of Quadriceps Tendon With Patellar Bone Block Anterior Cruciate Ligament Reconstruction in Adolescent Patients With a Minimum 2-Year Follow-up. *Am J Sports Med.* 2020;48(1):93-98.
24. Getgood A, Moatshe G. Lateral Extra-articular Tenodesis in Anterior Cruciate Ligament Reconstruction. *Sports Med Arthrosc Rev.* 2020;28(2):71-78.
25. 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 Sport Med.* 2020;48(2):285-297.
26. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med.* 2016;50(13):804-808.
27. Hamner DL, Brown CH, Steiner ME, Hecker AT, Hayes WC. Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. *J Bone Joint Surg Am.* 1999;81(4):549-557.
28. Hart D, Gurney-Dunlop T, Leiter J, et al. Biomechanics of hamstring tendon, quadriceps tendon, and bone-patellar tendon-bone grafts for anterior cruciate ligament reconstruction: a cadaveric study. *Eur J Orthop Surg Traumatol.* 2023;33(4):1067-1074.

29. Haybäck G, Raas C, Rosenberger R. Failure rates of common grafts used in ACL reconstructions: a systematic review of studies published in the last decade. *Arch Orthop Trauma Surg.* 2022;142(11):3293-3299.
30. Hogan DW, Burch MB, Rund JM, et al. No Difference in Complication Rates or Patient-Reported Outcomes Between Bone-Patella Tendon-Bone and Quadriceps Tendon Autograft for Anterior Cruciate Ligament Reconstruction. *Arthrosc Sports Med Rehabil.* 2022;4(2):e417-e424.
31. Hurley ET, Calvo-Gurry M, Withers D, et al. Quadriceps Tendon Autograft in Anterior Cruciate Ligament Reconstruction: A Systematic Review. *Arthroscopy.* 2018;34(5):1690-1698.
32. Hurt JA, Berry JH, Replogle W, et al. Efficacy of Two Techniques in Anterior Cruciate Ligament Reconstruction. *J Knee Surg.* 2017;30(6):606-611.
33. Jacobs CA, Burnham JM, Makhni E, et al. Allograft Augmentation of Hamstring Autograft for Younger Patients Undergoing Anterior Cruciate Ligament Reconstruction. *Am J Sports Med.* 2017;45(4):892-899.
34. Jeffers KW, Shah SA, Calvert DD, et al. High Return to Play and Low Reinjury Rates in National Collegiate Athletic Association Division I Football Players Following Anterior Cruciate Ligament Reconstruction Using Quadrupled Hamstring Autograft. *Arthroscopy.* 2022;38(1):99-106.
35. Johnston PT, Feller JA, McClelland JA, Webster KE. Knee strength deficits following anterior cruciate ligament reconstruction differ between quadriceps and hamstring tendon autografts. *Knee Surg Sports Traumatol Arthrosc.* 2022;30(4):1300-1310.
36. 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.
37. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR. Age, Graft Size, and Tegner Activity Level as Predictors of Failure in Anterior Cruciate Ligament Reconstruction With Hamstring Autograft. *The American Journal of Sports Medicine.* 2013;41(8):1808-1812.
38. Kane PW, Wascher J, Dodson CC, et al. Anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft versus allograft in skeletally mature patients aged 25 years or younger. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(11):3627-3633.
39. Kessler MA, Behrend H, Henz S, et al. Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(5):442-448.
40. Kohl S, Stutz C, Decker S, et al. Mid-term results of transphyseal anterior cruciate ligament reconstruction in children and adolescents. *Knee.* 2014;21(1):80-85.
41. LaBella CR, Hennrikus W, Hewett TE, Council on Sports Medicine and Fitness aSoO. Anterior cruciate ligament injuries: diagnosis, treatment, and prevention. *Pediatrics.* 2014;133(5):e1437-1450.
42. Larson CM, Heikes CS, Ellingson CI, et al. Allograft and Autograft Transphyseal Anterior Cruciate Ligament Reconstruction in Skeletally Immature Patients: Outcomes and Complications. *Arthroscopy.* 2016;32(5):860-867.
43. 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.

44. Matava MJ, Siegel MG. Arthroscopic reconstruction of the ACL with semitendinosus-gracilis autograft in skeletally immature adolescent patients. *Am J Knee Surg.* 1997;10(2):60-69.

45. McCarroll JR, Shelbourne KD, Porter DA, Rettig AC, Murray S. Patellar tendon graft reconstruction for midsubstance anterior cruciate ligament rupture in junior high school athletes. An algorithm for management. *Am J Sports Med.* 1994;22(4):478-484.

46. McIntosh AL, Dahm DL, Stuart MJ. Anterior cruciate ligament reconstruction in the skeletally immature patient. *Arthroscopy.* 2006;22(12):1325-1330.

47. Mohtadi NG, Chan DS, Dainty KN, Whelan DB. Patellar tendon versus hamstring tendon autograft for anterior cruciate ligament rupture in adults. *Cochrane Database Syst Rev.* 2011;2011(9):CD005960.

48. Monaco E, Pisanu G, Carrozzo A, et al. Translation, cross-cultural adaptation, and validation of the Italian version of the anterior cruciate ligament-return to sport after injury (ACL-RSI) scale and its integration into the K-STARTS test. *J Orthop Traumatol.* 2022;23(1):11.

49. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Fifteen-Year Survival of Endoscopic Anterior Cruciate Ligament Reconstruction in Patients Aged 18 Years and Younger. *Am J Sports Med.* 2016;44(2):384-392.

50. Mouarbes D, Dagneaux L, Olivier M, et al. Lower donor-site morbidity using QT autografts for ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2020;28(8):2558-2566.

51. Mouarbes D, Menetrey J, Marot V, et al. 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.

52. Nelson IR, Chen J, Love R, et al. A comparison of revision and rerupture rates of ACL reconstruction between autografts and allografts in the skeletally immature. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(3):773-779.

53. Nikolaou P, Kalliakmanis A, Bousgas D, Zourntos S. Intraarticular stabilization following anterior cruciate ligament injury in children and adolescents. *Knee Surg Sports Traumatol Arthrosc.* 2011;19(5):801-805.

54. Offerhaus C, Albers M, Nagai K, et al. Individualized Anterior Cruciate Ligament Graft Matching: In Vivo Comparison of Cross-sectional Areas of Hamstring, Patellar, and Quadriceps Tendon Grafts and ACL Insertion Area. *Am J Sports Med.* 2018;46(11):2646-2652.

55. 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.

56. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med.* 2010;38(10):1968-1978.

57. Pennock AT, Johnson KP, Turk RD, et al. Transphyseal Anterior Cruciate Ligament Reconstruction in the Skeletally Immature: Quadriceps Tendon Autograft Versus

Hamstring Tendon Autograft. *Orthopaedic Journal of Sports Medicine.* 2019;7(9):232596711987245.

58. Pennock AT, Johnson KP, Turk RD, et al. Transphyseal Anterior Cruciate Ligament Reconstruction in the Skeletally Immature: Quadriceps Tendon Autograft Versus Hamstring Tendon Autograft. *Orthop J Sports Med.* 2019;7(9):2325967119872450.

59. 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.

60. Petit CB, Slone HS, Diekfuss JA, et al. Sex-Specific Outcomes After Anterior Cruciate Ligament Reconstruction Using an All-Soft Tissue Quadriceps Tendon Autograft in a Young Active Population. *Am J Sports Med.* 2024;52(10):2450-2455.

61. Popovic M, Myhre JR, Holen JIH, et al. Reduced Knee Flexion Strength 18 Years After ACL Reconstruction With Hamstring Tendon Versus Patellar Tendon. *Am J Sports Med.* 2024;52(11):2750-2757.

62. Rao AJ, Macknet DM, Stuhlman CR, et al. Allograft Augmentation of Hamstring Autograft in Anterior Cruciate Ligament Reconstruction Results in Equivalent Outcomes to Autograft Alone. *Arthroscopy.* 2021;37(1):173-182.e172.

63. Rauck RC, Apostolakos JM, Nwachukwu BU, et al. Return to Sport After Bone-Patellar Tendon-Bone Autograft ACL Reconstruction in High School-Aged Athletes. *Orthop J Sports Med.* 2021;9(6):23259671211011510.

64. Redler LH, Brafman RT, Trentacosta N, Ahmad CS. Anterior cruciate ligament reconstruction in skeletally immature patients with transphyseal tunnels. *Arthroscopy.* 2012;28(11):1710-1717.

65. Runer A, Csapo R, Hepperger C, et al. Anterior Cruciate Ligament Reconstructions With Quadriceps Tendon Autograft Result in Lower Graft Rupture Rates but Similar Patient-Reported Outcomes as Compared With Hamstring Tendon Autograft: A Comparison of 875 Patients. *Am J Sports Med.* 2020;48(9):2195-2204.

66. Salem HS, Varzhapetyan V, Patel N, et al. Anterior Cruciate Ligament Reconstruction in Young Female Athletes: Patellar Versus Hamstring Tendon Autografts. *Am J Sports Med.* 2019;47(9):2086-2092.

67. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21(8):948-957.

68. Samuelsen BT, Webster KE, Johnson NR, Hewett TE, Krych AJ. Hamstring Autograft versus Patellar Tendon Autograft for ACL Reconstruction: Is There a Difference in Graft Failure Rate? A Meta-analysis of 47,613 Patients. *Clin Orthop Relat Res.* 2017;475(10):2459-2468.

69. Sanada T, Iwaso H, Fukai A, et al. Anatomic Anterior Cruciate Ligament Reconstruction Using Rectangular Bone-Tendon- Bone Autograft Versus Double-Bundle Hamstring Tendon Autograft in Young Female Athletes. *Arthrosc Sports Med Rehabil.* 2021;3(1):e47-e55.

70. Schilaty ND, Bates NA, Sanders TL, et al. Incidence of Second Anterior Cruciate Ligament Tears (1990-2000) and Associated Factors in a Specific Geographic Locale. *Am J Sports Med.* 2017;45(7):1567-1573.

71. Schwarzer G, Carpenter, J. R., & Rücker, G. *Meta-Analysis with R* . Springer. *Journal*. 2015(Issue).
72. Schwery NA, Kiely MT, Larson CM, et al. Quadriceps Strength following Anterior Cruciate Ligament Reconstruction: Normative Values based on Sex, Graft Type and Meniscal Status at 3, 6 & 9 Months. *Int J Sports Phys Ther.* 2022;17(3):434-444.
73. Shani RH, Umpierez E, Nasert M, Hiza EA, Xerogeanes J. Biomechanical Comparison of Quadriceps and Patellar Tendon Grafts in Anterior Cruciate Ligament Reconstruction. *Arthroscopy.* 2016;32(1):71-75.
74. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med.* 2009;37(2):246-251.
75. Smith AH, Capin JJ, Zarzycki R, Snyder-Mackler L. Athletes With Bone-Patellar Tendon-Bone Autograft for Anterior Cruciate Ligament Reconstruction Were Slower to Meet Rehabilitation Milestones and Return-to-Sport Criteria Than Athletes With Hamstring Tendon Autograft or Soft Tissue Allograft : Secondary Analysis From the ACL-SPORTS Trial. *J Orthop Sports Phys Ther.* 2020;50(5):259-266.
76. Smith PA, Cook CS, Bley JA. All-Inside Quadrupled Semitendinosus Autograft Shows Stability Equivalent to Patellar Tendon Autograft Anterior Cruciate Ligament Reconstruction: Randomized Controlled Trial in Athletes 24 Years or Younger. *Arthroscopy.* 2020;36(6):1629-1646.
77. Snaebjornsson 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.
78. 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.
79. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ.* 2016;355:i4919.
80. Takazawa Y, Ikeda H, Saita Y, et al. Return to Play of Rugby Players After Anterior Cruciate Ligament Reconstruction Using Hamstring Autograft: Return to Sports and Graft Failure According to Age. *Arthroscopy.* 2017;33(1):181-189.
81. Thompson SM, Salmon LJ, Waller A, et al. Twenty-Year Outcome of a Longitudinal Prospective Evaluation of Isolated Endoscopic Anterior Cruciate Ligament Reconstruction With Patellar Tendon or Hamstring Autograft. *Am J Sports Med.* 2016;44(12):3083-3094.
82. Thorolfsson B, Svantesson E, Snaebjornsson T, et al. Adolescents Have Twice the Revision Rate of Young Adults After ACL Reconstruction With Hamstring Tendon Autograft: A Study From the Swedish National Knee Ligament Registry. *Orthop J Sports Med.* 2021;9(10):23259671211038893.
83. Tomihara T, Hashimoto Y, Okazaki S, et al. Bone-patellar tendon-bone autograft is associated with a higher rate of return to preinjury levels of performance in high-level athletes than anterior cruciate ligament reconstruction using hamstring autograft. *Knee Surg Sports Traumatol Arthrosc.* 2024;32(6):1384-1395.

84. Toritsuka Y, Horibe S, Mitsuoka T, et al. Comparison between the cross-sectional area of bone-patellar tendon-bone grafts and multistranded hamstring tendon grafts obtained from the same patients. *Knee Surg Sports Traumatol Arthrosc.* 2003;11(2):81-84.
85. 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.
86. Vaughn NH, Dunleavy ML, Jackson T, Hennrikus W. The outcomes of quadriceps tendon autograft for anterior cruciate ligament reconstruction in adolescent athletes: a retrospective case series. *Eur J Orthop Surg Traumatol.* 2022;32(4):739-744.
87. Webster KE, Feller JA. Exploring the High Reinjury Rate in Younger Patients Undergoing Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine.* 2016;44(11):2827-2832.
88. Webster KE, Feller JA, Leigh WB, Richmond AK. Younger Patients Are at Increased Risk for Graft Rupture and Contralateral Injury After Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine.* 2014;42(3):641-647.
89. Widner M, Dunleavy M, Lynch S. Outcomes Following ACL Reconstruction Based on Graft Type: Are all Grafts Equivalent? *Curr Rev Musculoskelet Med.* 2019;12(4):460-465.
90. Wilson TW, Zafuta MP, Zobitz M. A biomechanical analysis of matched bone-patellar tendon-bone and double-looped semitendinosus and gracilis tendon grafts. *Am J Sports Med.* 1999;27(2):202-207.
91. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S. Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med.* 1991;19(3):217-225.
92. Xie X, Liu X, Chen Z, et al. A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *Knee.* 2015;22(2):100-110.
93. Yabroudi MA, Björnsson H, Lynch AD, et al. Predictors of Revision Surgery After Primary Anterior Cruciate Ligament Reconstruction. *Orthop J Sports Med.* 2016;4(9):2325967116666039.
94. Yao S, Fu BS, Yung PS. Graft healing after anterior cruciate ligament reconstruction (ACLR). *Asia Pac J Sports Med Arthrosc Rehabil Technol.* 2021;25:8-15.

Appendix:

Appendix 1: PubMed Search Query

PubMed (NLM):

Dates searched: January 1, 1946-March 3, 2022; March 3, 2022-January 16, 2024; January 16, 2024-August 28, 2024
Filters: English
Filters: Use of Boolean "NOT" to exclude case reports, comments, reviews, letters, and editorials

1. ("hamstring tendons/transplantation"[MeSH] OR ("hamstring tendons"[MeSH] AND ("transplantation"[MeSH:noexp] OR transplant*[TW])) OR "hamstring tendons transplant*"[TW] OR "Semitendinosus Tendon"[TW] OR "semitendinosus gracilis"[TW]) AND ("autografts"[MeSH Terms:noexp] OR "Transplantation, Autologous"[Mesh] OR "Autologous Transplant*"[TW] OR "autograft*"[TW] OR "autologous repair"[TW] OR autotransplant*[TW])
2. ("Patellar Ligament/transplantation"[MESH] OR ("patellar ligament"[TW] AND ("transplantation"[MESH:noexp] OR transplant*[TW] OR graft*[TW])) OR ("patella"[MESH] AND "ligaments"[MESH] AND ("transplantation"[MESH:noexp] OR transplant*[TW]))) AND ("autografts"[MESH:noexp] OR "Transplantation, Autologous"[Mesh] OR "Autologous Transplant*"[TW] OR autograft*[TW] OR "autologous repair"[TW] OR autotransplant*[TW])
3. ("Bone-Patellar Tendon-Bone Grafts"[Mesh] OR (("BPTB"[TW] OR "Bone patellar tendon bone"[TW] OR "bone patellar bone"[TW] OR "bone tendon bone"[TW] OR "Tendon Bone Graft*"[TW] OR ("patella"[MESH] AND "tendons"[MESH:noexp]) OR "patellar tendon"[TW]) AND ("transplantation"[MESH:noexp] OR transplant*[TW] OR graft*[TW]))) AND ("autografts"[MESH:noexp] OR "Transplantation, Autologous"[Mesh] OR "Autologous Transplant*"[TW] OR autograft*[TW] OR "autologous repair"[TW] OR autotransplant*[TW])
4. ((("Quadriceps Muscle"[MeSH Terms] AND "Tendons"[MeSH Terms:noexp]) OR "bone quadriceps tendon"[TW]) AND ("autografts"[MeSH Terms:noexp] OR "Transplantation, Autologous"[Mesh] OR "Autologous Transplant*"[TW] OR "autograft*"[Text Word] OR "autologous repair"[TW] OR autotransplant*[TW])) OR "soft tissue quadriceps tendon autograft"[TW] OR "Quadriceps tendon autograft"[TW] OR "quad tendon autograft"[TW] OR "quad autograft"[TW] OR "quadriceps autograft"[TW] OR "Quadriceps tendon autograft"[TW] OR "quadriceps autograft"[TW]
5. "Anterior Cruciate Ligament Injuries/surgery"[MESH] OR "Anterior Cruciate Ligament/surgery"[MESH] OR "Anterior Cruciate Ligament Reconstruction"[Mesh] OR "anterior cruciate ligament*"[TW] OR ACLR[TW] OR ACL[TW] OR "Knee Joint/surgery"[MESH] OR "knee injuries/surgery"[MESH] OR ("knee joint"[TW] OR "knee injur*"[TW] AND (surg*[TW] OR repair[TW] OR reconstruct*[TW]))
6. (#1 OR #2 OR #3 OR #4) AND #5
7. (#6 AND English[LA]) NOT ("review"[PT] OR "systematic review"[PT] OR "systematic review"[TI] OR "meta-analysis"[PT] OR "meta analysis"[TI] OR "case reports"[PT] OR case report*[TI] OR "literature review"[TI] OR "narrative review"[TI] OR "scoping review"[TI] OR letter[PT] OR letter[TI] OR editorial[PT] OR editorial[TI] OR comment[PT] OR comment*[TI] OR booksdocs[Filter] OR preprint[PT])