Interaction between the ACL graft and MCL in a combined ACL+MCL knee injury using a goat model

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ABSTRACT – The optimal treatment for the MCL in the combined ACL and MCL-injured knee is still controversial. Therefore, we designed this study to examine the mechanical interaction between the ACL graft and the MCL in a goat model using a robotic/universal force-moment sensor testing system. The kinematics of intact, ACL-deficient, ACL-reconstructed, and ACL-reconstructed/MCL-deficient knees, as well as the in situ forces in the ACL, ACL graft, and MCL were determined in response to two external loading conditions: 1) anterior tibial load of 67 N and 2) valgus moment of 5 N-m.

With an anterior tibial load, anterior tibial translation in the ACL-deficient knee significantly increased from 2.0 and 2.2 mm to 15.7 and 18.1 mm at 30° and 60° of knee flexion, respectively. The in situ forces in the MCL also increased from 8 to 27 N at 60° of knee flexion. ACL reconstruction reduced the anterior tibial translation to within 2 mm of the intact knee and significantly reduced the in situ force in the MCL to 17 N. However, in response to a valgus moment, the in situ forces in the ACL graft increased significantly by 34 N after transecting the MCL. These findings show that ACL deficiency can increase the in situ forces in the MCL while ACL reconstruction can reduce the in situ forces in the MCL in response to an anterior tibial load. On the other hand, the ACL graft is subjected to significantly higher in situ forces with MCL deficiency during an applied valgus moment. Therefore, the ACL-reconstructed knee with a combined ACL and MCL injury should be protected from high valgus moments during early healing to avoid excessive loading on the graft.

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The treatment of combined anterior cruciate ligament (ACL) and medial collateral ligament (MCL) injuries remains a subject of debate (Larson 1980, Miyasaka et al. 1991, Shelbourne and Porter 1992, Shelbourne and Patel 1995, Hull 1997). While clinical experience has shown that isolated MCL injuries can heal with closed treatment (Indelicato 1983, 1995, Kannus 1988, Indelicato et al. 1990), the results on healing of the MCL in a combined ACL and MCL injury have not been encouraging (Woo et al. 1990). Some authors have recommended acute treatment of all damaged structures, others have reported a high incidence of arthrofibrosis with this method (Shelbourne and Baele 1988). Several animal studies have shown that ACL reconstruction for combined ACL and MCL injuries can restore functional stability of the MCL (Engle et al. 1994, Ohno et al. 1995). Nevertheless, the quality of the healed MCL was inferior when compared to those in isolated MCL injuries. Conversely, some authors have reported that the percentage of ACL graft failures depends on the severity of the MCL injury (Noyes and Barber-Westin 1995).

In the light of these controversial issues, a reliable animal model should be developed to compare various treatments. Due to the difficult surgical technique for ACL reconstruction using smaller animals such as rabbits, the goat knee was chosen as an experimental model because it has had long-term success with ACL reconstruction (Ng et al. 1996a, b). Furthermore, the use of robotic technology has facilitated the study of knee kinematics in multiple degrees-of-freedom (DOF) and determination of in situ forces in individual ligaments (Fujie et al. 1995, Rudy et al. 1996).

Therefore, we examined the interaction between ACL reconstruction and the MCL with 1) an anterior tibial load of 67 N and 2) a 5 N-m valgus moment. These two conditions permit extensive evaluation of the function of the ACL, ACL graft, and MCL. In this study, we hypothesized that ACL deficiency would increase the force in the MCL while reconstruction of the ACL might reduce the force in the MCL. We also hypothesized that the ACL graft will be subjected to higher forces in the MCL-deficient knee in response to externally applied loads to the knee. We utilized the robotic/UFS testing system to determine the knee kinematics and in situ forces of various ligaments in response to the above loading conditions.

Animals and methods

We tested 8 skeletally mature, fresh-frozen Saanen bred goat knees (35–45 kg). Radiographs were taken of each lower extremity to confirm skeletal maturity as well as no joint abnormalities. The knees were then wrapped in saline-soaked gauze and stored in air-tight plastic bags and kept frozen at –20 °C until the day prior to testing (Woo et al. 1986). After thawing at room temperature for 24 hours, the surrounding skin and muscles were dissected 10 cm proximal and distal to the knee joint. The femur and tibia were then potted in epoxy putty.

We used a robotic/UFS testing system (Fujie et al. 1995, Rudy et al. 1996) to measure the changes in knee kinematics and the in situ forces in the MCL following transection and reconstruction of the ACL. We also determined the changes in knee kinematics and the in situ forces in the ACL graft with the intact and MCL-deficient knee to test the hypotheses. The femur was fixed to the base of the robotic manipulator (Puma Model 762, Unimate, Inc.), while the tibia was rigidly attached to the end-effector of the robot through a universal force-moment sensor (UFS) (Model 4015, JR3, Inc., Woodland, California) (Figure 1). The robotic manipulator is capable of position control in six-DOF, while the UFS simultaneously measures three orthogonal forces and moments. The UFS can provide force-moment feedback to the robotic manipulator, thus enabling the robot to operate in a force control mode as well. In combination, this testing system enables the measurement of knee kinematics in multiple DOF and in situ forces in the MCL when the knee is subjected to externally applied loads to the tibia.

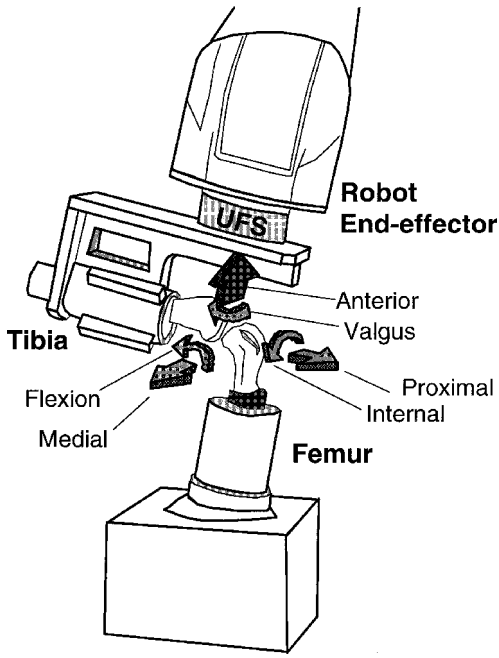

Figure 1. The robotic/UFS testing system.

We determined first the path of passive flexion-extension of the knee from 30° to 90° of knee flexion by the robotic/UFS testing system, while operating in force-control mode. This system found the positions of the knee throughout the range of flexion in 1° increments, while minimizing all external forces and moments as measured by the UFS. We chose a minimum flexion angle of 30° because the goat hindlimb cannot be completely extended. The positions determined by this procedure served as the starting points for the ensuing experiments that put external loads on the tibia.

A summary of the testing protocol is shown in Table 1. Briefly, an anterior tibial load of 67 N was applied at 30°, 60° and 90° of flexion, and the knee was allowed to translate in the medial-lateral, proximal-distal and anterior-posterior directions as well as undergo varus-valgus and internal-external rotation (5 DOF), while the resulting knee motion was recorded. Then a valgus moment of 5 N-m was applied at 60° of flexion with inter-

Table 1. Outline of experimental protocol and data acquired

Protocol	Data acquired
I. Intact knee	Intact knee kinematics
Path of passive flexion-extension	
A. 67 N anterior tibial load	
B. 5 N-m valgus moment	
Section ACl	In situ forces in ACL
Repeat kinematics (I-A and B)	
II. ACL-deficient knee	ACL-deficient knee kinematics
Reapply A and B	
Reconstruct ACL	
III. ACL-reconstructed knee (MCL intact)	ACL-reconstructed knee kinematics
Reapply A and B	(MCL intact)
Section MCL	In situ forces in MCL for
Repeat kinematics (I, II and III-A and B)	Intact knee, ACL-deficient knee and ACL-reconstructed knee
IV. ACL-reconstructed knee (MCL-deficient)	ACL-reconstructed knee kinematics
Reapply A and B	(MCL deficient)
Release ACL graft	In situ forces in ACL graft for
Repeat knee kinematics (III and IV-A and B)	ACL-reconstructed/MCL intact knee and ACL-reconstructed/MCL-deficient knee

nal-external tibial rotation restricted due to the large range of motion in this rotational plane in the goat knee that affects the application of valgus moment. The valgus moment was applied only at 60° of flexion because the in situ force in the MCL was greatest at this flexion angle during preliminary experiments, indicating its importance in limiting valgus rotation. The corresponding knee motion in 4 DOF was recorded.

We then transected the ACL through an anterior midline skin incision that was also used for harvesting the central third of the patellar tendon. The knee kinematics from the applied 67 N anterior load at each flexion angle as well as the knee motion from the applied 5 N-m valgus moment at 60° of flexion were then repeated. The UFS measured a new set of forces and moments for each condition. Using the principle of superposition, the change in forces measured before and after the removal of the ACL represented the in situ force in the ACL (Fujie et al. 1995, Livesay et al. 1995). The kinematics of the ACL-deficient knee in response to these loading conditions were also determined in the same manner as described previously.

We then performed an ACL reconstruction using a 6 mm wide bone-patellar tendon-bone (BPTB) autograft from the central third of the patellar tendon (Figure 2). The reconstruction was achieved with 5 mm diameter tunnels, drilled at the anatomic ACL insertion sites in the tibia and femur. Femoral fixation was accomplished using a press-fit technique of the 6 mm wide bone block in the 5mm diameter femoral tunnel (Georgoulis et al. 1997) and the fixation was augmented with a button on the lateral femoral cortex. The length of the goat BPTB autograft required the tibial bone

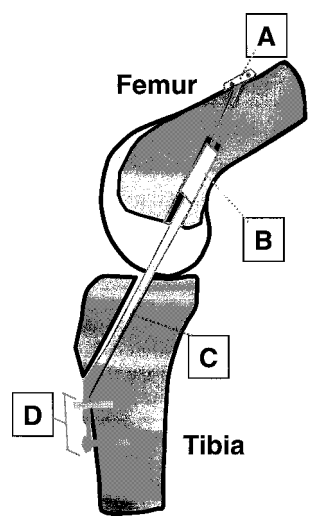

Figure 2. ACL reconstruction using bone-patellar tendon-bone autograft. A) Press-fit fixation augmented with a button on the lateral femoral cortex. B) Bone-bone interface. C) Bone-tendon interface. D) Staple and suture-postfixation.

Table 2. Knee kinematics in response to an anterior tibial load of 67 N and valgus moment of 5 N-m for various knee conditions. Mean (SD)

	Anterior tibial translation (mm)			Valgus rotation (°)
	30º	60º	90º	60º
Intact	2.0 (0.3)	2.2 (0.8)	2.0 (1.0)	4.8 (1.5)
ACL deficient	15.7 (2.6) [a]	18.1 (2.5) [a]	15.7 (2.9) [a]	6.4 (2.5)
ACL-reconstructed	3.7 (2.7) [a]	4.8 (1.7) [a]	3.8 (1.2) [a]	5.4 (1.4)
ACL-reconstructed/ MCL-deficient	4.9 (3.2) [b]	6.3 (2.6) [b]	4.7 (1.3)	15.2 (2.9) [b]

[a] Significant difference from the intact knee ($p < 0.05$)
[b] Significant difference from the ACL-reconstructed knee ($p < 0.05$)

block to be pulled through the tibial tunnel and fixed on the medial surface of the tibia using a 6.4 mm soft-tissue staple (Smith and Nephew, Memphis, TN) and suture-post. After 5 cycles of manual preconditioning, we fixed the graft under manual tension, such that positive translations did not occur during a manual Lachman test. The kinematics in response to the anterior tibial load and valgus moment were subsequently determined for the ACL-reconstructed knee.

We then transected the MCL and repeated the previously recorded knee motion for the intact, ACL-deficient and ACL-reconstructed knee. The in situ force in the MCL was found using the principle of superposition in a manner like that described for the ACL. Finally, the kinematics in response to the anterior tibial load and valgus moment were determined for the ACL-reconstructed and MCL-deficient knee. The ACL graft was subsequently released and the previously recorded knee motions for the ACL-reconstructed and ACL-reconstructed/MCL-deficient knee were repeated to determinate the in situ forces in the ACL graft during these knee motions.

In summary, the knee kinematics in response to an anterior tibial load of 67 N at 30°, 60°, and 90° of flexion and a valgus moment at 60° of flexion were obtained for four knee conditions: 1) intact knee, 2) ACL-deficient knee, 3) ACL-reconstructed knee, and 4) ACL-reconstructed and MCL-deficient knee. The in situ force in the MCL was determined for: 1) intact knee, 2) ACL-deficient knee, and 3) ACL-reconstructed knee. Finally, the in situ force in the intact ACL or ACL graft was determined for: 1) intact knee, 2) ACL-reconstructed knee, and 3) ACL-reconstructed and MCL-deficient knee.

Statistical analysis was performed using a two-factor repeated-measures analysis of variance (ANOVA) because all tests were performed on the same specimen. The dependent variables investigated were knee condition and flexion angle. This analysis is sensitive to relative changes occurring in an individual knee and thus specimen variability is minimized. Significance was set at $p < 0.05$.

Results

In response to an anterior tibial load of 67N, the anterior tibial translation of the intact goat knee was approximately 2 mm (Table 2). After transection of the ACL, a significant increase in anterior tibial translation, ranging from 13–14 mm, occurred at all flexion angles examined ($p < 0.05$). Following ACL reconstruction, the anterior tibial translation was restored to within 2 mm of the intact knee; however, these increases were still statistically significant ($p < 0.05$). MCL deficiency in an ACL-reconstructed knee led to only a small increase, between 1–1.5 mm, when compared to the ACL-reconstructed knee, in anterior tibial translation. This increase was significant only at 30° of flexion ($p < 0.05$).

In contrast, the amount of valgus rotation in response to the application of a valgus moment did not differ significantly between the intact, ACL-deficient and ACL-reconstructed knee (Table 2). However, with MCL deficiency, the ACL-reconstructed knee had a significant increase in valgus rotation to 15.2° (SD 2.9), approximately a 300% increase as compared to the intact knee.

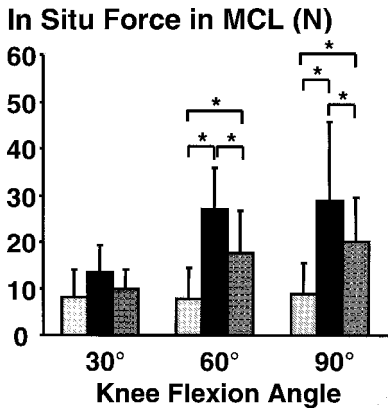

Figure 3. In situ forces in MCL in response to an anterior 67 N tibial load at 30°, 60°, and 90° of knee flexion (mean ± SD). Light gray – intact, black – ACL deficient, and dark gray – ACL reconstructed.

ACL deficiency had a significant effect on the in situ forces in the MCL (Figure 3). In response to an anterior tibial load of 67N, the in situ forces in the MCL increased ($p < 0.05$) from 8 (SD 7) N in the intact knee to 27 (SD 9) N in the ACL-deficient knee, representing almost a 300% increase at 60° of flexion. Reconstructing the ACL significantly reduced the in situ forces in the MCL at 60° and 90° of flexion, but the amount of force was still greater than those of the intact knee ($p < 0.05$).

The in situ forces in the ACL and ACL graft in response to an anterior tibial load of 67 N were found to be approximately 70 N at 30° of flexion (Figure 4). No significant differences were found ibn the intact, ACL-reconstructed, and ACL-reconstructed/MCL-deficient knees examined at this flexion angle. The in situ force in the ACL graft was lower by approximately 12N ($p < 0.05$) than the force in the intact ACL at 60° and 90° of flexion. On the other hand, the in situ forces in the ACL graft with MCL deficiency increased in response to the anterior tibial load when compared to the ACL-reconstructed knee. However, this change was only statistically significant ($p < 0.05$) at 90° of flexion.

In response to a valgus moment, the in situ forces in the MCL also increased significantly from the intact knee (28 (SD 8) N) to the ACL-deficient knee (36 (SD 9) N) by 29% at 60° of flexion. ACL reconstruction reduced the in situ forces in the MCL. However, there was no difference ($p > 0.05$) between the in situ forces in the MCL for the intact knee and ACL-reconstructed knee. Furthermore, in response to a valgus moment, no significant differences could be demonstrated for the in situ forces in the MCL between the ACL-deficient and ACL-reconstructed knee.

The in situ forces in the ACL graft for the ACL-

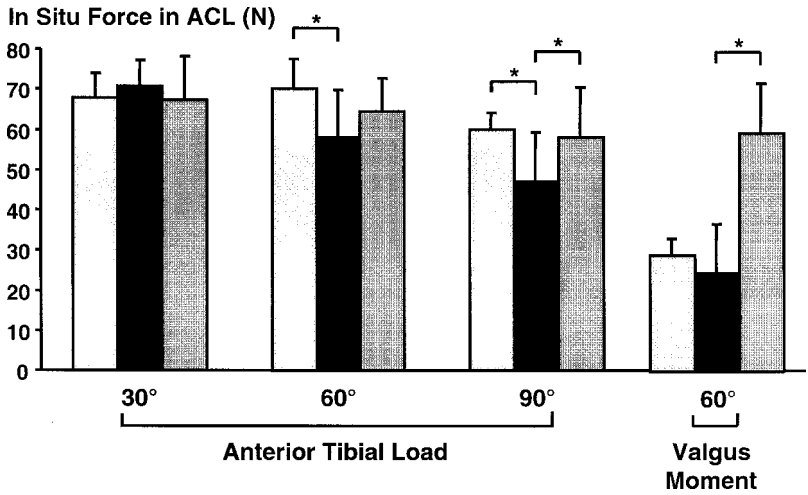

Figure 4. In situ force in ACL and ACL graft in response to an anterior tibial load of 67 N at 30°, 60°, and 90° of knee flexion and a valgus torque of 5 N-m at 60° of knee flexion (mean ± SD). Light gray – intact, black – ACL reconstructed, and dark gray – ACL reconstructed/MCL deficient.

reconstructed knee did not differ ($p > 0.05$) from the ACL at 60° of flexion. However, with MCL deficiency in the ACL-reconstructed knee, the in situ forces in the ACL graft increased ($p < 0.05$) by 34 (SD 18) N (Figure 4). These forces in the ACL graft were almost 2.5 times higher than those in the ACL-reconstructed knee with an intact MCL.

Discussion

In this study, we have utilized the robotic/UFS testing system to determine the interdependence of the ACL, ACL graft, and MCL in a goat model. Our results confirmed the hypothesis that ACL deficiency led to significant increases of the in situ forces in the MCL while ACL reconstruction could reduce the in situ forces in the MCL to levels near those with an intact ACL, but only in response to an anterior tibial load. The reduction of in situ forces in the MCL after ACL reconstruction may help to explain the improved healing of the MCL reported in clinical (Sandberg et al. 1987, Shelbourne and Patel 1995) and laboratory (Anderson et al. 1992, Engle et al. 1994, Yamaji et al. 1996) studies with this treatment protocol. The results also suggest that primary repair of the MCL may not be necessary if an ACL reconstruction can effectively restore knee stability.

Our results also partially support the hypothesis that the ACL graft will be subjected to higher forces in the MCL-deficient knee. In response to a valgus moment, the in situ forces in the ACL graft for the ACL-reconstructed knee with MCL deficiency were significantly higher than the forces in the ACL and the ACL graft with an intact MCL. The in situ forces in the ACL graft were 2.5 times higher in the ACL-reconstructed knee with MCL deficiency than in the intact knee. This was not the case with an applied anterior tibial load. This increase of in situ forces in the replacement graft may help explain the failures of the ACL grafts previously reported (Yamaji et al. 1996) when the combined ACL and MCL injury was examined using a rabbit model. In these studies, the MCL was shown to recover functionally following ACL reconstruction at 6 and 12 weeks (Anderson et al. 1992, Engle et al. 1994, Ohno et al. 1995). However, failure of the ACL grafts at 52 weeks (Yamaji et al. 1996) led to an increase in anterior-posterior laxity of the knee. Our results suggest that significantly higher forces in the ACL graft with MCL deficiency could increase the loads that the ACL grafts must sustain. Therefore, the ACL graft in a knee with a combined ACL and MCL injury should probably be protected from excessive valgus moments during the early healing period.

In this study, a goat model was utilized to study the behavior of the ACL, ACL graft and MCL. Animal studies like those in rabbits, canine and sheep have routinely been used to study ligament healing and have provided useful data on the healing process of the MCL. However, these models have proved to have limited long-term success, as results of ACL reconstruction in rabbits have been highly variable due to its small size (Ballock et al. 1989, Engle et al. 1994, Ohno et al. 1995, Yamaji et al. 1996). ACL reconstruction using a canine model shows early degenerative changes after this type of intraarticular procedure (Setton et al. 1994, Jarvinen et al. 1995). However, recent studies have reported long-term success, up to 3 years, when studying ACL reconstruction in a goat model (Jackson et al. 1987, 1993, Ng et al. 1996a, b). Our study suggests that the proposed ACL reconstruction technique can successfully restore the kinematics of an intact knee and permit observation of the strong interaction between ACL reconstruction and the MCL.

This combined ACL and MCL injury model using goats can now be extended to examine long-term healing of the MCL and ACL graft. Furthermore, the effect of growth factors on the quality of healing tissue and bone-to-bone and tendon-to-bone healing can be examined at various times to help obtain more definitive answers for the treatment of such severe knee injuries.

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