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Meta-analysis of In vitro and Intra-operative Laxities after Single Bundle and Double Bundle Anterior Cruciate Ligament Reconstructions

Hemanth R Gadikota, MS^a, Jong Keun Seon, MD^{a,b}, Chih-Hui Chen, MD^{a,c}, Jia-Lin Wu, MD^{a,d}, Thomas J Gill, MD^a, and Guoan Li, PhD^a

^aBioengineering Laboratory, Department of Orthopaedic Surgery, Massachusetts General Hospital and Harvard Medical School, Boston, MA

^bDepartment of Orthopaedic, Chonnam National University Hwasun Hospital, Jeonnam, South Korea

^cDepartment of Orthopaedic Surgery, Taichung Veterans General Hospital, Taichung City, Taiwan

^dDepartment of Orthopaedic Surgery, Tri-Service General Hospital, National Defense Medical Center, Taipei, Taiwan

Abstract

Purpose—The purpose of this study was to objectively evaluate if the double bundle ACL reconstruction can better restore the normal translational and rotational laxities than the conventional single bundle ACL reconstruction among the reported biomechanical studies.

Methods—A systematic literature search was conducted to identify in vitro and in vivo (intra-operative) biomechanical studies that compared the laxities (anterior or anteroposterior or rotational) between single and double bundle ACL reconstructions. Due to a large variability among the loading conditions and testing methods used to determine the rotational laxities between the studies, a meta-analysis of rotational laxities was not feasible.

Results—Seven in vitro and three in vivo studies were included in this analysis based on the predefined inclusion criteria. The overall mean difference calculated by the random effects model in the anteroposterior laxity between the single bundle and double bundle ACL reconstruction techniques at 0°, 30°, 60° and 90° of flexion were 0.99 mm, 0.38 mm, 0.34 mm, and 0.07 mm respectively. No statistical significant difference was noted between the two treatments at all flexion angles. Among the nine studies that compared the rotational laxity of single bundle and double bundle ACL reconstructions, four studies reported that double bundle reconstruction can provide a better rotational control compared to the single bundle reconstruction. The other five studies could not identify any significant difference between the two reconstructions in terms of the rotational laxity.

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Correspondence to: Guoan Li, PhD, Bioengineering Laboratory, Massachusetts General Hospital/Harvard Medical School, 55 Fruit Street - GRJ 1215, Boston, MA 02114 (gli1@partners.org), Tel: (617) 726-6472, fax: (617) 724-4392.

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Conclusions—Both single and double bundle treatment options for anterior cruciate ligament injury result in similar anteroposterior knee joint laxity at time-zero. No 1 conclusive evidence on the superiority of one reconstruction technique over the other in terms of rotation laxity can be obtained due to several variations in the experimental protocol and the parameters used to measure the rotational laxity among the studies.

Level of Evidence—Level III

INTRODUCTION

Due to a large number of anterior cruciate ligament (ACL) injuries not only among the high performance athletes but also among the general population, there have been numerous efforts aimed at effectively managing an ACL injury. Single bundle ACL reconstruction has been the most commonly employed operative treatment for an ACL injury where an autogenous or allogeneic graft is fixed in a single tibial and femoral tunnel.¹ However, it is reported that only 67% to 76% of the ACL reconstructed patients with either hamstring tendon graft or bone-patellar tendon-bone graft could return to their preinjury level of activity.² Further, development of degenerative changes in the knee joint remains a major concern after such surgical interventions.^{3,4} Some of these complications have been attributed to inefficient control of tibial rotation after single bundle ACL reconstruction.⁵⁻⁸

To further improve on the current single bundle ACL reconstruction techniques and with a greater understanding of the ACL anatomy, double bundle ACL reconstruction techniques are being advocated to reproduce the native anatomy of the ACL more closely and hence potentially provide a better stability to the knee joint.⁹⁻¹¹ While there is an apparent theoretical advantage of reconstructing both bundles of the ACL, a consensus has yet to be established on the superiority of double bundle ACL reconstruction over the conventional single bundle ACL reconstruction.¹¹⁻¹³

Recently, a meta-analysis of outcomes showed a significantly smaller side-to-side difference in KT-1000 arthrometer measurement after a double bundle ACL reconstruction compared to single bundle ACL reconstruction, but this difference was deemed to be clinically insignificant.¹³ Further, they found no significant difference between the two reconstructions in terms of the pivot shift testing when the results were dichotomized as normal/nearly normal versus abnormal/severely abnormal. However, “nearly normal” could be argued as not being good enough, especially in young and high performance ACL injured patients.¹⁴ Furthermore, current clinical outcome measurements have been criticized for the lack of accuracy, reliability and are known to be subjective.¹⁵⁻¹⁹ In order to accurately assess the superiority of a particular reconstruction technique for the treatment of ACL injury, such confounding factors need to be minimized. Various in vitro and in vivo biomechanical studies have used more objective, accurate and reliable testing tools such as the navigation system and robotic testing system to evaluate the efficacy of various reconstruction techniques.^{11,19-25} Therefore, the primary objective of this study was to systematically review the literature on the efficacy of double and single bundle ACL reconstruction techniques in restoring normal joint laxity among the in vitro and in vivo (intra-operative) biomechanical studies. We hypothesized that double bundle ACL reconstruction can better restore the translational and rotational knee joint laxities compared to single bundle ACL reconstruction at time-zero.

MATERIALS AND METHODS

DATA SOURCES

A systematic search of MEDLINE and EMBASE (January 1990 – March 2010) was conducted to identify in vitro and in vivo (intra-operative) biomechanical studies that compared the laxity (anterior or anteroposterior or rotational) between double bundle and single bundle ACL reconstructions. These databases were searched for the relevant articles by using the following key words: *anterior cruciate ligament*, *single bundle anterior cruciate ligament*, *double bundle anterior cruciate ligament*, *anterior cruciate ligament reconstruction*, and *anterior cruciate ligament biomechanics*. References of each selected article were manually searched for any articles that may have been missed during the database search. Two authors performed the search for the relevant articles and the identified articles were included in this study on consensus.

STUDY SELECTION

The selected articles were further screened to be included in this systematic review based on the following inclusion criteria. All studies included have reported at least one of the laxity (anterior or anteroposterior or rotational) measurement regardless of the language that they were published in. There were no restrictions applied to the source of grafts or fixation devices used in the reconstruction procedures. Studies which did not use human knees or that used synthetic graft materials were excluded from this analysis. Furthermore, included studies were analyzed to ensure that reported data were not duplicated in different reports of the same trial. Sensitivity analyses were performed to examine if there were any significant differences in the conclusion when the analysis was performed on studies grouped as 1) in vitro studies, 2) in vivo studies, 3) studies that used two tibial tunnels for double bundle reconstruction, and 4) studies that used one tibial tunnel for double bundle reconstruction.

DATA EXTRACTION

Data extraction from each included study was performed by 2 different authors independently and was recorded in a Microsoft Excel worksheet (Microsoft, CA). The following data was extracted from each included study: first author, year of publication, number of specimens/ subjects used in each treatment group, mean anterior/anteroposterior laxity measurements at 0°, 30°, 60° and 90° of flexion angles and their corresponding variance. All the outcomes were extracted as continuous variables from the included studies. The means and variances that were only reported in the form of a figure were extracted by open source digitizing software (Engauge Digitizer 4.1). Figure 4 from Yagi et al²⁶ was digitized to obtain the mean and variance at full extension and 60° of flexion. Similarly, figure 4A from Mae et al²⁴ was digitized for the mean and variance at 60° and 90° flexion. Additional data that were extracted included number of femoral and tibial tunnels, tunnel positions, graft material, graft fixation angle, initial graft tension and loading conditions.

DATA ANALYSIS AND STATISTICAL METHODS

The absolute difference between means, variance and the 95% confidence interval for each individual trial were calculated. In order to account for both the between-study and within-study variances, a random effects model was used to calculate the overall mean difference between the two treatments and its corresponding 95% confidence interval. Four²⁴·26–28 among the ten¹¹·24–32 studies included in the meta-analysis had a paired study design where the efficacy of each treatment was investigated by use a robotic testing system in the same specimen. The other six¹⁰·11·25·29·31·32 studies used two independent groups of patients/ specimens for each treatment. Paired analyses results for three²⁴·26·28 of the four studies that used a paired design were not available from the manuscript. These studies only

reported the means and standard deviations for each treatment separately. Therefore, measurements reported for each treatment were included in the meta-analysis as if they were obtained from independent groups for each treatment. Another approach to include the studies with a paired design in the meta-analysis was explored by an attempt to approximate the paired analysis. Paired analysis results were estimated by imputing the correlation coefficient from Seon et al.²⁷ for three studies.^{24,26,28} The results of this analysis is presented in detail in the appendix.

To assess the robustness of the meta-analysis results, the influence of variables (in vitro/ in vivo study design, number of tibial tunnels used in double bundle reconstruction and graft source) on the pooled estimate of the treatment difference was explored by performing a series of subgroup analyses. All statistical analysis was performed by using RevMan 5.0.18.³³

Due to a large variability among the loading conditions and testing methods used to determine the rotational laxity between the studies, a meta-analysis of these studies was not feasible. Instead, the results from the original articles on the rotational laxities are presented as a systematic review.

RESULTS

Our literature search produced 21 biomechanical studies (in vitro and in vivo) that compared the laxities following single bundle and double bundle ACL reconstructions.^{9,11,22–32,34–41} Ten studies from these 21 studies were excluded, four^{22,23,39,41} because no variance and/or means were reported, one⁹ study that used prosthetic ligament for reconstruction, one³⁷ study that used sheep knee specimens, one³⁴ study that used a rectangular femoral tunnel for single bundle ACL reconstruction, two^{38,40} studies due to duplication of data and one³⁵ review article. One of the included studies reported only rotational laxity.³⁶ Seven in vitro^{24–29,32} and three in vivo^{11,30,31} studies were selected based on the predefined inclusion criteria for this analysis. Of the included studies, four of the seven in vitro studies^{24,26,28,29} used two femoral tunnels and one tibial tunnel for their double bundle ACL reconstructions and three studies^{25,27,32} reamed two separate tunnels for each of the bundles on the femur and tibia. All of the included in vivo studies used two separate tunnels for each of the bundles on the femur and tibia for the double bundle ACL reconstruction. A summary of the data extracted from these studies is presented in table 1 and table 2.

Anterior Laxity

When all the included studies were analyzed together, the overall mean difference calculated by the random effects model in the anteroposterior laxity between the single bundle and double bundle ACL reconstruction techniques at 0° of flexion was 0.99 mm (95% CI: –0.15 to 2.13). This mean difference implies that on average a knee reconstructed by single bundle ACL reconstruction is 0.99 mm more lax in the anteroposterior direction at 0° than a knee reconstructed by double bundle ACL reconstruction. Similarly, the overall mean difference calculated by the random effects model in the anteroposterior laxity between the single bundle and double bundle ACL reconstruction techniques at 30°, 60° and 90° of flexion are 0.38 mm (95% CI: –0.40 to 1.16), 0.34 mm (95% CI: –0.14 to 0.81) and 0.07 mm (95% CI: –0.43 to 0.58) respectively. These results of the meta-analysis for 0°, 30°, 60° and 90° of flexion are presented in figures 1, 2, 3 and 4 respectively. No statistical significant difference was noted between the two treatments at all flexion angles. Similar overall mean differences between the two treatments were observed in the analysis where the correlation coefficient was imputed (appendix).

When in vitro and in vivo studies were analyzed separately, the overall mean difference between the single bundle and double bundle ACL reconstruction techniques at 30° of flexion was 0.64 mm (95% CI: -0.55 to 1.84) and 0.07 mm (95% CI: -1.21 to 1.35) respectively, with no statistical significant difference between the two treatments in either groups. Analysis of the in vitro studies as two separate groups (one tibial tunnel^{24·26·28·29} and two tibial tunnels^{25·27·32}) revealed that the overall mean difference between the two treatments was < 1.0 mm which was not statistically significant. Finally, when in vitro^{25·27} and in vivo^{11·30·31} studies that used two tibial tunnels for their double bundle reconstructions were compared to the single bundle reconstructions, we found an overall mean difference of 0.38 mm (95% CI: -0.15 to 0.92) between the two techniques at 30° of flexion. Semitendinosus and gracilis tendons were used as graft material in eight of the ten included studies. Subgroup analyses of these studies resulted in an overall mean difference between the two treatments of 1.29 mm (95% CI: -0.16 to 2.73), 0.42 mm (95% CI: -0.71 to 1.56), 0.80 mm (95% CI: 0.03 to 1.58), and 0.29 mm (95% CI: -0.50 to 1.09) at 0°, 30°, 60° and 90° of flexion respectively.

Due to the low standard deviation reported in Albuquerque et al.²⁹ study at 60° and 90° of flexion, the weights assigned to this study were rather high 63% and 59% respectively. A sensitivity analysis was performed by excluding this study from the meta-analysis to explore its influence on the overall treatment difference. The overall mean differences between the single bundle and double bundle ACL reconstruction techniques with the exclusion of Albuquerque et al.²⁹ at 60° and 90° of flexion were 0.80 mm (95% CI: 0.03 to 1.58) and 0.29 mm (95% CI: -0.50 to 1.09), respectively.

Rotational Laxity

Six in vitro^{22·25·28·36} and 3 in vivo^{11·30·31} biomechanical studies that compared the rotational laxities following single bundle and double bundle reconstruction techniques were identified. Various loading conditions have been used to evaluate the rotational laxity among these studies. The measurements reported following the application of these loads included anterior, anterior-posterior translations and internal, external, internalexternal rotations. The rotational laxities reported among the included studies are summarized in table 3. Among these 9 studies that compared the rotational laxities following single and double bundle ACL reconstructions, 2 in vitro^{26·27} studies and 2 in vivo^{11·31} studies found significant differences between the two techniques. The other five^{22·25·28·30·36} studies could not find any significant difference in the rotational laxities between single and double bundle reconstructed knees.

DISCUSSION

This study was undertaken to investigate if there is a consensus on the superiority of one reconstruction technique over the other among the biomechanical studies that compared the knee joint laxities following single bundle and double bundle ACL reconstructions. Meta-analysis of the ten included studies that reported anteroposterior laxity demonstrated no significant difference between the two treatment options for ACL injury at 0°, 30°, 60° and 90° of flexion. In regards to rotatory knee laxity, double bundle ACL reconstruction was reported to provide greater rotational stability than single bundle ACL reconstruction in four^{11·26·27·31} of the included studies and the remaining five^{22·25·28·30·36} studies could not find any significant advantage of one reconstruction technique over the other.

Our meta-analysis showed an overall mean difference between the two reconstructions ranging from 0.07 mm to 0.99 mm at 90° and 0° of flexion respectively with no statistical significant difference between the two treatments. Consistent with these findings, recently a meta-analysis of the clinical outcomes found that double bundle ACL reconstruction

resulted in anterior stability closer to the intact knee by 0.52 mm compared to single bundle ACL reconstruction.¹³ While such differences in the biomechanical outcomes may have some clinical implications, currently the ability to detect these narrow differences accurately and reliably in the clinical setting is limited. There is a strong need for development of new tools that could accurately and reliably provide quantitative data in a clinical setting.

One of the main rationales for the introduction of double bundle ACL reconstruction was to address the persistent rotational instability of the knee after conventional surgical interventions.⁴² Currently the primary evaluation of rotational stability in clinical setting is performed by the pivot-shift examination. However, this physical examination has been criticized as being highly subjective in nature.^{17,43} Several confounding factors such as the concomitant soft tissue injuries, the amount of force used for the maneuver and patient guarding have been identified to hinder an accurate assessment of rotational stability using the pivot-shift examinations.⁴³ Further, this examination is reported to have a high specificity (98%), but a low sensitivity (24%)¹ and is prone to false positive result due to joint laxity in the absence of trauma.⁴³ Even among the biomechanical studies that evaluated the rotational laxities, we noticed large variations in the experimental designs and the reported measurements. For example, various loading conditions such as manual internal/external torques, 10/5 N·m internal/external torques and combined valgus moment with iliotibial band force have been used by different authors and they have reported the rotational laxity in terms of translations (anterior or anterior-posterior), rotations (Internal or external or internal-external) or both. Due to these variations we were unable to perform a meta-analysis on the rotational joint laxity.

A recent meta-analysis of clinical outcome studies could not find any statistically significant difference in the pivot-shift results between the two reconstruction techniques.¹³ Although, four of the nine biomechanical studies that reported rotational laxities found that a double bundle ACL reconstruction could resist rotational loads better than a single bundle ACL reconstruction, it is not feasible to draw any unbiased conclusions on the rotational stability provided by these two reconstruction techniques due to large variations that we observed between the studies. Kocher et al⁴⁴ have found that the pivot-shift examination provides a better indication of the patients' functional outcomes than the instrumented knee laxity or Lachman examination. Recently few authors have proposed innovative methods using open magnetic resonance imaging, computer navigation system and electromagnetic devices to quantitatively measure the rotational stability in a clinical setting.^{17,19,45} More emphasis needs to be placed on evaluating the applicability of such techniques as clinical tools to measure rotational stability quantitatively.

This study has certain limitations. We were unable to perform a quantitative meta-analysis of the rotational laxities among the biomechanical studies. While such an analysis could potentially answer an important question of whether a double bundle ACL reconstruction can restore the rotational stability better than a single bundle ACL reconstruction, there needs to be more investigations with a standardized measure to help better answer such a question. Since this is an analysis of only biomechanical studies which represent measurements at time-zero, we can not speculate on how the differences observed between the two techniques in this analysis may reflect in a clinical setting, nor hold up over time. Results of the meta-analysis are based on a relatively small sample size especially at 0° flexion. Most studies included in the analysis at this angle had a repeated measures design which have high precision even with a small sample size compared to independent group design. Finally, we did not take into account the various parameters of the reconstructions such as the graft fixation method, graft fixation angle and initial graft tensions as standard for these parameters is yet to be established.

More randomized controlled trials with accurate measurements of the outcomes need to be conducted which could play a significant role in confirming or refuting the superiority of a particular reconstruction over another. We hope that the readers of this article understand and appreciate the importance of the confounding factors and exercise greater caution while interpreting the published results of laboratory studies before they form the basis for any crucial clinical practice. Finally, it is imperative to emphasize the need for developing new tools that can accurately and reliably quantify clinical outcomes in conjunction with the current trend of proposing new and innovative surgical techniques.

CONCLUSION

Both single and double bundle treatment options for anterior cruciate ligament injury result in similar anteroposterior knee joint laxity at time-zero. No conclusive evidence on the superiority of one reconstruction technique over the other in terms of rotation laxity can be obtained due to several variations in the experimental protocol and the parameters used to measure the rotational laxity among the studies.

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Appendix

Four^{1–4} among the ten^{1–10} studies included in the meta-analysis had a paired study design where the efficacy of each treatment was investigated by use a robotic testing system in the same specimen. Paired analyses results for three of the four studies that used a paired design were not available. The standard deviation of the mean difference between the two treatments for these three studies was estimated by imputing the correlation coefficients (0.53, 0.38, 0.70, and 0.77 for 0°, 30°, 60° and 90° of flexion respectively) from Seon et al.² study. A detailed description of the imputation procedure is given in Cochrane Handbook for Systematic Reviews of Interventions.¹¹

When all the included studies were analyzed together, the overall mean differences calculated by the random effects model in the anteroposterior laxity between the single bundle and double bundle ACL reconstruction techniques were 1.11mm (95% CI: -0.08 to 2.30), 0.48mm (95% CI: -0.31 to 1.27), 0.65mm (95% CI: 0.15 to 1.15), 0.40mm (95% CI: -0.29 to 1.08), at 0°, 30°, 60° and 90° of flexion respectively. These differences were not statistically significant except at 60° of flexion. These results of the meta-analysis for 0°, 30°, 60° and 90° of flexion are presented in figures 1, 2, 3 and 4 respectively.

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Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 0° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 2.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 30° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 3.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 60° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 4. Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 90° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 1.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 0° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 2.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 30° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 3.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 60° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Figure 4.

Forest plot of anterior/ anteroposterior laxities of SB and DB ACL reconstructions at 90° of flexion. The mean difference in laxities for each study is represented by the square and its size represents the weight of the study; the horizontal line running through the square represents the 95% confidence interval; the overall estimate of the mean difference is represented as a diamond, with its horizontal tips representing the 95% confidence interval.

Summary of in vitro biomechanical studies

Table 1

Study	Femoral tunnel placement	Tibial tunnel placement	Graft material	Graft fixation angle/Tension	Testing equipment/Loading conditions	Graft fixation methods	Conclusion
Albuquerque et al ²⁹	SB: "30° from the central position"	SB: 5 mm anterior to the medial intercondylar tubercle	SB: QT	SB: 30°/ manual	Universal Kratos® Model K5002 testing machine/ 100 N anterior force	Tibia: Bicortical screw and washer Femur: Suture and bicortical screw	Both the ACL reconstruction techniques are not capable of restoring intact knee stability
Ho et al ²⁵	DB: AMB: same as SB with a smaller diameter PLB: 2mm posterior-inferior from AMB SB: 25% and 28.5% from posterior femoral cortex and Blumensaat line respectively DB: AMB: Center of AMB PLB: Center of PLB	DB: same as SB SB: 44% and 43% from medial tibial cortex and anterior tibial cortex	DB: AMB: Split QT PLB: Split QT	DB: AMB: 30°/ manual PLB: 30°/ manual	Navigation system/ 133 N anterior force	Tibia: BioRCL biointerference screw	Both reconstruction s can equally restore joint stability
Mae et al ²⁴	SB: 11:00/ 1:00 o'clock DB: AMB: 11:00/ 1:00 o'clock PLB: 9:30/ 2:30 o'clock	SB: Center of ACL footprint DB: same as SB	DB: AMB: ST PLB: GRA SB: ST/ GRA	DB: AMB: 60°/ 67 N PLB: full extension/ 67 N SB: 20°/ 44N and 88N	Robotic simulator/ 100 N anterior & posterior force	Femur: EndoButton CL	Two femoral sockets ACL reconstruction provided better anteriorposterior stability compared to single femoral socket ACL reconstruction
Shih et al ³²	SB: 11:00/ 1:00 o'clock DB: AMB: 11:00/ 1:00 o'clock PLB: 9:30/ 2:30 o'clock	SB: Posteromedial portion of the ACL footprint DB: AMB: 7–8 mm anterior to the PLB PLB: Anterior to anterolateral tibial spine, 7 mm anterior to PCL	SB: ST/ GRA DB: AMB: ST PLB: GRA	SB: NI/ 50N DB: AMB: 20°/ 22N and 44N PLB: 20°/ 22N and 44N	Rollimeter™/ maximum manual force	Femur: EndoButton Tibia: Interference screw with staples	DB ACL reconstruction only resulted in a small improvement in anterior laxity compared to SB ACL reconstruction
Seon et al ²⁷	SB: 10:30/ 1:30 o'clock DB: AMB: Center of AMB PLB: Center of PLB	SB: Center of ACL footprint DB: AMB: Center of AMB PLB: Center of PLB	SB: ST/ GRA DB: AMB: ST PLB: GRA	SB: Full extension/ 40N DB: AMB: 60°/ 20N PLB: Full extension/ 20N	Robotic testing system/ 134 N anterior load	Femur: Suture and bicortical screw Tibia: Tibial IntraFix	DB ACL reconstruction can better restore the AP laxity than SB ACL reconstruction
Yagi et al ²⁶	SB: 11:00/ 1:00 o'clock	SB: 5–7 mm anterior to PCL	SB: ST/ GRA	SB: 30°/ 44N	Robotic testing system/ 134 N anterior load	Femur: EndoButton CL Tibia: Bicortical screw and washer	DB ACL reconstruction provides better

Study	Femoral tunnel placement	Tibial tunnel placement	Graft material	Graft fixation angle/ Tension	Testing equipment/ Loading conditions	Graft fixation methods	Conclusion
Yamamoto et al ²⁸	DB: AMB: Center of AMB PLB: Center of PLB	DB: same as SB	DB: AMB: ST PLB: GRA	DB: AMB: 60°/ 22N PLB: 15°/ 22N		Femur: EndoButton CL	rotational stability than SB ACL
	SB: “approximate the PL bundle of the ACL”	SB: 5–7 mm anterior to PCL	SB: ST/ GRA	SB: 30°/ 44N	Robotic testing system/ 134 N anterior load	Tibia: Spiked washer and screw	Lateralized SB ACL reconstruction is comparable to DB ACL reconstruction at low flexion angles
	DB: AMB: Center of AMB PLB: Center of PLB	DB: same as SB	DB: AMB: ST PLB: GRA	DB: AMB: 60°/ 22N PLB: 15°/ 22N		Femur: EndoButton CL	

AMB, Anteromedial bundle; AP, Anterior-Posterior; BPTB, Bone-patellar tendon-Bone; DB, Double bundle ACL reconstruction; GRA, Gracilis tendon; NI, No information available; PCL, posterior cruciate ligament; PLB, Posterolateral bundle; QT, Quadriceps tendon; SB, Single bundle ACL reconstruction; ST, Semitendinosus tendon

Table 2

Summary of in vivo biomechanical studies

Study	Femoral tunnel placement	Tibial tunnel placement	Graft material	Graft fixation angle/Tension	Testing equipment/Loading conditions	Graft fixation methods	Conclusion
Ferretti et al ³⁰	SB: 11:00/ 1:00 o'clock	SB: 7 mm anterior to PCL	SB: ST/ GRA	SB: NI	Navigation system/ maximum manual force	Tibia: SB: Evolvegate DB: Interference screws	Both reconstruction s improved anteroposterior and rotational stability without any significant differences between them
	DB: AMB: insertion site of AMB PLB: insertion site of PLB	DB: AMB: insertion site of AMB PLB: insertion site of PLB	DB: AMB: ST PLB: GRA	DB: AMB: 60°/ manual PLB: 15°/ manual		Femur: SB: SwingBridgeDB: Mini-SwingBridge	
Hofbauer et al ³¹	SB: 10:00/ 2:00 o'clock	SB: Center of AMB footprint	SB: ST (17 patients), ST/ GRA (10 patients)	SB: NI	Navigation system/ maximum manual force	Tibia: Suture disc	No significant difference between the two techniques was observed in terms of AP laxity
	DB: AMB: 11:00/1:00 o'clock PLB: 9:30/ 2:30 o'clock	DB: NI	DB: ST (5 patients), ST/ GRA (23 patients). Thicker graft for AMB and thinner graft for PLB	DB: NI		Femur: EndoButton CL	
Song et al ¹¹	SB: 11:00/1:00 o'clock	SB: Center of ACL footprint	SB: tibialis anterior	SB: 10°-20°/ manual maximal tension	Navigation system/ maximum manual force	Tibia: Bioabsorbable interference screws and staple	DB ACL reconstruction can provide better anteroposterior and rotational stability than SB ACL reconstruction
	DB: AMB: 11:00/1:00 o'clock PLB: 5 to 8 mm anterior to LFC cartilage and 3 to 5 mm from the inferior LFC cartilage at 90° of flexion.	DB: AMB: 7 mm anterior and 5 mm medial to the PLB tunnel PLB: center of PLB footprint	DB: AMB: tibialis anterior PLB: tibialis anterior	DB: AMB: 60°-70°/ manual maximal tension PLB: 10°-20°/ manual maximal tension		Femur: EndoButton	

AMB, Anteromedial bundle; AP, Anterior-Posterior; BPTB, Bone-patellar tendon-Bone; DB, Double bundle ACL reconstruction; GRA, Gracilis tendon; NI, No information available; PCL, posterior cruciate ligament; PLB, Posterolateral bundle; QT, Quadriceps tendon; SB, Single bundle ACL reconstruction; ST, Semitendinosus tendon

Table 3

Rotational laxities of single bundle and double bundle ACL reconstructions

Study	Loading condition	Flexion Angle (deg)	Anterior/Posterior Translation (Mean ± Standard Deviation [mm])		Internal/ External Rotation (Mean ± Standard Deviation [deg])	
			SB	DB	SB	DB
Ferretti et al30	Manual Internal/External load	30°	×	×	16.3 ± 5.4 (I)	16.6 ± 3.8 (I)
Ho et al25	10 N·m Internal torque	30°			15.7 ± 4.3 (E)	15.1 ± 2.4 (E)
		30°	6.9 ± 4.5 (A)	8.8 ± 4.1 (A)	24.1 ± 6.5 (I)	24.8 ± 8.0 (I)
		60°	4.7 ± 5.3 (A)	4.5 ± 3.5 (A)	18.6 ± 8.8 (I)	18.5 ± 0.0 (I)
		30°	0.1 ± 3.5 (P)	0.9 ± 1.9 (P)	17.5 ± 2.4 (E)	16.3 ± 3.7 (E)
Hofbauer et al31	Manual Internal/External load	60°	3.7 ± 2.8 (P)	4.6 ± 2.9 (P)	14.8 ± 2.3 (E)	15.2 ± 5.7 (E)
		30°	×	×	20.3 ± 0.2 (I)	12.3 ± 0.3 ^a (I)
		21° – 36°	9.4 ± 6.3 (AP)	6.8 ± 4.6 ^a (AP)	11.2 ± 5.2 (IE)	11.1 ± 5.3 (IE)
					11.5 ± NI (I)	10.4 ± NI (I)
Markolf et al1,36, [‡]	Valgus moment (2.5 – 4.3 N·m) and Iliotibial band force (19.9 – 37.3 N)	0°	×	×	20.4 ± NI (I)	19.5 ± NI (I)
Markolf et al22, [‡]	5 N·m Internal Torque	15°	×	×	25.1 ± NI (I)	24.7 ± NI (I)
		30°	×	×	30.1 ± NI (I)	30.6 ± NI (I)
		60°	×	×	33.2 ± NI (I)	33.9 ± NI (I)
		90°	×	×	12.7 ± 5.2 (I)	9.9 ± 4.5 ^a (I)
Seon et al27	5 N·m Internal and 10 N·m Valgus Tibial Torques	0°	2.0 ± 3.7 (A)	0.6 ± 3.1 ^a (A)	19.1 ± 6.7 (I)	18.2 ± 6.1 (I)
Song et al11	Manual Internal/External load	30°	3.1 ± 4.4 (A)	1.4 ± 3.9 ^a (A)	29.5 ± 3.8 (IE)	23.3 ± 4.0 ^a (IE)
		15°	×	×	×	×
		30°	8.5 ± 3.2 (A)	6.1 ± 2.8 ^a (A)	×	×
		30°	9.5 ± 2.6 (A)	7.5 ± 2.3 ^a (A)	×	×
Yagi et al26	5 N·m Internal and 10 N·m Valgus Tibial Torques	15°	4.8 ± 3.0 (A)	4.8 ± 2.4 (A)	15.6 ± 7.1 (I)	16.0 ± 8.4 (I)
Yamamoto et al28	5 N·m Internal and 10 N·m Valgus Tibial Torques	30°	6.5 ± 3.0 (A)	6.7 ± 2.4 (A)	19.1 ± 7.2 (I)	19.4 ± 8.1 (I)

A, Anterior translation; AP, Anterior-posterior translation; DB, Double bundle ACL reconstruction; IE, Internal-external rotation; NI, No information available; P, Posterior translation; SB, Single bundle ACL reconstruction;

^ap<0.05;significantly different from single bundle reconstruction.

[‡]Double bundle data is from protocol “DB1”