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Comparative Evaluation of Functional Outcomes Following Double-Bundle and Single-Bundle Anterior Cruciate Ligament Reconstruction

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ABSTRACT

Background: The anterior cruciate ligament (ACL) consists of two distinct functional components, namely the anteromedial (AM) and posterolateral (PL) bundles, which collectively contribute to controlling anterior tibial translation and rotational stability of the knee joint. Although single-bundle (SB) ACL reconstruction effectively restores sagittal plane stability, concerns remain regarding its ability to completely restore rotational control. Consequently, anatomical double-bundle (DB) reconstruction techniques have been developed to more closely replicate native ACL anatomy. However, the clinical superiority of DB reconstruction over SB reconstruction remains controversial.

Methods: This prospective comparative study included 80 patients diagnosed with isolated complete ACL rupture who underwent reconstruction using hamstring tendon autografts. Participants were allocated to either the single-bundle group (SB; n = 50) or the double-bundle group (DB; n = 30). Clinical and functional outcomes were evaluated after a minimum follow-up period of 24 months using the Lysholm Knee Score, International Knee Documentation Committee (IKDC) Subjective Score, Tegner Activity Scale, KT-1000 arthrometer measurements, Lachman and pivot-shift examinations, return-to-sport rates, and postoperative complications.

Results: Both reconstruction techniques resulted in substantial and clinically significant improvements in knee function. Functional outcome measures and patient-reported scores demonstrated no statistically meaningful differences between the two groups. Nevertheless, objective assessments of rotational stability, including pivot-shift findings and the proportion of patients exhibiting less than 3 mm side-to-side laxity on KT-1000 testing, showed a tendency to favor the double-bundle technique. Surgical duration was significantly longer in the DB group compared with the SB group.

Conclusion: Single-bundle and double-bundle ACL reconstruction provide comparable short- and mid-term functional outcomes. Although double-bundle reconstruction may offer improved objective rotational stability, these benefits are accompanied by increased operative complexity and prolonged surgical time. Therefore, the choice of reconstruction technique should be individualized according to patient characteristics, anatomical considerations, and surgeon expertise.

Keywords: Anterior cruciate ligament, ACL reconstruction, single-bundle technique, double-bundle technique, functional outcomes, knee stability, rotational laxity.

INTRODUCTION

The anterior cruciate ligament (ACL) serves as the primary stabilizing structure against anterior translation of the tibia and acts as an important secondary restraint to rotational and valgus stresses across the knee joint. Anatomical and biomechanical investigations have demonstrated that the ACL is composed of two distinct functional bundles: the anteromedial (AM) and posterolateral (PL) bundles, which are named according to their tibial attachment sites. These bundles function synergistically throughout the range of knee motion. The AM bundle becomes increasingly tensioned during knee flexion and predominantly resists anterior tibial displacement, whereas the PL bundle is most taut near full extension and plays a critical role in controlling rotational stability. The coordinated interaction between these bundles ensures maintenance of normal knee kinematics during dynamic activities. [1–3]

Anterior cruciate ligament injury represents one of the most frequently encountered severe ligamentous injuries of the knee, particularly among young, active, and athletic populations. Epidemiological studies have reported a steadily increasing incidence of ACL reconstruction worldwide over recent decades. If left untreated, ACL deficiency may result in recurrent episodes of instability, secondary meniscal tears, progressive articular cartilage damage, and early degenerative changes within the knee joint. Consequently, ACL reconstruction has become the preferred treatment modality for symptomatic and physically active individuals seeking restoration of knee stability and function. [4–6]

Single-bundle (SB) ACL reconstruction has long been regarded as the standard surgical technique and aims to restore ligament function through placement of a single graft, typically reproducing the anteromedial bundle. This procedure has consistently demonstrated favorable clinical outcomes, reliable restoration of anteroposterior stability, and high rates of patient satisfaction. However, biomechanical and in vivo studies have suggested that certain patients continue to exhibit residual rotational laxity following SB reconstruction. Persistent pivot-shift phenomena and altered tibiofemoral kinematics during functional activities indicate that restoration of anterior stability alone may not fully replicate the biomechanics of the native ACL. [6,7]

To address these limitations, anatomical double-bundle (DB) ACL reconstruction was developed with the objective of reproducing both the AM and PL bundles of the native ligament. By reconstructing these two functional components separately, the technique seeks to more accurately restore normal knee biomechanics. Experimental cadaveric investigations and robotic biomechanical studies have demonstrated that DB reconstruction provides superior restoration of rotational stability and more closely reproduces native knee kinematics when compared with conventional SB reconstruction. These findings have led to the hypothesis that DB reconstruction may reduce residual rotational instability and potentially improve long-term functional outcomes and joint preservation. [8–10]

Despite its theoretical and biomechanical advantages, the clinical superiority of DB reconstruction remains a subject of ongoing debate. Several comparative studies have reported improved objective stability measures following DB reconstruction, particularly with regard to rotational control. Nevertheless, randomized controlled trials and systematic reviews have frequently demonstrated comparable patient-reported outcomes between SB and DB techniques, with only marginal differences in objective stability parameters. Furthermore, the increased surgical complexity, prolonged operative duration, requirement for additional bone tunnels, and potential challenges during revision procedures have raised concerns regarding the overall clinical benefit of the double-bundle approach. [11–14]

In view of these considerations, the present study was undertaken to compare the functional outcomes and objective stability achieved following double-bundle and single-bundle ACL reconstruction in a single-center patient cohort. Using validated clinical assessment tools and objective stability measurements, this study aims to determine whether the additional technical demands associated with double-bundle reconstruction translate into clinically meaningful advantages in routine orthopaedic practice.

MATERIAL & METHODOLOGY

Study Population and Eligibility Criteria

Patients aged 18–45 years presenting with symptomatic, arthroscopically confirmed complete ACL rupture were considered eligible for participation in this study. Inclusion criteria comprised isolated ACL deficiency, skeletal maturity with closed physes, and the ability and willingness to adhere to the prescribed postoperative rehabilitation program and follow-up schedule.

Patients were excluded if they had associated multiligamentous knee injuries, concomitant grade III or higher collateral ligament injuries, a history of ACL deficiency or previous surgical intervention in the contralateral knee, advanced chondral damage (Outerbridge grade III–IV), generalized ligamentous laxity, prior surgery on the affected knee, inflammatory joint disorders, or a follow-up duration of less than 24 months.

Eligible participants were assigned to either the single-bundle (SB) reconstruction group or the double-bundle (DB) reconstruction group according to the study allocation protocol. Allocation was performed through

[randomization/alternate assignment/technical feasibility of creating separate anatomical tunnels], and the specific allocation method should be clearly defined in the study methodology.

Surgical Technique
All surgical procedures were performed by experienced orthopaedic surgeons under either spinal or general anesthesia. A quadrupled semitendinosus-gracilis hamstring tendon autograft was utilized in all cases. Diagnostic arthroscopy was initially performed to confirm ACL deficiency and to identify and address any associated intra-articular pathology, including meniscal tears or chondral lesions.

Anatomical tunnel placement was achieved based on the native ACL footprint. Femoral and tibial tunnels were created using standard arthroscopic techniques to restore the anatomical orientation of the ligament. In the single-bundle (SB) reconstruction group, a single graft was placed within the native ACL footprint using an independent femoral drilling approach to reproduce the functional characteristics of the ligament.

In the double-bundle (DB) reconstruction group, separate anteromedial (AM) and posterolateral (PL) bundle grafts were reconstructed using two femoral and two tibial tunnels positioned at their respective anatomical insertion sites. The procedure was performed according to established principles of anatomic double-bundle ACL reconstruction, aiming to restore both anteroposterior and rotational stability of the knee.

Graft fixation on the femoral side was achieved using suspensory fixation devices, while tibial fixation was secured with interference screws. The PL bundle was tensioned and fixed near full knee extension, whereas the AM bundle was fixed at approximately 45°–60° of knee flexion. Appropriate tunnel dimensions, graft tensioning, and fixation techniques were employed to ensure optimal graft stability and anatomical restoration.

Rehabilitation Protocol
A standardized rehabilitation program was implemented for all patients irrespective of the reconstruction technique. Early postoperative management focused on pain control, restoration of knee range of motion, reduction of swelling, and activation of the quadriceps musculature.

Progressive weight-bearing was initiated as tolerated, accompanied by supervised physiotherapy emphasizing closed kinetic chain strengthening exercises and neuromuscular training. Functional rehabilitation progressed in a criterion-based manner, with gradual advancement according to individual recovery milestones.

Light jogging and running activities were generally permitted at approximately three months postoperatively, provided adequate strength and functional recovery had been achieved. Return to pivoting, cutting, and competitive sporting activities was allowed between six and nine months following surgery after successful completion of functional performance testing and achievement of satisfactory clinical stability and muscle strength.

Outcome Measures
All participants underwent preoperative evaluation and were subsequently assessed at regular follow-up intervals for a minimum duration of 24 months. The primary outcome measures included patient-reported functional assessment of the knee using the Lysholm Knee Scoring Scale and the International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form. Functional activity levels were evaluated using the Tegner Activity Scale.

Objective knee stability was assessed through standardized clinical examinations, including the Lachman test and pivot-shift test, with pivot-shift grading recorded on a scale ranging from Grade 0 to Grade III. Instrumented assessment of anterior knee laxity was performed using a KT-1000 arthrometer, and results were documented as the side-to-side difference in anterior tibial translation compared with the contralateral unaffected knee.

Secondary outcome parameters included knee range of motion, duration required for return to pre-injury sporting activities, incidence of graft failure, requirement for revision surgery, and postoperative complications. Wherever possible, all clinical evaluations were conducted by an independent examiner who was not involved in the primary surgical procedure, thereby minimizing assessment bias and enhancing the reliability of outcome measurements.

Statistical Analysis
Statistical analysis was performed using appropriate analytical methods. Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were presented as frequencies and percentages. Comparisons between the single-bundle and double-bundle groups were conducted using the independent-samples t-test for normally distributed continuous variables or the Mann–Whitney U test for non-normally distributed data. Categorical variables were analyzed using the Chi-square test or Fisher's exact test whenever applicable.

Changes in outcome measures within each group over the study period were evaluated using paired statistical tests or repeated-measures analysis, depending on the nature and distribution of the data. A two-sided p-value of less than 0.05 was considered indicative of statistical significance.

All statistical analyses were performed using [SPSS Version XX (IBM Corp., Armonk, NY, USA)/R software/Stata Version XX]. Sample size estimation was conducted prior to study initiation to ensure adequate statistical power for detecting clinically meaningful differences between the study groups.

RESULTS

A total of 80 patients successfully completed the minimum follow-up period of 24 months and were included in the final analysis. Of these, 50 patients underwent single-bundle (SB) ACL reconstruction, while 30 patients underwent double-bundle (DB) ACL reconstruction. Baseline demographic and clinical characteristics were comparable between the two groups, with no statistically significant differences observed regarding age, sex distribution, body mass index (BMI), side of injury, mechanism of injury, interval between injury and surgery, or the incidence of concomitant meniscal lesions requiring treatment (Table 1). These findings indicate that both cohorts were well matched at baseline, thereby minimizing potential confounding factors and allowing for a reliable comparison of postoperative outcomes

Table 1: Baseline Demographic and Clinical Characteristics of the Study Population

Characteristic	SB Group (n=50)	DB Group (n=30)	p-value
Number of patients	50	30	—
Mean age (years)	27.6 ± 6.4	28.1 ± 6.9	0.71
Male : Female	42 : 8	25 : 5	0.93
Mean BMI (kg/m²)	24.8 ± 2.9	25.1 ± 3.1	0.63
Side of injury (Right : Left)	29 : 21	17 : 13	0.91
Time from injury to surgery (months)	5.2 ± 3.1	5.6 ± 3.4	0.55
Meniscal lesions treated, n (%)	21 (42.0%)	13 (43.3%)	0.91

Data are presented as mean ± standard deviation (SD) or frequency (%).
SB = single-bundle; DB = double-bundle; BMI = body mass index.

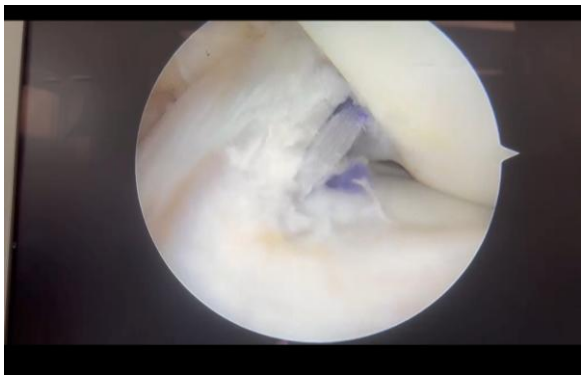


Image 1: Single bundle Acl reconstruction intraoperative arthroscopic image

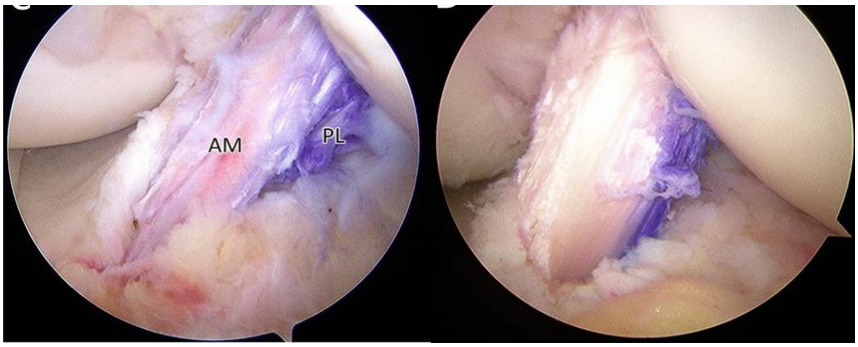


Image 2: Double bundle Acl reconstruction intraoperative arthroscopic image

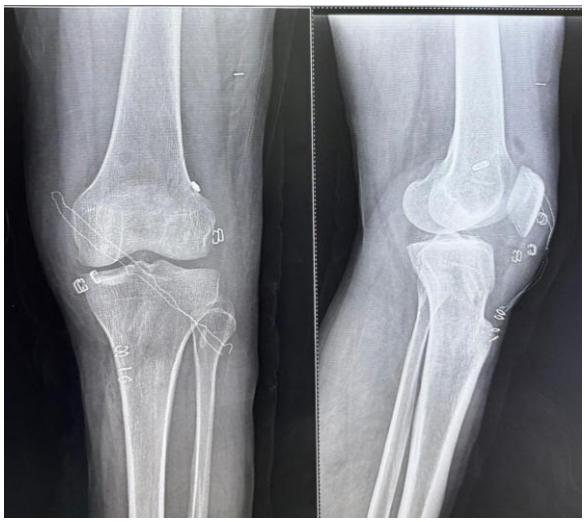


Image 3: Post-op Single bundle Acl reconstruction radiograph

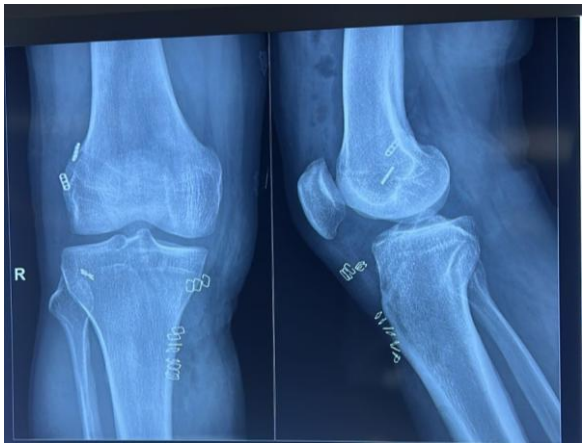


Image-4: Post-op Double bundle Acl reconstruction radiograph

Functional Outcome Scores

Both the single-bundle (SB) and double-bundle (DB) reconstruction groups demonstrated significant improvement in functional outcomes from the preoperative assessment to the final follow-up evaluation. At 24 months postoperatively, the mean Lysholm Knee Score was 90.4 ± 6.1 in the SB group and 91.8 ± 5.8 in the DB group. Similarly, the mean IKDC subjective score improved to 87.1 ± 7.3 and 88.6 ± 6.9 in the SB and DB groups, respectively. The mean Tegner Activity Scale score at final follow-up was 6.2 ± 1.1 in the SB group compared with 6.4 ± 1.0 in the DB group.

Table 2: Functional Outcome Scores at 24-Month Follow-up

Outcome Measure	SB Group (n=50)	DB Group (n=30)
Lysholm Knee Score	90.4 ± 6.1	91.8 ± 5.8
IKDC Subjective Score	87.1 ± 7.3	88.6 ± 6.9
Tegner Activity Scale	6.2 ± 1.1	6.4 ± 1.0

Values are expressed as mean ± standard deviation (SD).
SB = Single-Bundle; DB = Double-Bundle; IKDC = International Knee Documentation Committee.

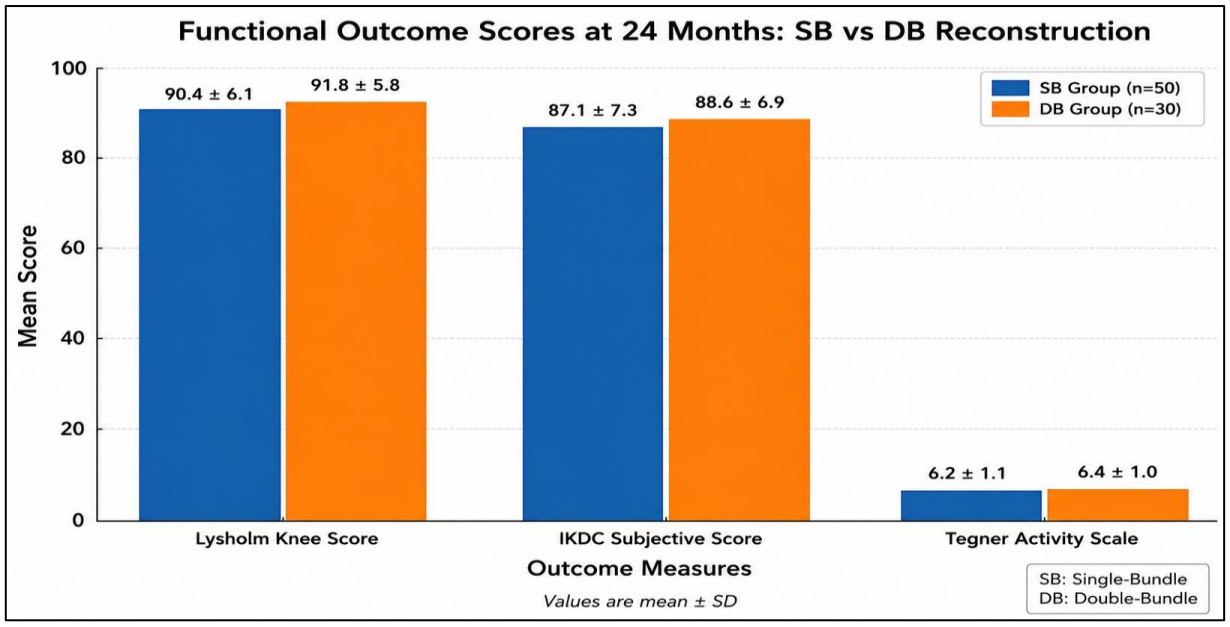
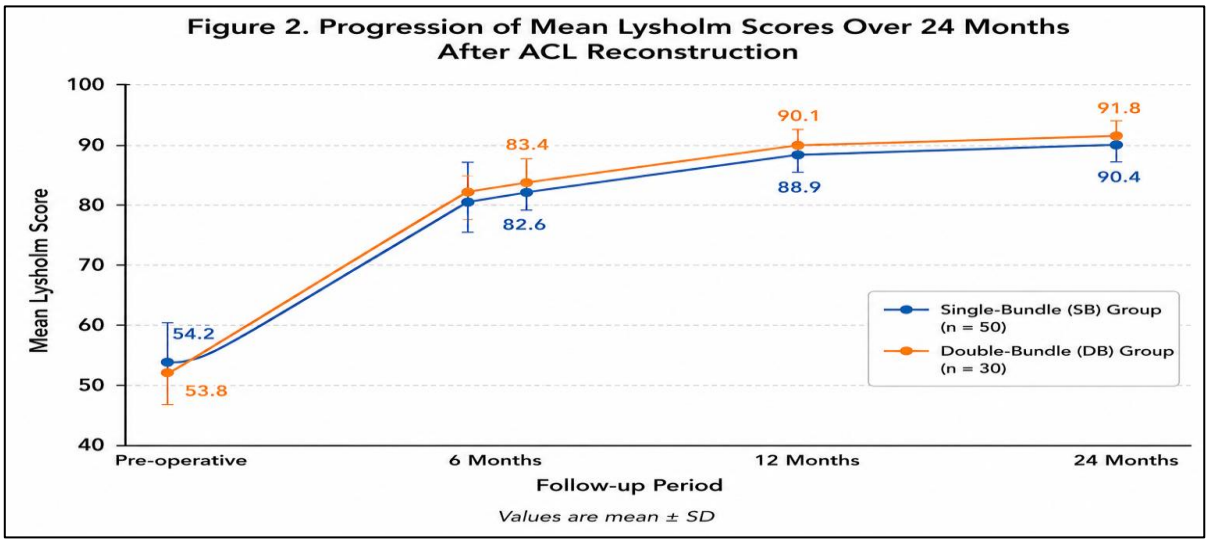


Figure 1: Comparison of Functional Outcome Scores at 24-Month Follow-up Following Single-Bundle and Double-Bundle ACL Reconstruction

Although both groups exhibited substantial functional recovery, no statistically significant differences were observed between the two reconstruction techniques with respect to Lysholm, IKDC, or Tegner scores at the final follow-up assessment (Table 2, Figure 1). Furthermore, serial evaluation of Lysholm scores throughout the follow-up period demonstrated a consistent and progressive improvement in knee function in both groups, with comparable recovery patterns observed over time (Figure 2).



Knee Stability

Assessment of objective knee stability demonstrated a trend favoring the double-bundle (DB) reconstruction technique, particularly with respect to rotational stability parameters. A negative pivot-shift test was observed in 78.0% (39/50) of patients in the single-bundle (SB) group compared with 90.0% (27/30) in the DB group. Similarly, the proportion of patients demonstrating a KT-1000 side-to-side anterior laxity difference of less than 3 mm was higher in the DB group (90.0%, 27/30) than in the SB group (80.0%, 40/50) (Table 3, Figure 3).

The mean side-to-side difference measured using the KT-1000 arthrometer was 2.4 ± 1.3 mm in the SB group and 1.8 ± 1.1 mm in the DB group, indicating superior restoration of anterior knee stability in patients undergoing DB reconstruction. In contrast, differences in Lachman test grading between the two groups were minimal.

Although the DB group consistently demonstrated better objective stability outcomes, statistical significance was observed only for the mean KT-1000 side-to-side difference. No significant differences were identified for the proportion of negative pivot-shift tests, KT-1000 values below the 3-mm threshold, or Lachman test results. The absence of statistical significance

for these categorical variables may be attributable, in part, to the relatively smaller sample size of the DB cohort. Detailed statistical comparisons are presented in Table 3 and Figure 3.

Table 3: Objective Knee Stability Outcomes at Final Follow-up

Stability Measure	SB Group (n=50)	DB Group (n=30)	p-value
Negative Pivot-Shift Test, n (%)	39 (78.0%)	27 (90.0%)	0.17
KT-1000 Difference < 3 mm, n (%)	40 (80.0%)	27 (90.0%)	0.24
Mean KT-1000 Difference (mm)	2.4 ± 1.3	1.8 ± 1.1	0.03*
Normal/Near-Normal Lachman, n (%)	42 (84.0%)	27 (90.0%)	0.45

* Statistically significant difference ($p < 0.05$).
Values are presented as frequency (%) or mean ± standard deviation (SD).

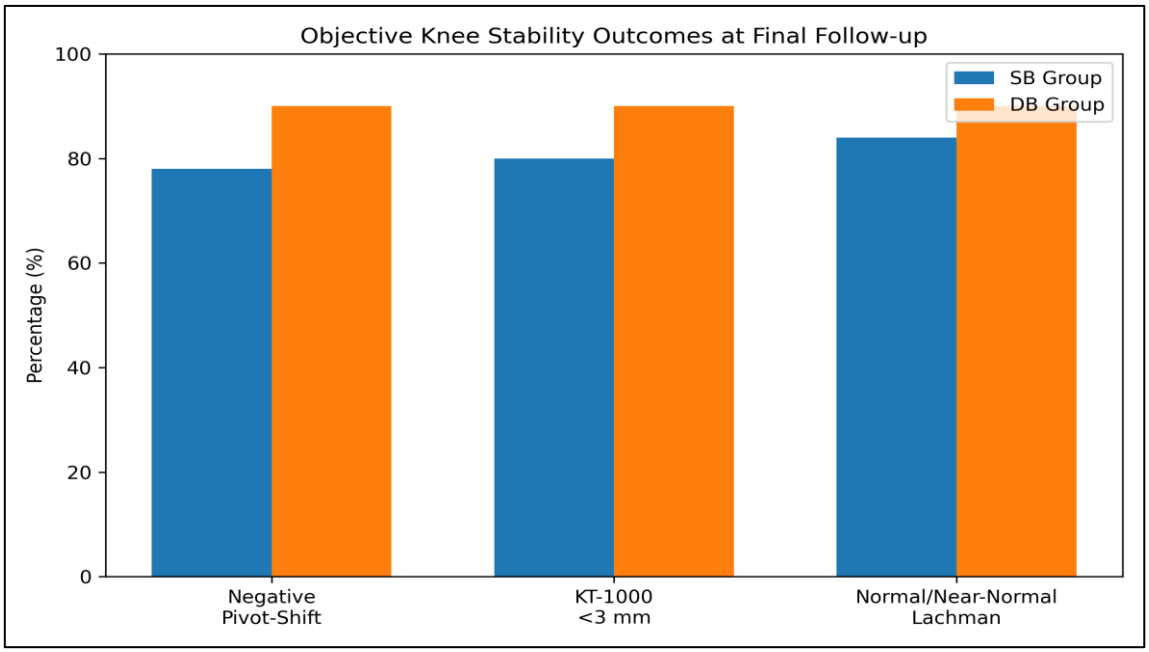


Figure 3: Comparison of Objective Knee Stability Outcomes Between Single-Bundle and Double-Bundle ACL Reconstruction at Final Follow-up

Return to Sport, Operative Characteristics, and Complications

Return to the pre-injury level of sporting activity was achieved in 72.0% (36/50) of patients who underwent single-bundle (SB) ACL reconstruction and 76.7% (23/30) of those treated with double-bundle (DB) reconstruction. The average time required to resume sports participation was comparable between the two groups.

The mean operative duration was significantly greater in the DB group compared with the SB group (78.4 ± 11.2 minutes versus 61.7 ± 9.8 minutes), reflecting the increased technical complexity associated with the double-bundle procedure.

Graft failure necessitating revision surgery was observed in two patients in the SB group and one patient in the DB group. Postoperative complications, including arthrofibrosis, superficial wound infection, and donor-site morbidity, occurred at similar frequencies in both groups. Overall, both reconstruction techniques demonstrated favorable safety profiles with low complication rates and comparable postoperative outcomes (Table 4).

Table 4: Return to Sport, Operative Characteristics, and Postoperative Complications

Variable	SB Group (n=50)	DB Group (n=30)	p-value
Return to Pre-injury Sport, n (%)	36 (72.0%)	23 (76.7%)	0.64
Mean Operative Time (minutes)	61.7 ± 9.8	78.4 ± 11.2	<0.001*
Graft Failure / Revision, n	2	1	0.62
Arthrofibrosis, n	2	3	0.68
Superficial Infection, n	1	1	1.00

* Statistically significant difference ($p < 0.05$).

Values are expressed as mean ± standard deviation (SD) or frequency (%).

DISCUSSION

The most important finding of the present study is that both single-bundle (SB) and double-bundle (DB) anterior cruciate ligament reconstruction techniques resulted in significant improvement in knee function and patient-reported outcomes at short- to mid-term follow-up. Although subjective functional scores were comparable between the two groups, the DB reconstruction technique demonstrated a tendency toward superior objective knee stability, particularly with respect to rotational control. However, this advantage was accompanied by a significantly longer operative duration. These findings are consistent with the majority of contemporary literature evaluating the clinical efficacy of SB and DB ACL reconstruction.[12-14]

Several randomized controlled trials have investigated the comparative effectiveness of these two surgical techniques. Previous studies have demonstrated that DB reconstruction may provide improved control of rotational laxity and superior instrumented stability measurements when compared with conventional SB reconstruction.[15-17] Nevertheless, these biomechanical advantages have not consistently translated into clinically meaningful improvements in patient-reported functional outcomes. Similar observations have been reported in studies with long-term follow-up, where improved objective stability and lower graft failure rates were observed following DB reconstruction without significant differences in subjective knee function.[18-20]

The results of the present study further support the concept that restoration of anatomical graft positioning may be more important than the number of reconstructed bundles. Earlier investigations comparing conventional SB, anatomic SB, and DB reconstruction have suggested that accurate anatomical tunnel placement substantially improves rotational stability, thereby reducing the clinical differences between the two techniques. Consequently, optimization of graft positioning may play a greater role in determining postoperative outcomes than the reconstruction method itself.

Several clinical studies have also reported comparable functional outcomes between SB and DB reconstruction.[21,22] Despite occasional improvements in objective stability parameters favoring DB reconstruction, patient-reported outcome measures such as the Lysholm, IKDC, and Tegner scores generally remain similar between groups. This recurring observation suggests that improvements detected through objective stability testing may not always correspond to differences perceived by patients during routine daily activities and sports participation.

Evidence from systematic reviews and meta-analyses has further clarified this relationship. Although some pooled analyses have demonstrated statistically significant advantages of DB reconstruction in terms of rotational stability and instrumented laxity measurements, the magnitude of these benefits is often modest. Furthermore, most reviews have failed to demonstrate a consistent superiority of DB reconstruction regarding validated functional outcome scores. These findings indicate that enhanced biomechanical restoration does not necessarily result in improved clinical function or patient satisfaction.[19,23,24]

The biomechanical rationale supporting DB reconstruction remains compelling. Experimental cadaveric studies and robotic simulations have demonstrated that reconstruction of both the anteromedial and posterolateral bundles more closely reproduces native ACL anatomy and knee kinematics. Such reconstruction may provide superior control of rotational forces and reduce residual pivot-shift phenomena. However, contemporary anatomical SB techniques have also shown excellent restoration of knee stability, thereby narrowing the functional gap between the two procedures. [25-28]

From a clinical perspective, the potential benefits of DB reconstruction must be balanced against its increased technical demands. The procedure requires additional femoral and tibial tunnels, longer operative time, greater surgical expertise, and may present challenges during revision surgery. Therefore, selection of the reconstruction technique should be individualized based on patient characteristics, activity level, anatomical considerations, and surgeon experience rather than adopting a universal preference for either approach.

Several limitations of this study should be acknowledged. First, the follow-up period was limited to short- and mid-term outcomes, and therefore long-term differences in graft survival, osteoarthritis progression, and joint preservation could not be evaluated. Second, the unequal sample sizes between the SB and DB groups may have reduced the statistical power to detect subtle differences in patient-reported outcomes. Third, the single-center design may limit the generalizability of the findings. Finally, assessment of knee stability relied partly on clinical examination, which is subject to interobserver variability, while objective rotational laxity was not quantified using advanced instrumented methods.

Despite these limitations, the present study provides valuable evidence supporting the effectiveness of both reconstruction techniques. Future multicenter randomized controlled trials with larger sample sizes, longer follow-up periods, and advanced objective assessment tools are required to further clarify the long-term clinical significance of the modest stability advantages observed with double-bundle ACL reconstruction.

CONCLUSION

Both single-bundle (SB) and double-bundle (DB) anterior cruciate ligament reconstruction techniques resulted in significant improvements in knee function and clinical outcomes during short- to mid-term follow-up. Functional outcome measures, including patient-reported scores and activity levels, were comparable between the two groups, indicating that both procedures are effective in restoring knee function following ACL injury.

Although double-bundle reconstruction demonstrated superior objective knee stability, particularly with respect to rotational control and instrumented laxity assessment, these advantages did not translate into significantly better functional outcomes in the present study. Furthermore, the DB technique was associated with increased operative duration and greater surgical complexity when compared with conventional SB reconstruction.

Based on these findings, neither technique can be considered universally superior. The choice between single-bundle and double-bundle ACL reconstruction should be individualized according to patient-specific factors, including activity level, anatomical characteristics, functional requirements, and surgeon expertise. Further large-scale, multicenter studies with longer follow-up durations are warranted to determine whether the improved objective stability observed with double-bundle reconstruction translates into superior long-term graft survival, reduced osteoarthritis progression, and enhanced joint preservation.

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