Original Article

Impact of Partial and complete rupture of anterior cruciate ligament on medial meniscus: A cadavaric study

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Abstract

Background: The clinical relationship between medial meniscus tear and anterior cruciate ligament (ACL) rupture has been well documented. However, the mechanism of this clinical phenomenon is not exactly explained. Our aim is to investigate the biomechanical impact of partial and complete ACL rupture on different parts of medial meniscus.

Materials and Methods: Twelve fresh human cadaveric knee specimens were divided into four groups: ACL intact (ACL-I), anteromedial bundle transection (AMB-T), posterolateral bundle transection (PLB-T), and ACL complete transection (ACL-T) group. Strain on the anterior horn, body part, and posterior horn of medial meniscus were measured under 200 N axial compressive tibial load at 0°, 30°, 60°, and 90° of knee flexion, respectively.

Results: Compared with the control group (ACL-I), the ACL-T group had a higher strain on whole medial meniscus at 0°, 60°, and 90° of flexion. But at 30°, it had a higher strain on posterior horn of meniscus only. As to PLB-T group, strain on whole meniscus increased at full extension, while strain increased on posterior horn at 30° and on body of meniscus at 60°. However, AMB-T only brought about higher strain at 60° of flexion on body and posterior horn of meniscus.

Conclusions: Similar to complete rupture, partial rupture of ACL can also trigger strain concentration on medial meniscus, especially posterior horn, which may be a more critical reason for meniscus injury associated with chronic ACL deficiency.

Key words: Anterior cruciate ligament, biomechanics, medial meniscal tear, anterior cruciate ligament rupture

Introduction

Meniscus tears, particularly medial meniscus tears, have been well known to be in association with anterior cruciate ligament (ACL) injuries.[1-4] The incidence of medial meniscus lesion following ACL rupture can even be up to 90%.[1] For exposing the mechanism of this phenomenon, numerous studies investigating the effects of ACL injury on the biomechanics of medial meniscus have been performed. Allen *et al*.[5] employed a robotic/universal force-moment sensor testing system to measure the resultant force in medial meniscus following transection of the ACL, and reported that the resultant force in the medial meniscus of the ACL-deficient knee increased by a minimum of 10.1 N (52%) at full knee extension to a maximum of 50.2 N (197%) at 60° of flexion. Subsequently, Papageorgiou *et al*.[6] demonstrated that the resultant forces on the medial meniscus, ranging from 52±30 N to 63±51 N, between full extension and 90° of knee flexion in the intact knee, were doubled as a result of ACL-D. Using a finite element model, Bendjaballah *et al*.[7] also proved increased medial meniscus loading in the ACL-deficient knee. The same results were mentioned in Hollis *et al*.'s report also.[8]

Despite the documents in previous section which provided kinetics evidence for earlier reconstruction to ACL full injuries, little is known about the biomechanical disorder in partial ACL rupture cases and its impact on different parts of meniscal strain under various loading conditions. As a more prevalent pattern of ACL injuries, the association between incomplete ACL rupture and medial meniscus has also been observed.[9-11] Based on this background, we hypothesized that the resultant force on medial meniscus

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was significantly elevated in incomplete ACL transection knee just like complete transection. To test this hypothesis, we employed a biomechanical testing system to measure the strain on the different parts of medial meniscus (anterior, posterior horn, and body of meniscus) under different conditions, including intact ACL, anteromedial bundle transection (AMBT), posterolateral bundle transection (PLBT), and ACL complete transection (ACLT) at 0°, 30°, 60°, and 90° of knee flexion, respectively.

Materials and Methods

Specimen preparation

Approval for the study was obtained from the local Hospital Ethics Committee. Twelve fresh frozen male cadaveric knee specimens (six left and six right specimens) were used in this study, with the average age being 30.6 years (range 25–38 years). All the specimens underwent macroscopic inspection and the anterior drawer test to rule out gross anomalies, degeneration, fracture, tumor, and ACL damage. Prior to experiments, the femur and tibia were cut to approximately 30 cm from the joint line, the proximal portion of the fibula was retained and secured to the tibia at its anatomic position using a cortical screw, and soft tissues were carefully removed except quadriceps muscle and joint capsule.

Twelve specimens were subsequently each fixed in cylindrical clamps of universal testing machine (CSS-88100, ChangChun, China) which is capable of applying a specific load or positioning the knee at a predetermined flexion angle with the femur on lower fixture and tibia on the upper [Figure 1a]. The strain transducer gauge (BX120-1AA, HY Corp., ZheJiang, China) consisting of a small tube within which a core slides with changes in length was then chosen for real time meniscus strain measurement. This strain gauge has been used successfully in previous studies to measure the intradiscal pressures. It converts tissue strain into voltage change which could be recorded by a computer equipped with an analog-to-digital converter. In our experiment, 5 mm × 4 mm of tissue in the anterior horn, body, and posterior horn of medial meniscus was exposed. Exposed parts were then burnished using abrasive paper, followed by degreasing. When dried, a strain gauge was fixed vertically with αcyanoacrylate in a direction consistent with the load [Figure-1b]. Subsequently, the joint capsule was closed and strain foil inside was connected to the output of static strain indicator (DH-3818, DH Corp., JiangSu, China) [Figure 1a].

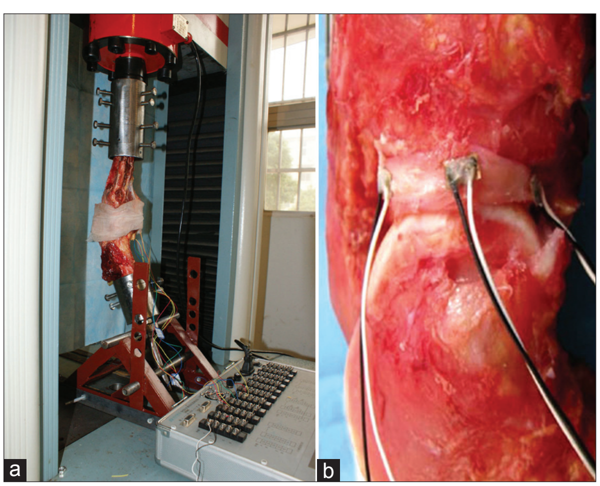

Figure 1: (a) Biomechanical test instrumentation setup and (b) transducer strain gauges fixed in different parts of medial meniscus

Group of experiments and test procedures

The specimens were divided into four groups: the control, AMB-T, PLB-T, and ACL-T groups. In each group, the specimens were positioned at 0°, 30°, 60°, and 90° of flexion in sequence.

At the beginning, we conducted the specimens 20 times at a load of 250 N with a speed of 0.5 mm/s to eliminate the influence of the innate viscosity. After that, the static strain measuring device was calibrated in balance and then continuous axial load (0–200 N) was loaded at a speed of 0.5 mm/s. Data at 200 N from every channel of the device were documented (με, microstrain). The same procedure was repeated when it came to 30°, 60°, and 90° of flexion, with an interval of 10 min to allow restoration of elasticity. Finishing the tests above, we separated the 12 specimens randomly and equally into PLB-T and AMB-T groups, followed by same test as mentioned above. Next, the ACLs of all 12 specimens were severed completely, modeling complete rupture of the ACL. Then, the same biochemical test was performed on the newly treated specimens again. During the whole test, the specimens were kept at a humidity of 60–80% and a temperature of 25°C.

Statistical analysis

SPSS 16.0 (Chicago, IL, USA) was used for data management and statistical analysis. Data were expressed

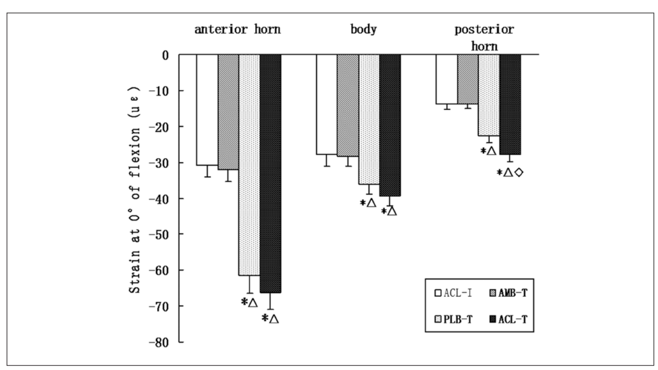

Figure 2: Strain value on medial meniscus at 0° of flexion. Both complete rupture and PLB rupture cause higher strain than intact group in all parts of medial meniscus. No increase has been noted in AMB-T group yet (με, microstrain; *, $P < 0.05$ compared to ACL-I; Δ, $P < 0.05$ compared to AMBT; ◊, $P < 0.05$ compared to PLB-T)

as mean ± SD. A *P* value less than 0.05 were taken as statistically significant. A one-way analysis of variance (ANOVA) was performed to determine whether there were statistically significant ($P < 0.05$) differences among the experimental groups. Further, the Student-Newman-Keuls q test was used for comparisons between individual groups and to determine which means differed statistically significantly ($P < 0.05$). When the variances were not equal among the groups, comparisons between groups were made using Kruskal–Wallis H test.

Results

Strain analysis at 0° of flexion

At 0°, the strain value in whole medial meniscus was negative in response to 200 N axial load, indicating that the strain in this position was a compressive strain [Figure 2]. Compared to untreated ACL group, strain on whole medial meniscus increased obviously in both ACL-T and PLB-T groups ($P < 0.05$), while there was no change in the AMB-T group ($P > 0.05$). Also, complete rupture group and PLB-T group had higher strain value than AMB-T group ($P < 0.05$). However, compared to PLB rupture, increase in strain value was found only in posterior horn of meniscus in complete ACL rupture ($P < 0.05$).

Strain analysis at 30° of flexion

At 30° of flexion, compression strain still existed in whole medial meniscus [Figure 3]. When compared to ACL-I group, strain value on posterior horn increased relatively in ACL-T and PLB-T groups ($P < 0.05$), but there was no significant increase observed on whole meniscus in AMB-T group ($P > 0.05$). Besides, ACL-T group had higher strain value than PLBT group and AMB-T group on both body part and posterior horn ($P < 0.05$). However, there was no difference between AMB rupture and PLB rupture in whole meniscus ($P > 0.05$).

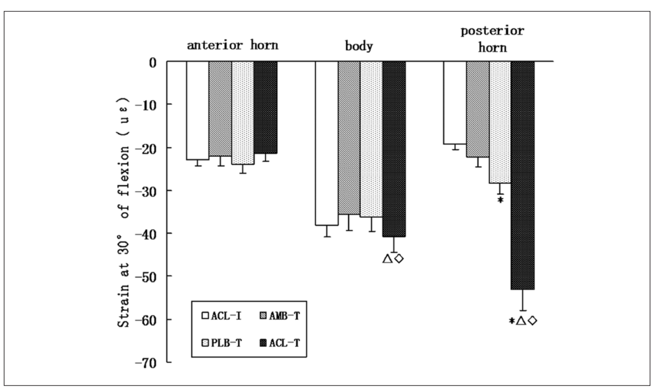

Figure 3: Strain value on medial meniscus at 30° of flexion. ACL-T and PLB-T groups had a higher strain compared to the ACL-I in posterior horn only (με, microstrain; *, $P < 0.05$ compared to ACL-I; Δ, $P < 0.05$ compared to AMBT; ◊, $P < 0.05$ compared to PLB-T)

Strain analysis at 60° of flexion

When flexed to 60°, strain value of anterior horn was found positive in all groups, indicating that compressive strain turned to tension strain in this position [Figure 4]. Compared to the control, complete transection produced greater strain value in all parts of meniscus ($P < 0.05$), whereas PLB-T group had a higher strain only in the body of meniscus ($P < 0.05$). Also, in AMB-T group, elevation was noted in both body and posterior horn ($P < 0.05$). In comparison with AMB rupture, strain value was higher in anterior horn and body part in ACL-T group, while it was lower in body and posterior horn in PLB-T group ($P < 0.05$). Moreover, strain change observed on body and posterior horn in ACL-T group was much greater than in PLB-T group ($P < 0.05$).

Strain analysis at 90° of flexion

Similar to the results obtained at 60° of knee flexion, tension strain was found in anterior horn of meniscus in all groups at 90° [Figure 5]. When compared with the other three groups, strain value of whole meniscus increased obviously in complete rupture group ($P < 0.05$). Nevertheless, no significant difference was found among intact, AMB-T, and PLB-T groups ($P > 0.05$).

Discussion

ACL, as a primary stabilizing structure of knee, is the most common disrupted ligament in acute trauma. In US, 80,000–100,000 acute ACL injuries happen every year.[12,13] However, isolated ACL tears are scarce. Instead, among patients with chronic ACL insufficiency, the incidence of medial meniscus lesions may be as high as 90–98%.[1,14] Furthermore, secondary medial meniscus tears are considered as the main reason of osteoarthritis,

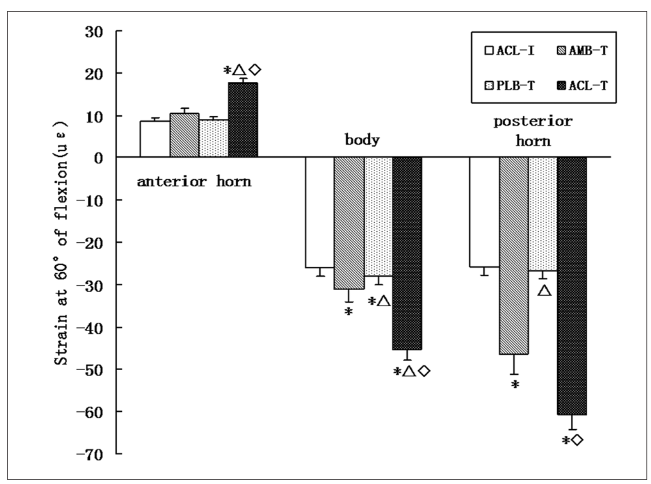

Figure 4: Strain value on medial meniscus at 60° of flexion. Compared to the control, strain value increased significantly on whole meniscus in ACL-T group, on body part in PLB-T group, and on both body and posterior horn in AMB-T group (με, microstrain; *, $P < 0.05$ compared to ACL-I; ◊, $P < 0.05$ compared to AMB-T; Δ, $P < 0.05$ compared to PLB-T)

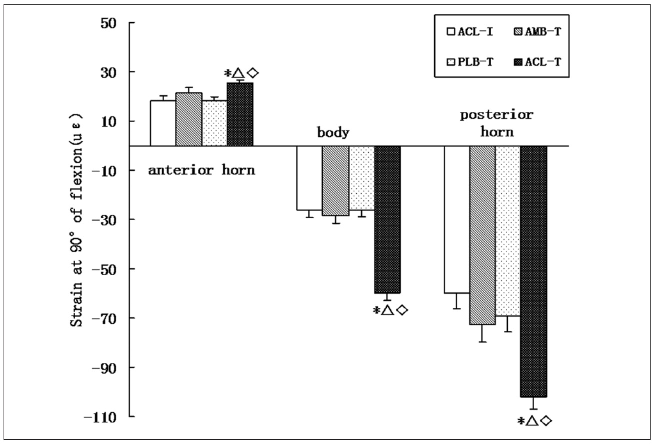

Figure 5: Strain value on medial meniscus at 90° of flexion. Significant higher strain value on whole meniscus was found in ACL-T group compared with the other three groups. But no significant difference was noted among ACL-I, AMB-T, and PLB-T groups (με, microstrain; *, $P < 0.05$ compared to ACL-I; Δ, $P < 0.05$ compared to AMB-T; ◊, $P < 0.05$ compared to PLB-T)

followed by ACL deficiency.[15] To better understand the mechanism of this clinical issue, some authors have focused the kinetics change on medial meniscus in ACL-deficiency knees using finite element model or cadaveric model.[5-8] They indicated that increased load on meniscus resulting from ACL injury may be an explanation of associated medial meniscus rupture. However, whether incomplete rupture of ACL also contributes to increased strain on meniscus is not fully documented. Moreover, responses and changes in different areas of the medial meniscus toward strain resulting from ACL injury are also unclear. So, we conducted the experiment aiming to measure the strain on three parts of medial meniscus in different positions to get better treatment strategies for ACL rupture, especially for partial rupture.

Our study proved that in physiological status, the knee joint harbored the biggest strain at 0° on anterior horn, 1.22 times of when it was on posterior horn. At 30° of flexion, strain decreased on anterior horn, while it increased to the maximum when it came to the body. Physiologically, weight bearing area of medial meniscus locates on its body which carries the maximum load at a flexion angle range of 30°–60°. Thus, abnormal strains generated from anterior/posterior translation and internal/external rotation of medial femoral condyle in this extent cause rupture of medial meniscus body more easily.[16] When flexed at an angle more than 60°, as the motion center of medial femoral condyle shifted, strain of the body decreased so that the posterior horn instead of the body became the major weight bearing area with a load 3.3 times larger than it was at 0°. At this situation, posterior horn played the major part of knee joint stability maintenance and constrained the anterior translation of tibia.[17,18]

On ACL complete rupture, biomechanical traits of medial meniscus were altered in the process of flexion and extension.[8] Allen *et al.* proved that stress of medial meniscus had a three times increase when ACL was injured, causing the high frequency of medial meniscus injury.[5] Our study found that strain concentrated on the anterior horn when ever extended at 0° with a strain 1.28 times higher than when it was in intact group. However, a more obvious strain increase was spotted when PLB was ruptured. At 90°, posterior horn grew to be the most concentrated spot of stress, 70% stronger than when it was in uninjured ACL group, 84% stronger than when it was at 60°, and 2.67 times stronger than strain of posterior horn at 0°. Apparently, on ACL complete rupture, anterior stability was destroyed so that abnormal movement of tibia followed[5,6,19-21] leading to strain concentration of medial meniscus, especially on its posterior horn part. This might be the biomechanical reason of what was called “ramp” injury and radial rupture in clinical work.[22-24]

Despite the fact that partial rupture of AMB and PLB could not cause severe instability of the knee joint, the induced redistribution of strain still altered part of biomechanical traits of medial meniscus. On AMB rupture at 0°–30°, strain of medial meniscus equaled to what it was on ACL uninjured. However, it increased when flexed angle was more than 60°, especially on the body and posterior horn. This finding was consistent with the theory in most of the studies that AMB strained in the process of flexion.[25,26] While on PLB rupture, strains of medial meniscus of all parts demonstrated a higher level than what they were on ACL uninjured and AMB rupture at 0°. Especially, strain of anterior horn on PLB rupture was 1.29 times higher than on ACL uninjured and was 1.71 times higher than it was at other flexed angles, which suggested that PLB played a significant role in anterior movement constraint on knee full extension.[25-28] Nevertheless, when it came to flexion, AMB functioned compensatively and covered the hazard of PLB rupture. Similarly, in our PLB-T group, only posterior horn showed an enhanced strain at 30°. At 90°, despite 2.05 times of posterior horn strain enhancement when compared with that at 0°, the strain was basically the same as what it is on ACL uninjured.

In view of this, we can easily recognize that the two bundles of ACL contribute to the stabilization of knee joint in a complementary manner and medial meniscus strain can remarkably elevate no matter which part of ACL is transected. This could be the biomechanical reason for the results in previous studies that meniscal repairs performed with concomitant ACL reconstruction have a higher healing rate than those performed in isolation.[29,30] Also, the results of the present study provide support to the beneficial outcome of earlier medical treatment for ACL partial injuries.[31] Considering the increased risk of stiffness postoperatively in patients who receive immediate reconstruction, we agree with the reports of other groups.[32] No less than 3 weeks rest and controlled strengthening exercises prior to intervention should be conducted. When it comes to surgery, a thorough examination of the whole knee structure, especially posterior horn of medial meniscus, is essential before ACL reconstruction. Furthermore, if medial meniscus injury exists, surgery should take both structures into account simultaneously.

The limitations of the present study are (a) the cadaveric knee specimens from young donors used in the present study might not be able to represent status of all population especially senior people (b) The dissection of soft tissue surrounding the knee joint could have some influence on the exact value in different loading conditions, but is not the trend (c) Only 200 N axial load and sagittal plane range of motion was analyzed in this study. To fully elucidate the association between ACL rupture and medial meniscus tear, internal–external and/or varus–valgus rotational tests should also be performed in the future.

Subject to the study limitations, the current study not only demonstrates that partial rupture of ACL triggers strain concentration on medial meniscus, but also provides clinically relevant data to help making the treatment plan for partial ACL-deficient knee.

Acknowledgments

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