Abstract

Surgical repair of the anterior cruciate ligament is a fairly common necessity in knee injuries, usually with good to excellent outcomes. However, a successful repair and return to activities for a subpopulation of patients, 10% to 30%, remain elusive. Additionally, some athletes have arthritic changes, even with ligament repair. These issues are likely multi-factorial in nature but the debate continues even over which primary operative technique will produce the most favorable outcome. This review examines and discusses the anatomic and historical rationale of double-bundle ACL reconstruction techniques, the published kinematics of double-bundle reconstructions, and the clinical literature comparing double-bundle outcomes to those of the more traditional single-bundle constructs. Conclusions regarding surgical care include a need for more standardization of measuring parameters and the future application of advanced technologies that would inform more correct models of knee kinematics for comparison to various ACL construction approaches, potentially allowing improvement in the techniques of ACL reconstruction.

In the past decade, estimates quote the annual incidence of anterior cruciate ligament (ACL) injury as nearly 1 in every 3000 people in the United States. As a result, over 100,000 ACL reconstruction procedures are performed each year. Published outcomes, both short- and mid-term, have been favorable with regard to postoperative stability, functional scores, and return to activity. These same results, however, have revealed a subset of 10% to 30% of patients who do not have such favorable outcomes. Objective outcome measures, such as anteroposterior laxity, pivot shift, and Lysholm knee scores, have demonstrated that a subpopulation of patients have residual laxity or functional deficits that prevent a return to previous levels of activity and function.

The published incidence of arthrosis following ACL reconstruction also has been less than encouraging. Several investigators have reported results that demonstrate arthritic changes in athletes despite reconstruction of the ACL following knee injury. This progression is reported even more commonly if the ACL injury is associated with a meniscal tear. Some investigators have suggested that the rate of arthritis progression after ACL injury and reconstruction is equal to or worse than would have occurred after nonoperative treatment. With these studies reporting a subset of patients with poorer outcomes, the question that begs to be answered is whether the current practices of ACL reconstruction are adequately anatomic, and, if not, what techniques may need to be developed for improvement? This, in part, has been the driving force behind the increased interest in performing double-bundle ACL reconstructions and will be the focus of this review.

Anatomy of the ACL

Although the ACL has been recognized as a structure for thousands of years, a description of two distinct ACL bundles did not appear in the literature until 1975 and, consequently, is generally credited to Girgis and colleagues. They named the two bundles anteromedial (AM) and posterolateral (PL), based on the insertion of the two bundles on the proximal tibia. Ferretti and coworkers reference a paper published,
in 1979, by Norwood and Cross, who also described the ACL, but as a three-bundle structure. Since these early descriptions, numerous articles have described a variable number of fascicles and grouped bundles comprising the ACL. Anatomic studies from fetal specimens support a distinct double-bundle composition of the ACL during fetal development. Although as many as four bundles have been described, the consensus is that the ACL functions as a combination of two bundles, as first described by Girgis and associates (Fig. 1). The AM bundle originates more superiorly and anteriorly on the lateral femoral condyle, is taut in flexion, and more relaxed in extension. The PL bundle originates more inferiorly and posteriorly and tightens in extension. Although named for the tibial insertion site, it is the location of the origins that determines the role of the bundles through the range of knee motion. Proponents of double-bundle reconstruction use these anatomically described groupings of fascicles as support for the rationale of double-bundle reconstruction (Fig. 2).

**History of Double-Bundle Reconstruction**

The earliest published discussions of double-bundle ACL reconstruction are from the 1980s. However, by the time Mott published his surgical technique of a “double-bundle” reconstruction, in 1983, he had been using the technique for 5 years. As this was a surgical technique only, he did not include follow-up, treatment group descriptions, or outcome measures. His reconstruction described using a semitendinosus autograft through two tunnels in both the femur and tibia. Soon after, Zaricznyj published a similar technique, using two tibial tunnels and one femoral tunnel. He followed 14 patients for 2 years and noted that 12 of the 14 patients scored good-excellent by the Hospital for Special Surgery (HSS) knee score. Zaricznyj also noted that none of the patients had a pivot shift following reconstruction, but three knees had a 1+ anterior drawer test. No mention was made of whether these patients were able to resume their previous activity levels or their previous occupations.

Several years after these published techniques, Radford and Amis reported their biomechanical assessment of double- versus single-bundle reconstruction. In this study, the investigators tested the flexion stability of six ACL intact cadaveric knees at both 20° and 90°. The native ACL was then removed, and testing was repeated with an over-the-top reconstruction method simulating the AM bundle, and then a trans-lateral femoral-condyle reconstruction simulating the PM bundle. A double-bundle construct was also simulated by the combination of the two. Of note, the reconstructed bundles were synthetic, created with polyes-
ter tape instead of biological components. The grafts were tensioned according to the investigators’ estimation of the laxity of the native ACL before sectioning. They reported that the AM bundle simulation stabilized best at 90° of flexion, and the PM bundle simulation stabilized best at 20° of flexion. The addition of both bundles replicated the stability of the native knee before disruption of the native ACL. They concluded that double-bundle reconstruction most closely reproduced the stability of a native knee.21

Interestingly, the same group published an animal model study 4 years later, looking again at single- versus double-bundle reconstruction. Using three groups of eight sheep each, the native ACL was reconstructed with an over-the-top AM bundle, a trans-condylar PL bundle, or the combination of both. The reconstructed ligaments were again comprised of polyester tape. After 6 months in vivo, the sheep were sacrificed, and the knees were examined grossly and then evaluated biomechanically. All knees that had been reconstructed were found to contain fibrous tissue and to be unacceptably lax when compared to the native or unreconstructed knee. In the double-bundle group, the investigators also found more degeneration of cartilage around the area of the tunnels than in the other two groups. This was explained by the fact that the double-bundle procedure required more tunnels than the other two. Because of a failure to provide satisfactory stability and the increased surgical complexity, the investigators concluded that double-bundle reconstruction offered no advantage in the clinical setting.22 They acknowledged that the limitations of these studies included the use of synthetic graft material. Two years earlier, Radford and colleagues23 had published a long-term study of polyester ligament replacements in sheep that showed similar cartilage degeneration and increased laxity of the knees over time. Despite these inferior results, the same graft materials were chosen for their comparison of reconstruction techniques. Subsequent studies have shown that polyester and polyester tape graft substitutions provide inadequate stability after cyclic loading and contribute to synovitis and cartilage destruction through particle wear.24-29 Even with inferior materials used for grafts, after analysis of the double-bundle technique in sheep by Radford and colleagues,30 all mention of double-bundle reconstruction stopped for the next several years.

**Kinematics**

To better understand the differences in outcome of ACL reconstruction, a number of in vivo studies have examined the kinematics of traditional single-bundle ACL reconstructions and the resulting control of knee motion during physical activity. These kinematic studies have demonstrated that standard single-bundle ACL reconstruction does not completely recreate the kinematics of an ACL-intact knee during functional activities. Although anteroposterior stability seems to be reasonably reconstituted, studies done with a variety of grafts, methods of fixation, and physical loading activities are universally abnormal when tibial rotation or transverse motion are compared to native knees.30-36 Outcome studies also have demonstrated that abnormal transverse movement or rotation, such as that exhibited by a residual pivot shift, leads to less favorable scores on self-assessment scales and decreased patient satisfaction, as compared to patients without a pivot shift.9,10 This would suggest that traditional single-bundle trans-tibial ACL reconstruction does not recreate normal transverse rotation and that abnormal transverse rotation leads to less favorable outcomes. In an effort to achieve better anatomic motion, the double-bundle ACL reconstruction technique has been proposed to better recreate the kinematics of the ACL intact knee.

Kinematic studies of double-bundle techniques are not as plentiful in the literature. An in vitro cadaveric study of five knees, performed by Steckel and associates,37 used computer tracking techniques to model the motion of the femur on the tibia during flexion. By modeling first the native knee, then reconstructing first the AM bundle, and then reconstructing the PL bundle, they produced three groups of knees for comparison. These groups consisted of the native knee, a single-bundle group, and a double-bundle group. The investigators found that both single- and double-bundle groups restored anterior translation comparable to the intact state at 0° flexion, but that the double-bundle group was significantly more stable at 15° and 75° of flexion. The double-bundle group also was significantly more stable with Lachman and anterior drawer tests, as compared to the single-bundle reconstruction group. When rotatory stability was measured, the single bundle showed significantly less stability than the native or double-bundle knees.37

In another in vitro study, Belisle and colleagues38 measured the strain pattern of the two bundles of the ACL in four native cadaveric knees during passive flexion-extension, with a constant axial load. They then sacrificed the ACL and repeated the test with just the AM bundle reconstructed and then both the AM and PL. They found a significant difference between the strain patterns of the native ACL and the single-bundle construction, whereas the strain patterns of the double bundle were nearly identical to the native knee.

Seon and coworkers39 performed an in vivo study, in which they examined 10 patients after single-bundle ACL and 10 patients after double-bundle ACL at 1 year following surgery. They measured magnetic resonance images (MRI) of the non-weightbearing reconstructed knee at 0°, 30°, 60°, 90° and 120° and compared the images to the native knee at the same angles. They found no differences between the three groups with respect to the medial femoral condyle but did find significant differences with respect to the lateral femoral condyle. The single-bundle ACL group had significantly more translation of the lateral femoral condyle through the range of flexion, compared to the double bundle and native groups. The double bundle and native groups had no significant difference, suggesting that the rotation and translation
of the femoral condyles of the double-bundle reconstructed knees behave more similar to native knees.

**Clinical Trials and Outcomes**

Clinical studies involving double-bundle reconstruction have been available for several years. In 1999, Muneta and associates\(^4\) published the results of a 2-year follow-up of 54 of 62 consecutive patients who underwent double-bundle reconstruction. They reported a “trend” toward enhanced anterior tibia translational stability, compared to their previous experience using single-bundle techniques but no patient data or parameters were available. A year later, Kubo and colleagues\(^4\) reported on 14 patients who underwent double-bundle reconstruction. They only evaluated 4 of the 14 for anterior tibial translational knee stability and reported a “good” result. They indicated that their technique was a “useful method” and a “physiologically more durable ACL reconstruction,” but patient outcome data were not described. In the same year, Hara and coworkers\(^4\) published a technique of double-bundle reconstruction that they called “physiologically more durable,” but patient outcomes or statistics were not reported.

Soon after these first studies, prospective studies with objective outcomes emerged. Hamada and associates\(^5\) looked at 160 non-randomized patients prospectively divided into single- and double-bundle groups. With 106 available after 2 years for follow-up, they reported no statistical difference between the two groups for IKDC (International Knee Documentation Committee) knee ligament evaluation grade or anterior tibial translational laxity. Though the investigators found no statistical difference, they reported that the double-bundle group did display a trend toward better anterior translational stability. Adachi and colleagues\(^6\) looked at 108 patients who were prospectively randomized into a double- or single-bundle group. All reconstructions were performed with hamstring tendons, and a standard rehabilitation protocol was used for all participants. At an average of 32 months follow-up, they found no difference in anterior laxity measured with KT-2000 at 20° or 70° and no difference with regard to proprioception. Aglietti and coworkers\(^7\) prospectively assigned 75 consecutive patients to three groups: 1. single bundle, 2. double bundle with two tibial and two femoral tunnels, and 3. double bundle with a figure-of-eight graft through two tunnels. They found a significant difference in anterior stability measured with KT-1000, with group three better than two, and two better than one. They also found significantly less pivot shift in group three and higher subjective functional scores.

Muneta and associates\(^8\) looked at 68 patients prospectively randomized into double- and single-bundle groups. These patients were followed an average of 25 months. They found a statistically significant difference between the two groups with respect to anterior and rotational stability, based on measurements made with KT-1000 and pivot shift testing, but no subjective or self-reported differences.

One year earlier, Muneta and colleagues\(^9\) had reported on a retrospective case control series, consisting of 79 double-bundle patients and 56 single-bundle patients as a control. They found statistically significant differences in the anterior stability as measured by KT-1000, Lachman, and anterior drawer testing, with the double-bundle group more stable at an average follow-up of 4 months. However, the Lysholm scores and IKDC scores were equivalent.

Yasuda and coworkers\(^10\) published a prospective comparative cohort study of 72 patients with ACL reconstructions that were divided into three groups, consisting of a single-bundle group, a nonanatomic double-bundle group, and an anatomic double-bundle group. These patients were examined 2 years after surgery. The investigators found a significant difference in anterior laxity, as measured by KT-2000, between the anatomic double-bundle groups and the single-bundle groups, as well as by pivot shift tests. They reported no significant differences in knee ROM, muscle torque, or IKDC scores. Yagi and associates\(^11\) reported on 60 consecutive patients randomly assigned to one of three groups: single-bundle AM, single-bundle PL, and double bundle. All patients were examined 1 year after surgery. Anteroposterior laxity was measured with KT-1000 arthrometry, and pivot shift testing was measured both clinically and by three-dimensional electromagnetic sensors. Clinical examinations and KT-1000 results were equal, but the electromagnetic sensors demonstrated significantly better control of complex and rotational stability on the double-bundle group.

Asagumo and colleagues\(^12\) reported on a retrospective comparison of 123 consecutive patients, 71 of whom had double-bundle reconstructions and 52 of whom had single-bundle reconstructions. Follow-up was reported for an average of 33 months. Evaluated outcomes included manual knee laxity, anterior laxity with KT-1000, knee ROM, peak torque, and Lysholm scores. No significant differences regarding Lachman, pivot shift, KT-1000, or Lysholm scores were noted; but they did report a significant difference in range of motion (ROM) with the double-bundle group measured at less flexion.

Järvelä\(^13\) randomized 77 patients into three different groups: single-bundle reconstruction with bioabsorbable interference screw fixation, single bundle with metal screw fixation, and double-bundle reconstruction. Seventy-three patients were then assessed at 2 years, using a clinical pivot shift exam, KT-1000, and IKDC or Lysholm scores. They found no significant differences in Lysholm or IKDC scores but did find significant differences in pivot shift testing, with the double-bundle group more stable. They also reported six graft ruptures in the single-bundle group and none in the double-bundle group. The same investigators\(^14\) had previously published a similar study of 65 patients randomized to a single- or double-bundle reconstruction group. Twenty-nine patients from the single-bundle group and 30 of the double-bundle group were available at 1 year for follow-up assessment, using KT-1000, pivot shift testing,
IKDC, and Lysholm scores. A significant difference in pivot testing was found, with the double-bundle group statistically superior. The study also reported graft failure in four of the single-bundle group and none in the double-bundle group (Table 1).

Approaching the same question from a different perspective, Isibashi and coworkers recorded intraoperative rotational stability of knees at various points of double-bundle reconstruction, reporting on rotational and translational stability of 32 patients after reconstruction of the AM, the PL, and both bundles, using a navigation system. They found a significant improvement to both anterior and rotational stability when both bundles had been reconstructed, as opposed to one bundle alone. Follow up data for these patients were not reported. In a similar design, Kondo and Yasuda examined 136 of 178 consecutive patients who had undergone double-bundle reconstruction with second look arthroscopies at 1 to 2 years after the original surgery. They found significant differences in anterior laxity and pivot shift testing in the group with arthroscopically confirmed intact bundles, as compared to those in whom one or more bundles appeared deficient.

### Table 1 Comparison of Clinical Outcome Studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>Type of Study</th>
<th>Year Published</th>
<th>Number of Patients</th>
<th>Technique Studied</th>
<th>Average Length of Follow-up</th>
<th>Measured Outcome Parameters</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamada et al.43</td>
<td>Non-randomized</td>
<td>2001</td>
<td>106</td>
<td>S vs D</td>
<td>2 years</td>
<td>Anterior tibial translational laxity</td>
<td>No statistical significance</td>
</tr>
<tr>
<td>Adachi et al.44</td>
<td>Prospective randomized</td>
<td>2004</td>
<td>108</td>
<td>S vs D</td>
<td>32 months</td>
<td>KT-2000, proprioception</td>
<td>No statistical difference</td>
</tr>
<tr>
<td>Muneta et al.47</td>
<td>Retrospective non-randomized</td>
<td>2006</td>
<td>135</td>
<td>S vs D</td>
<td></td>
<td>KT-1000, Lachman, anterior drawer test, Lysholm and IKDC scores</td>
<td>Double bundle: Significantly less translation, no difference in Lysholm or IKDC scores</td>
</tr>
<tr>
<td>Yasuda et al.48</td>
<td>Prospective randomized</td>
<td>2006</td>
<td>72</td>
<td>S vs AD vs NAD</td>
<td>2 years</td>
<td>KT-2000, pivot shift testing, knee ROM, muscle torque and IKDC score</td>
<td>NAD and AD groups less laxity by KT-2000 and pivot shift test. No difference in other parameters</td>
</tr>
<tr>
<td>Aglietti et al.45</td>
<td>Prospective randomized</td>
<td>2007</td>
<td>75</td>
<td>S vs AD vs NAD</td>
<td></td>
<td>KT-1000, pivot shift testing</td>
<td>Significantly less translation and pivot shifting for AD and NAD groups</td>
</tr>
<tr>
<td>Muneta et al.46</td>
<td>Prospective randomized</td>
<td>2007</td>
<td>68</td>
<td>S vs D</td>
<td>25 months</td>
<td>KT-1000, pivot shift testing</td>
<td>Significantly less translation and pivot shifting in D group</td>
</tr>
<tr>
<td>Yagi et al.49</td>
<td>Non randomized</td>
<td>2007</td>
<td>60</td>
<td>AM bundle vs PL bundle vs D</td>
<td>1 year</td>
<td>KT-1000, pivot shift test</td>
<td>KT-1000 equal, better control of complex rotation in D group</td>
</tr>
<tr>
<td>Asagumo et al.50</td>
<td>Non randomized</td>
<td>2007</td>
<td>123</td>
<td>S vs D</td>
<td>33 months</td>
<td>KT-1000, Lachman, peak muscle torque and Lysholm scores</td>
<td>No significant difference except D group demonstrating less knee ROM</td>
</tr>
<tr>
<td>Järvelä et al.52</td>
<td>Prospective randomized</td>
<td>2007</td>
<td>77</td>
<td>S vs D</td>
<td>2 years</td>
<td>KT-1000, pivot shift test, IKDC and Lysholm score</td>
<td>Less pivot in D group, no difference in other parameters</td>
</tr>
</tbody>
</table>

S (Single), D (Double), AD (Anatomic Double), NAD (Non-Anatomic Double), AM (Anteromedial), PL (Posterolateral)
Using a computer navigation model, Monaco and associates published a study comparing 20 consecutive patients alternately assigned to a single bundle with extra-articular lateral tenodesis or a double-bundle group. The knees were then digitally registered and tested intraoperatively to compare anterior motion and rotational stability. The investigators found that both anatomic double-bundle and single-bundle approaches with extra-articular tenodesis performed equally with regard to anterior stability and external rotation, but the single-bundle procedure with extra-articular tenodesis provided better control during maximal internal rotation.

Conclusion
The above referenced kinematic studies have several limitations as a group. The follow-up was short, with 2-years being the longest. Little information was given in the studies about how randomization, if any, was used to form the separate groups, and sample sizes were small. Several different surgical techniques also were represented, which can make pooling the data difficult. Very little information was available regarding postoperative therapy regimens, complications, and reported return to play or return to work measures. Inherent in these studies is that there was no true objective measurement for rotational laxity during follow-up. KT-1000 or 2000 arthrometry is the most reliable and reproducible parameter for measurement of anterior translation available. There is no such device readily available to accurately measure rotational stability, and clinical testing remains the standard of reporting. Pivot shift testing, although generating more interest as a postoperative parameter, is difficult to reproduce or quantify accurately in a postoperative setting. More of these parameters will need to be standardized before cross sectional studies will allow a comparison across many patient groups, skill levels, and functional levels. Certainly more follow-up and larger populations will need to be compared to determine which method of ACL reconstruction holds advantages for various patient groups.

Future directions for ACL reconstruction may help with a determination to pursue how advanced technologies biomechanically and clinically can refine surgical planning and technique that results in more normal, stable postoperative function. With the growing popularity of computer navigational technology in orthopaedics, navigation could help with tunnel placement, creating a more anatomic reconstruction, regardless of the number of bundles used in reconstruction. The combination of advanced imaging and modeling may help to pinpoint in real time the natural motion in native knees and to compare that with the motion of ACL reconstructed knees in both traditional single-bundle techniques as well as double-bundle techniques. If this were accomplished, more useful data could be gleaned regarding the differences in postoperative knee kinematics, with better understanding if not resolution of the controversies surrounding the single- and double-bundle schools of thought.

Disclosure Statement
None of the authors have a financial or proprietary interest in the subject matter or materials discussed, including, but not limited to, employment, consultancies, stock ownership, honoraria, and paid expert testimony.

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