Systematic Review

Anatomic Anterior Cruciate Ligament Reconstruction via Independent Tunnel Drilling: A Systematic Review of Randomized Controlled Trials Comparing Patellar Tendon and Hamstring Autografts

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Purpose: To collect the highest level of evidence comparing anatomic anterior cruciate ligament (ACL) reconstruction via independent tunnel drilling using bone−patellar tendon−bone (BTB) and hamstring tendon (HT) autografts in terms of clinical outcome and failure rate. **Methods:** We performed a systematic review of clinical trials that randomized patients to ACL reconstruction with either BTB or HT autografts with a minimum 2-year follow-up. Only trials using independent tunnel drilling, including outside-in and anteromedial portal techniques, for both autografts were eligible for inclusion, whereas all transtibial studies were excluded. Study design, demographics, surgical technique, rehabilitation protocol, and clinical outcomes were compiled. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed. Quality assessment was performed using the Coleman Methodological Scale (CMS). **Results:** Six published studies reporting on 5 randomized controlled trials (RCTs) met the inclusion criteria. No study reported a difference in rerupture rate between BTB and HT. BTB-reconstructed knees experienced a greater incidence of anterior knee pain or crepitus in 2/7 trials and radiographic evidence of degenerative change in 3/7 trials. HT-reconstructed knees had increased instrumented laxity in 2/7 trials and less knee flexion strength postoperatively. **Conclusions:** This study collects all available Level I and II evidence for anatomic ACL reconstruction using BTB and HT grafts. According to the data presented in these studies, clinical outcome scores and failure rates showed no differences for anatomic reconstruction using either autograft. However, in some studies, BTB-reconstructed knees experienced a greater incidence of anterior knee pain and radiographic evidence of degenerative change, and in others, HT-reconstructed knees had increased laxity and less knee flexion strength. In our opinion, both BTB and HT autografts remain valid options for ACL reconstruction when using anatomic drilling techniques, providing a stable knee with reliable return to activity. **Level of Evidence:** Level II, systematic review of Level I and II studies.

There remains no consensus on the optimal graft choice for anterior cruciate ligament (ACL) reconstruction, with both bone−patellar tendon−bone (BTB) and hamstring tendon (HT) autografts used extensively. Overall, both BTB and HT autografts have had excellent clinical results with low complication rates.[1,2] Attempts to conclusively show superiority of one technique over the other with respect to these 2 graft choices are challenging, as subjective success rates after ACL reconstruction are very high, thereby necessitating high-powered studies. To address this issue, several systematic reviews and meta-analyses have been published that compile data from multiple trials in an attempt to draw more robust conclusions.[3-9] This topic has been covered in such depth that a systematic review of the systematic reviews has also been published.[10] These studies have generally found only minor differences in outcome, including increased kneeling pain in BTB autografts and slightly increased laxity in KT-1000 testing with HT grafts.[8]

Traditionally, transtibial drilling techniques, which involve drilling the femoral tunnel through the tibial tunnel, have been used in ACL reconstruction. An

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The authors report the following potential conflicts of interest or sources of funding: F.T. receives support from Smith & Nephew (payment for lectures including service on speakers bureaus, in an Honorarium capacity). K.B.F. receives support from Mitek Sports Medicine (consultancy fees).

Received August 4, 2016; accepted January 5, 2017.

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0749-8063/16716/$36.00
http://dx.doi.org/10.1016/j.arthro.2017.01.033

increased emphasis on replication of the anatomic footprint of the original ACL (the so-called anatomic ACL) has led many surgeons to evolve their technique by independently drilling the tibial and femoral tunnels.[11-13] Although descriptions of independent drilling exist as early as the 1980s, these techniques have become more popular over the last decade. ACL reconstruction that incorporates the native tibial and femoral footprints provides better kinematics and rotational stability after ACL reconstruction.[14-22] Anatomically drilled ACL reconstructions more predictably place the graft in these footprints than transtibial drilling.[23-26]

Biomechanical studies suggest that anatomic ACL reconstruction places higher graft forces on the reconstructed ACL than more vertical transtibial grafts.[5] In addition, there are some recent data to suggest that despite anatomic placement, the failure rate could actually be higher with anatomic ACL reconstruction than traditional transtibial techniques.[27-30] It is unclear if there could be differences in failure rates with anatomic ACL reconstruction comparing BTB and HT autografts. We attempted to address this issue by conducting a systematic review of randomized controlled trials (RCTs) that compared outcomes after BTB and HT ACL reconstruction using anatomic drilling techniques. The purpose of this systematic review was to collect the highest level of evidence comparing anatomic ACL reconstruction via independent anteromedial portal drilling using BTB and HT autografts in terms of clinical outcome and failure rate. We hypothesized that no significant difference exists between these techniques with regard to clinical outcome or graft failure.

Methods

Study Eligibility Criteria

We performed a systematic review of prospective clinical trials of patients undergoing arthroscopic ACL reconstruction performed with independent tunnel drilling (anatomic ACL) enrolled randomly to receive either a BTB or HT autograft. All included studies were RCTs with a minimum 2-year follow-up. Studies that used a transtibial drilling technique for femoral tunnel placement or an insufficiently detailed description of the surgical technique were excluded.

Literature Search

Our literature search consisted of searches in Medline, PubMed, Google Scholar, Embase, and the Cochrane Central Register of Controlled Trials for the terms “anterior cruciate ligament,” “patellar tendon,” “hamstring,” and “randomized” from the inception of these search engines till February 2016. To ensure that no relevant studies were missed, the reference sections of all studies selected for final analysis were additionally reviewed. All potentially relevant papers were compiled to determine whether they fit the previously established inclusion criteria. The included articles identified by the search were each analyzed by a senior author (KBF) to ensure they were appropriate. Only RCTs comparing BTB and HT autograft and using independent tunnel drilling were included. Exclusion criteria included non−English language studies, nonhuman studies, techniques that did not use independent femoral drilling (i.e. transtibial), studies with insufficient description of surgical technique, nonrandomized studies, studies using historical controls, follow-up less than 2 years, use of allograft BTB or HT for reconstruction, and retracted articles. Inclusion and exclusion criteria are presented in Table 1. The results of this literature review are outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram in Figure 1.

Data Extraction

The data from each of the 6 trials meeting criteria for our systematic review was compiled. We collected demographic data, such as the sex ratio, proportion of patients with meniscus pathology, average age, average preinjury activity level, number of reconstructions performed, and number of patients remaining at each follow-up point. The surgical technique, postoperative pain control regimen, and postoperative rehabilitation protocol were recorded in all trials that reported them. All outcome measures were recorded for qualitative analysis. This included return to preinjury activity levels, time to return to sporting activity, Lysholm score, Lachman test, pivot shift, International Knee Documentation Committee (IKDC) activity grade, Tegner activity score, range of motion (ROM), loss of motion, pain with activity, pain when kneeling, anterior knee pain, single-leg hop test, isokinetic extension and flexion, kneeling test, knee walking test, KT-1000 interval, reoperations, graft failures, additional meniscus lesions, complications, and patient satisfaction. A meta-analysis was not performed because of the heterogeneity of the included studies in terms of both surgical technique and outcome assessment. Formal heterogeneity calculations were not performed.

Quality Assessment

To assess the quality of each study, the Coleman Methodological Scale (CMS) was used.[4] This tool is based on the CONSORT statement[31] and was originally developed for patellar tendinopathy but has since been used for other surgical operations. We used the same adaptations to the scale for ACL reconstruction as Gabler et al.[32] in a recent meta-analysis. There are 10 categories in the assessment and a maximum score of 100, with a higher score indicating increased avoidance

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Randomized controlled trials comparing BTB and HT autograft ACL reconstruction using independent drilling of the femoral tunnel	Techniques that used independent tunnel drilling (i.e. transtibial)
	Insufficient description of surgical technique
	Nonrandomized
	Historical controls
	Follow-up less than 2 years
	Allograft BTB or HT
	Retracted articles
	Non-English language
	Nonhuman studies

ACL, anterior cruciate ligament; BTB, bone−patellar tendon−bone; HT, hamstring tendon.

of chance, biases, and confounding factors in influencing results.

Results

An overview of the 6 included studies with year and journal of publication, level of evidence, follow-up, study size with percentage of patients at final follow-up, and key findings is provided in Table 2.

Study Design

The literature review described above yielded 6 manuscripts that met all inclusion criteria (see PRISMA flow diagram, Fig 1). Two of these manuscripts described the same series of patients in Slovenia at 2 different time points, 5- and 11-year follow up.[34,35] The remaining 4 studies described unique populations: 3 from the United States and 1 from Germany.[33,36-38] Years of publication ranged from 1991 to 2011, although 5 of the 6 manuscripts have been published since 2002. All studies had a minimum 2-year follow-up. Mean follow-up ranged from 29 months to 11 years. Follow-up rates for the studies, either explicitly stated or calculated from provided data, ranged from 69% to 90%. Study design data, including specific exclusion criteria and randomization methodology, is summarized in Appendix Table 1 (available at www.arthroscopyjournal.org).

Demographics

Demographic data are summarized in Appendix Table 2 (available at www.arthroscopyjournal.org). Within the individual studies, mean patient age ranged from 22.6 to 32.2 years. In all studies, there was no significant difference in age between the BTB and HT groups. Percentage of male patients ranged from 50% to 69%. Reported mean time from injury to surgery ranged from 11.2 weeks to 24 months. One study did not report time from injury to surgery.[36] Four studies reported the proportion of athletic participation among their patients.[33,36,38] Two studies (Shaieb et al.[33] and Wipfler et al.[38]) explicitly included all athletes, professional or recreational, whereas Marder et al.[36] reported that 80% of their patients were athletes (53 recreational, 11 competitive, and no professional athletes). Beynnon et al.[37] reported that 82% of their patients sustained their injury during a sports activity, and Sajovic et al.[34,35] did not address the proportion of athletes included in their studies.

Surgical Technique and Rehabilitation

All studies described femoral tunnel placement using an accessory anteromedial portal. Surgical technique and postoperative rehabilitation protocol data is summarized in Appendix Table 3 (available at www.arthroscopyjournal.org). Marder et al.[36] used a strain gauge to confirm tunnel positioning, accepting less than 2 mm of observed strain while the knee was flexed from 0° to 90° prior to graft placement. The remaining studies used standard drill guides and direct visualization for tunnel placement.[33-35,37] No study explicitly indicated whether it used curved or straight guides. Only Wipfler et al.[38] described a method of using K-wire and fluoroscopic C-arm guidance to confirm tunnel positioning. No study used routine intra- or postoperative computed tomography or magnetic resonance imaging to evaluate tunnel placement.

All BTB autografts were harvested from the central third of the patellar tendon and were 9 to 11 mm in width. BTB grafts were secured with interference screws in both the femur and tibia in 4 of 6 included studies.[33-35,37] Marder et al.[36] used a post-and-washer technique for both femoral and tibial fixation. Wipfler et al.[38] used a press-fit technique with the BTB bone plug into the femoral tunnel and a suture-bone bridge for tibial fixation.

All HT grafts included both semitendinosus and gracilis tendons harvested using commonly described tendon-stripping techniques. All studies except Beynnon et al. explicitly described “looping” or “doubling” of the HT graft to create a quadrupled graft. Two of the studies used interference screws in both the femur and tibia for fixation of their HT grafts.[33-35] Beynnon et al.[37] used staples for HT graft fixation. Marder et al.[36] used the same post-and-washer technique they described for fixation of their BTB grafts. Wipfler et al.[38] used a femoral bottleneck with a diameter equal to the

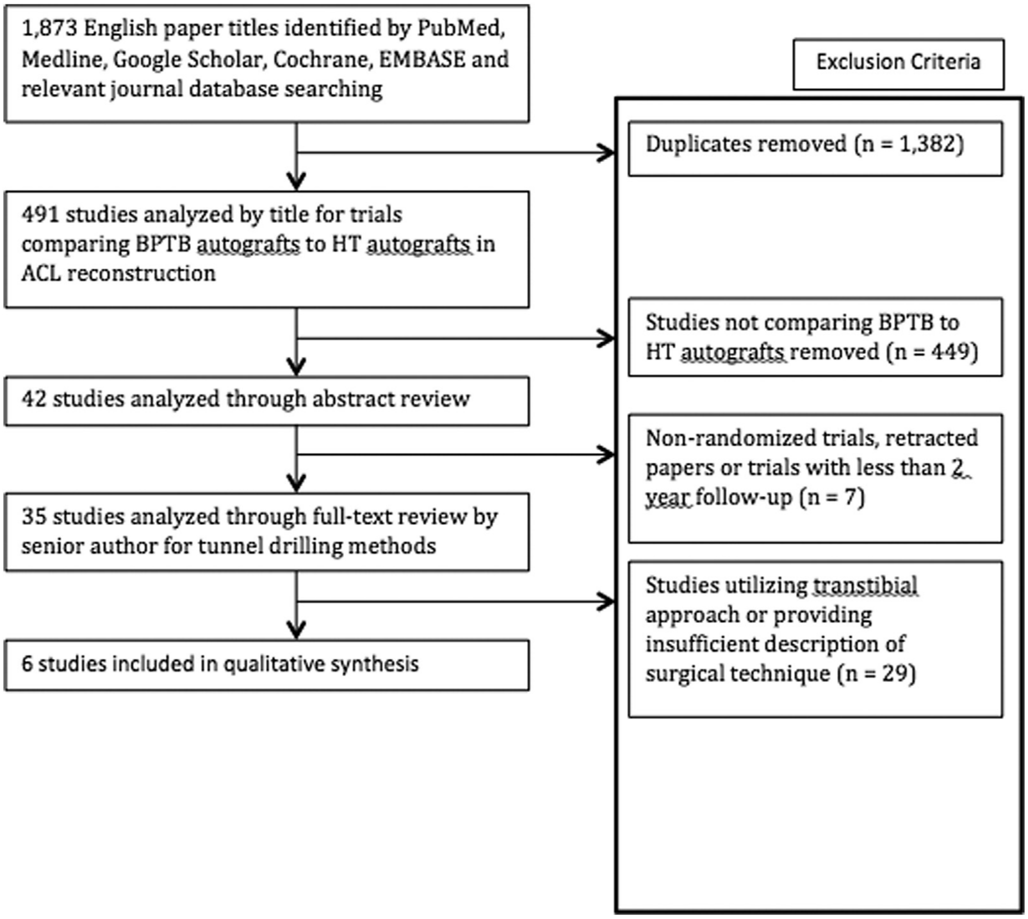

Fig 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram detailing the inclusion and exclusions of all studies identified by the initial literature search.

tendon loops but less than the tendon knot to secure the graft proximally and used a tibial bone bridge distally.

Significant heterogeneity existed with regard to rehabilitation programs among the studies. Four studies used a brace initially after surgery.[34-38] Three studies allowed weight bearing as tolerated by the end of the first postoperative week.[34,35,38] Beynnon et al.[37] progressed to weight bearing as tolerated by 3 weeks postoperation. Marder et al.[36] was the most conservative, progressing to full weight-bearing by 6 weeks postoperatively. Three studies encouraged early full ROM.[34,35,38] Beynnon et al.[37] progressed ROM over a period of 8 weeks. Marder et al.[36] did not allow unrestricted active ROM until 6 months.

Variations in return to activity also existed. Two studies allowed running at 2 months postoperatively.[33-35] Two studies allowed jogging/running at 3 and 4 months postoperatively, respectively.[37,38] Marder et al.[36] did not allow running prior to 7 months postoperatively. Four studies allowed return to sport as early as 5-6 months postoperatively.[33-35,37,38] However, Marder et al.[36] did not allow return to full activity prior to 10-12 months postoperatively. Two studies described the objective criteria for return to sports, including isokinetic strength 90% or greater compared with the contralateral leg, absence of an effusion, full ROM, <1 cm difference in thigh circumference, single-leg hop >90%, and firm end point for anterior tibial translation on clinical evaluation.[34,35,37]

Clinical Assessment

Clinical assessment data is presented in 2 tables; clinical and instrumented laxity as well as isokinetic strength testing are summarized in Appendix Table 4 (available at www.arthroscopyjournal.org) whereas graft failure, functional outcome scores and radiographic assessment are presented in Appendix Table 5 (available at www.arthroscopyjournal.org). Five studies explicitly reported on postoperative clinical stability testing. Wipfler et al.,[38] Shaieb et al.,[33] and Marder et al.[36] reported no statistically significant difference in Pivot Shift. Beynnon et al.[37] found superior Pivot-Shift and Lachman results in their BTB group. Three studies reported no difference in KT-1000 or KT-2000 instrumented arthrometry,[34-36,38] whereas Beynnon et al.[37] and Shaieb et al.[33] both reported statistically significantly greater laxity in the HT group.

Table 2. Included Study Overview

	Year of Publication (Journal)	Level of Evidence	Follow-Up	Patients: Enrolled/Final Follow-Up (%)	Positive Findings
Shaieb et al.[33]	2002 (*AJSM*)	1	2 years	n = 82/70 (85%)	1. Instrumented laxity: KT-1000 with greater side-to-side difference in laxity with HT than BTB
Sajovic et al.[34,35]	2006 and 2011 (*AJSM*)	1	5 and 11 years	n = 64/52 (82%)	1. Radiographic changes: BTB with greater IKDC grade B or worse findings on radiographs at 5 and 11 years
Marder et al.[36]	1991 (*AJSM*)	1	29 months	n = 80/72 (90%)	1. Flexion strength: HT with less peak torque at 60°/sec side-to-side than BTB
Beynnon et al.[37]	2002 (*JBJS*)	2	1 and 3 years	n = 56/44 (78%)	1. Clinical laxity: Lachman and Pivot shift greater in HT at 3 years 2. Instrumented laxity: KT-1000 with greater laxity in HT at 3 years 3. Flexion strength: HT with less peak flexion torque at 240°/sec side-to-side than BTB at 3 years
Wipfler et al.[38]	2011 (*Arthroscopy*)	2	1 and 9 years	n = 62/54 (87%)	1. Flexion strength: BTB with greater isokinetic flexion strength side-to-side at 1 year (no difference at 9 years) 2. Outcome scoring: IKDC activity grade significantly better in HT at 9 years 3. Radiographic changes: BTB with greater number of grade 3 or 4 chondral lesions in operated knee than contralateral on MRI

AJSM, American Journal of Sports Medicine; BTB, bone−patellar tendon−bone autograft; HT, hamstring tendon autograft; IKDC, International Knee Documentation Committee; *JBJS, Journal of Bone and Joint Surgery, American;* MRI, magnetic resonance imaging.

All studies reported on postoperative ROM. Beynnon et al.,[37] Marder et al.,[36] and Wipfler et al.[38] reported equivalent results in both groups. Shaieb et al.[33] also reported superior ROM in the HT group, although this was less than 5°.

Four studies reported some form of postoperative strength assessment. Sajovic et al.[34,35] reported no difference between groups in single-leg hop. Shaieb et al.[33] reported no difference in thigh circumference at final follow-up. Two studies performed isokinetic strength testing postoperatively, and each reported superior strength in the BTB group.[33-35] Wipfler et al.[38] reported significantly greater strength in the BTB group at 1 year, which had equilibrated by the 9-year follow-up in their study.

All studies reported on either anterior knee/patellofemoral pain or crepitus. Wipfler et al.[38] reported a significantly greater incidence of patellofemoral crepitus among BTB-reconstructed knees (73% vs 29%) at final follow-up. Shaieb et al.[33] reported a significantly greater incidence of patellofemoral pain in the BTB group (48% compared with 20% in the HT group).

All studies reported on graft failure rates, and no study reported a statistically significant difference between BTB and HT autografts. No study reported an association between recurrent injury, reoperation, or complications and a specific graft type.

Four studies used a postoperative scoring instrument. Two studies used the IKDC score and 2 reported no statistically significant difference between BTB and HT grafts.[37,38] Wipfler et al.[38] reported superior IKDC scores in their HT group. Similarly, 3 studies used the Lysholm score, and none reported a significant difference among groups at either time point.[33-35,38] Satisfaction was reported as equivalent by Wipfler et al.,[38] Beynnon et al.,[37] Shaieb et al.,[33] and Marder et al.[36]

Radiographic outcomes were reported by 2 studies, reporting statistically significantly greater degenerative changes on plain radiographs of BTB-reconstructed knees compared with HT-reconstructed knees.[34,35,38] Specific findings regarding IKDC grading of radiographic degenerative changes are presented in Appendix Table 5 (available at www.arthroscopyjournal.org). Wipfler et al.[38] used postoperative MRI for radiographic assessment and reported that BTB knees had a significantly greater number of grade 3 or 4 chondral lesions in the operated knee than in the contralateral knee; this was not found to be true among HT-reconstructed knees. Significant chondral degeneration was seen in both knees. No difference was noted in meniscal degeneration between the BTB and HT groups.

Quality Assessment

The mean CMS score for the included trials was 92.67, with a standard deviation of 5.57. The full results of the quality assessment are presented in Table 3. The primary reasons that studies lost points were the lack of independent or blinded observers, lack of written subjective examinations, and lack of reporting of the percentage of recruited patients who consented to be part of the trial. The high average CMS indicates that the trials had a low likelihood of being influenced by bias or confounding factors.

Discussion

The included studies found no difference in rerupture rate between BTB and HT, although there was some evidence of a greater incidence of anterior knee pain or radiographic change in BTB and instrumented laxity and lower knee flexion strength in HT. Despite being the most commonly reconstructed ligament in the knee, there is still considerable debate about which autograft source provides the best outcome for ACL reconstruction. Numerous level I RCTs have been conducted to analyze the relative merits of the 2 procedures, and the huge amount of data published on the topic has been used for several systematic reviews.[5-9,39,40] This is a dynamic pool of evidence, however, as evolution of surgical techniques may lead to improved outcomes. In particular, the use of independent femoral drilling through a dedicated portal may better re-create the femoral footprint, leading to more anatomic reconstruction, greater knee stability, and improved outcomes.[41-46] There remains controversy over any differences in outcome between BTB and HT autografts in terms of graft stability and complications. Previous systematic reviews evaluating this topic included trials using transtibial drilling techniques for graft placement. Whether or not any differences in clinical outcomes between differing graft sources are affected by anatomic graft placement remains unclear. We attempted to address this issue by conducting a new systematic review, analyzing only the evidence from RCTs using anatomic reconstruction techniques. This allowed us to analyze the highest-quality, most current evidence on this topic.

There is biomechanical evidence that anatomic ACL reconstruction provides more natural knee kinematics and rotational control after ACL reconstruction.[47] There is also evidence, however, that anatomic ACL reconstruction creates greater initial strain on the ACL graft than grafts placed transtibially.[47] BTB grafts incorporate within 6-12 weeks as a result of bone-to-bone tunnel healing, compared with 12 weeks for soft tissue grafts.[48-54] This difference in early healing could be more pronounced in early rehabilitation for anatomically placed ACL grafts, and therefore lead to greater differences in early failure comparing BTB and HT autografts. However, based on our systematic review, there was no difference in failure rate between the 2 grafts with anatomic techniques. It is important to note that the included studies were likely underpowered to definitely confirm that no statistical difference exists for failure rates between the 2 techniques. However, the fact that no difference has thus far been seen is encouraging.

The authors of the included studies came to a number of conclusions. Marder et al.[36] felt that results were comparable for BTB and HT autografts despite finding some statistically significant knee flexor weakness in their HT group compared with BTB. Beynnon et al.[37] concluded that although BTB and HT grafts were comparable in patient satisfaction, activity level, and knee function, BTB was superior with regard to knee laxity and strength of the knee flexors. Shaieb et al.[33] saw no difference in outcome or ability to play sports, but did note more patellofemoral pain in BTB reconstruction. This was similarly highlighted by Wipfler et al.[38] Finally, both Sajovic et al.[34,35] studies highlighted an increased prevalence of degenerative change in BTB-reconstructed knees at the 5- and 11-year follow-ups, as well as greater laxity in the form of a pivot shift in the BTB group at final follow-up.

The results of any group of studies can be difficult to synthesize into cohesive conclusions to guide clinical practice. Some results may even appear contradictory. However, we believe that some potentially useful conclusions can be drawn from our systematic review of the literature on anatomic ACL reconstruction comparing BTB and HT autografts. All other studies reported no statistically significant difference in outcome or return to play. Critically, no study found a difference with regard to graft rerupture rate. This is consistent with the results of a recent meta-analysis that included lower-quality evidence than our systematic review to analyze graft failure between anatomically placed HT autografts and anatomically placed BTB autografts.[32] With regard to knee laxity, one study suggested superiority of HT whereas another study suggested superiority of BTB. Residual knee laxity as measured by clinical evaluation such as Lachman or Pivot Shift Tests or by KT-1000/2000 arthrometer may not be clinically significant in terms of return to sports or residual symptoms. Some, but not all, studies noted an increased prevalence of anterior knee pain in those knees from which a BTB graft was harvested. No study identified a greater prevalence of anterior knee pain or kneeling pain in HT-reconstructed knees. Finally, 3 of the studies reported radiographic follow-up as late as 11 years postoperative and 2 of the 3 reported greater degenerative changes in BTB-reconstructed knees. No study reported greater degenerative changes in HT-reconstructed knees. Nonanatomic graft placement is commonly cited as a source of degenerative change after ACL reconstruction. However, this study reveals that anatomically placed ACLs may still lead to degenerative changes over time, and likely at a higher rate with BTB autografts.

Table 3. Coleman Methodology Scores

	Part A: Only 1 Score to be Given for Each of the 7 Sections							Part B: Scores May be Given for Each Option in Each of the 3 Sections if Applicable			
	1. Study Size: Number of ACL Reconstructions (n)	2. Mean Follow-Up (mo)	3. Number of Different Surgical Procedures Included in Each Reported Outcome	4. Type of Study	5. Diagnostic Certainty Described	6. Description of Surgical Procedure Given	7. Description of Postoperative Rehabilitation	1. Outcome Criteria	2. Procedure for Assessing Outcomes	3. Description of Subject Selection Process	Total Score
Possible score	10	5	10	15	5	5	10	10	15	15	100
Shaieb et al.[33]	10	5	10	15	5	5	10	10	9	15	94
Sajovic et al.[34,35]	10	5	10	15	5	5	10	10	15	15	100
Marder et al.[36]	10	5	10	15	5	5	10	8	5	15	88
Beynnon et al.[37]	7	5	10	15	5	5	10	10	8	10	85
Wipfler et al.[38]	10	0	10	15	5	5	10	10	12	10	92

ACL, anterior cruciate ligament.

This study has several strengths. It analyzes the highest level of evidence on this topic by including only Level I and II RCTs. Because previous systematic reviews included studies using transtibial approaches to compare BTB to HT autografts for ACL reconstruction, their results may not be predictive of outcomes for reconstructions performed using anatomically drilled tunnels. By limiting our inclusion criteria to only studies using anatomically drilled tunnels, we attempted to address whether or not anatomic drilling leads to any differences in failure rate or laxity when comparing BTB and HT autografts. No previous systematic review has analyzed the evidence in this fashion. Furthermore, our study presents results on many of the parameters that surgeons consider when selecting an autograft: clinical and instrumented laxity, isokinetic strength, patellofemoral pain and crepitus, failure/rerupture rate, functional outcome scoring instruments, and radiographic follow-up, rather than limited to graft failure alone. Our exclusion of all nonrandomized trials also limited the influence of confounding variables in influencing our results.

Limitations

This study also has several limitations. First, there are a limited number of studies performed using anatomic drilling techniques for ACL reconstruction comparing BTB and HT autografts. Like all systematic reviews, it is possible that the results discussed here are influenced by confounding factors or biases in the studies meeting our inclusion criteria. We have attempted to limit the influence of these factors by only including high-quality, Level I and II RCTs. Our focus on reconstructions using an anteromedial drilling technique also reduced the volume of available evidence, as only 7 studies met our inclusion criteria. In addition, we used independent drilling techniques as a surrogate for anatomic ACL placement. There is no definitive correlation that the independent drilling techniques used in each study represented true anatomic placement of the graft. In addition, this systematic review evaluated one technical aspect of reconstruction by analyzing studies using anatomic femoral tunnel placement drilled via an anteromedial portal. We also recognize that anatomic graft placement may be achieved with an "outside in" drilling approach, but there were no RCTs comparing these graft types with this drilling technique to achieve anatomic ACL placement. In addition, other technical aspects of surgery, such as graft tensioning and graft fixation may be equally critical for achieving stability in the reconstructed knee. As mentioned previously, the studies included in this analysis revealed a variety of confounding variables in this regard, such as method of graft fixation, rehabilitation timing, and return to play criteria, all of which could have had an impact on the final outcomes of these patients As noted above, the included studies were likely limited in terms of statistical power to definitively address a difference in failure rate. Finally, no meta-analysis was performed because of heterogeneity of the techniques used.

Conclusions

This study collects the highest level of evidence for anatomic ACL reconstruction using BTB and HT grafts. Based on the data presented in these Level I and II studies, the clinical outcome scores and failure rate showed no differences for anatomic reconstruction using either type of autograft. However, in some studies, BTB-reconstructed knees experienced a greater incidence of anterior knee pain and radiographic evidence of degenerative change, and in others, HT-reconstructed knees had increased laxity and less knee flexion strength. In our opinion, both BTB and HT autografts remain valid options for ACL reconstruction when using anatomic drilling techniques and can provide a stable knee with reliable return to activity.

References

1. Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q. A meta-analysis of bone—patellar tendon—bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. *Knee* 2015;22:100-110.
2. Webster KE, Feller JA, Hartnett N, Leigh WB, Richmond AK. Comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction: A 15-year follow-up of a randomized controlled trial. *Am J Sports Med* 2016;44:83-90.
3. Barrett GR, Noojin FK, Hartzog CW, Nash CR. Reconstruction of the anterior cruciate ligament in females. *Arthroscopy* 2002;18:46-54.
4. Coleman B, Khan K, Maffulli N, Cook J, Wark J. Studies of surgical outcome after patellar tendinopathy: Clinical significance of methodological deficiencies and guidelines for future studies. *Scand J Med Sci Sports* 2000;10:2-11.
5. Goldblatt JP, Fitzsimmons SE, Balk E, Richmond JC. Reconstruction of the anterior cruciate ligament: Meta-analysis of patellar tendon versus hamstring tendon autograft. *Arthroscopy* 2005;21:791-803.
6. 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:CD005960.
7. Prodromos CC, Joyce BT, Shi K, Keller BL. A meta-analysis of stability after anterior cruciate ligament reconstruction as a function of hamstring versus patellar tendon graft and fixation type. *Arthroscopy* 2005;21: 1202.e1-1202.e9.
8. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE Jr. Anterior cruciate ligament reconstruction autograft choice: Bone-tendon-bone versus hamstring: Does it really matter? A systematic review. *Am J Sports Med* 2004;32:1986-1995.
9. Yunes M, Richmond JC, Engels EA, Pinczewski LA. Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: A meta-analysis. *Arthroscopy* 2001;17:248-257.
10. Poolman RW, Abouali JA, Conter HJ, Bhandari M. Overlapping systematic reviews of anterior cruciate ligament reconstruction comparing hamstring autograft with bone-patellar tendon-bone autograft: Why are they different? *J Bone Joint Surg Am* 2007;89:1542-1552.
11. Riboh JC, Hasselblad V, Godin JA, Mather RC 3rd. Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: A systematic review, meta-analysis, and meta-regression. *Am J Sports Med* 2013;41:2693-2702.
12. Howell SM, Gittins ME, Gottlieb JE, Traina SM, Zoellner TM. The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. *Am J Sports Med* 2001;29:567-574.
13. O'Donnell JB, Scerpella TA. Endoscopic anterior cruciate ligament reconstruction: Modified technique and radiographic review. *Arthroscopy* 1995;11:577-584.
14. Bedi A, Maak T, Musahl V, et al. Effect of tunnel position and graft size in single-bundle anterior cruciate ligament reconstruction: An evaluation of time-zero knee stability. *Arthroscopy* 2011;27:1543-1551.
15. Bedi A, Musahl V, Steuber V, et al. Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: An anatomic and biomechanical evaluation of surgical technique. *Arthroscopy* 2011;27:380-390.
16. Dalldorf PG, Alexander J, Lintner DM. One- and two-incision anterior cruciate ligament reconstruction: A biomechanical comparison including the effect of simulated closed-chain exercise. *Arthroscopy* 1998;14:176-181.
17. Driscoll MD, Isabell GP, Conditt MA, et al. Comparison of 2 femoral tunnel locations in anatomic single-bundle anterior cruciate ligament reconstruction: A biomechanical study. *Arthroscopy* 2012;28:1481-1489.
18. Kato Y, Maeyama A, Lertwanich P, et al. Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2013;21:816-823.
19. Musahl V, Plakseychuk A, VanScyoc A, et al. Varying femoral tunnels between the anatomical footprint and isometric positions: Effect on kinematics of the anterior cruciate ligament-reconstructed knee. *Am J Sports Med* 2005;33:712-718.
20. Musahl V, Voos JE, O'Loughlin PF, et al. Comparing stability of different single-and double-bundle anterior cruciate ligament reconstruction techniques: A cadaveric study using navigation. *Arthroscopy* 2010;26:S41-S48.
21. Sim JA, Gadikota HR, Li JS, Li G, Gill TJ. Biomechanical evaluation of knee joint laxities and graft forces after anterior cruciate ligament reconstruction by anteromedial portal, outside-in, and transtibial techniques. *Am J Sports Med* 2011;39:2604-2610.
22. Steiner ME, Battaglia TC, Heming JF, Rand JD, Festa A, Baria M. Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med* 2009;37:1912-1919.
23. Gadikota HR, Sim JA, Hosseini A, Gill TJ, Li G. The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and

the anterior cruciate ligament footprint. *Am J Sports Med* 2012;40:882-888.
24. Kaseta MK, DeFrate LE, Charnock BL, Sullivan RT, Garrett WE Jr. Reconstruction technique affects femoral tunnel placement in ACL reconstruction. *Clin Orthop* 2008;466:1467-1474.
25. Strauss EJ, Barker JU, McGill K, Cole BJ, Bach BR Jr, Verma NN. Can anatomic femoral tunnel placement be achieved using a transtibial technique for hamstring anterior cruciate ligament reconstruction? *Am J Sports Med* 2011;39:1263-1269.
26. Tompkins M, Milewski MD, Brockmeier SF, Gaskin CM, Hart JM, Miller MD. Anatomic femoral tunnel drilling in anterior cruciate ligament reconstruction: Use of an accessory medial portal versus traditional transtibial drilling. *Am J Sports Med* 2012;40:1313-1321.
27. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC. Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: Results from the Danish Knee Ligament Reconstruction Register. *Arthroscopy* 2013;29:98-105.
28. 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;21:948-957.
29. Snow M, Campbell G, Adlington J, Stanish WD. Two to five year results of primary ACL reconstruction using doubled tibialis anterior allograft. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1374-1378.
30. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH. Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. *Am J Sports Med* 2012;40: 800-807.
31. Altman DG, Schulz KF, Moher D, et al. The revised CONSORT statement for reporting randomized trials: Explanation and elaboration. *Ann Intern Med* 2001;134: 663-694.
32. Gabler CM, Jacobs CA, Howard JS, Mattacola CG, Johnson DL. Comparison of graft failure rate between autografts placed via an anatomic anterior cruciate ligament reconstruction technique: A systematic review, meta-analysis, and meta-regression. *Am J Sports Med* 2016;44:1069-1079.
33. Shaieb MD, Kan DM, Chang SK, Marumoto JM, Richardson AB. A prospective randomized comparison of patellar tendon versus semitendinosus and gracilis tendon autografts for anterior cruciate ligament reconstruction. *Am J Sports Med* 2002;30:214-220.
34. Sajovic M, Vengust V, Komadina R, Tavcar R, Skaza K. A prospective, randomized comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: Five-year follow-up. *Am J Sports Med* 2006;34:1933-1940.
35. Sajovic M, Strahovnik A, Dernovsek MZ, Skaza K. Quality of life and clinical outcome comparison of semitendinosus and gracilis tendon versus patellar tendon autografts for anterior cruciate ligament reconstruction: An 11-year follow-up of a randomized controlled trial. *Am J Sports Med* 2011;39:2161-2169.
36. Marder RA, Raskind JR, Carroll M. Prospective evaluation of arthroscopically assisted anterior cruciate ligament reconstruction. Patellar tendon versus semitendinosus and gracilis tendons. *Am J Sports Med* 1991;19:478-484.
37. Beynnon BD, Johnson RJ, Fleming BC, et al. Anterior cruciate ligament replacement: Comparison of bone-patellar tendon-bone grafts with two-strand hamstring grafts. A prospective, randomized study. *J Bone Joint Surg Am* 2002;84:1503-1513.
38. Wipfler B, Donner S, Zechmann CM, Springer J, Siebold R, Paessler HH. Anterior cruciate ligament reconstruction using patellar tendon versus hamstring tendon: A prospective comparative study with 9-year follow-up. *Arthroscopy* 2011;27:653-665.
39. Dauty M, Tortellier L, Rochcongar P. Isokinetic and anterior cruciate ligament reconstruction with hamstrings or patella tendon graft: Analysis of literature. *Int J Sports Med* 2005;26:599-606.
40. Biau DJ, Tournoux C, Katsahian S, Schranz PJ, Nizard RS. Bone-patellar tendon-bone autografts versus hamstring autografts for reconstruction of anterior cruciate ligament: Meta-analysis. *BMJ* 2006;332:995-1001.
41. Alentorn-Geli E, Samitier G, Álvarez P, Steinbacher G, Cugat R. Anteromedial portal versus transtibial drilling techniques in ACL reconstruction: A blinded cross-sectional study at two-to five-year follow-up. *Int Orthop* 2010;34:747-754.
42. Alentorn-Geli E, Lajara F, Samitier G, Cugat R. The transtibial versus the anteromedial portal technique in the arthroscopic bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1013-1037.
43. Duffee A, Magnussen RA, Pedroza AD, Flanigan DC. MOON Group, Kaeding CC. Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am* 2013;95:2035-2042.
44. Franceschi F, Papalia R, Rizzello G, Del Buono A, Maffulli N, Denaro V. Anteromedial portal versus transtibial drilling techniques in anterior cruciate ligament reconstruction: Any clinical relevance? A retrospective comparative study. *Arthroscopy* 2013;29:1330-1337.
45. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. *Am J Sports Med* 2012;40:512-520.
46. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: Comparisons among 3 different procedures. *Arthroscopy* 2006;22:240-251.
47. Araujo PH, Asai S, Pinto M, et al. ACL graft position affects in situ graft force following ACL reconstruction. *J Bone Joint Surg Am* 2015;97:1767-1773.
48. Ekdahl M, Nozaki M, Ferretti M, Tsai A, Smolinski P, Fu FH. The effect of tunnel placement on bone-tendon healing in anterior cruciate ligament reconstruction in a goat model. *Am J Sports Med* 2009;37:1522-1530.
49. Kondo E, Yasuda K, Katsura T, Hayashi R, Kotani Y, Tohyama H. Biomechanical and histological

evaluations of the doubled semitendinosus tendon autograft after anterior cruciate ligament reconstruction in sheep. *Am J Sports Med* 2012;40: 315-324.

50. Kanazawa T, Soejima T, Murakami H, Inoue T, Katouda M, Nagata K. An immunohistological study of the integration at the bone-tendon interface after reconstruction of the anterior cruciate ligament in rabbits. *J Bone Joint Surg Br* 2006;88:682-687.
51. Liu SH, Panossian V, Al-Shaikh R, et al. Morphology and matrix composition during early tendon to bone healing. *Clin Orthop* 1997;339:253-260.
52. Ma CB, Kawamura S, Deng XH, et al. Bone morphogenetic proteins-signaling plays a role in tendon-to-bone healing: A study of rhBMP-2 and noggin. *Am J Sports Med* 2007;35:597-604.
53. Rodeo SA, Suzuki K, Deng XH, Wozney J, Warren RF. Use of recombinant human bone morphogenetic protein-2 to enhance tendon healing in a bone tunnel. *Am J Sports Med* 1999;27:476-488.
54. Kuang G, Yau W, Lu WW, Chiu K. Osteointegration of soft tissue grafts within the bone tunnels in anterior cruciate ligament reconstruction can be enhanced. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1038-1051.

Appendix Table 1. Study Design for Included Studies

	Level of Evidence	Years of Publication	Journal	Number of Operating Surgeons	Country of Study Performance	Years of Patient Enrollment	Randomization Method	Inclusion Criteria	Exclusion Criteria	Interval 1 Time Point	Interval 2 Time Point
Shaieb et al.[33]	Level I	2002	*American Journal of Sports Medicine*	1	USA	1994-1996	Odd/even birthdate	Need for ACL reconstruction	Any concomitant ligament injury, prior ACL reconstruction	2 years	
Sajovic et al.[34,35]	Level I	2006, 2011	*American Journal of Sports Medicine*	1	Slovenia	1999-2000	Operative registration list position (even number = BTB, odd number = HT)	ACL rupture	Associated ligament injury, previous meniscectomy, radiographic abnormality, contralateral pathology, revision during follow-up period	5 years	11 years
Marder et al.[36]	Level I	1991	*American Journal of Sports Medicine*	1	USA	1986-1988	Alternating allocation	Chronic laxity, including patients with previous ACL reconstruction	Full-thickness chondral lesions, previous meniscectomy	29 months (range 24-40)	
Beynnon et al.[37]	Level II	2002	*Journal of Bone and Joint Surgery*	3	USA	1990-1991	Random number table	ACL tear	Previous operation on either knee, concurrent PCL/PLC/LCL or MCL grade 3 injury, concurrent fracture, osteoarthritis	1 year	3 years
Wipfler et al.[38]	Level II	2011	*Arthroscopy*	1	Germany	1998-1999	Coin flip	Acute ACL rupture	Any concomitant ligament or meniscus injury, any previous surgery, chondral lesion > grade 2, any damage to contralateral knee	1 year	9 years

ACL, anterior cruciate ligament; BTB, bone−patellar tendon−bone autograft; HT, hamstring autograft; LCL, lateral collateral ligament; MCL, medial collateral ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.

Appendix Table 2. Patient Demographics of Included Studies

	Enrolled/ Randomized	Lost to Follow-Up	Follow-Up Rate	Hamstring Mean Time to Surgery	BTB Mean Time to Surgery	Hamstring Male/ Female Ratio	BTB Male/ Female Ratio	Preinjury Sports Activity
Shaieb et al.[33]	82	12	57/82 = 69%	18.9 weeks (n = 37)	19.5 weeks (n = 33)	21 M/16 F	26 M/7 F	64 recreational, 18 competitive
Sajovic et al.[34,35]	64	10	54/64 = 85% (5 years), 52/64 = 82% (11 years)	25 months (range = 1-84 months) (n = 28)	23 months (range = 1-60 months) (n = 26)	13 M/15 F	14 M/12 F	Not addressed
Marder et al.[36]	80	8	72/80 = 90%	Not given	Not given	26 M/9 F	24 M/13 F	53 recreational, 11 competitive
Beynnon et al.[37]	56	12	44/56 = 78%	15.6 weeks (range = 17-270 days) (n = 22)	11 weeks (range = 18-305) (n = 22)	18 M/10 F	13 M/15 F	Not addressed, but 82% injured during a sports activity
Wipfler et al.[38]	62	8	54/62 = 87%	11.1 weeks (n = 31)	11.2 weeks (n = 31)	19 M/12 F	18 M/13 F	All recreational or competitive athletes

F, female; M, male.

Appendix Table 3. Surgical Technique and Postoperative Rehabilitation Protocol in Each Included Trial

	BTB Femoral Fixation	HT Femoral Fixation	BTB Tibial Fixation	HT Tibial Fixation	HT Strands	Graft Fixation Flexion Angle	Graft/Tunnel Position Verification	Postoperative Brace	Postoperative Weight Bearing	Postoperative ROM Limitations	Return to Activity
Shaieb et al.[33]	Interference screw	Interference screw	Interference screw	Interference screw	4	Not stated	Drill guide/direct visualization	Not addressed	Full WBAT by end of 1st week	Full ROM by end of 1st week	Running at 2 months; Sports at 5-6 months
Sajovic et al.[34,35]	Interference screw	Interference screw	Interference screw	Interference screw	4	10°	Drill guide/direct visualization	Brace × 3 weeks	Immediate full WBAT	Immediate full ROM	Running at 8 weeks; Sports at 6 months
Marder et al.[36]	Suture	Suture	Suture	Suture	2	30°	Intraoperative strain gauge	Brace × 6 weeks	Initially toe-touch weight bearing; Full WBAT by 6 weeks	Active flexion at tolerated TID allowed starting POD1	Running at 7 months; Sports at 10-12 months
Beynnon et al.[37]	Interference screw	Staples	Interference screw	Staples	2	Not stated	Drill guide/direct visualization	Brace × 4 weeks	Initially TTWB on crutches × 3 week then WBAT	Locked at 10° flexion for 1 week; 0°-70° till week 3; 0°-90° until brace discontinued at week 5; encouraged to achieve full ROM at week 8	Running at 4 months; Sports at 6-8 months if isokinetic strength 90% of contralateral leg, no effusion, full ROM
Wipfler et al.[38]	Bone plug	Knotted tendons in bottleneck tunnel	Bone plug	Suture	4	10°	Intraoperative fluoroscopy	Brace × 6 weeks	Immediate full WBAT	Immediate full ROM	Jogging at 3 months; minimum 6 months to sports

BTB, bone−patellar tendon−bone autograft; HT, hamstring tendon autograft; POD, postoperative day; ROM, range of motion; TTWB, toe-touch weight bearing; WBAT, weight bearing as tolerated.

Appendix Table 4. Clinical and Instrumented Laxity and Isokinetic Strength Testing

	Clinical Stability	Instrumented Arthrometry	Isokinetic Testing
Shaieb et al.[33]	Postoperative pivot shift (no difference) (*P* = not given) HT: 1+ in 4 patients (n = 4/35) BTB: 1+ in 5 patients (n = 5/31) Postoperative Lachman (no difference) (*P* = not given) HT: 0.4 (mean) (n = 35) BTB: 0.35 (mean) (n = 31)	KT-1000 with greater side-to-side difference in laxity at 89 N with HT than BTB (*P* = .08) HT: 2.4 mm (n = 35) BTB: 1.4 mm (n = 31)	Not stated
Sajovic et al.[34,35]	Postoperative pivot shift (*P* = .036) HT: 1+ in 2 patients (n = 2/27) BTB: 1+ in 7 patients (n = 7/25)	No difference in laxity measured on KT-2000 at 5 years (*P* = .646) HT: 1.6 ± 2.4 mm (n = 28) BTB: 1.9 ± 2.0 mm (n = 26) No difference in laxity measured on KT-1000 at 11 years (*P* = .069) HT: 1.5 ± 2.0 mm (n = 27) BTB: 2.5 ± 1.7 mm (n = 25)	Not stated
Marder et al.[36]	Postoperative pivot shift (no difference) (*P* = not given) HT: 0.5 (mean) (n = 35) BTB: 0.3 (mean) (n = 37) Postoperative Lachman (no difference) (*P* = not given) HT: 0.7 (mean) (n = 35) BTB: 0.5 (mean) (n = 37)	KT-1000 with no difference in side-to-side laxity (*P* = not given) HT: 1.9 ± 1.3 mm (n = 35) BTB: 1.6 ± 1.4 mm (n = 37)	HT with less peak torque at 60°/sec than the uninjured side (*P* = .025) HT: 83 ± 16% (n = 35) BTB: 91 ± 18% (n = 37)
Beynnon et al.[37]	Lachman greater in HT at 3 years (*P* = .001) HT: 59% with 2+ or greater (n = 13/22) BTB: 9% with 2+ or greater (n = 2/22) Pivot shift greater in HT at 3 years (*P* = .024) HT: 59% without a pivot shift (n = 13/22) BTB: 86% without a pivot shift (n = 19/22)	KT-1000 with greater laxity in HT at 3 years (*P* = .004) HT: 55% with greater than 3 mm laxity (n = 12/22) BTB: 23% with greater than 3 mm laxity (n = 5/22)	HT with 11% decrease in peak flexion torque at 240°/sec at 3 years than the uninjured side (*P* = .039) HT: 100.3% (n = 22) BTB: 89.3% (n = 22)
Wipfler et al.[38]	No difference in Lachlan at 9 years (*P* = .481) HT: 0.45 ± 0.11 (SEM) (n = 25) BTB: 0.56 ± 0.10 (SEM) (n = 29) No difference in pivot shift at 9 years (*P* = .439) HT: 0.18 ± 0.08 (SEM) (n = 25) BTB: 0.28 ± 0.09 (SEM) (n = 29)	No difference in KT-1000 at 9 years (*P* = .553) HT: 0.64 mm ± 0.36 (SEM) (n = 25) BTB: 0.90 mm ± 0.27 (SEM) (n = 29)	BTB with greater isokinetic flexion strength than the uninjured leg than HT at 1 year (*P* = .009) HT: 90.34% ± 1.43% (SEM) (n = 25) BTB: 99.14% ± 2.87% (SEM) (n = 29) No difference in isokinetic flexion at 9 years (*P* = .588) HT: 95.06% ± 3.31% (SEM) (n = 25) BTB: 100.29% ± 3.08% (SEM) (n = 29)

BTB, bone–patellar tendon–bone autograft; HT, hamstring autograft; SEM, standard error of the mean.

Appendix Table 5. Functional Outcomes and Complications

	Rerupture Rate	Scoring Instruments	Radiographic Evaluation
Shaieb et al.[33]	No significant difference in failure rate (*P* = not given) 4 total failures (4/70 = 5.7%) HT: 2 failures (n = 2/35) BTB: 2 failures (n = 2/31)	No difference in number of excellent to good Lysholm scores (*P* = .6) HT: 87% (n = 35) BTB: 94% (n = 31)	Not stated
Sajovic et al.[34,35]	No significant difference in failure rate (*P* = not given) 4 failures at 5 years (4/64 = 6.3%) HT: 2 failures (n = 2/28) BTB: 2 failures (n = 2/26) 6 failures at 11 years (6/64 = 9.4%) HT: 2 failures (n = 2/27) BTB: 4 failures (n = 4/25)	No difference in Lysholm score at 11 years (*P* = .314) HT: 95 (mean) (n = 27) BTB: 94 (mean) (n = 25)	Significantly more frequent IKDC grade B or C in BTB compared HT at 5 years (*P* = .012) HT: 17% (n = 5/28) BTB: 50% (n = 12/26) Significantly more frequent IKDC grades B-D in BTB than HT at 11 years (*P* = .008) HT: 63% (n = 17/27) BTB: 84% (n = 21/25)
Marder et al.[36]	No significant difference in failure rate (*P* = not given) 2 failures (2/72 = 2.8%) HT: 1 failure (n = 1/35) BTB: 1 failure (n = 1/37)	Not stated	Not stated
Beynnon et al.[37]	No significant difference in failure rate (*P* = not given) 0 failures (0/44 = 0.0%) HT: 0 failures (n = 0/22) BTB: 0 failures (n = 0/22)	No difference in Tegner score at 3 years (*P* = not given) HT: 5 points (median) (n = 22) BTB: 6 points (median) (n = 22) No difference in IKDC activity scores at 3 years (*P* = not given) HT: 86% Grade I or II (n = 22) BTB: 82% Grade I or II (n = 22)	Not stated
Wipfler et al.[38]	No significant difference in failure rate (*P* = not given) 6 failures (6/62 = 9.6%) HT: 3 failures (n = 3/25) BTB: 3 failures (n = 3/29)	No difference in Lysholm score at 9 years (*P* = .073) HT: 91.82 ± 1.76 (SEM) (n = 25) BTB: 87.28 ± 1.71 (SEM) (n = 29) No difference in Tegner score at 9 years (*P* = .9) HT: 6.14 ± 0.37 (SEM) (n = 25) BTB: 6.20 ± 0.35 (SEM) (n = 29) IKDC grade significantly better in HT at 9 years (*P* = .002) HT: 1.55 ± 0.13 (SEM) (*P* = 25) BTB: 2.08 ± 0.09 (SEM) (*P* = 29)	BTB with greater number of grade 3 or 4 chondral lesions on operated knee than contralateral on MRI (*P* = .040) BTB operated knee: 30.4% BTB contralateral knee: 13.0%

BTB, bone−patellar tendon−bone autograft; HT, hamstring tendon autograft; IKDC, International Knee Documentation Committee score; MRI, magnetic resonance imaging; SEM, standard error of the mean.