Biomechanical Variation of Double-Bundle Anterior Cruciate Ligament Reconstruction

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Introduction

Surgical reconstruction with replacement grafts after anterior cruciate ligament (ACL) injury continues to be an area of considerable debate. A large number of techniques have been reported with success rates ranging from 83% to 95% at short-term follow-up [10, 12, 36]. However, in the long term, a number of studies have found that 20–25% of patients experience less than satisfactory results, with the presence of osteoarthritis in a significant number [2, 5, 7, 8, 11, 22]. These findings have led many to carefully examine and appreciate the complex anatomy of the ACL, including recognition of its two functional bundles: the anteromedial (AM) and the posterolateral (PL) bundles [16, 19, 32]. These two bundles work in concert and allow the ACL to resist excessive joint loads throughout the range of knee flexion.

Since the early 1980s, Mueller, Peterson, and Mott pioneered surgical techniques by reconstructing both of the bundles of the ACL [31, 32]. In the 1990s, this approach was adopted and refined by Muneta and other surgeons in Japan [20, 33, 35, 45]. Later on, its popularity increased in the USA as well as other countries. To date, despite the theoretical advantages of double-bundle procedures, substantial improvements over single-bundle procedures in terms of knee stability or patient outcomes have yet to be demonstrated [3, 21, 28, 34, 35, 42, 46]. One potential reason is the complexity of double-bundle reconstruction as the number of surgical variables is significantly increased, and all can impact the outcome of these new procedures.

In this chapter, we wish to provide the readers a brief review of some of the published studies, especially with our focus on the biomechanical variation of double-bundle ACL reconstruction. We will show how biomechanics can be involved in the evaluation of double-bundle ACL reconstruction procedures. Specifically, by introducing our novel robotic/universal force-moment sensor (UFS) testing system, we can quantitatively assess the contribution of the ACL and ACL reconstruction grafts to overall stability of cadaver knees. Additionally, with this testing system, the importance of key surgical variables, such as tunnel placement and graft fixation, can be addressed. Finally, we will suggest the future

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roles biomechanics will play in gaining in vivo data and how to use them to further improve the results of double-bundle ACL reconstruction.

Biomechanical Studies Using Human Cadavers of Single-Bundle Versus Double-Bundle ACL Reconstruction

The Robotic/UFS Testing System

The need to know the function of various soft tissues in and around diarthrodial joints has led to the design and development of a large number of biomechanical testing devices. However, to study multiple-degree-of-freedom joint kinematics as well as the in situ forces in these tissues and their contribution to joint stability, our research center has chosen to develop a unique robotic/UFS testing system in 1993 (Fig. 1) [14, 15, 25, 26, 37]. The robotic manipulator provides six degrees-of-freedom motion and is capable of recording and reproducing positions in the three-dimensional space with an accuracy of <0.2 mm and 0.2°. In combination with a UFS which could measure three forces and three moments about and along a Cartesian coordinate system fixed with respect to the sensor, the testing system can operate in both force-control and position-control modes to allow for information on knee kinematics as well as the forces carried by the ACL to be collected. In force-control mode, the robot applies an external load to the specimen and the corresponding kinematics can be obtained. Alternatively, the robotic/universal force-moment sensor testing system can operate under position-control mode by moving the specimen exactly along a previously recorded motion path so that the UFS can record a new set of force and moment data. As such, the in situ force in a specific tissue can be calculated in a noncontact manner by determining the changes in measured forces for a given set of kinematics before and after removing that tissue (e.g., cutting the ACL), on the basis of the principle of superposition [4, 37, 41].

This testing system offers distinct advantages. First, a reference position for a joint can be established and used as a common starting position for all experimental conditions. This allows direct one-to-one comparisons of multiple experimental conditions in the same cadaver knee specimen (e.g., the knee in which the ACL is intact compared with the same knee following ACL reconstruction). Furthermore, this reduces the effect of interspecimen variation and greatly increases the statistical power of the data. To date, we have used this novel apparatus to test over 700 knee specimens and have reported the results in nearly 60 manuscripts on the knee alone. Over the years, more than a dozen other laboratories have also adopted this testing system [13, 17].

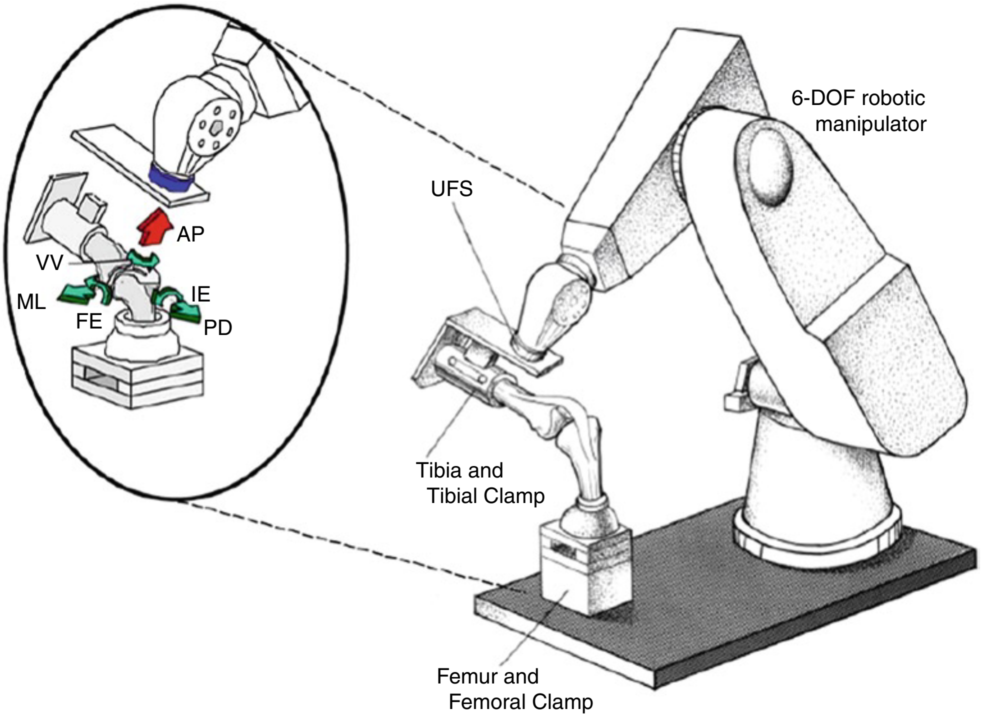


Fig. 1 Schematic drawing illustrating the robotic/universal force-moment sensor (*UFS*) testing system and the six degrees of freedom (*DOF*) of motion of the human knee joint (anterior-posterior (*AP*), medial-lateral (*ML*), and proximal-distal (*PD*) translations; flexion-extension (*FE*), internal-external (*IE*), and varus-valgus (*VV*) rotations) (With permission from [4])

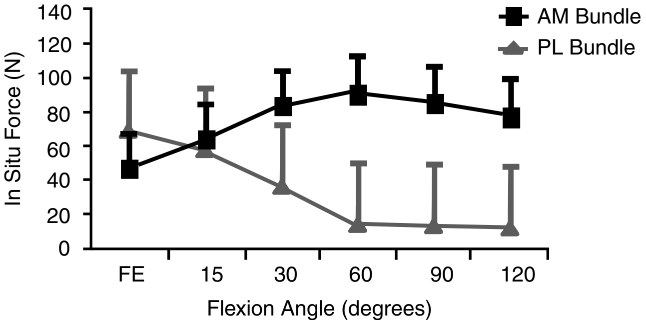


Fig. 2 Magnitude of the in situ force in the intact *AM* and *PL* bundles in response to a 134 N anterior tibial load (mean +/−SD, *n* = 10) (With permission from [16])

Early studies done using the robotic/UFS testing system were performed to gain an understanding of the function of the AM and PL bundle. It was found that under an applied anterior tibial load, the in situ force in the PL bundle was larger than that in the AM bundle when the knee was near full extension. With knee flexion, their contribution changes as the AM and PL bundles almost evenly shared the load at 15° of flexion (Fig. 2) [16, 38]. With further flexion, the AM bundle would carry the majority of the load. Thus, we learned that the PL bundle functions more near full knee extension while the AM bundle plays a greater role in flexion.

We have also examined the role of the AM and PL bundles when the knee is subjected to a combined rotatory load of valgus and internal tibial torques [16]. In this case, the AM and PL bundles almost evenly shared the load at 15° of knee flexion. Even though PL bundle is the smaller of the two, it plays a significant role in controlling rotatory knee stability, especially with the knee near extension, because of the more lateral position of its femoral insertion site.

Femoral Tunnel Placement for Double-Bundle ACL Reconstruction

In a preliminary study, we compared how well a single-bundle bone-patellar tendon-bone (BPTB) autograft could restore knee stability when it was placed at the PL or AM insertion site of the femoral condyle [27]. When the reconstructed knee was subjected to an anterior tibial load, both reconstruction procedures were able to restore anterior tibial translation similar to that of the intact knee. The only exception was that at knee flexion angles over 90°, the graft placement at the insertion site of the PL bundle could not restore the anterior tibial translation. Under combined rotatory loading, however, graft placement at the insertion site of the PL bundle could better restore the coupled anterior tibial translation and in situ force in the ACL graft to the levels of the intact knee at 15° and 30° of knee flexion, compared to graft placement at the insertion site of the AM bundle. Thus, even though the ACL grafts placed at either the femoral insertion site of the AM or PL bundles could effectively resist an anterior tibial load, graft placement at the insertion site of the PL bundle was more effective in resisting rotatory loads, particularly when the knee was near extension.

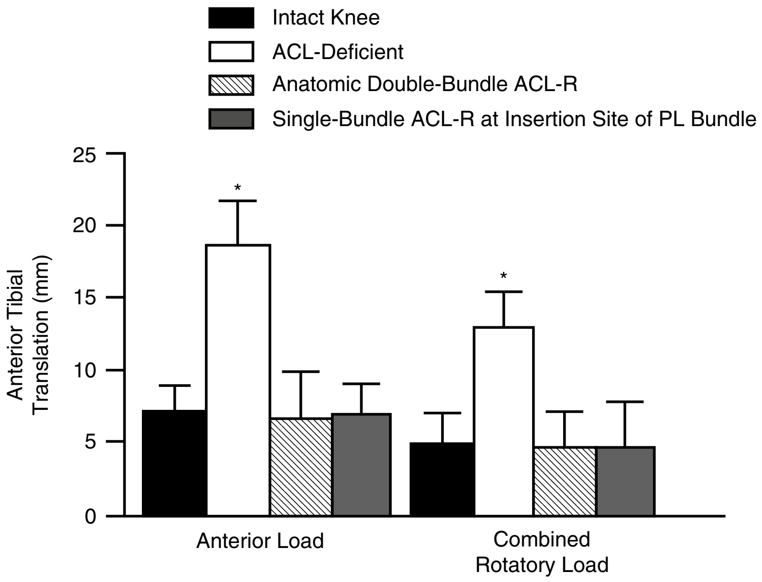
To improve the issue of rotatory instability following ACL reconstruction, we studied the potential of a double-bundle ACL reconstruction. In a study where a double-bundle ACL reconstruction was compared with a single-bundle ACL reconstruction placed at the femoral insertion site of the AM bundle, we have found that both reconstructions could restore knee kinematics and in situ force of the ACL under anterior tibial loading [43]. Under combined rotatory loading, the anatomic double-bundle reconstruction could better restore knee stability compared to the single-bundle ACL reconstruction placed at the femoral insertion site of the AM bundle. For example, under combined rotatory loads at 30° of flexion, the in situ force normalized to the normal ACL was 91% ± 35% and 66% ± 40%, respectively. Thus, the anatomic double-bundle reconstruction was found to be superior to the single-bundle reconstruction at the femoral insertion site of the AM bundle.

A similar study was also done to compare an anatomic double-bundle reconstruction to a more laterally placed single-bundle reconstruction at the femoral insertion site of the PL bundle [44]. In this case, in response to anterior tibial and combined rotatory loads, both reconstructions were able to restore anterior tibial translation and in situ force in the ACL graft near those of the intact knee at flexion angles near knee extension. For example, under the combined rotatory loads at 15° of flexion, the coupled anterior tibial translation was 4.8 ± 2.4 mm versus 4.8 ± 3.0 mm for the anatomic double-bundle and graft placement at the insertion site of the PL bundle, respectively (Fig. 3). To reproduce the complex function of the ACL throughout the range of knee flexion, reproducing both bundles of the ACL may have biomechanical advantages. On the other hand, a more laterally placed reconstruction, such as graft placement at the insertion site of the PL bundle, may also work quite well, especially with the knee near extension where the ACL is most needed.

Graft Fixation in Double-Bundle ACL Reconstruction

As double-bundle ACL reconstruction procedures involve the use of two separate grafts, an elevated or imbalanced force distribution between the grafts placed at the AM and PL bundle insertion sites could predispose one or both to a higher risk of failure. In particular, the graft placed at the PL

Fig. 3 Anterior tibial translation (mean ± SD) in the intact, anterior cruciate ligament deficient (*ACL-D*), and ACL-reconstructed (*ACL-R*) knees (anatomic double-bundle and a single-bundle graft placed at the femoral insertion of the posterolateral (*PL*) bundle) in response to an anterior tibial load and combined rotatory load at 15° of knee flexion. An *asterisk* indicates a statistically significant difference ($p < 0.05$) (With permission from [44])



bundle insertion site may have an especially high risk of failure because it is smaller in size as well as shorter in length than the AM graft. Thus, it could experience excessively higher loading near full knee extension [9, 35, 45].

In the literature, authors have advocated fixation of both grafts at wide variety of angles of knee flexion, ranging between 10° and 90° [1, 33, 35, 45]. In the light of these inconsistencies, our research center has performed biomechanical studies in order to recommend a suitable range of angles of knee flexion for graft fixation that would be safe, that is, to avoid overloading.

In our first study, two graft fixation protocols for double-bundle ACL reconstruction were compared [30]. In the first protocol, the grafts placed at the femoral insertion sites of the AM and PL bundles were both fixed at 30° of flexion, while in the second protocol the grafts placed at the femoral insertion sites of the AM and PL bundle were fixed at 60° and full extension, respectively. It was found that the AM graft was not overloaded when the AM and PL grafts were both fixed at 30° of flexion (Fig. 4). However, the PL graft was overloaded by an average of 34% above the intact PL bundle under an applied 134 N anterior tibial load, and 67% under a combined rotatory load of 10 Nm of valgus torque and 5 Nm of internal tibial torque. On the other hand, the PL graft was not overloaded when the AM and PL grafts were fixed at 60° and full extension, respectively, but the graft at the AM insertion site was overloaded by an average of 46% compared with the intact AM bundle under a 134 N anterior tibial load (Fig. 4). As a result, it is suggested that the graft at the AM insertion site should be fixed at a knee flexion angle of less than 60°, while the graft at the PL insertion site should be fixed closer to extension.

A follow-up study was done to further narrow the range of appropriate flexion angles for graft fixation [40]. In this study, the graft at the insertion site of the PL bundle was fixed at 15°, while fixation of the graft at the insertion site of the AM bundle was fixed at 45° or 15° of flexion. Both groups could restore the knee kinematics to within 2 mm of the intact knee and in situ force of overall grafts similar to the intact ACL. However, under the anterior tibial load, the in situ forces for the graft at the insertion site of the AM bundle when both grafts were fixed at 15° were significantly different (79.3% and 77.9% of the intact AM bundle) at 30° and 45° of knee flexion. In conclusion, knee flexion angles between 15° and 45° for graft fixation were found to be safe for the graft at the insertion site of the AM bundle, while 15° of knee flexion was safe for the graft at the insertion site of the PL bundle. Studies from other research centers have found similar results [24].

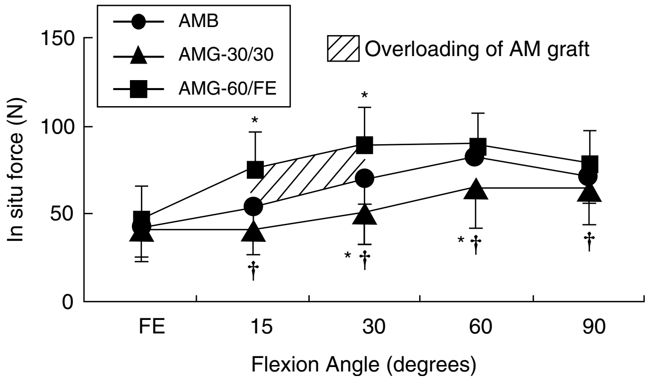


Fig. 4 In situ force in the anteromedial (*AM*) bundle (*AMB*) and graft placed at the femoral insertion of the AM bundle (AMG) in response to 134-N anterior tibial load for the two different fixation protocols (the grafts placed at the femoral insertion sites of the AM and PL bundles fixed at 30° of flexion (AMG-30/30) or at 60° and full extension, respectively (AMG-60/FE)). *$p < 0.05$ compared with AMB. †$p < 0.05$ compared with AMG-60/FE (With permission from [30])

Clinical Outcome Studies

A growing number of clinical studies have compared the outcome of single-bundle versus double-bundle ACL reconstruction [1, 3, 6, 21, 23, 29, 34, 35, 39, 42, 46]. Several prospective clinical trials have reported that the double-bundle procedures were significantly better than the single-bundle procedures in terms of knee stability when the pivot-shift test or Lachman tests were used at the end of the surgery [3, 21, 42, 46]. Nevertheless, not all of the investigations shared the results of a significant difference in postoperative knee stability [1, 6, 35, 39]. At short-term follow-up (2–3 years postoperatively), those studies showed subjective and functional test scores, for example, Lysholm score and International Knee Documentation Committee evaluation, between the two procedures were similar. Unfortunately, long-term clinical data are not yet available. It should be noted that there are challenges when evaluating clinical outcome data between studies as the pivot-shift test is subjective and there are a large number of surgical variables that need to be controlled. Nevertheless, better clinical outcomes with double-bundle ACL reconstruction procedures are yet to be demonstrated [28].

A Word of Caution in Interpretation of Data

There exist several factors which should be considered when interpreting the data between different studies. One factor is the method of describing the graft tunnel position. Many surgeons and researchers have used the “o’clock position method” to describe femoral tunnel position in the frontal plane. However, that method fails to appreciate the three-dimensional orientation of the femoral ACL insertion site within the notch, which changes with the angle of knee flexion. As many terms have been used to describe the femoral tunnel positions, a comparison of results between studies can be difficult. For the tibial tunnel position, there are similar problems, as many studies have not described tibial tunnel in sufficient detail to identify any differences between studies. Although the tibial tunnel is thought to have relatively minor effects on knee rotatory stability as compared to the femoral tunnel, it should still be better described. In an effort to avoid these problems, more information pertaining to surgical techniques and arthroscopic pictures, with the angle of knee flexion noted, should be utilized, and three-dimensional CT images could be incorporated when available. In conclusion, there is a need for better descriptions of tunnel placement to avoid confusion in interpreting data between studies.

A second factor is the different protocols for graft fixation. Due to the many variables involved, for example, knee flexion angle, pretension, and sequence of fixation, there are many different protocols used. Therefore, since these factors might affect the final result, attention should be paid to the protocol used in each study. Finally, testing systems as well as experimental procedures for evaluation should allow multiple degrees of knee motion, since this has been shown to largely affect the relative contribution of the ACL to knee function. Thus, appropriate experimental tools to obtain biomechanical data must be carefully considered.

Future Directions: Advancing from In Vitro to In Vivo Studies

In this chapter, many in vitro biomechanical studies that contributed to the understanding of the function of the ACL and its bundles as well as double-bundle ACL reconstruction procedures have been presented in detail. Indeed, significant contributions have been made in advancing the issues on the effects of tunnel placement, proper knee flexion angles for graft fixation, graft selection, initial graft tension, and graft tunnel motion, among others. These studies have also prepared us to move into in vivo studies. In the future, kinematics during activities of daily living will need to be measured and reproduced on cadaver knees, utilizing the robotic/UFS testing system in order to determine in situ forces in the ACL during these in vivo activities (Fig. 5). With the advent of a biplanar fluoroscopy system, it has become possible to measure in vivo knee kinematics with an accuracy of <0.2 mm and 0.3° for knee motions [18].

Meanwhile, a new high-payload robotic/UFS testing system design has been made available to accommodate the level of loads during these in vivo activities. Using cadaver knees and the in vivo data on knee motion, the in situ forces in the ACL and ACL replacement grafts can be determined. Moreover, in vivo kinematics can be integrated into three-dimensional finite element models of the knee, which incorporate the complex anatomy and geometry of the ACL, that is, including the AM and PL bundles, variable cross-sectional area along the ACL, and so on. Once the model is validated with experimental data, it can be used to compute stress and strain distributions in the ACL and ACL replacement grafts during complex in vivo motions that could not be done in laboratory experiments.

With such a combined experimental and computational approach, it will be possible to develop a database of the in situ forces, stresses, and strains in ligaments for patients of different age, sex, and size and to identify mechanisms of ACL and other ligament injuries, to improve reconstruction procedures, and to optimize rehabilitation protocols. We believe that such a biomechanics-based approach will provide clinicians and surgeons with valuable scientific information as well as enable them to devise better methods for

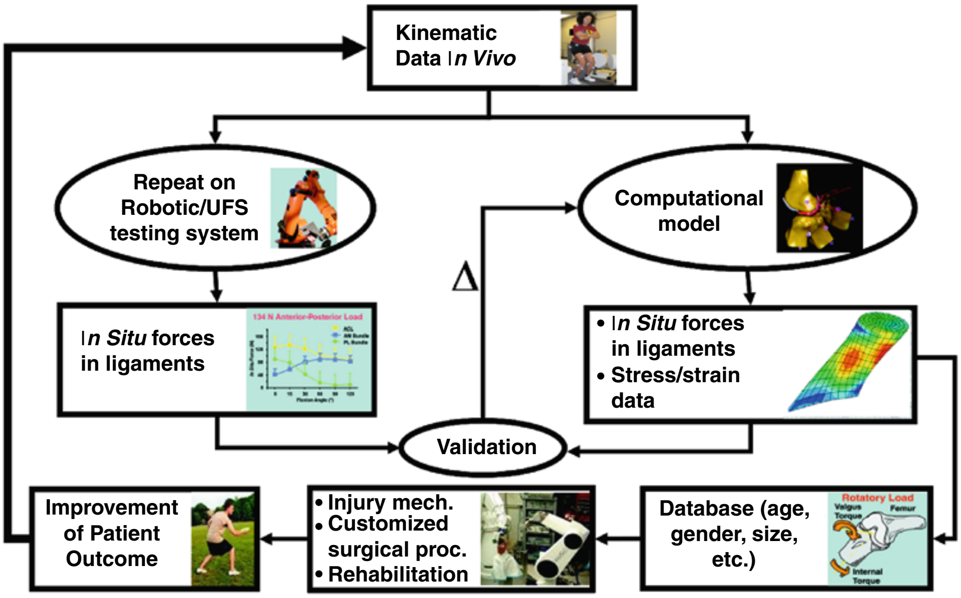


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Fig. 5 A Flow chart showing the utilization of in vivo kinematics data to drive experimental and computational methodologies leading to improved patient outcome (With permission from [41])

ACL reconstruction in order to restore normal structure and function of the knee. In the end, the new information should provide patients with better long-term patient outcome.

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