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. 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. This topic has been covered in such depth that a systematic review of the systematic reviews has also been published. 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.

Traditionally, transtibial drilling techniques, which involve drilling the femoral tunnel through the tibial tunnel, have been used in ACL reconstruction. An
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. 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. Anatomically drilled ACL reconstructions more predictably place the graft in these footprints than trans-tibial drilling.

Biomechanical studies suggest that anatomic ACL reconstruction places higher graft forces on the reconstructed ACL than more vertical transtibial grafts. 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. 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. trans-tibial), 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. This tool is based on the CONSORT statement 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. 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
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. The remaining 4 studies described unique populations: 3 from the United States and 1 from Germany. 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 2.

Demographics
Demographic data are summarized in Appendix Table 2. 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. Four studies reported the proportion of athletic participation among their patients. Two studies (Shaieb et al. and Wipfler et al.) explicitly included all athletes, professional or recreational, whereas Marder et al. reported that 80% of their patients were athletes (53 recreational, 11 competitive, and no professional athletes). Beynnon et al. reported that 82% of their patients sustained their injury during a sports activity, and Sajovic et al. 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. Marder et al. 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. Study explicitly indicated whether it used curved or straight guides. Only Wipfler et al. 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. Marder et al. used a post-and-washer technique for both femoral and tibial fixation. Wipfler et al. 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. Marder et al. used staples for HT graft fixation. Marder et al. used the same post-and-washer technique they described for fixation of their BTB grafts. Wipfler et al. used a femoral bottleneck with a diameter equal to the
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. Three studies allowed weight bearing as tolerated by the end of the first postoperative week. Beynnon et al. progressed to weight bearing as tolerated by 3 weeks postoperation. Marder et al. was the most conservative, progressing to full weight-bearing by 6 weeks postoperatively. Three studies encouraged early full ROM. Beynnon et al. progressed ROM over a period of 8 weeks. Marder et al. did not allow unrestricted active ROM until 6 months.

Variations in return to activity also existed. Two studies allowed running at 2 months postoperatively. Two studies allowed jogging/running at 3 and 4 months postoperatively, respectively. Marder et al. did not allow running prior to 7 months postoperatively. Four studies allowed return to sport as early as 5-6 months postoperatively. However, Marder et al. 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.

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., Shaieb et al., and Marder et al. reported no statistically significant difference in Pivot Shift. Beynnon et al. found superior Pivot-Shift and Lachman results in their BTB group. Three studies reported no difference in KT-1000 or KT-2000 instrumented arthrometry, whereas Beynnon et al. and Shaieb et al. both reported statistically significantly greater laxity in the HT group.
All studies reported on postoperative ROM. Beynnon et al., Marder et al., and Wipfler et al. reported equivalent results in both groups. Shaieb et al. 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. and Wipfler et al. reported superior BTB group strength at 1 year, which had equilibrated by the 9-year follow-up in their study.

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 reported no statistically significant difference between BTB and HT autografts. Wipfler et al. 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.

Satisfaction was reported as equivalent by Wipfler et al., Beynnon et al., Shaieb et al., and Marder et al.

Radiographic outcomes were reported by 2 studies, reporting statistically significant degenerative changes on plain radiographs of BTB-reconstructed knees compared to the contralateral knee. This was not found to be the case in the HT-reconstructed knee. A specific finding was increased tibial plateaus, which was greater in the HT-reconstructed knee. Significant chondral degeneration was seen in both knees. No difference was noted in meniscal degeneration between the BTB and HT groups.

The mean CMS score for the included trials was 92.67, with a standard deviation of 5.57. The full results are presented in Table 2.

### Table 2. Included Study Overview

<table>
<thead>
<tr>
<th>Year of Publication (Journal)</th>
<th>Level of Evidence</th>
<th>Follow-Up</th>
<th>Patients: Enrolled/Final Follow-Up (%)</th>
<th>Positive Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaieb et al.33 2002 (AJSM)</td>
<td>1</td>
<td>2 years</td>
<td>n = 82/70 (85%)</td>
<td>1. Instrumented laxity: KT-1000 with greater side-to-side difference in laxity with HT than BTB</td>
</tr>
<tr>
<td>Sajovic et al.34,35 2006 and 2011 (AJSM)</td>
<td>1</td>
<td>5 and 11 years</td>
<td>n = 64/52 (82%)</td>
<td>1. Radiographic changes: BTB with greater IKDC grade B or worse findings on radiographs at 5 and 11 years</td>
</tr>
<tr>
<td>Marder et al.36 1991 (AJSM)</td>
<td>1</td>
<td>29 months</td>
<td>n = 80/72 (90%)</td>
<td>1. Flexion strength: HT with less peak torque at 60°/sec side-to-side than BTB</td>
</tr>
<tr>
<td>Beynnon et al.37 2002 (JBJS)</td>
<td>2</td>
<td>1 and 3 years</td>
<td>n = 56/44 (78%)</td>
<td>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</td>
</tr>
<tr>
<td>Wipfler et al.38 2011 (Arthroscopy)</td>
<td>2</td>
<td>1 and 9 years</td>
<td>n = 62/54 (87%)</td>
<td>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</td>
</tr>
</tbody>
</table>

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.3-9,39,40 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 translabral 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.57 There is also evidence, however, that anatomic ACL reconstruction creates greater initial strain on the ACL graft than grafts placed transtibially.17 BTB grafts incorporate within 6-12 weeks as a result of bone-to-bone tunnel healing, compared with 12 weeks for soft tissue grafts.38-54 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. Beynon 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 Wippler 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.12 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.
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 only 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


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...


### Appendix Table 1. Study Design for Included Studies

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

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

<table>
<thead>
<tr>
<th>Study</th>
<th>Enrolled/Randomized</th>
<th>Lost to Follow-Up</th>
<th>Follow-Up Rate</th>
<th>Hamstring Mean Time to Surgery</th>
<th>BTB Mean Time to Surgery</th>
<th>Hamstring Male/Female Ratio</th>
<th>BTB Male/Female Ratio</th>
<th>Preinjury Sports Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaieb et al.33</td>
<td>82</td>
<td>12</td>
<td>57/82 = 69%</td>
<td>18.9 weeks (n = 37)</td>
<td>19.5 weeks (n = 33)</td>
<td>21 M/16 F</td>
<td>26 M/7 F</td>
<td>64 recreational, 18 competitive</td>
</tr>
<tr>
<td>Sajovic et al.34,35</td>
<td>64</td>
<td>10</td>
<td>54/64 = 85%</td>
<td>25 months (range = 1-84 months)</td>
<td>23 months (range = 1-60 months)</td>
<td>13 M/15 F</td>
<td>14 M/12 F</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Marder et al.36</td>
<td>80</td>
<td>8</td>
<td>72/80 = 90%</td>
<td>Not given</td>
<td>Not given</td>
<td>26 M/9 F</td>
<td>24 M/13 F</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Beynnon et al.37</td>
<td>56</td>
<td>12</td>
<td>44/56 = 78%</td>
<td>15.6 weeks (range = 1-270 days)</td>
<td>11 weeks (range = 1-805)</td>
<td>18 M/10 F</td>
<td>13 M/15 F</td>
<td>Not addressed, but 82% injured during a sports activity</td>
</tr>
<tr>
<td>Wipfler et al.38</td>
<td>62</td>
<td>8</td>
<td>54/62 = 87%</td>
<td>11.1 weeks (n = 31)</td>
<td>11.2 weeks (n = 31)</td>
<td>19 M/12 F</td>
<td>18 M/13 F</td>
<td>All recreational or competitive athletes</td>
</tr>
</tbody>
</table>

F, female; M, male.
### Appendix Table 3. Surgical Technique and Postoperative Rehabilitation Protocol in Each Included Trial

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

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

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

BTB, bone–patellar tendon–bone autograft; HT, hamstring autograft; SEM, standard error of the mean.
### Appendix Table 5. Functional Outcomes and Complications

<table>
<thead>
<tr>
<th>Rerupture Rate</th>
<th>Scoring Instruments</th>
<th>Radiographic Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shaieb et al.</strong>&lt;sup&gt;33&lt;/sup&gt;</td>
<td>No significant difference in failure rate ($P$ = not given)</td>
<td>No difference in number of excellent to good Lysholm scores ($P$ = .6)</td>
</tr>
<tr>
<td>4 total failures (4/70 = 5.7%)</td>
<td>HT: 2 failures (n = 2/35)</td>
<td>HT: 87% (n = 35)</td>
</tr>
<tr>
<td>BTB: 2 failures (n = 2/31)</td>
<td>BTB: 94% (n = 31)</td>
<td></td>
</tr>
<tr>
<td>4 total failures (4/70 = 5.7%)</td>
<td>No difference in Lysholm score at 11 years ($P$ = .314)</td>
<td></td>
</tr>
<tr>
<td>HT: 2 failures (n = 2/28)</td>
<td>HT: 95 (mean) (n = 27)</td>
<td>Significantly more frequent IKDC grade B or C in BTB compared HT at 5 years ($P$ = .012)</td>
</tr>
<tr>
<td>BTB: 2 failures (n = 2/26)</td>
<td>BTB: 94 (mean) (n = 25)</td>
<td>HT: 17% (n = 5/28)</td>
</tr>
<tr>
<td>6 failures at 11 years (6/64 = 9.4%)</td>
<td></td>
<td>BTB: 50% (n = 12/26)</td>
</tr>
<tr>
<td>HT: 2 failures (n = 2/27)</td>
<td></td>
<td>Significantly more frequent IKDC grades B-D in BTB than HT at 11 years ($P$ = .008)</td>
</tr>
<tr>
<td>BTB: 4 failures (n = 4/25)</td>
<td></td>
<td>HT: 63% (n = 17/27)</td>
</tr>
<tr>
<td><strong>Marder et al.</strong>&lt;sup&gt;36&lt;/sup&gt;</td>
<td>No significant difference in failure rate ($P$ = not given)</td>
<td>No difference in IKDC activity scores at 3 years ($P$ = not given)</td>
</tr>
<tr>
<td>2 failures (2/72 = 2.8%)</td>
<td>No difference in Tegner score at 3 years ($P$ = not given)</td>
<td></td>
</tr>
<tr>
<td>HT: 1 failure (n = 1/35)</td>
<td>HT: 5 points (median) (n = 22)</td>
<td></td>
</tr>
<tr>
<td>BTB: 1 failure (n = 1/37)</td>
<td>BTB: 6 points (median) (n = 22)</td>
<td></td>
</tr>
<tr>
<td><strong>Beynnon et al.</strong>&lt;sup&gt;37&lt;/sup&gt;</td>
<td>No significant difference in failure rate ($P$ = not given)</td>
<td>No difference in IKDC grade scores at 9 years ($P$ = .002)</td>
</tr>
<tr>
<td>0 failures (0/44 = 0.0%)</td>
<td>No difference in Tegner score at 3 years ($P$ = not given)</td>
<td>BTB with greater number of grade 3 or 4 chondral lesions on operated knee than contralateral on MRI ($P$ = .040)</td>
</tr>
<tr>
<td>HT: 0 failures (n = 0/22)</td>
<td>HT: 5 points (median) (n = 22)</td>
<td>BTB operated knee: 30.4%</td>
</tr>
<tr>
<td>BTB: 0 failures (n = 0/22)</td>
<td>BTB: 6 points (median) (n = 22)</td>
<td>BTB contralateral knee: 13.0%</td>
</tr>
</tbody>
</table>

**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.