The Role of Extra-Articular Tenodesis in Combined ACL and Anterolateral Capsular Injury

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Background: The "gold standard" treatment of anterolateral capsular injuries in anterior cruciate ligament (ACL)-deficient knees has not been determined. The purpose of this study was to determine the effects of ACL reconstruction and extra-articular reconstruction on joint motion in the ACL-deficient knee and in the combined ACL and anterolateral capsule-deficient knee.

Methods: An anterior tibial load of 134 N and internal tibial torque of 7 Nm were applied to 7 fresh-frozen cadaveric knees using a robotic testing system continuously throughout the range of flexion. The resulting joint motion was recorded for 6 knee states: intact, ACL-deficient, ACL-reconstructed, combined ACL and anterolateral capsule-deficient, ACL-reconstructed + anterolateral capsule-deficient, and ACL-reconstructed + extra-articular tenodesis.

Results: Anterior tibial translation of the ACL-reconstructed + anterolateral capsule-deficient knee in response to an anterior tibial load was restored to that of the intact knee at all knee-flexion angles ($p > 0.05$). However, for this knee state, internal tibial rotation in response to internal tibial torque was not restored to that of the intact knee at 60° or 90° of knee flexion ($p < 0.05$). For the knee state of ACL-reconstructed + extra-articular tenodesis, internal rotation in response to internal tibial torque was restored to the motion of the intact knee at each of the tested knee-flexion angles ($p > 0.05$). Compared with the intact knee, 2 of 7 specimens showed decreased internal tibial rotation with ACL reconstruction + extra-articular tenodesis.

Conclusions: In this study, an extra-articular tenodesis was necessary to restore rotatory knee stability in response to internal tibial torque in a combined ACL and anterolateral capsule-deficient knee. The amount of rotatory knee instability should be carefully assessed to avoid over-constraint of the knee in these combined ligament-reconstruction procedures.

Clinical Relevance: On the basis of our findings, the surgical procedure needs to be personalized depending on the amount of rotatory knee instability in the injured knee and the amount of rotation in the contralateral knee.

Current single-bundle, anterior cruciate ligament (ACL) reconstruction methods fail to restore normal knee function[1]. A potential reason could be the underestimation of additional injuries to the anterolateral structures. Considerable clinical interest exists regarding injuries to the anterolateral capsule and the ACL and the potential need for surgical treatment of the anterolateral capsule at the time of ACL surgery. The undetected presence of such an injury could contribute to persistent instability following ACL reconstruction.

The "gold standard" treatment of combined anterolateral capsule and ACL injuries has not been determined but might include extra-articular tenodesis. Some have postulated that combined ACL reconstruction and extra-articular tenodesis can achieve improved postoperative stability[2]. The concept of extra-articular tenodesis was first popularized in the 1970s, when open surgery was the standard procedure for ACL reconstruction. Extra-articular tenodesis was introduced with the aim of restoring rotatory knee stability[3,4]. With the establishment and advancement of arthroscopic ACL reconstruction, extra-articular tenodesis became less common. Restricted range of motion has been shown to be a disadvantage of extra-articular tenodesis[5,6], leading potentially to higher joint contact pressures in the lateral knee compartment[7]. Furthermore, extra-articular tenodesis was demonstrated to be a detriment compared with intra-articular ACL reconstruction because of a higher incidence of patellofemoral crepitation and loss of motion[8].

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TABLE I Experimental Protocol and Data Acquired*

Knee State	Reconstruction Performed	Kinematic Data Acquired
Intact	—	Intact
ACL-deficient	—	ACL-deficient
ACL-deficient	ACL reconstruction	ACL reconstruction in ACL-deficient
ACL-deficient + ALC-deficient	—	ACL-deficient + ALC-deficient
ACL-deficient + ALC-deficient	ACL reconstruction	ACL reconstruction in ACL-deficient + ALC-deficient
ACL-deficient + ALC-deficient	ACL reconstruction + EAT	ACL reconstruction + EAT in ACL-deficient + ALC-deficient

*ACL = anterior cruciate ligament, ALC = anterolateral capsule, and EAT = extra-articular tenodesis.

Combined procedures are being performed to address these combined injuries, as the need for improved surgical outcomes is more apparent. Some authors who advocate for combined reconstruction contend that the longer lever arm of the extra-articular tenodesis allows efficient control of tibial rotation[9]. In addition, extra-articular tenodesis may provide a "backup" for the ACL graft in cases in which the intra-articular graft is not functioning well[10]. Finally, extra-articular tenodesis has been found to decrease the stress on the intra-articular graft by >40%, lending credence to the possible load-sharing role of the native structure[9,11].

Intra-articular ACL reconstruction has been shown to be effective in limiting anterior translation[12]. However, intra-articular ACL reconstruction has not been as effective in reducing internal tibial rotation[13]. Therefore, the purpose of the current study was to determine the effects of ACL reconstruction and extra-articular tenodesis on joint motion in ACL-deficient knees and in combined ACL and anterolateral capsule-deficient knees. It was hypothesized that a combined intra-articular and extra-articular reconstruction would restore internal rotation in knees with combined ACL and anterolateral capsule deficiency.

Materials and Methods

Seven fresh-frozen human cadaveric knees (mean donor age, 53.7 years; range, 46 to 59 years) were used in this study, which received ethical committee approval. Each specimen was examined manually and radiographically before testing to exclude any specimens with ligamentous or osseous abnormalities. Specimens were thawed at room temperature for 24 hours before testing[14], and the tibia and femur were cut 20 cm from the joint line. The fibula was fixed to the tibia using a bicortical screw to maintain its anatomic position. The skin and musculature were removed, exposing the femoral and tibial shafts, with the knee joint left intact. During the experimental protocol, each specimen was kept moist with saline solution[14]. The femur and tibia were potted in an epoxy compound (Bondo; 3M) and secured within custom-made aluminum clamps. The knee was mounted in a robotic testing system.

The robotic testing system (MJT model FRS2010; Technology Service) consists of a 6-degree-of-freedom (6-DOF) manipulator. A universal force-moment sensor (UFS; Delta IP60 [SI-660-60]; ATI Industrial Automation) is utilized to provide feedback to the controller. Control of the system is accomplished through a LabVIEW program (National Instruments) designed for knee-joint biomechanical testing and utilizes hybrid velocity impedance control. The position and orientation repeatability of the robotic manipulator are less than ± 0.015 mm and ± 0.01°. The measurement uncertainty of the UFS is approximately 1% of full scale[15].

The 6-DOF path of passive flexion-extension of the intact knee was first determined from full extension to 90° of knee flexion[16]. Throughout the range of motion, the positions that satisfied the condition of zero-force and zero-moment targets were determined as the path of passive flexion-extension.

Two loading conditions were applied to the intact knee while the knee was continuously flexed and the resulting 6-DOF kinematics were recorded[15]: (1) an anterior tibial load of 134 N and (2) internal tibial torque of 7 Nm. Previous studies utilized these loads to simulate physiological loading conditions[17,18]. After loading the intact knee, the ACL was transected arthroscopically so as not to damage the remaining structures. The ACL was then reconstructed arthroscopically. Subsequently, an anterolateral capsule deficiency was simulated by removing a 2-cm-wide strip of tissue from anterior to the lateral collateral

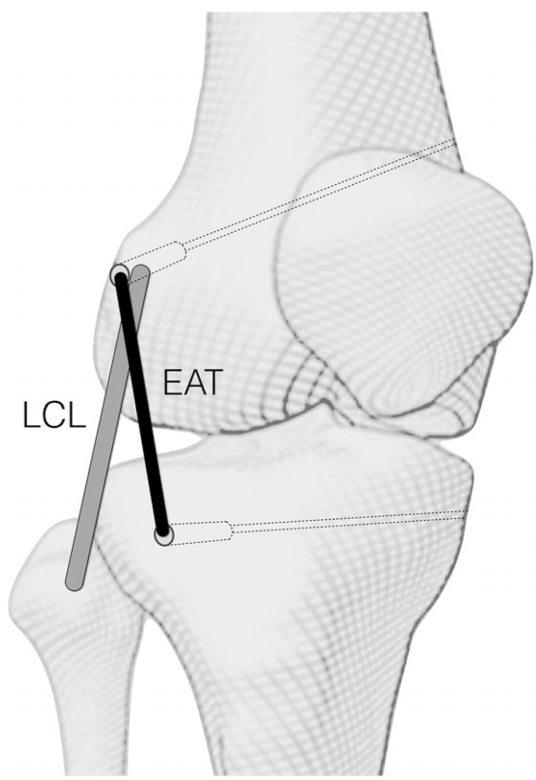

Fig. 1

The extra-articular tenodesis (EAT) was performed using a gracilis-tendon autograft. The graft was placed according to the anatomic description of the anterolateral ligament by Dodds et al.[19]. The graft was fixed crossing over the lateral collateral ligament (LCL).

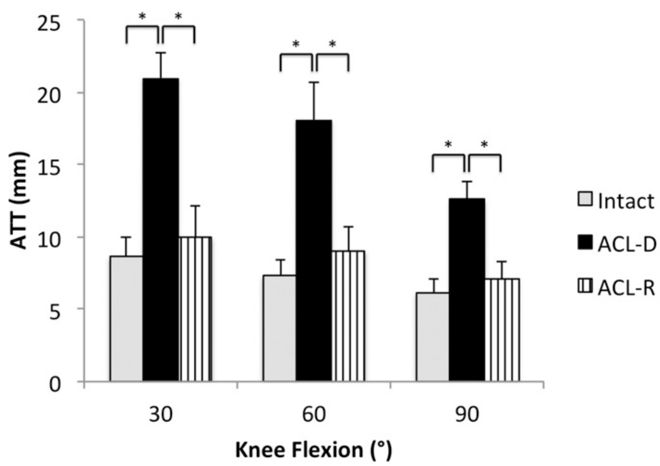

Fig. 2

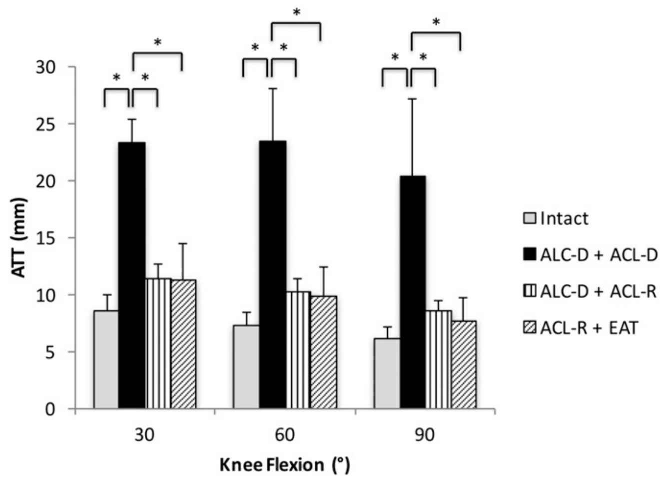

Fig. 3

Fig. 2 Mean anterior tibial translation (ATT) of the knee (and standard deviation) at the respective knee-flexion angles in response to anterior tibial load of 134 N. ACL-D = anterior cruciate ligament-deficient, and ACL-R = anterior cruciate ligament-reconstructed. *P < 0.05. **Fig. 3** Mean anterior tibial translation (ATT) of the knee (and standard deviation) at the respective knee-flexion angles in response to anterior tibial load of 134 N. ALC-D = anterolateral capsule-deficient, ACL-D = anterior cruciate ligament-deficient, ACL-R = anterior cruciate ligament-reconstructed, and EAT = extra-articular tenodesis. *P < 0.05.

ligament to proximal and lateral to the Gerdy tubercle. Afterward, an extra-articular tenodesis was performed. Finally, both reconstructions were removed. The 6-DOF kinematics were recorded after each change in knee state (Table I).

Reconstructions

The ACL was reconstructed arthroscopically using an anatomic single-bundle procedure with a 9-mm quadriceps autograft. An anterolateral portal and an anteromedial portal were created. A tunnel was created in the anatomic center of the femoral footprint through the anteromedial portal. An appropriate-sized reamer was used to create the femoral tunnel. The tibial tunnel was created using a tibial drill guide set at 55° (ACUFEX ACL tibial drill guide; Smith & Nephew). The tibial tunnel was created in the anatomic center of the tibial footprint. The wire was over-drilled using a drill-bit appropriate to the graft diameter. Sutures were placed into the free ends of the tendon graft. Preconditioning of the graft was performed at 89 N for 10 minutes. The graft was fixed at 30° of knee flexion by tying the sutures around a screw on the femur and tibia (suture post fixation).

The extra-articular tenodesis was performed using a gracilis-tendon autograft (Fig. 1). The graft was placed according to the anatomic description of the anterolateral ligament by Dodds et al.[19]. A guide pin was inserted into the femur in a slightly oblique manner in order to avoid interfering with the femoral ACL tunnel. The guide pin was over-reamed to a depth of 20 mm. Subsequently, a guide pin was inserted to mark the tibial tunnel. The guide pin was over-reamed to a depth of 20 mm. Pretensioning of the graft was performed at 44 N for 10 minutes. The graft was fixed crossing over the lateral collateral ligament while applying 10 N of tension at 30° of knee flexion and neutral tibial rotation using interference screws (BIOSURE PK; Smith & Nephew).

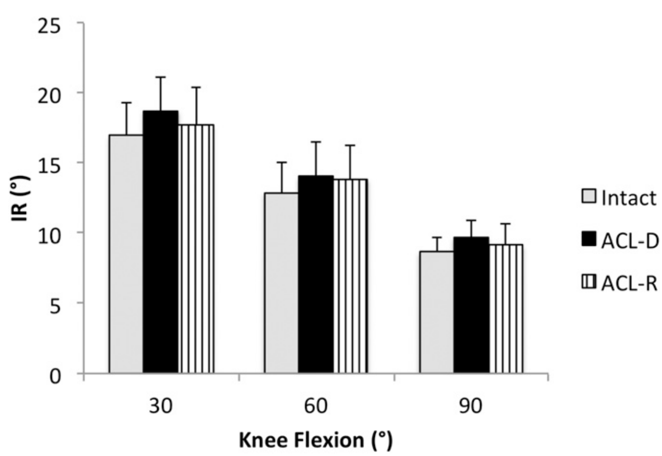

Fig. 4

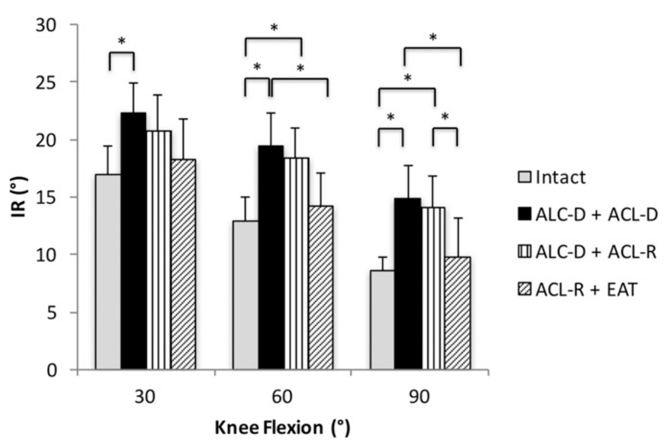

Fig. 5

Fig. 4 Mean internal tibial rotation (IR) of the knee (and standard deviation) at the respective knee-flexion angles in response to internal tibial torque of 7 Nm. ACL-D = anterior cruciate ligament-deficient, and ACL-R = anterior cruciate ligament-reconstructed. *P < 0.05. **Fig. 5** Mean internal tibial rotation (IR) of the knee (and standard deviation) at the respective knee-flexion angles in response to internal tibial torque of 7 Nm. ALC-D = anterolateral capsule-deficient, ACL-D = anterior cruciate ligament-deficient, ACL-R = anterior cruciate ligament-reconstructed, and EAT = extra-articular tenodesis. *P < 0.05.

TABLE II Kinematic Data for Each Specimen in Response to Internal Tibial Torque of 7 Nm*

		Internal Tibial Rotation in Response to Internal Tibial Torque of 7 Nm *(°)*					
	Specimen	Intact	ACL-D	ACL-R	ACL-D + ALC-D	ACL-R + ALC-D	ACL-R + EAT
30° of knee flexion							
	1	16.3	17.1	17.3	20.1	19.1	15.3
	2	16.8	18.7	17.7	21.9	19.6	17.9
	3	20.2	23.4	22.1	27.1	25.7	23.4
	4	13.0	16.7	13.3	18.3	15.3	12.5
	5	14.6	15.6	15.0	22.0	20.3	16.9
	6	18.5	19.7	18.9	23.4	21.5	20.1
	7	19.4	20.0	19.7	23.7	23.7	21.9
Mean and std. dev.		17.0 ± 2.6	18.7 ± 2.6	17.7 ± 2.9	22.4 ± 2.8	20.7 ± 3.4	18.3 ± 3.8
60° of knee flexion							
	1	12.3	12.9	12.8	16.3	15.2	10.3
	2	14.6	15.9	15.6	20.0	18.3	17.0
	3	17.0	19.0	18.6	24.9	24.1	17.9
	4	10.8	12.6	12.7	17.2	16.6	10.2
	5	11.7	12.4	12.5	20.9	19.4	15.4
	6	13.5	14.3	14.0	20.2	18.4	15.5
	7	10.5	11.2	10.7	16.2	16.5	13.1
Mean and std. dev.		12.9 ± 2.3	14.0 ± 2.7	13.8 ± 2.6	19.4 ± 3.1	18.4 ± 2.9	14.2 ± 3.1
90° of knee flexion							
	1	7.8	8.4	7.9	10.6	9.1	5.8
	2	9.8	11.0	10.8	15.1	13.6	13.3
	3	9.0	11.0	10.7	19.0	18.4	10.1
	4	7.1	8.1	6.8	11.6	12.7	4.2
	5	9.9	10.7	10.2	18.3	16.5	13.8
	6	9.5	10.4	10.1	15.6	14.4	11.1
	7	7.5	8.2	7.4	14.2	14.3	10.3
Mean and std. dev.		8.7 ± 1.2	9.7 ± 1.4	9.1 ± 1.7	14.9 ± 3.1	14.1 ± 2.9	9.8 ± 3.6

*ACL-D = anterior cruciate ligament-deficient, ACL-R = anterior cruciate ligament-reconstructed, ALC-D = anterolateral capsule-deficient, and EAT = extra-articular tenodesis.

Statistical Analysis

Anterior tibial translation in response to an anterior tibial load and internal tibial rotation in response to internal tibial torque in each knee state were compared using SPSS (version 20.0; IBM). Since the loading conditions were applied within the same knee specimen, statistical analyses were performed using a repeated 1-factor analysis of variance (ANOVA) with multiple contrasts to analyze the variations of the kinematics at 30°, 60°, and 90° of knee flexion. A Mann-Whitney U test was used for non-normally distributed data; significance was set at $p < 0.05$.

Results

In response to an anterior tibial load, anterior tibial translation of the ACL-reconstructed knee was restored to the level of the intact knee at all degrees of knee flexion tested ($p > 0.05$) (Fig. 2). Compared with that of the intact knee, anterior tibial translation of the combined ACL and anterolateral capsule-deficient knee was increased by 170.9%, 222.0%, and 228.7% at 30°, 60°, and 90° of knee flexion, respectively ($p < 0.05$). In the ACL-reconstructed + anterolateral capsule-deficient knee, anterior tibial translation was restored to the level of the intact knee at all degrees of knee flexion tested ($p > 0.05$). Anterior tibial translation for the knee state of ACL-reconstructed + extra-articular tenodesis did not differ significantly from that observed for the ACL-reconstructed + anterolateral capsule-deficient knee at 30°, 60°, and 90° of knee flexion ($p > 0.05$) (Fig. 3).

In response to internal tibial torque of 7 Nm, internal tibial rotation of the ACL-reconstructed knee was restored to the level of the intact knee at all degrees of knee flexion tested

TABLE III Kinematic Data for Each Specimen in Response to Anterior Tibial Load of 134 N *

		Anterior Tibial Translation in Response to Anterior Tibial Load of 134 N *(mm)*					
	Specimen	Intact	ACL-D	ACL- R	ACL-D + ALC-D	ACL-R + ALC-D	ACL-R + EAT
30° knee flexion							
	1	9.7	21.2	13.4	22.8	12.8	13.3
	2	8.5	20.5	9.7	22.7	11.6	12.0
	3	8.2	23.9	10.2	27.6	12.4	15.8
	4	9.0	22.1	9.0	23.1	9.9	8.1
	5	6.0	19.7	5.8	23.2	8.9	5.8
	6	8.2	21.8	9.8	23.9	11.7	10.6
	7	10.6	17.9	12.1	20.2	12.5	13.2
Mean and std. dev.		8.6 ± 1.4	21.0 ± 1.9	10.0 ± 2.4	23.4 ± 2.2	11.4 ± 1.4	11.3 ± 3.4
60° knee flexion							
	1	8.6	16.5	10.5	17.7	10.4	9.4
	2	7.8	19.2	9.8	23.4	11.5	12.0
	3	7.4	22.6	9.1	31.2	11.1	13.7
	4	6.4	19.7	9.8	26.7	9.7	7.9
	5	5.6	17.3	5.5	25.5	8.0	5.5
	6	6.5	17.6	8.5	23.0	10.2	8.8
	7	8.8	13.8	10.3	16.9	11.2	11.6
Mean and std. dev.		7.3 ± 1.2	18.1 ± 2.8	9.1 ± 1.7	23.5 ± 5.0	10.3 ± 1.2	9.8 ± 2.8
90° knee flexion							
	1	7.7	12.6	8.0	12.9	7.9	7.1
	2	5.9	12.0	7.5	15.1	9.1	9.7
	3	6.1	13.3	7.1	28.8	9.1	10.3
	4	5.9	12.7	8.0	29.2	9.0	6.2
	5	5.0	14.0	4.6	26.3	6.9	4.5
	6	5.3	13.8	6.5	16.7	8.0	6.4
	7	7.5	10.1	8.3	13.4	10.0	9.6
Mean and std. dev.		6.2 ± 1.1	12.6 ± 1.3	7.1 ± 1.3	20.3 ± 7.4	8.6 ± 1.0	7.7 ± 2.2

*ACL-D = anterior cruciate ligament-deficient, ACL-R = anterior cruciate ligament-reconstructed, ALC-D = anterolateral capsule-deficient, and EAT = extra-articular tenodesis.

($p > 0.05$) (Fig. 4). Compared with that of the intact knee, internal tibial rotation of the combined ACL and anterolateral capsule-deficient knee increased by 31.9%, 50.3%, and 72.2% at 30°, 60°, and 90° of knee flexion, respectively ($p < 0.05$). At 30° of knee flexion, internal tibial rotation of the ACL-reconstructed + anterolateral capsule-deficient knee was restored to that of the intact knee ($p > 0.05$). For the knee with ACL reconstruction + extra-articular tenodesis, internal tibial rotation did not differ significantly from that of the ACL-reconstructed + anterolateral capsule-deficient knee at 30° and 60° of knee flexion ($p > 0.05$). At 60° and 90° of knee flexion, internal tibial rotation of the ACL-reconstructed + anterolateral capsule-deficient knee was increased by 42.2% and 63.4%, respectively, compared with the intact knee ($p < 0.05$). Internal tibial rotation for the knee state of ACL-reconstructed + extra-articular tenodesis did not differ significantly from that of the intact knee at any of the tested levels ($p > 0.05$) (Fig. 5).

Two of the 7 specimens showed decreased internal tibial rotation for ACL reconstruction + extra-articular tenodesis compared with that observed for the intact knee. In 1 specimen, internal tibial rotation for this knee state was decreased by a maximum of 25.7% compared with the intact knee, and in the other specimen, it was decreased by a maximum of 40.9% compared with the intact knee. This effect was observed specifically at a higher knee flexion angle (90° of knee flexion). Tables II and III show the kinematic data for each specimen, state of reconstruction, and loading condition.

Discussion

The most important finding of our study was that, at higher flexion angles, an extra-articular tenodesis added rotational stability to ACL reconstruction alone in a knee with combined ACL and anterolateral capsule deficiency, supporting the hypothesis of the study. In this investigation, anterior tibial translation in response to anterior tibial load was not affected by the addition of an extra-articular tenodesis. For the isolated ACL-deficient knee, our findings suggest that an additional extra-articular tenodesis is unnecessary, as an ACL reconstruction alone was able to restore the kinematics of the intact knee.

Our novel robotic testing system is uniquely able to apply loading conditions throughout the range of flexion. The continuous loading method was shown to be more efficient than the static method and completely characterizes the response of the knee throughout flexion. The high rigidity of the manipulator also provides optimal positional repeatability on the order of 0.001 mm[20]. Other advantages include real-time control utilizing velocity impedance algorithms that decrease the amount of time required to apply loading conditions to the knee.

Our results suggest that extra-articular tenodesis adds significant rotatory knee stability to an ACL reconstruction alone in a combined ACL and anterolateral capsule-deficient knee and that the utilization of extra-articular tenodesis in an isolated ACL-deficient knee is not indicated. The ACL is the primary restraint to anterior tibial translation in the intact knee[18]. Furthermore, the anterolateral capsule is a restraint to internal rotation in the intact knee and becomes an important restraint to an anterior tibial load in the ACL-deficient knee. The forces in the ACL decrease with higher knee flexion angles in response to an anterior tibial load or internal tibial torque. Thus, injuries to the anterolateral capsule may have more impact on knee instability at higher knee flexion angles. An isolated ACL reconstruction might not be sufficient to stabilize the knee at higher knee flexion angles with combined injuries, and an extra-articular reconstruction could be a solution. However, this conclusion is based on in vitro study lacking tension on the quadriceps tendon and patellar tendon. At higher knee flexion angles, the patellofemoral and tibiofemoral compressive forces are increased in vivo as is the tibiofemoral anterior shear force[21]. Additional clinical studies are needed to confirm the indications for extra-articular tenodesis in the combined ACL and anterolateral capsule-deficient knee.

Over-constraining the knee that has undergone ACL reconstruction with extra-articular tenodesis can potentially be an issue. Two of the specimens with values for internal tibial rotation at the low end of the range in the intact knee state were over-constrained after an extra-articular tenodesis was performed. However, no trends could be found in the individual-specimen data, suggesting that internal tibial rotation in response to internal tibial torque applied to the intact knee leads to over-constraint. Some specimens with an amount of internal tibial rotation similar to that noted for the intact knee state were not over-constrained post-surgery. One explanation may be differences in the tissue properties of the gracilis-tendon autografts. In addition, osseous morphology, repair technique, or other soft-tissue constraints might have contributed to the resulting amount of internal tibial rotation.

Our findings are in agreement with those of previous biomechanical studies. Using a finite element model of the knee, an extra-articular reconstruction reduced internal tibial rotation when compared with the intact knee[6]. Another study found that an isolated ACL reconstruction in knees with an injury to the anterolateral structures was not sufficient to restore internal tibial rotation to that of the intact knee[5]. However, an additional extra-articular reconstruction over-constrained the knee at all knee flexion angles tested. In contrast to our study, the graft was fixed while applying 88 N of tension with the knee at 75° of flexion.

In the present study, the extra-articular tenodesis was fixed at 30° of knee flexion and neutral tibial rotation while applying 10 N of tension. The extra-articular tenodesis was fixed according to the anatomic description of the anterolateral ligament by Dodds et al.[19]. These attachment points were shown to be most isometric among the proposed ligaments on the anterolateral side, decreasing in length between 30° and 80° of knee flexion[22]. Other authors[23] described decreased anterior tibial translation with a modified Lemaire technique[3] compared with an "anatomic reconstruction" of the anterolateral ligament[24] during a simulated pivot-shift test applied by a hip simulator. With the modified Lemaire technique, a graft is fixed at 70° of knee flexion passing underneath the lateral collateral ligament. Their findings differed from our results, in part, because of the lack of ACL reconstruction, the differing graft-fixation angles, and the differing origins and insertions of the respective reconstruction techniques. A graft attached proximal to the lateral femoral epicondyle and running deep to the lateral collateral ligament prevented excessive tightening or slackening during knee motion[22]. The graft in the Lemaire technique[3] has been shown to be even more isometric than the anterolateral ligament described by Dodds et al.[19], while the anterolateral ligament described by Claes et al.[24] has been demonstrated to be less isometric[22].

When extra-articular tenodesis is considered as a treatment option, quantification of the injury and individualized surgery are of high importance to enable proper patient selection and improve the patient's outcome. In some cases, an extra-articular tenodesis might be a component of the treatment plan; however, little has been reported on the incidence and magnitude of injury to the anterolateral complex. In the present study, an extra-articular tenodesis over-constrained 2 of 7 knees despite a large capsular defect of 2 cm from anterior to the lateral collateral ligament to proximal and lateral to the Gerdy tubercle. In the setting of clinical practice, the amount of rotatory knee instability will need to be quantified and correlated with the pattern of injury to enable the surgeon to adapt the operative procedure on the basis of the instability. This can be achieved using tools such as the PIVOT software[25], which measures the distance between markers attached to the lateral side of the knee during the pivot shift. In this way, patients with a high-grade pivot-shift can selectively be addressed. The initial tension of the graft may be varied according to the evaluation outcome, and the anterolateral capsule should be thoroughly assessed to determine if the injured region should be repaired, reconstructed, or treated nonoperatively to let the tissue heal. Concomitant injuries to the menisci and the posterolateral structures have to be ruled out, and anterolateral capsule deficiency has to be detected clearly before an extra-articular tenodesis should be considered.

Standardization of the reconstruction procedure was required for our study and may have produced one of its limitations. The magnitude of tension in the graft and position for fixation of the extra-articular tenodesis are not well described in the literature. Individuals have a different amount of tibial rotation in the healthy knee. On the basis of the degree of instability created with our injury model, our extra-articular tenodesis can lead to over-constraint in patients with less tibial rotation. In clinical application, the fixation angle and the tension of the graft should be individually adapted. In addition, the injury model utilized in this study did not reflect a typical injury to the anterolateral capsule; a section of the anterolateral capsule was completely removed. In the clinical setting, the anterolateral capsule is stretched and permanently deformed rather than completely ruptured. We excised the anterolateral capsule because an accepted injury model for the anterolateral capsule has not, to our knowledge, been established, and excising the anterolateral capsule represents the "worst-case scenario." Future studies should aim to develop injury models for the anterolateral capsule that are more similar to those observed in the clinical setting.

In conclusion, in this study, an extra-articular tenodesis was necessary to restore rotatory knee stability in response to an internal tibial moment in a combined ACL and anterolateral capsule-deficient knee at 60° and 90° of knee flexion. However, the amount of rotatory knee instability should be carefully assessed to avoid over-constraint of the knee in these combined ligament-reconstruction procedures. ■

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