Knee Stability After Articulated External Fixation

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Background: Articulated external fixation has been proposed as a method to protect ligament reconstructions while allowing aggressive and early postoperative rehabilitation after knee dislocation. However, the ability of these fixators to protect and stabilize the knee joint has not been clearly determined.

Hypothesis: Articulated external fixation can reduce anteroposterior translation in the cruciate-deficient knee and reduce cruciate ligament strain in cases of intact or reconstructed ligaments.

Study Design: Controlled laboratory study.

Methods: Knee stability was assessed by 3 standard clinical stability tests (Lachman, anterior drawer, and posterior drawer) on 7 human cadaveric lower extremities. Instrumented forces of 100 N were applied to the tibia to measure cruciate ligament forces and tibiofemoral displacement in intact and cruciate-deficient specimens with and without articulated external fixation to determine the degree to which a fixator can protect cruciate ligaments and stabilize the knee. Articulated external fixation was applied using monolateral and bilateral fixators to comparatively analyze the effectiveness of each construct. Statistical analysis was performed using 2-tailed, paired Student *t* tests.

Results: Application of the monolateral articulated external fixator to specimens with intact ligaments significantly reduced cruciate ligament forces by 1.0 N ($P = .011$), 1.7 N ($P = .046$), and 1.4 N ($P = .009$) for Lachman, anterior drawer, and posterior drawer tests, respectively. In the cruciate ligament–deficient knees, the application of a monolateral fixator significantly reduced tibiofemoral translation by 49%, 70%, and 46% for Lachman, anterior drawer, and posterior drawer tests, respectively. No significant differences between the monolateral and bilateral fixator frames, in terms of ligament protection and joint stabilization, were observed.

Conclusion and Clinical Relevance: Articulated external fixation of the knee can reduce stress in the cruciate ligaments after multiligament reconstructions and can decrease anteroposterior translation in the cruciate-deficient knee.

Keywords: knee; external fixation; tibial displacement; cruciate ligaments; ligament protection; ligament forces

Multiple ligament reconstructions after traumatic knee dislocations are complicated by high rates of arthrofibrosis and recurrent instability.[12,15,17,22,23] Articulated external fixation, which would allow for more aggressive postoperative physical therapy while protecting the reconstruction, has recently been proposed as an adjunct to standard multiligament reconstruction of the dislocated knee.[3,14,16,21] In a recent study of ligament reconstructions after knee dislocations, markedly decreased failure rates relative to a standard postoperative hinged knee brace were noted with use of articulated external fixation.[21] Articulated external fixation about the knee has also been advocated for chronic knee dislocations[14,18,19] and for the treatment of severe periarticular fractures of the knee.[3,13]

Previous biomechanical studies showed that a single-axis hinged external fixator is able to reproduce the normal kinematics of the knee over a significant portion of the range of motion without adversely loading the periarticular structures.[20,25] Given the favorable clinical outcomes and the lack of detrimental loading of the periarticular structures, the ability of the fixator to control anteroposterior motion of the joint and forces within the cruciate ligaments becomes an important factor in determining the clinical utility of articulated external fixation. The only

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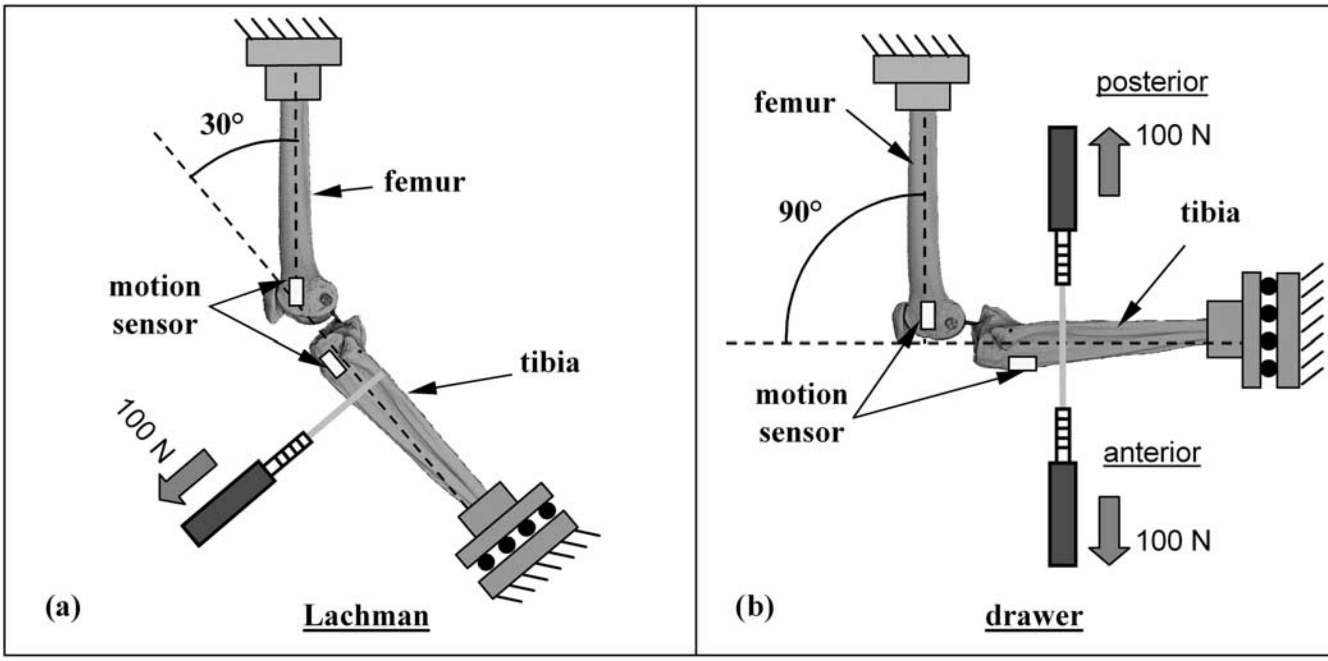

Figure 1. Test configuration for Lachman testing at 30° of knee flexion (a) and anterior drawer and posterior drawer testing at 90° of knee flexion (b).

previous study that attempted to measure the ability of an articulated external fixator to control anteroposterior motion showed that aligning the fixator with an axis determined by palpating the femoral epicondyles could not adequately control posterior translation of the tibia.[25] The current study investigated the ability of 2 different articulated external fixator constructs to reduce cruciate ligament stresses in the cruciate-intact knee and to control anteroposterior motion in the cruciate-deficient knee when the fixator axis was aligned with a radiographically determined knee axis of rotation.

MATERIALS AND METHODS

Seven fresh-frozen cadaveric specimens (age, 76 ± 8 years) were clinically determined to be free of ligamentous abnormalities and radiographically determined to be free of arthritis. The specimens were prepared by removing all superficial soft tissues while carefully preserving the joint capsule and supporting ligaments. The femur and tibia were sectioned 25 cm from the joint line, and the shafts were potted in polymethyl-methacrylate cylinders. Each specimen was mounted to a custom testing apparatus with the femur being rigidly affixed. The tibia was attached to an x-y table allowing anteroposteriorly directed tibial displacement that facilitated the performance of controlled and reproducible Lachman, anterior drawer, and posterior drawer tests (Figure 1). Electromagnetic motion sensors (PC Bird, Ascension Technology Corp, Burlington, Vt) were rigidly mounted on the femur and tibia to measure relative tibiofemoral motion. We previously evaluated the distortional effects of various materials on the electromagnetic system and found that stainless steel, unlike ferromagnetic materials, had no significant effect on recorded data.[1,2] Therefore, to avoid measurement errors, only nonferrous materials (ie, stainless steel, carbon fiber, Plexiglas) were used near the sensors and between the sensors and transmitter. Small anterior and posterior arthrotomies not exceeding 2 cm were made, and 1 force sensor each (AIFP, Microstrain, Burlington, Vt) was implanted into the midsubstance of the ACL and PCL.

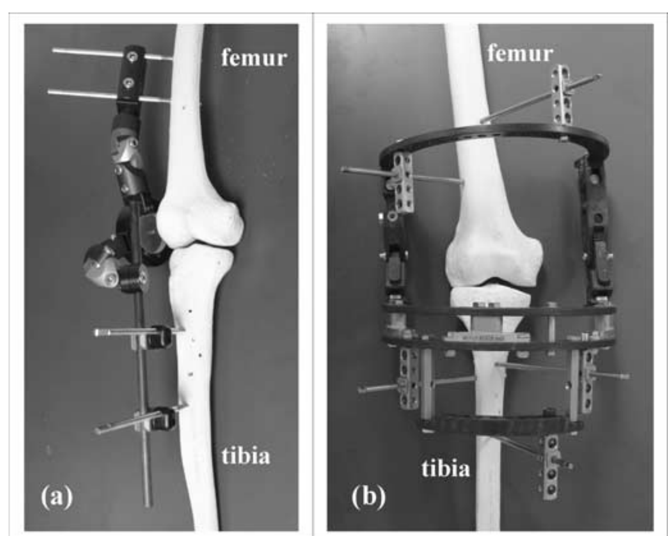

Figure 2. Articulated external knee fixators mounted on sawbone specimens; monolateral (a) and bilateral (b) constructs.

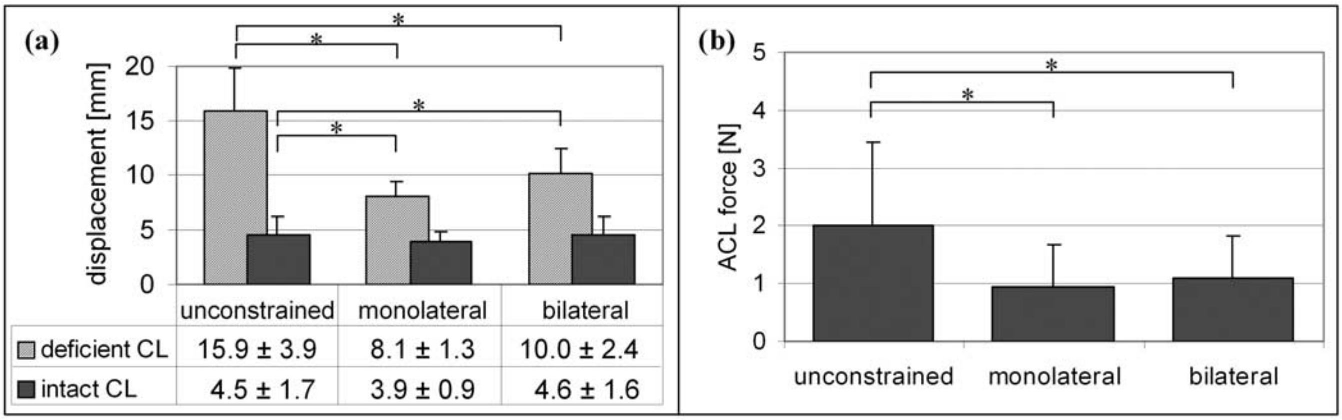

Figure 3. Lachman test: anterior displacement (a) and ACL forces (b) as a result of 100-N anterior pull with the knee at 30° of flexion. *$P < .05$; CL, cruciate ligament.

These force sensors measured transverse forces within the ligament, which are nominally proportional to the tensile forces within the ligament.[5]

For the Lachman tests, the knee was mounted at 30° of flexion in the custom apparatus and an anteriorly directed force of 100 N was applied at a point 7 cm below the tibial tubercle using a linear force scale (Accuweigh T-20, capacity 100 N, accuracy 1%, Alpha Group Weigh Inc, Miami, Fla) (Figure 1a). In a similar manner, a 100-N anteriorly directed force was applied to the tibia with the knee in 90° of flexion, simulating an anterior drawer test (Figure 1b). Finally, posteriorly directed forces of 100 N were applied through the same point on the tibia with the knee in 90° of flexion to simulate a posterior drawer test (Figure 1b). The resulting ACL and PCL forces and displacement of the tibia relative to the femur were recorded from the force sensors and motion sensors, respectively. The tibial force of 100 N was chosen to be in the midrange of the commercially available knee ligament arthrometer (MEDmetric Corp, San Diego, Calif) (67 N to 133 N) and was based on previously published studies investigating cruciate ligament stability.[6,8-10,25]

The knee was initially tested without external fixator constraints, simulating a normal knee. The flexion-extension axis was then located fluoroscopically using a previously described method that relies on radiographic landmarks.[4,7,11] In this method, fluoroscopic images with the x-ray source located laterally were used to align the posterior aspects of the femoral condyles to be concentric, with the lateral condyle appearing larger in radius than the medial condyle. Subsequently, 2 articulated external fixators with differing frame geometry were aligned to the flexion-extension axis of the knee and applied using the manufacturer's recommended technique. One fixator was a monolateral construct (EBI, Parsippany, NJ) (Figure 2a), whereas the other was a bilateral construct (Compass Hinge, Smith & Nephew, Memphis, Tenn) (Figure 2b). The monolateral construct was attached to the tibia and femur by stainless steel pins 6 mm in diameter, with 2 pins placed in the lateral femur and 2 pins in the anteromedial tibia. The bilateral fixator was applied in a multiplane configuration with 2 titanium 5-mm pins in the femur and 3 titanium 5-mm pins in the tibia. Pin position and spread in both fixation constructs was controlled and kept constant for each knee specimen. Both fixators were applied with the knee in 30° of flexion. Instrumented Lachman, anterior drawer, and posterior drawer tests were again performed.

Upon completion of testing specimens with intact cruciate ligaments, both the ACL and PCL were sectioned and the entire testing cycle was repeated for each specimen. First, the unconstrained cruciate-deficient knee was tested, followed by testing of the knee constrained by either fixation construct. Care was taken to return the tibia to the neutral position relative to the femur before each testing cycle. For cruciate-deficient specimens, only the tibiofemoral displacement was recorded because no force measurements could be obtained.

Statistical analysis of tibiofemoral displacement and ligament forces was performed using 2-tailed, paired Student t tests with a 95% confidence level. This analysis was conducted for the unconstrained as well as the monolateral and bilateral configurations to test the hypothesis that articulated external fixation can significantly reduce cruciate ligament forces and anteroposterior knee laxity.

RESULTS

Lachman Testing

Lachman testing of the intact knee resulted in an average anterior tibial translation of 4.5 ± 1.7 mm (Figure 3a). Subsequent application of the external fixators to the intact knee resulted in no change in anterior translation of the tibia. Forces in the ACL significantly decreased from 2.0 ± 1.44 N for the unconstrained knee to 0.96 ± 0.71 N ($P = .011$) and 1.11 ± 0.72 N ($P = .026$) for monolateral and bilateral fixators, respectively (Figure 3b). Lachman testing of the cruciate-deficient knee without the fixator resulted in a significant ($P = .0003$) displacement increase to 15.9 ± 3.9 mm as compared to the intact knee.

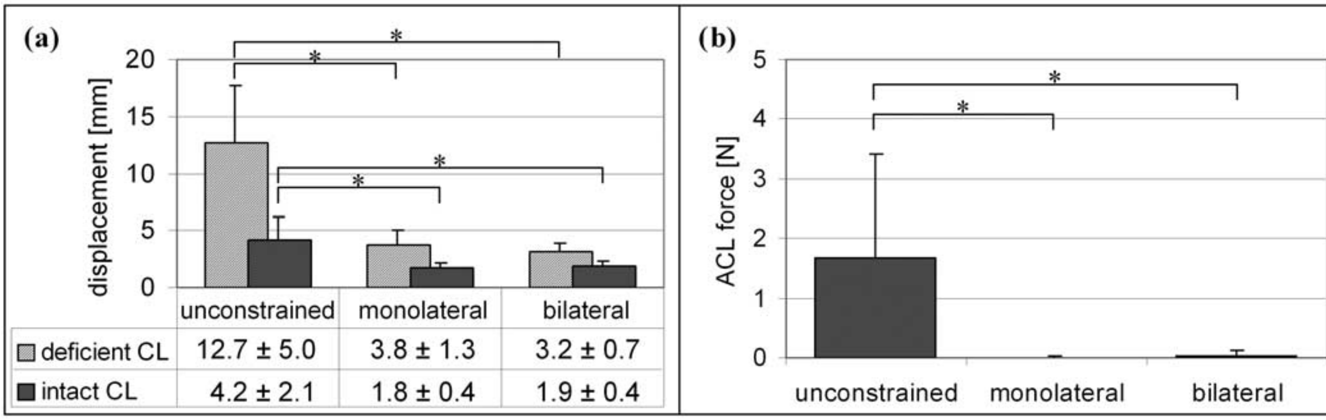

Figure 4. Anterior drawer test: anterior displacement (a) and ACL forces (b) as a result of 100-N anterior pull with the knee at 90° of flexion. *$P < .05$; CL, cruciate ligament.

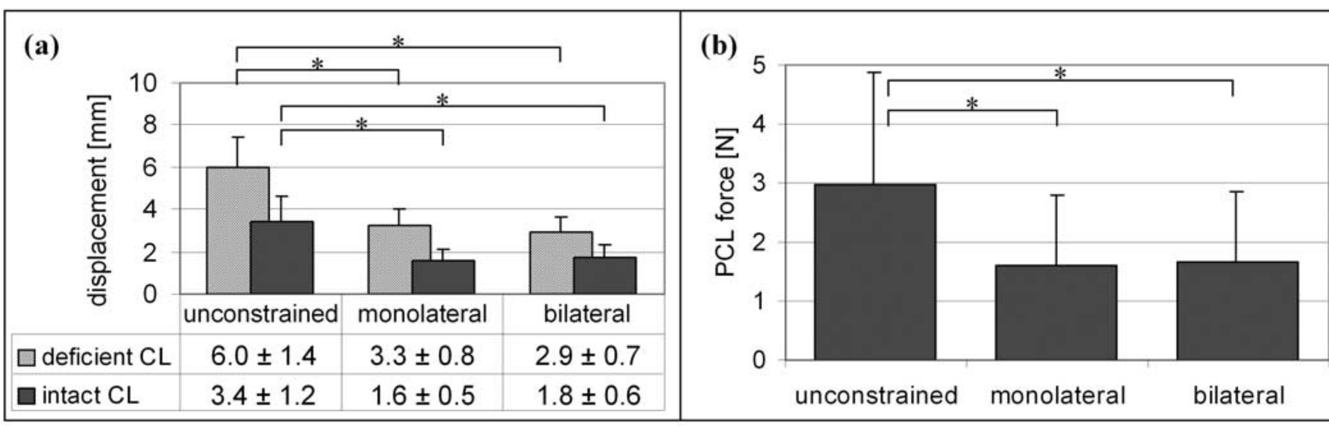

Figure 5. Posterior drawer test: posterior displacement (a) and PCL forces (b) as a result of 100-N posterior pull with the knee at 90° of flexion. *$P < .05$; CL, cruciate ligament.

Subsequent application of the monolateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .0005$) decrease in anterior translation of the tibia to 8.1 ± 1.3 mm, a 49% decrease relative to the unconstrained cruciate-deficient knee. Application of the bilateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .001$) decrease in anterior translation to 10.0 ± 2.4 mm, representing a 37% decrease relative to the unconstrained cruciate-deficient knee (Figure 3a). The external fixators did not, however, decrease the amount of translation to the level of the cruciate ligament–intact knee (monolateral $P = .003$; bilateral $P = .002$).

Anterior Drawer Testing

Anterior drawer testing of the intact knee resulted in an average anterior tibial translation of 4.2 ± 2.1 mm (Figure 4a). Subsequent application of the external fixators to the intact knee significantly decreased anterior tibial translation to 1.8 ± 0.4 mm (monolateral $P = .014$) and 1.9 ± 0.4 mm (bilateral $P = .017$). Forces within the ACL also significantly decreased from 1.67 ± 1.75 N for the unconstrained knee to 0 ± 0.03 N ($P = .046$) and 0.04 ± 0.09 N ($P = .049$) for monolateral and bilateral fixators, respectively (Figure 4b). Anterior drawer testing of the cruciate-deficient knee without the fixator resulted in a significant ($P = .001$) displacement increase to 12.7 ± 5.0 mm as compared to the intact knee. Subsequent application of the monolateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .003$) decrease in anterior translation of the tibia to 3.8 ± 1.3 mm, a 70% decrease relative to the unconstrained cruciate-deficient knee. Application of the bilateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .002$) decrease in anterior translation of the tibia to 3.2 ± 0.7 mm, a 75% decrease relative to the unconstrained cruciate-deficient knee (Figure 4a). The external fixators decreased the amount of anterior tibial translation to the level of the intact knee.

Posterior Drawer Testing

Posterior drawer testing of the intact knee resulted in an average posterior tibial translation of 3.4 ± 1.2 mm (Figure 5a). Subsequent application of the external fixators to the intact knee significantly decreased posterior tibial translation to 1.6 ± 0.5 mm (monolateral $P = .004$) and 1.8 ± 0.6 mm (bilateral $P = .016$). Forces within the PCL also significantly decreased from 2.96 ± 1.91 N for the unconstrained knee to 1.61 ± 1.17 N ($P = .004$) and 1.67 ± 1.19 N ($P = .005$) for monolateral and bilateral fixators, respectively (Figure 5b). Posterior drawer testing of the cruciate-deficient knee without the fixator resulted in a significant ($P = .002$) displacement increase to 6.0 ± 1.4 mm as compared to the intact knee. Subsequent application of the monolateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .001$) decrease in posterior translation of the tibia to 3.3 ± 0.8 mm, a 46% decrease relative to the unconstrained cruciate-deficient knee. Application of the bilateral external fixator to the cruciate-deficient knee resulted in a significant ($P = .0005$) decrease in posterior translation of the tibia to 2.9 ± 0.7 mm, a 51% decrease relative to the unconstrained cruciate-deficient knee (Figure 5a). The external fixators decreased the amount of posterior tibial translation to the level of the intact knee.

DISCUSSION

A series of recent publications have advocated the treatment of knee dislocations or periarticular fractures with a hinged external fixator.[3,13,14,16,18-21,25] Stannard et al[21] showed a significant improvement in outcomes in patients undergoing acute reconstruction for knee dislocation when acute ligament reconstructions were augmented with an articulated fixator rather than with a standard hinged knee brace. They found a 7% failure rate of ligament reconstructions performed with hinged external fixator augmentation and a 29% failure rate with a postoperative hinged knee brace. Evaluation of the specific ligament injuries showed a significantly higher ACL and posterolateral corner failure rate, with no significant difference in the PCL reconstruction failure rate when hinged bracing was used. The authors advocated the use of hinged external fixation augmentation to allow more aggressive postoperative rehabilitation after multiple ligament reconstruction. There have also been 2 case reports describing the use of articulated external fixation for chronic knee dislocations. In both cases, the authors felt that the technique was successful in these limited case series.[18,19] Deszczynski et al[3] reported successful healing in 6 intraarticular and periarticular fractures treated with the Dynastab hinged external fixator, yielding full knee extension and only slightly decreased flexion.

If articulated external fixation of the knee is to be successful, the fixator must not place abnormally high forces on the periarticular structures as the knee moves through its range of motion. Ideally, it would also decrease forces in the reconstructed structures, allowing for more aggressive therapy without an increased risk of failure. In a biomechanical study, Sommers et al[20] showed that a limited range of motion could be obtained without inducing excessive forces on the periarticular structures when constraining the knee with an external fixator hinge that is aligned with the radiographic knee flexion-extension axis. Application of the external fixator decreased the knee range of motion from 122° to 79° within a 1-N·m moment envelope. Importantly, knee extension was decreased to 19° short of full extension, which poses one of the challenges to the clinical use of articulated external fixation. Especially for the knee, such a prolonged decrease in extension can evoke negative effects on long-term joint function, including patella infera and arthrofibrosis. These previous results demonstrated that application of articulated external fixation to the knee will necessarily reduce the obtainable range of motion. However, we found in further studies that applying the fixator at 30° instead of 60° of knee flexion provided for a more functional range of motion, which fell only 7° short of full extension.

Only 1 previous study has evaluated the ability of an articulated external fixator to control posterior motion in the cruciate-deficient knee. Wroble et al[25] applied a monolateral external fixator to cadaveric knees. They investigated 2 fixator axis locations, one aligned with an axis determined by palpating the femoral epicondyles and another that was aligned with the "fibular styloid" position, located distal to the joint line and posterior to the flexion axis. They found that only the fibular styloid position was able to control posterior translation at flexion angles greater than 30°.

Unlike Wroble et al,[25] the current study used the same radiographic knee axis employed by Sommers et al to align the external fixator.[20] Application of the fixator to the cruciate-intact knee simulated a scenario in which both ligaments had been anatomically reconstructed. Because the ligaments were intact, forces within the ACL and PCL could be measured. After application of the external fixators, there was a significant decrease in the force within both ligaments in response to standard clinical stability tests (Lachman, anterior drawer, and posterior drawer). This finding suggests that the external fixator and the cruciate ligaments were able to share the applied load; this effect was seen at both 30° and 90° of knee flexion. Load sharing between the ligaments and the fixator may allow for more aggressive rehabilitation after multiligament reconstructions without increasing the risk of graft failure.

Application of the fixator to the cruciate-deficient knee resulted in significant decrease of anterior and posterior tibial translation with the knee at 30° and 90° of flexion. However, the amount of translation decreased to a level equal to knees with intact cruciate ligaments only at 90° of knee flexion. This result is likely a function of fixator frame stability, with the frame providing more stability at 90° of flexion. With the knee at 30° of flexion, the distance between the proximal and distal pins is greater than at 90° of knee flexion, allowing greater flex in the construct and more anterior displacement during a Lachman test.

The data do not show a significant difference between the bilateral and monolateral fixator geometries. We felt it crucial to follow the specific manufacturer recommendations when applying the fixators. This method resulted in the use of different pin sizes and materials, which affect the relative stability of each fixator frame. Changes in these configurations will alter the rigidity of the fixator constructs and will affect the anteroposterior stability. With the mounting parameters used in this study, the monolateral frame was at least as effective as the bilateral hinge in controlling anteroposterior translation, which was important because a laterally based monolateral frame has advantages for patients compared with bilateral or circular frames.

The purpose of an articulated external fixator is to protect the reconstructed ligaments during motion in the early postoperative period. The results of this study confirm the ability of the fixator to protect the cruciate ligaments, but they are limited to ligament strain assessment at 30° and 90° of knee flexion. Since only 2 knee flexion angles were tested, fixator performance in other positions can only be estimated by extrapolation. It is likely that there are other external fixator application techniques and fixator axis locations that would also protect the cruciate ligaments, although it is unknown if these positions will cause excessive periarticular loads that would obviate their use in a clinical situation. However, in combination with the study of Sommers et al,[20] the results of this study are reassuring in that as long as the radiographic axis is properly identified and the fixator is aligned with this axis, the reconstructed ligaments are protected within a limited range of motion. Alternatively, if the knee axis and fixator axis are not coincident, the knee-fixator construct will "bind," resulting in excessive forces on the periarticular structures, including the cruciate ligaments. These forces could lead to failure of cruciate ligament reconstructions.

The fixator was able to reduce forces in the cruciate ligaments. This result led to stress shielding of the reconstructed ligaments and the graft-bone interface that may otherwise adversely affect ligament healing, maturation, and graft incorporation. However, since neither fixator construct was sufficiently stiff to eliminate stresses from the cruciate ligaments, some level of mechanical stimulation for ligament healing is likely to remain.

An additional limitation of this study was the restriction of soft tissue injuries to the ACL and PCL in our model. In reality, one can expect injuries to additional soft tissues after a knee dislocation, including the collateral ligaments and the posterolateral corner. However, ACL and PCL injuries are present in nearly all knee dislocations, whereas these other ligaments are inconsistently injured.[24,26] This study did not address these additional injuries but instead focused on the most common injury pattern.

This cadaveric study showed an advantage to the use of articulated external fixation to protect ligamentous reconstructions; however, these results need to be considered in light of the possible complications associated with the use of external fixator pins. The use of external fixator pins, especially in the thigh, is associated with problems including pain at the pin site during knee motion, frequent drainage, and occasional pin tract infections. These problems are preventable with adequate soft tissue releases at the time of surgery and adherence to standard pin care protocols. Certainly, the introduction of motion at the knee will increase the risk of pin irritation problems, and it may require an even more aggressive approach to pin site care.

In conclusion, both articulated fixator geometries were able to control anteroposterior translation in the cruciate-deficient knee. The reduction of anteroposterior motion was greater with the knee in 90° of flexion (anterior drawer and posterior drawer tests) than in 30° of flexion (Lachman test). In addition, the fixators were able to significantly decrease the forces in both the ACL and PCL in response to standard clinical stress tests. These findings indicate a load-sharing protective effect of the fixator, which may prove beneficial after multiple ligament reconstructions for knee dislocations.

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