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# Quadriceps tendon autograft ACL reconstruction has less pivot shift laxity and lower failure rates than hamstring tendon autografts

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## Abstract

**Purpose** Quadriceps tendon (QT) autograft ACL reconstruction was hypothesized to possess less anterior knee laxity, pivot shift laxity, and lower failure rates than hamstring tendon (HT) autografts.

**Methods** Terms "hamstring tendon autograft" and "ACL reconstruction" or "quadriceps tendon autograft" and "ACL reconstruction" were searched in Embase and PubMed. Inclusion criteria required that studies included patients treated for primary ACL injury with reconstruction using either a QT autograft (Group 1) or a HT autograft (Group 2) and instrumented anterior knee laxity assessment. Extracted information included surgical fixation method, graft type, graft thickness or diameter, single vs. double bundle surgical method, publication year, time between the index knee injury and surgery, % women, initial and final subject number, subject age, follow-up length, side-to-side anterior knee laxity difference, Lysholm Score, Subjective IKDC score, anterior knee laxity side-to-side difference grade, ipsilateral pivot shift laxity grade, and failure rate. The Methodological Index for Nonrandomized Studies was used to evaluate study methodological quality.

**Results** The QT group (Group 1) had 17 studies and the HT group (Group 2) had 61 studies. Overall, Group 2 had greater pivot shift laxity (OR 1.29, 95% CI 1.05–1.59, $p = 0.005$). Group 2 suspensory femoral fixation had greater pivot shift laxity (OR 1.26, 95% CI 1.01–1.58, $p = 0.02$) than Group 1 compression femoral fixation. Group 2 compression femoral fixation also had more anterior knee laxity (OR 1.25, 95% CI 1.03–1.52, $p = 0.01$) than Group 1 compression femoral fixation and higher failure rates based on initial (OR 1.69, 95% CI 1.18–2.4, $p = 0.002$) and final (OR 1.89, 95% CI 1.32–2.71, $p = 0.0003$) subject number. Failure rate for HT compression femoral fixation was greater than suspensory femoral fixation based on initial (OR 2.08, 95% CI 1.52–2.84, $p < 0.0001$) and final (OR 2.26, 95% CI 1.63–3.16, $p < 0.0001$) subject number.

**Conclusions** Overall, QT autografts had less pivot shift laxity and lower failure rates based on final subject number than HT autografts. Compression QT autograft femoral fixation had lower pivot shift laxity than suspensory HT autograft femoral fixation. Compression QT autograft femoral fixation had less anterior knee laxity and lower failure rates than compression HT autograft femoral fixation. Suspensory HT autograft femoral fixation had lower failure rates than compression HT autograft femoral fixation. Greater knee laxity and failure rates may be related to a combination of HT autograft diameter and configuration (tissue quality and dimensions, strands, bundles, and suturing method) variability and fixation mode.

**Level of evidence** Level IV.

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## Introduction

Successful anterior cruciate ligament (ACL) reconstruction involves factors such as surgical approach, graft placement, fixation method, and graft type. In addition to autograft biomechanical properties, other surgical considerations that may influence patient outcomes include graft thickness and insertional dimensions, collagen fiber orientation, and the likelihood of early, long-term, and/or permanent harvest

site morbidity [21, 33]. Concerns related to long-term or permanent harvest site complaints such as patellofemoral joint osteoarthritis and prolonged quadriceps femoris muscle group inhibition has led surgeons to search for options other than the traditional "gold standard", bone-patellar tendon-bone autograft [4]. For this reason and because of its greater tissue strength, hamstring (semitendinosus and gracilis, or semitendinosus alone) autograft use has increased. However, hamstring tendon (HT) autograft use possesses its own unique harvest region morbidity such as cutaneous numbness or paresthesia, knee flexor-internal rotator neuromuscular weakness or inhibition, and reduced dynamic medial knee stability [4, 8]. For these reasons, surgeons continue to seek an autograft source that possesses strength and mechanical stiffness similar to the native ACL, but with less harvest-related morbidity. Quadriceps tendon (QT) autograft use for ACL reconstruction has been increasing [15, 26, 27, 33]. Recent studies have suggested that the quadriceps tendon (QT) may provide an effective ACL reconstruction autograft alternative in skeletally mature [33] and immature [31] patients when HT autograft size is deemed to be inadequate or less than optimal [3]. Belk et al. [4] reported no failure rate difference between HT and QT autograft ACL reconstruction groups, although HT autografts had slightly greater anterior and pivot shift knee laxity. Their research, however, was limited to studies that directly compared the clinical outcomes of patients that underwent ACL reconstruction using QT autograft or HT autograft in the same study. With this criteria, only eight total studies were included in their review, sample size was low, and no study represented level I evidence [4]. Wilkerson et al. [32] suggested that group treatment intervention differences expressed by odds ratios (OR) may be more useful to clinical decision-making than the "*p*" values associated with hypothesis testing even when randomized controlled research study designs are used. Research designs based solely on higher evidence level studies may neglect a large segment of clinically relevant orthopaedic sports medicine research evidence. The purpose of this systematic literature review and meta-analysis was to compare the efficacy of QT autograft use for ACL reconstruction compared to HT autograft use based on anterior knee laxity, pivot shift knee laxity, and failure rates. The study hypothesis was that ACL reconstruction using QT autograft would display less knee laxity and lower failure rates.

## Materials and methods

### Study identification

Using key words "hamstring tendon autograft" and "anterior cruciate ligament reconstruction" or "quadriceps tendon

autograft" and "anterior cruciate ligament reconstruction" with the Boolean operator "AND", the Embase and PubMed (using Ovid) databases were searched by the primary investigator. No year restrictions were used for these searches.

### Study selection

Following initial identification, studies were screened by two investigators (AH, JN) for study type and use of instrumented anterior knee laxity assessment. When more than one autograft tendon type was used, only data related specifically to HT or QT autografts were included in the study. Data collection ended on May 30, 2019.

### Study inclusion and exclusion criteria

The inclusion criteria required that all studies included patients treated for primary ACL injury with reconstruction using either a QT autograft or a HT autograft with the inclusion of instrumented anterior knee laxity assessment. Literature reviews, editorials, narrative descriptions, commentaries, surgical or rehabilitation technique papers, single case reports, and letters to the editor were excluded. Data were managed following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [20]. To prevent selection bias, when studies were identified that likely used complete or partial data from previous publications, only the most recent report with the longest post-operative follow-up time was selected for analysis [28].

### Data extraction

Extracted information included surgical fixation method, graft type, graft thickness or diameter, single vs. double bundle surgical method, publication year, time between the index knee injury and surgery, % women, initial and final subject number, subject age, follow-up length, side-to-side anterior knee laxity difference, Lysholm Score [30], Subjective IKDC score [7], anterior knee laxity side-to-side difference grade, ipsilateral pivot shift laxity grade, and failure rate. The Methodological Index for Nonrandomized Studies (MINORS) was used to evaluate the methodological quality of each contributing study [1, 29].

Each study was evaluated by three independent reviewers (AH, SS, JN). Two reviewers extracted the data, and a third reviewed each accepted study record for completeness and accuracy (JN). Study evidence levels were categorized following the Knee Surgery, Sports Traumatology, Arthroscopy (KSSTA) levels of evidence criteria (1 = randomized controlled study; 2 = prospective cohort study; 3 = retrospective cohort or comparative study; 4 = case series). When investigator evidence levels or MINORS scores differed, consensus was obtained through group discussions. When more

than one femoral autograft fixation method was used for any study, subject result subsets were analyzed.

## Endpoint

When studies performed clinical follow-up measurements at multiple time points or through follow-up publications, to help control for selection bias, only data from the last follow-up period were included in the systematic literature review and meta-analysis.

## Statistical analysis

Descriptive and continuous group data comparisons were performed using SPSS version 24.0 software (SPSS-IBM, Armonk, NY, USA). Data normality was assessed using Kolmogorov–Smirnov tests. Since knee laxity data and MINORS scores displayed non-normal distributions, non-parametric statistical analysis was performed. Mann–Whitney "$U$" tests were used to compare group demographic characteristics. A Chi-square test was used to evaluate group differences for the proportion of comparative and non-comparative studies. Spearman Rho correlations were used to determine the relationship of MINORS scores to primary outcome variables anterior knee laxity, pivot shift laxity, and failure rates. One-tailed statistical significance tests were calculated based on an overall alpha level of $p < 0.05$.

Systematic reviews that combine studies with diverse subject demographics and methodological research quality may be influenced by heterogeneity which can potentially influence data interpretation and clinical meaningfulness [10, 11, 13]. To address potential study heterogeneity issues, median values were determined for each study variable and dichotomous scores were generated with "1" representing a study that met or exceeded the group median and "2" representing a study that was less than the group median. These scores were then compared using a Cochran's $Q$ test and Higgins $I^2$ index to determine group study heterogeneity. The Higgins $I^2$ index estimates study heterogeneity magnitude and the relative "fit" for each variable of interest. Higgins et al. [11] suggested that an $I^2$ score of 25% represented low heterogeneity, 50% represented moderate heterogeneity and 75% represented high heterogeneity. A disadvantage of Higgins $I^2$, however, is that it represents a proportion rather than an absolute value and there are no empirically determined cut-points regarding how much study patient population and treatment heterogeneity diversity is acceptable [12, 14]. Clinical judgement is essential when deciding if the studies that contribute to a meta-analysis are clinically similar enough to make a study valid and clinically important [2, 5, 11–13, 24].

A secondary sensitivity analysis was also performed to determine the potential influence of individual studies on final outcomes. When the proportion of subjects within any study had anterior knee laxity greater than 2 mm (normal), had positive pivot shift laxity or displayed a failure rate that met or exceeded the group 75th percentile, it was removed and odds ratios were re-calculated to determine its influence on final study outcome. The odds ratios that we report represent those values most representative of the overall groups without adverse influence by any one disproportionate study.

## Results

### Group demographics

A total of 17 studies using QT autografts (Group 1) and 61 studies using HT autografts (Group 2) contributed to this systematic literature review and meta-analysis (Fig. 1) (Online Appendix I). More subjects contributed to Group 2 ($n = 4095$) than Group 1 ($n = 1412$); however, groups otherwise displayed comparable study demographic and key variable values (Table 1).

### Evidence quality

Overall, Group 2 displayed a higher proportion of comparative studies than Group 1 ($p = 0.029$) and had higher MINORS scores ($18.9 \pm 3.7$ vs. $15.9 \pm 4$, $p = 0.005$) (Online Appendix IIA and IIB). Spearman Rho correlational analysis failed to reveal statistically significant relationships between study MINORS scores and primary study variables anterior knee laxity, pivot shift laxity and failure rates. Based on $I^2$ score interpretation as described by Higgins et al. [11], the comparison groups displayed low heterogeneity for all demographic and primary study variables with the exception of MINORS score. An $I^2$ value of 71% was identified for MINORS score, suggesting moderate-to-high heterogeneity for this variable. Based on low heterogeneity for the primary variables of study interest, anterior knee laxity, pivot shift laxity, and failure rates, and their lack of statistically significant relationships with MINORS scores, the decision was made to proceed with data pooling and meta-analysis [2, 5, 9]. Simple odds ratio calculations of group anterior laxity, pivot shift laxity, and failure rates were performed [18].

### Surgical methods

Group 1 studies relied more on boned ($n = 11$) than non-boned QT autografts ($n = 5$), with one study using both types. Sixteen studies reported QT autograft thickness ranging from 6–9 mm, with one study not reporting thickness. Group 1 femoral fixation consisted of metal interference screws ($n = 5$), bioabsorbable interference screws ($n = 3$), combined bioabsorbable interference screw-Endopearl
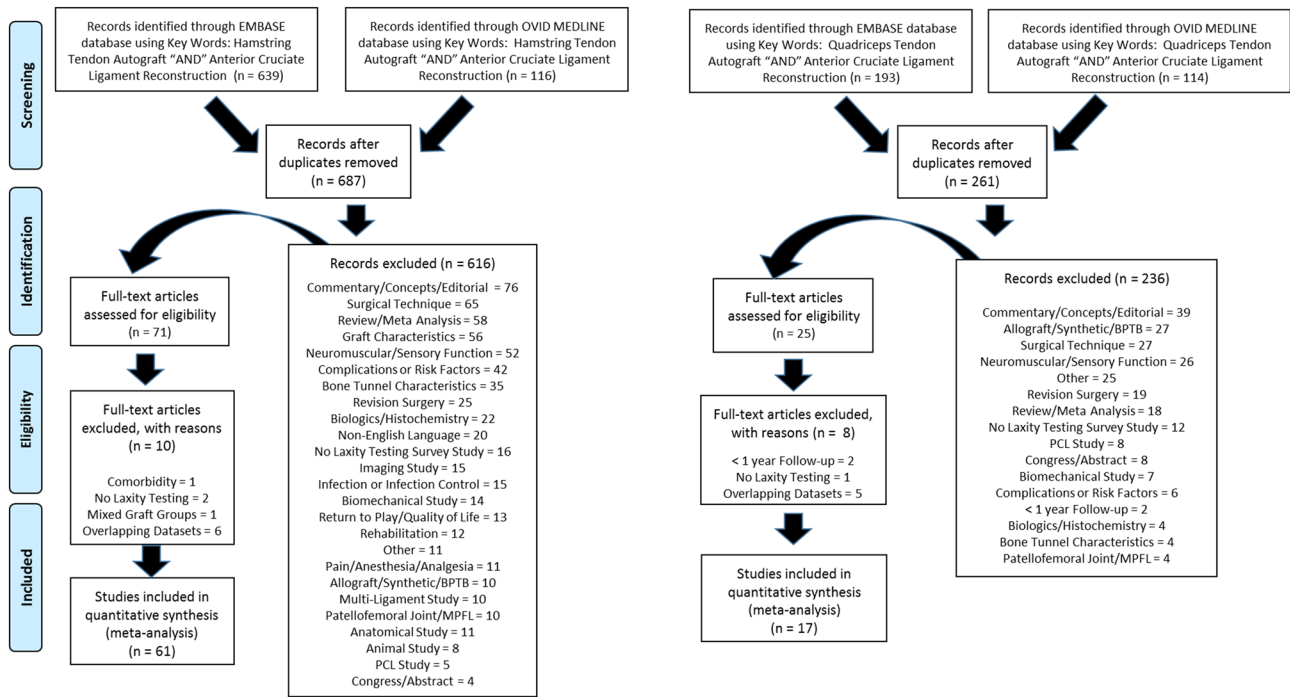
**Fig. 1** PRISMA flow diagram of the process that lead to the final selection of the studies that contributed to this systematic review and meta-analysis

**Table 1** QT and HT autograft groups did not display significant demographic variable differences, with the exception of the HT autograft group displaying a greater MINORS score

| | Quadriceps tendon ($n=17$) | | | Hamstring tendon ($n=61$) | | | $p$ value |
|---|---|---|---|---|---|---|---|
| | Median | 25th percentile | 75th percentile | Median | 25th percentile | 75th percentile | |
| Publication year | 2013 | 2009 | 2017 | 2013 | 2009 | 2017 | n.s. |
| Evidence level | 2 | 2 | 3 | 2 | 1 | 3 | n.s. |
| MINORS score | 16 | 11.5 | 19 | 20 | 18 | 21.5 | 0.005* |
| Time between index injury and surgery (mos) | 16.4 | 10.6 | 21.2 | 12 | 3 | 19 | n.s. |
| % of women | 22 | 14.3 | 40.6 | 36 | 18.3 | 46.4 | n.s |
| Initial subject number/study | 37.5 | 21 | 76.5 | 39.5 | 28 | 62 | n.s. |
| Final subject number/study | 37.5 | 21 | 76.5 | 39.5 | 28 | 62 | n.s. |
| Age at surgery (years) | 29 | 26.8 | 31.7 | 28.6 | 26.5 | 31.1 | n.s. |
| Timing of last follow-up (mos) | 29.5 | 23 | 44 | 32.8 | 24 | 51 | n.s. |
| Side-to-side anterior laxity difference (mm) | 1.6 | 1.0 | 2.1 | 1.8 | 1.4 | 2.3 | n.s. |
| Pre-Surgical Lysholm Score | 70.7 | 62.1 | 75.8 | 64.6 | 56.9 | 71 | n.s. |
| Post-Surgical Lysholm Score | 90 | 89 | 91.9 | 92 | 90.2 | 93.9 | n.s. |
| Pre-surgical subjective IKDC | NA | NA | NA | 50.9 | 42.8 | 53.9 | NA |
| Post-surgical subjective IKDC | 85.1 | 83.1 | 87.3 | 86.9 | 83.1 | 91 | n.s. |
| +Anterior knee laxity/total subjects tested | 0.23 | 0.13 | 0.32 | 0.24 | 0.14 | 0.40 | n.s. |
| +Pivot shift knee laxity/total subjects tested | 0.15 | 0.05 | 0.20 | 0.15 | 0.10 | 0.21 | n.s. |
| Failure rate based on subject number at study initiation | 0.031 | 0.00 | 0.07 | 0.023 | 0.00 | 0.06 | n.s. |
| Failure rate based on subject number at study completion | 0.031 | 0.00 | 0.07 | 0.026 | 0.00 | 0.07 | n.s. |

*NA* not applicable, *n.s.* non-significant (*$p < 0.05$)

(ConMed Linvatec, Largo, FL) ($n=2$), one or two crosspins ($n=2$), press fit fixation ($n=2$), button ($n=2$), and bone screw-washer combination ($n=1$). Group 1 tibial fixation consisted of bioabsorbable interference screws ($n=8$), bioabsorbable interference screws with suture ($n=2$), bone screw-washer ($n=2$), suture-bone bridge ($n=2$) and single cross pin, Intrafix (Depuy Synthes, Raynham, MA), and suture-bone bridge (each $n=1$).

Group 2 studies primarily used both semitendinosus and gracilis tendons in the HT autograft ($n=52$), although some used the semitendinosus tendon alone ($n=7$), semitendinosus tendon with bone or semitendinosus tendon (sometimes with the gracilis tendon) (each $n=1$). Group 2 studies performed single bundle ACL reconstruction ($n=54$), double bundle ACL reconstruction ($n=5$), or an undefined combination of each ($n=2$). For ACL reconstruction using single bundle techniques, 24 studies did not report HT autograft diameter, 13 studies used 7–9 mm graft diameter, nine studies used 8–9 mm HT autograft diameter, seven studies used 6–9 mm HT autograft diameter, three studies used 9–10 mm HT autograft diameter, two studies used 8 mm HT autograft diameter and one study each used 9.5 mm, 7.7 mm and 7.5 mm HT autograft diameters. For ACL reconstruction using double bundle techniques, three studies reported posterolateral bundle HT autograft diameters of 6–7 mm, with one study reporting a 5–5.5 mm HT autograft diameter. One study each reported anteromedial bundle HT autograft diameters of 5.5–6 mm, 6–6.5 mm, and 7–8 mm.

Group 2 femoral fixation consisted of button ($n=24$) or button-bioabsorbable screw, cross pin or tape ($n=4$), metal interference screws ($n=10$), bioabsorbable interference screws ($n=8$), bioabsorbable or metal interference screws ($n=2$), one cross pin ($n=4$), two cross pins ($n=2$), staple or staples ($n=2$), bone mulch screw, suture-miniplate, press fit, bone screw – post, and Tight-rope (Arthrex, Naples, FL) (each $n=1$). Group 2 tibial fixation consisted of

bioabsorbable interference screws ($n=28$), either bioabsorbable or metal interference screws ($n=3$), or a bioabsorbable interference screw supplemented with a suture-bone bridge ($n=1$), staple ($n=2$), metal interference screw ($n=8$), metal interference screw-post ($n=1$), bone screw-post ($n=5$), staple ($n=3$), two staples ($n=1$), staple-tape ($n=1$), Intrafix (Depuy Synthes, Raynham, MA) ($n=1$), Intrafix with bone screw and washer ($n=2$), bone screw and washer ($n=2$), Washerloc (Zimmer Biomet, Warsaw, IN), button ($n=1$), Biointrafix (Depuy Synthes, Raynham, MA) ($n=1$), or Intrafix (Depuy Synthes, Raynham, MA) ($n=1$).

## Knee laxity and failure rates

Overall, Group 2 subjects displayed greater pivot shift laxity and higher failure rates based on subject number at study completion than Group 1 subjects (Table 2). Comparisons based on the primary femoral fixation method used for each group revealed that Group 2 with suspensory fixation had greater pivot shift laxity than Group 1 with compression fixation (Table 3, Fig. 2). Direct comparison of compression fixation for both groups, revealed greater anterior knee laxity for Group 2 compared to Group 1. In addition, whether calculated from initial or final study subject number, overall failure rate was greater for Group 2 compression femoral fixation than for Group 1 compression femoral fixation (Table 4, Fig. 3). Further comparison of HT autografts with femoral fixation provided by either suspensory or compression methods failed to identify significant anterior or pivot shift knee laxity group differences; however, the outright failure rate was greater for HT autografts with compression femoral fixation based on both initial and final study subject number than for HT autografts with suspensory femoral fixation (Table 5). Secondary sensitivity analysis of knee laxity or failure rate values of individual studies that exceeded the group 75th percentile failed to significantly modify overall

**Table 2** HT autograft group had greater pivot shift laxity at follow-up and had a higher failure rate based on subject number at study completion than the QT autograft group

| Variable | Quadriceps tendon group ($n=17$) | Hamstring tendon group ($n=61$) | Odds ratio | 95% confidence interval | $p$ value |
|---|---|---|---|---|---|
| Overall anterior knee laxity | 334 subjects > Grade I/1333 subjects = Grade I | 817 subjects > Grade I/2992 subjects = Grade I | 1.09 | 0.95–1.26 | n.s. |
| Overall pivot shift laxity | 129 subjects with + test/839 subjects with − test | 575 subjects with + test/2892 subjects with − test | 1.29 | 1.05–1.59 | 0.005* |
| Overall failure rate based on subject number at study initiation | 47 subjects failed out of 1412 at study initiation | 173 subjects failed out of 4127 at study initiation | 1.26 | 0.91–1.75 | n.s. |
| Overall failure rate based on subject number at study completion | 47 subjects failed out of 1362 at study completion | 173 subjects failed out of 3754 subjects at study completion | 1.34 | 0.96–1.85 | 0.04* |

*n.s.* Non-significant (*one-sided $p < 0.05$)

**Table 3** Comparison of the primary femoral fixation method for QT autografts (compression) and HT autografts (suspensory) revealed greater pivot shift laxity for the HT autograft group

| Variable | Quadriceps tendon group compression fixation ($n=13$) | Hamstring tendon group suspensory fixation ($n=32$) | Odds ratio | 95% confidence interval | $p$ value |
|---|---|---|---|---|---|
| Anterior knee laxity | 268 subjects > Grade I/1143 subjects = Grade I | 491 subjects > Grade I/1920 subjects = Grade I | 1.09 | 0.92–1.29 | n.s. |
| Pivot shift laxity | 129 subjects with + test/764 subjects with − test | 345 subjects with + test/1616 subjects with − test | 1.26 | 1.01–1.58 | 0.02* |
| Failure Rate based on Subject Number at Study Initiation | 47 subjects failed out of 1222 at study initiation | 75 subjects failed out of 2402 at study initiation | 0.81 | 0.56–1.18 | n.s. |
| Failure Rate based on Subject Number at Study Completion | 47 subjects failed out of 1172 at study completion | 75 subjects failed out of 2238 at study completion | 0.84 | 0.58–1.21 | n.s. |

*n.s.* Non-significant (*one-sided $p < 0.05$)

**Fig. 2** Forest plot of QT and HT autograft femoral fixation anterior and pivot shift laxity. Overall and in comparing QT compression to HT suspensory fixation, the QT group displayed less pivot shift laxity. QT compression fixation also displayed less anterior laxity than HT compression fixation
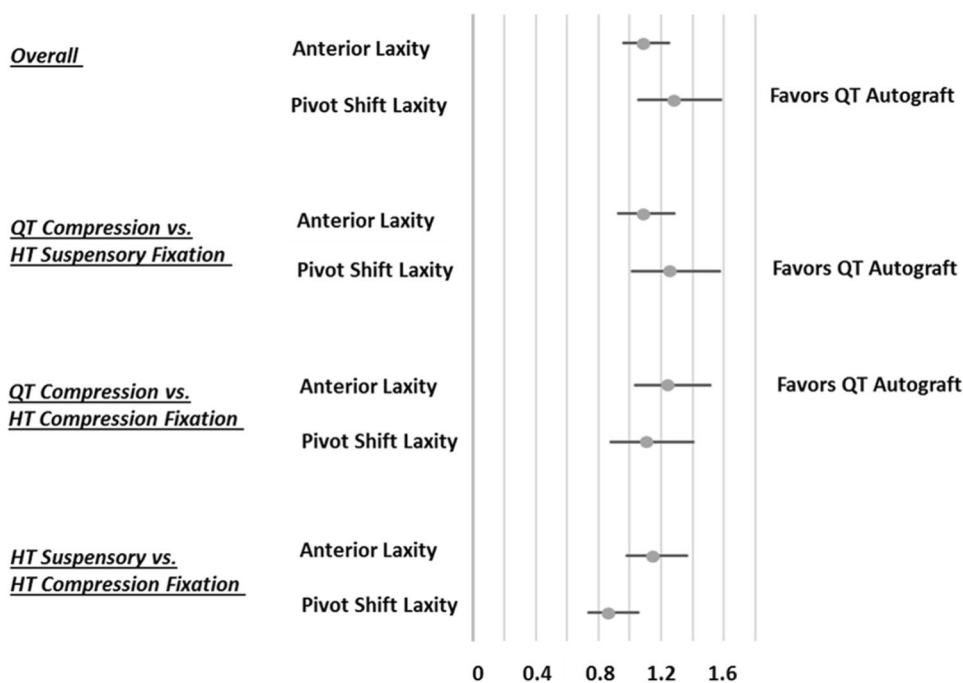


study findings or statistical significance. Results suggest that HT autograft compression femoral fixation is more likely to display outright graft rupture compared to similarly secured QT autografts.

## Discussion

The most important finding of the present study was that overall, ACL reconstruction using HT autografts was more likely to display greater pivot shift laxity and higher failure rates based on final study subject number. This finding partially agrees with the recent report of Belk et al. [4] which identified greater anterior knee laxity and pivot shift laxity. Greater knee laxity and failure rates may be related to a combination of HT autograft diameter and configuration (tissue quality and dimensions, strands, bundles, suturing method) variability [6, 22, 23], and fixation mode. Comparisons based on the primary femoral fixation method for both autograft types revealed that the HT autograft group with suspensory fixation displayed greater pivot shift laxity than the QT autograft group with compression fixation; however, failure rates did not differ. These findings suggest that suspensory HT autograft femoral fixation may be more

**Table 4** Comparison of the primary femoral fixation method for QT autografts (compression) with the second most common HT autograft fixation method (compression)

| Variable | Quadriceps tendon group compression fixation (n=13) | Hamstring tendon group compression fixation (n=24) | Odds ratio | 95% confidence interval | p value |
|---|---|---|---|---|---|
| Anterior knee laxity | 268 subjects > Grade I/1143 subjects = Grade I | 244 subjects > Grade I/831 subjects = Grade I | 1.25 | 1.03–1.52 | 0.01* |
| Pivot shift laxity | 129 subjects with + test/764 subjects with − test | 200 subjects with + test/1068 subjects with − test | 1.11 | 0.87–1.41 | n.s. |
| Failure rate based on subject number at study initiation | 47 grafts failed out of 1222 at study initiation | 91 grafts failed out of 1401 at study initiation | 1.69 | 1.18–2.4 | 0.002* |
| Failure rate based on subject number at study completion | 47 subjects failed out of 1172 at study completion | 91 grafts failed out of 1200 at study completion | 1.89 | 1.32–2.71 | 0.0003* |

This comparison revealed greater anterior laxity and higher failure rates for the HT autograft group

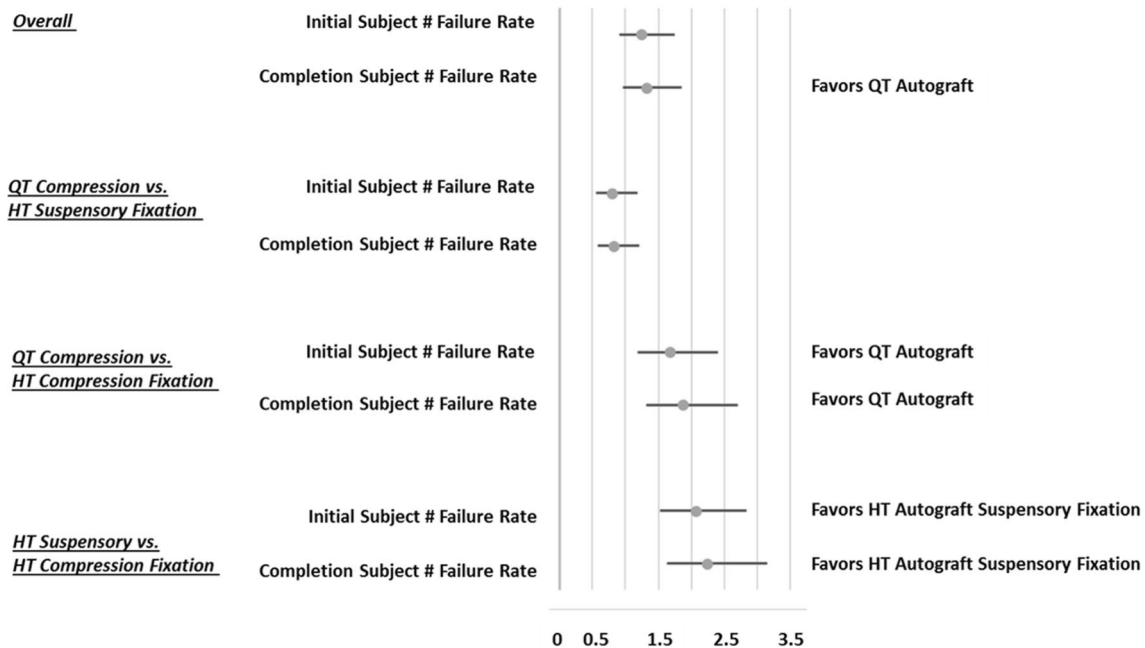*n.s.* Non-significant (*one-sided $p < 0.05$)



**Fig. 3** Forest plot of QT and HT autograft femoral fixation failure rates based on initial study subject number (#) and subject # at study completion. Based on subject # at study completion, the QT group displayed a lower failure rate. Based on initial study subject # and subject # at study completion the QT compression fixation group displayed lower failure rates than the HT compression fixation group. Based on initial study subject # and subject # at study completion the HT suspensory fixation group displayed lower failure rates than the HT compression fixation group

likely to stretch than rupture, while compression HT autograft femoral fixation may be more likely to rupture compared to QT autograft femoral fixation. Direct comparison of compression femoral fixation for both QT and HT autograft groups revealed increased anterior knee laxity for HT autografts compared to QT autografts. In addition, whether based on initial or final study subject number, failure rates were greater for HT autografts than for QT autografts when compression femoral fixation was used. This suggests that HT autograft compression femoral fixation may have greater graft failure potential compared to QT autografts. In association with a potentially less homogenous harvested HT or autograft construct, intra-tunnel compression fixation may contribute more to autograft failure among this group [16,

**Table 5** HT suspensory and compression femoral fixation did not display significant laxity differences

| Variable | Hamstring tendon group suspensory fixation ($n=32$) | Hamstring tendon group compression fixation ($n=24$) | Odds ratio | 95% confidence interval | p value |
|---|---|---|---|---|---|
| Anterior translation knee laxity | 491 subjects > Grade I/1920 subjects = Grade I | 244 subjects > Grade I/831 subjects = Grade I | 1.15 | 0.97–1.37 | n.s. |
| Pivot shift laxity | 345 subjects with + test/1616 subjects with − test | 200 subjects with + test/1068 subjects with − test | 0.87 | 0.73–1.06 | n.s. |
| Failure rate based on subject number at study initiation | 75 subjects failed out of 2402 at study initiation | 91 grafts failed out of 1401 at study initiation | 2.08 | 1.52–2.84 | < 0.0001* |
| Failure rate based on subject number at study completion | 75 subjects failed out of 2238 at study completion | 91 grafts failed out of 1200 at study completion | 2.26 | 1.63–3.16 | < 0.0001* |

Failure rates were higher for the compression fixation group

*n.s.* Non-significant (*one-sided $p < 0.05$)

19]. Direct comparisons between HT autografts with suspensory or compression femoral fixation, although insignificant for laxity differences, revealed that compression HT autograft femoral fixation displayed higher failure rates than suspensory fixation.

Diverse surgical methods make it difficult to make clear clinical decisions about the timing of safe rehabilitation milestone achievement and return to sports following ACL reconstruction. The best, if not perfect ACL graft may differ for each patient based on their unique anatomic or anthropometric characteristics and sports or vocational expectations [17, 21, 25]. Other factors that may influence ACL graft selection and rehabilitation program advancement may include past medical and surgical history, concomitant injuries to other knee tissues and adjacent joints, regional tissue quality, genetic laxity, distal femoral, and proximal tibial osseous anatomy such as notch dimensions and sagittal plane sloping, respectively, task-specific neuromuscular control skill, and the vocational or sporting activities to which the patient desires to return [17, 21, 25].

Most of the studies included in this systematic literature review represented prospective and retrospective non-comparative and comparative studies, not level I randomized controlled trials. More rigorous study selection criteria, however, would have excluded many studies and the important clinically meaningful information contained within. To better identify "real-world" conditions and the diverse clinical populations that they represent, this study consolidated information from multiple research study designs [9]. Careful screening by independent reviewers using study quality indicators such as heterogeneity assessments, PRISMA guidelines, KSSTA research evidence levels, secondary sensitivity assessments, MINORS evaluations and elimination of overlapping data sets helped control for bias [28], improve statistical power, and allowed for the inclusion of many studies that would have been omitted had more rigorous higher evidence level study inclusion restrictions been imposed.

Using established study identification and selection strategies [20] and bias control methods [28, 29], each study was assessed for knee joint laxity and failure rates. Based on low heterogeneity for the primary study variables of anterior knee laxity, pivot shift laxity, and failure rates, and the absence of statistically significant relationships between these variables and MINORS scores, data pooling was deemed appropriate. Each study that contributed to this meta-analysis used some form of instrumented anterior knee laxity assessment. However, several studies only reported anterior laxity as mean side-to-side anterior knee laxity differences, rather than graded laxity. Most studies graded anterior knee laxity using instrumented arthrometry, however, two Group 1 and three Group 2 studies graded laxity based on manual maximum anterior Lachman test methods. Finally, comparisons with suspensory QT autograft femoral fixation were not made as this group had small subject numbers with low statistical power.

## Conclusions

Overall, QT autografts displayed less pivot shift laxity and lower failure rates based on final subject number than HT autografts. Compression QT autograft femoral fixation had lower pivot shift laxity than suspensory HT autograft femoral fixation. Compression QT autograft femoral fixation had less anterior knee laxity and lower failure rates than compression HT autograft femoral fixation. Suspensory HT autograft femoral fixation had lower failure rates than compression HT autograft femoral fixation.

## Compliance with Ethical Standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** This manuscript is a systematic review and meta-analysis. Human participant research was not performed by any of the authors in carrying out this study.

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