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Original Article

Biomechanic effect of posterior cruciate ligament rupture on lateral meniscus

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Abstract: Objective: This study aims to investigate the biomechanical effect of posterior cruciate ligament (PCL) rupture on lateral meniscus. Method: The stresses of anterior horn, caudomedial part and posterior horn of lateral meniscus in cadaveric knees were recorded when the knee joints were loaded 200 to 1000 N at 0, 30, 60 and 90° of flexion. Twelve knees were tested before PCL transection (intact group), and 6 each were then tested after anterolateral bundle (ALB group) and postmedial bundle (PMB group) transection. The same knees were finally tested after complete PCL transection. Result: At 0°of knee flexion, the stresses of the anterior horn, caudomedial part and posterior horn were negative and compressive, and were not significantly different between intact and ALB groups, and between completely transected and PMB groups at 200 and 400 N. The stresses of the anterior horn and caudomedial part were greater in completely transected and PMB groups than in intact and ALB groups. The stresses of the posterior horn were smaller in PMB and completely transected groups than in intact and ALB groups. At 600-1000 N, the stresses were significantly different between the groups. The absolute stresses of the anterior horn and caudomedial part were in order of completely transected > PMB > ALB > intact group, while these of the posterior horn were reversed. At 30° of knee flexion, the stresses of the three parts were not significantly different between intact and PMB groups nor between completely transected and ALB groups at 200 and 400 N. The stresses in the anterior horn and caudomedial part were negative and different between completely transected and ALB groups, and positive and different between intact and PMB groups. The stresses in the posterior horn were positive and different between completely transected and ALB groups, and negative and different between intact and PMB groups. At loads of > 600 N, the stresses in the anterior horn and caudomedial part were negative in completely transected and ALB groups, and positive in intact and PMB groups. The stresses of the posterior horn were positive in completely transected and ALB groups and negative in intact and PMB groups, with significant difference between the groups. At 60° and 90° of flexion, the stresses of the anterior horn and caudomedial part were positive in completely transected and ALB groups and positive in intact and PMB groups, while the stresses of posterior horn were in the opposite directions and were significantly different between the groups at the same loads. Conclusion: Complete transection of PCL will result in stress changes in various parts of lateral meniscus. At 200 and 400 N, transection of ALB and PMB do not change the stress at 0° and 30° of flexion, respectively. At heavier loads (600-1000 N), the stresses at these angels are affected in ALB and PMB groups. At all loaded tested, transection of ALB and PMB results in changed stresses in all regions of lateral meniscus at 30-90° and 0-90° of flexion, respectively.

Keywords: PCL rupture, lateral meniscus, biomechanics, stress

Introduction

Posterior cruciate ligament (PCL) is an important structure to maintain the stability of knee joints [1] and prevent posterior displacement of the tibia. Impaired PCL may result in instable joint, pain and functional degradation of the joint. Since the 1990's, a number of studies have demonstrated that PCL injury could eventually result in osteoarthritis of the knee [2]. This study was carried out with cadaveric knees to investigate the biomechanical changes in lateral meniscus after partial or complete transection of PCL. The findings from the study will be useful to prevent the secondary injury after PCL injury and for PCL reconstruction.

Materials and methods

Knee

Twelve knees (6 left and 6 right sides asymmetrically) were donated voluntarily from 12 normal

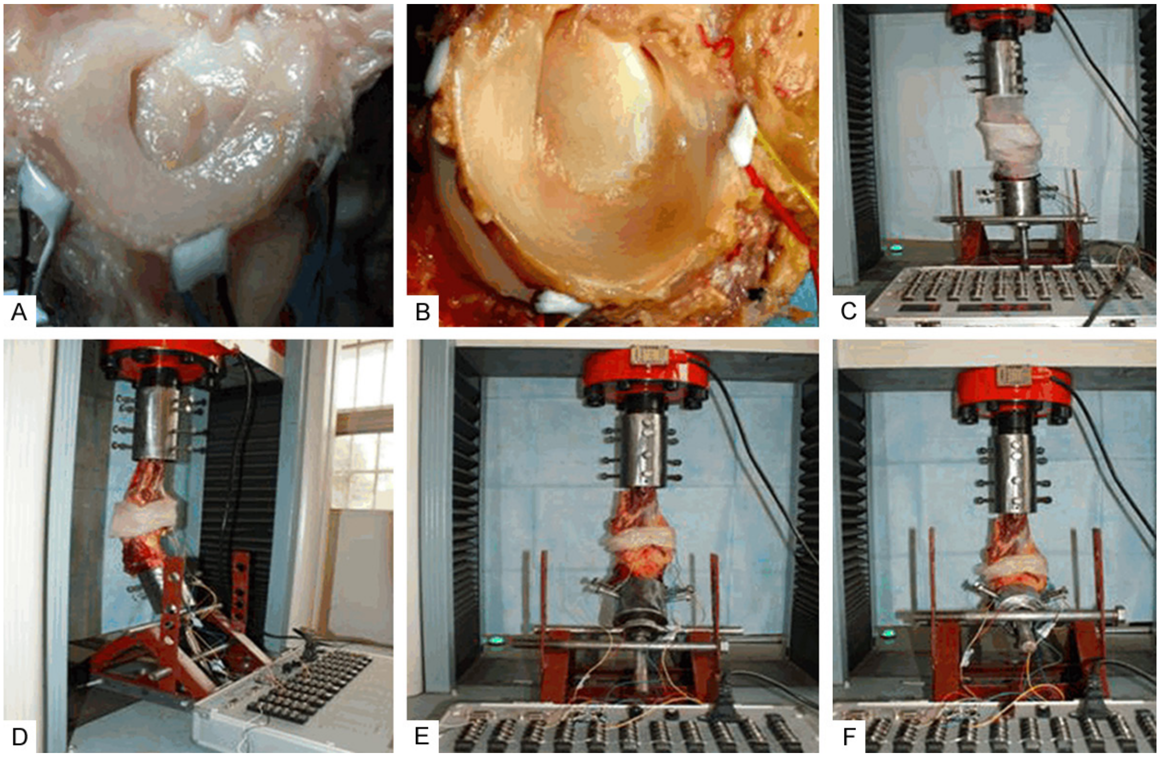

Figure 1. Measurement of biomechanic parameters. A, B: Sticking point of stress slice in lateral meniscus; C: Loading at the flexion angles of 0°; D: Loading at the flexion angles of 30°; E: Loading at the flexion angles of 60°; F: Loading at the flexion angles of 90°.

fresh young adult male cadavers, aged 25-38 years with an average age of 30.6 years. Sampling time was within 1 h after death. The knees were 30 cm long to the joint at each end with equal length of fibula and intact skin. The joints were eye- and X-ray-examined to exclude those with deformity, degeneration, fracture, tumor and osteoporosis. The posterior drawer test was performed to exclude PCL injury. The collected samples were wrapped with gauze soaked with physiological saline, sealed in double plastic bags and stored at -70°C for less than 3 months before being used for the study.

Sample preparation and grouping

The knees were tested sequentially with intact (12 samples), anterolateral bundle (ALB group)-transected (6 samples) or posteromedial bundle (PMB group)-transected (6 samples) and completely transected PCL (12 samples). The knees in intact group were randomly separately into two groups of 6 for ALB and PMB groups, which were then used for completely transected PCL group.

48 hours prior to the experiment, the knees were thaw for 24 h in refrigerator at 4°C and the skins, fascia and other soft tissues were removed. The knees were fasten at the distal ends of fibula and tibia and the proximal ends of the quadriceps femurs were braided with steel wires. Both ends of the steel wires were left aside for subsequent use. For intact group, longitudinal incisions (ca. 5 cm) lateral to knee-cap and to femur and medial to condyle were made to cut open the anterior and posterior joint capsules and expose the anterior and posterior horns of lateral meniscus. A longitudinal incision (ca. 3 cm) was then made on the lateral knee joint to expose the caudomedial part of lateral meniscus. A 5 mm × 5 mm measurement area was prepared on the lateral meniscus after clean up the soft tissue and smoothen with sandpaper, degreased and dried. For PMB group, the knees were flexed to 90°, and the relaxed fiber bundles of PCL at low 1/3 position were hooked up with a specially-made blunt hook at posterior midline incision. In straitening the knees, clear tension could be felt on the hook, indicating that this is PMB. It was transected. For ALB group, the knees were flexed to 0°, and the relaxed fiber bundles of PCL at low 1/3 position were hooked up with the blunt hook at posterior midline incision. By

Table 1. Stresses of the anterior horn of lateral meniscus with intact and transected PCL at different degrees of flexion and loadings ($\bar{x} \pm s$, με)

Flexion angle (°)	Load (N)	Intact	ALB group	PMB group	Complete transection
0	200	-18.00±1.28	-18.17±0.75	-26.17±1.47*	-26.08±1.37*
	400	-24.20±1.35	-24.60±0.99	-34.00±0.85*	-34.22±1.69*
	600	-30.30±1.29	-35.17±1.57	-40.20±1.00*	-43.80±1.84*
	800	-36.90±0.84	-42.62±2.04*	-47.80±1.03*	-54.14±1.24*
	1000	-40.10±0.86	-49.40±1.40*	-54.90±0.95*	-64.20±1.01*
30	200	12.08±1.23	-40.40±1.55*	10.60±0.98*	-40.56±0.96*
	400	20.00±1.04	-50.60±2.78*	18.00±1.20	-51.20±1.51*
	600	27.80±1.21	-57.40±1.01*	21.80±1.42*	-64.80±0.81*
	800	36.83±1.27	-67.00±1.43*	27.70±1.31*	-75.10±1.20*
	1000	43.50±0.86	-76.11±0.99*	34.80±1.00*	-84.23±0.96*
60	200	23.85±0.81	-57.00±0.75*	13.90±1.03*	-62.33±1.00*
	400	32.70±0.92	-67.00±0.89*	22.70±1.20*	-73.60±1.27*
	600	42.00±1.38	-76.40±1.23*	32.00±1.75*	-84.30±1.66*
	800	51.60±0.88	-86.50±0.88*	41.60±1.06*	-93.90±0.82*
	1000	60.42±0.71	-96.31±0.39*	50.52±1.43*	-102.31±1.16*
90	200	33.20±0.88	-66.17±1.01*	23.40±0.89*	-73.60±1.16*
	400	41.90±1.56	-80.00±1.29*	31.90±1.39*	-88.30±1.02*
	600	54.00±2.50	-90.20±4.22*	44.49±2.13*	-98.80±1.92*
	800	64.00±0.98	-100.70±1.09*	54.00±1.24*	-110.40±1.30*

*Compared with intact group, $P < 0.05$.

flexing the knee to 90°, clear tension could be felt on the hook, indicating that this is ALB. It was transected. For completely transected group, the knee was flexed to 90°, PCL was hooked and transected completely at low 1/3 position.

Biomechanic measurement

The measurement of biomechanic parameters was conducted essentially the same as reported [3] at the flexion angles of 0, 30, 60 and 90° and loads of 0, 200, 400, 600, 800 and 1000 N at loading rate of 0.5 mm/s. The knees were relaxed for 10 min before next measurement, and used for measurements in subsequent groups. The samples were surface-covered with a thin layer of gauze sprayed with saline solution to keep them moist. The measurements were conducted in triplicate at 25°C in humidity of 60-80% (**Figure 1**).

Statistical analysis

Data were processed using SPSS 15 for Windows and expressed as means ± SD (standard deviation). The comparison between means with homogeneous variance was made using the SNK-q test and with heterogeneous variance using the Dunnett-T3 test. Multiple variable variance was used to analyze the relationship among load, flexion angle, PCL transection and stress of lateral meniscus. The difference with $P < 0.05$ was considered sta tistically significant.

Results

Stresses of the anterior horn

Stress measurements of the lateral meniscus anterior horn with intact and transected PCL are shown in **Table 1**. When measured at flexion angle of 0°, the stresses were negative, indicating that the force is compressive strain. The absolute values of stresses increased with increasing weight of load and reached the maximum and minimum in the completely transected and intact groups, respectively. The stresses were similar between intact and ALB groups, and PMB and completely transected groups at 200 N. At the load, the absolute stresses of PMB and complete transected groups were remarkably greater than those of intact and ALB groups. The same results were also seen at 400 N. At 400 N, the stresses of intact and

Table 2. Stresses of the caudomedial part of lateral meniscus with intact and transected PCL at different degrees of flexion and loadings ($\bar{x} \pm s$, με)

Flexion angle (°)	*Load (N)*	*Intact*	*ALB group*	*PMB group*	*Complete transection*
	200	-11.60±0.61	-11.67±0.54	-16.63±1.90*	-18.40±0.92*
	400	-17.79±0.92	-18.32±0.79	-24.77±0.50*	-25.00±1.19*
0	600	-23.00±1.33	-26.80±0.71	-30.63±0.45*	-34.18±1.18*
	800	-29.63±0.85	-34.60±0.75*	-38.80±0.85*	-42.30±0.79*
	1000	-35.30±1.01	-42.30±1.13*	-46.20±1.00*	-50.30±0.88*
	200	7.90±0.76	-26.10±0.67*	5.90±0.90	-27.10±0.73*
	400	13.50±0.69	-31.00±1.00*	11.50±0.74	-31.81±0.98*
30	600	18.90±0.82	-35.47±0.57*	13.88±0.80	-39.80±0.96*
	800	24.20±0.80	-40.80±0.96*	18.20±0.92	-46.60±0.97*
	1000	30.20±0.74	-45.90±1.07*	23.30±0.97	-53.72±0.91*
	200	11.33±0.94	-30.02±0.65*	10.30±1.04	-33.90±1.32*
	400	17.40±0.80	-35.60±0.75*	15.20±0.75	-40.30±0.93*
60	600	23.18±0.93	-41.80±0.96*	17.20±1.18	-46.00±1.77*
	800	29.70±0.87	-47.60±0.83*	20.70±0.78*	-54.86±0.70*
	1000	35.50±0.79	-54.50±0.83*	24.83±0.79*	-62.90±0.87*
	200	18.51±0.54	-36.39±0.57*	17.64±0.94	-42.06±1.01*
	400	24.70±0.80	-43.00±0.71*	22.70±0.68	-48.90±1.12*
90	600	31.70±1.25	-52.00±0.88*	25.85±1.45*	-57.80±1.33*
	800	38.65±1.11	-59.57±1.01*	31.40±1.92	-65.60±1.12*
	1000	45.50±1.14	-66.50±0.91*	37.80±1.32	-73.90±1.00*

*Compared with intact group, $P < 0.05$.

ALB groups, as well as PMB and completely transected groups were essentially the same. At heavier loads (600, 800 and 1000 N), the absolute stresses were in order of intact < ALB < PMB < completely transected group. When determined at flexion angle of 30°and loads of 200 and 400 N, the stresses of intact and PMB groups were similar and positive, while those of ALB and completely transected groups were similar and negative. At heavier loads (600, 800 and 1000 N), the absolute stresses were greater in completely transected group than in ALB groups, and in intact group than in PMB group. At the flexion angle of 60°, the stresses were positive in intact and PMB groups and negative in ALB and completely transected groups at all loads. The absolute stresses were greater in completely transected group than in ALB group, and in intact group than in PMB group. At the flexion angle of 60°, the stresses increased with increasing loads in all groups. At the flexion angle of 90°, the stresses were positive in intact and PMB groups and negative in ALB and completely transected groups at all load levels. The absolute values of the stress were greater in completely transected group than in ALB group, and in intact group than in PMB group. The absolute values of the stress at the flexion angle of 90° increased with increasing weight of loads.

Statistical analysis of the data showed that there were significant ($P < 0.01$) difference in the stresses in the joints with different PCL transections, at different loads, and at different angles of flexion. Furthermore, there were significant ($P < 0.01$) interactions between PCL transection and loading, and between PCL transection and flexion angle, and between loading and flexion angle, and between PCL transection, loading and flexion angle.

At flexion angle of 0° and all loadings, no difference was seen between the stresses in the anterior horn in intact and completely transected groups ($P > 0.05$) and in PMB and completely transected groups ($P > 0.05$). However, the st-resses were significantly different between in-tact and PMB groups, intact and completely transected groups, in ALB and PMB groups and in ALB and completely transected groups ($P < 0.05$). When measured at flexion angle of

0° at 400 N, the anterior horn stresses were similar between intact and ALB transected groups (P > 0.05) and between PMB and completely transected groups (P > 0.05). However, the stresses were significantly different between intact and PMB groups (P < 0.05), and between intact and completely transected groups (P < 0.05), ALB and PMB or completely transected groups (P < 0.05). At higher loadings (> 600 N), the stresses were significantly different among the groups.

At flexion angle of 30°, 200 N loading did not generate significantly different stresses between intact and PMB groups (P > 0.05), nor between ALB and completely transected groups (P > 0.05). However, the stresses were significantly (P < 0.05) different between intact and ALB or completely transected groups, and PMB and ALB or completely transected groups. At 400 N, the stresses were similar (P > 0.05) be-tween intact and PMB groups, and ALB and completely transected groups. On the other hand, the differences were significant (P < 0.05) between intact and ALB or completely transected groups, and between PMB and ALB or completely transected groups. At increased loadings (600-1000 N), the stresses were significantly (P < 0.05) different among all the groups.

At flexion angle of 60°, the stresses were significantly (P < 0.05) differrent between groups at all loading levels, and the results were similar to the measurements obtained at flexion angle of 90°.

Stresses of the caudomedial part

Stress measurements of the lateral meniscus caudomedial part are shown in **Table 2**. The data showed that at the flexion angle of 0°, the measurements were negative, indicating that the force is compressive strain. The absolute stresses increased with increasing weights of load in all groups and were the highest and lowest in completed transected and intact groups, respectively. At 200 and 400 N, the stresses of intact and ALB groups, and PMB and completely transected groups were similar, while those of PMB and completely transected groups were greater than those of intact and ALB groups. At heavier loads (600-1000 N), the absolute stresses were in sequence of completely transected > PMB > ALB > intact group. At the flexion angle of 30° and loads of 200 and 400 N, the stresses were positive and similar in intact and PMB groups, and negative and similar in ALB and completely transected groups. At the heavier loads (600-1000 N), the absolute values of stress were greater in completely transected group than in ALB group, and in intact group than in PMB group. At the flexion angle of 60°, the stresses were positive in intact and PMB groups, and negative in ALB and completely transected groups. The absolute stresses were greater in completely transected and intact groups than in ALB and PMB groups. At the flexion angle 90°, the stresses increased with increasing weight of load and were positive in intact and PMB groups and negative in ALB and completely transected groups. The absolute values of the stresses were greater in completely transected and intact groups than in ALB and PMB groups.

The data were statistically analyzed and the results showed that the stresses were significantly (P < 0.01) different between different transections, load and flexion angle. There were significant interactions between transection and load (P < 0.05) or flexion angle (P < 0.01), and between load and flexion angle (P < 0.01). The three variables also had significant interactions (P < 0.01). Statistical analysis also showed that at flexion angle of 0°and loads of 200 and 400 N, the stresses were not different (P > 0.05) between intact and ALB groups, nor between PMB and completely transected groups. How-ever, the differences were significant (P < 0.05) between intact and PMB, or completely transected groups, and between ALB and PMB or completely transected groups. At heavier loads (600, 800 and 1000 N), the stresses were significantly (P < 0.05) different among all the groups.

Statistical analysis showed that at flexion of 30°, loads of 200 and 400 N resulted in similar (P > 0.05) stresses in completely transected and PMB or ALB groups, and significantly (P < 0.05) different stresses between intact and ALB or completed transected groups, and between PMB and ALB or completely transected groups. At further heavier loads (600-1000 N), the stresses were significantly (P < 0.05) different among all the groups. The same results were also obtained at flexion angles of 60° and 90° at all the loads.

Table 3. Stresses of the posterior horn of lateral meniscus with intact and transected PCL at different degrees of flexion and loadings ($\bar{x} \pm s$, με)

Flexion angle (°)	*Load (N)*	*Intact*	*ALB group*	*PMB group*	*Complete transection*
0	200	-11.33±1.23	-11.17±1.47	-6.00±1.27*	-6.33±1.15*
	400	-17.25±0.86	-17.17±1.47	-10.83±0.75*	-10.83±1.27*
	600	-24.42±0.90	-21.50±1.05	-18.00±0.89*	-14.67±1.07*
	800	-30.33±1.23	-27.00±1.41	-21.33±1.63*	-18.33±1.23*
	1000	-37.25±1.22	-33.00±1.41	-26.00±1.41*	-22.25±1.22*
30	200	-14.25±1.29	25.33±1.21*	-13.67±1.03*	26.08±1.17*
	400	-21.08±1.31	34.83±0.75*	-19.50±1.05	35.00±1.41*
	600	-27.25±1.22	39.17±1.47*	-22.83±1.47*	47.25±1.22*
	800	-33.00±1.60	45.50±1.87*	-26.67±1.03*	55.67±1.61*
	1000	-38.42±1.00	52.17±1.47*	-32.50±1.05*	63.58±1.31*
60	200	-20.17±1.12	31.17±1.47*	-16.00±0.89*	37.42±1.31*
	400	-27.50±1.17	40.00±1.41*	-22.50±1.05*	47.33±1.07*
	600	-34.00±1.35	48.33±1.63*	-28.00±0.89*	56.83±1.12*
	800	-42.25±1.14	57.50±1.87*	-33.17±1.17*	65.50±1.45*
	1000	-50.50±1.31	66.17±1.47*	-39.50±1.05*	74.25±1.29*
90	200	-26.50±1.00	36.50±1.05*	-22.83±0.75*	46.50±1.00*
	400	-33.50±1.00	48.67±1.03*	-28.83±1.17*	59.50±1.17*
	600	-40.25±1.29	59.00±1.41*	-35.17±0.75*	71.17±1.47*
	800	-51.58±1.00	72.00±1.41*	-40.67±1.03*	89.08±1.51*
	1000	-62.08±1.38	85.17±1.47*	-46.67±1.21*	107.17±1.53*

*Compared with intact group, $P < 0.05$.

Stresses of the posterior horn

Stress measurements of the lateral meniscus posterior horn are shown in **Table 3**. The data showed that at the flexion angle of 0°, the measurements were all negative, indicating that the force is compressive. The absolute stresses increased with increasing weights of load in all groups with the maximum and minimum in intact and completely transected groups, respectively. When tested at 200 and 400 N, the stresses of intact and ALB groups, and PMB and completely transected groups were similar, while the absolute values of the stress were greater in intact and ALB groups than in PMB and completely transected groups. At heavier loads, the absolute stresses in these groups were intact group > ALB group > PMB group > completely transected group. When measured at the flexion angle of 30°, the stresses were negative in intact and PMB groups and positive in ALB and completely transected groups, being compressive and stretching strain, respectively. The absolute values of the stresses in all groups increased with increasing weight of loads. At 200 and 400 N, the stresses were similar between intact and PMB groups and between ALB and completely transected groups. When determined at flexion angle of 30°, 600, 800 and 1000 N generated greater absolute stresses in completely transected and intact groups when compared with ALB and PMB groups, respectively. At deeper flexion angle (60°), the stresses were negative in intact and PMB groups and positive in ALB and completely transected groups. The absolute stresses increased with increasing loads in all groups. Furthermore, the absolute stresses were greater in completely transected and intact groups than in ALB and PMB groups, respectively. At the deepest angle tested (90°), the stresses were negative in intact and PMB groups and positive in ALB and completely transected groups. These stresses increased with increasing load in all groups. Furthermore, the absolute stresses were greater in completely transected and intact groups than in ALB and PMB groups, respectively.

Statistical analysis showed that the stresses was significantly different in the joints with different levels of PCL transection ($P < 0.01$), loads ($P < 0.05$) and flexion angles ($P < 0.01$). There were significant interactions between PCL transection and the load on the stresses ($P < 0.01$), as well as between the load and the flexion angle ($P < 0.01$), and among PCL transection, load and flexion angle ($P < 0.01$). At the flexion angle of 0° and loads of 200 and 400 N, the stresses were similar ($P > 0.05$) between intact and ALB transected groups and between PMB and completely transected groups. Under the-se conditions, the stresses were significantly ($P < 0.05$) different between intact and PMB groups, completely transected and intact gr-oups, ALS and PMB groups and ALS and completely transected groups. With increased lo-ads (600, 800 and 1000 N), the differences in the stresses became significant ($P < 0.05$) am-ong all groups. At the flexion angle of 30° and loads of 200 and 400 N, there was no significant ($P > 0.05$) difference in the stresses be-tween completely transected and PMB groups, nor between ALB and completely transected groups. However, the differences were significant ($P < 0.05$) between intact and ALB or completely transected groups, and between PMB and ALB or completely transected groups. At deeper loads (600-1000 N), the differences became significant ($P < 0.05$) among all the groups. Further increase of the flexion angle to 60 and 90°, the differences in the stresses were significant ($P < 0.05$) among all the groups at all load levels tested.

Discussion

PCL has very complex anatomic structure and biological function. PCL was considered to be the most powerful ligament of the knee, but recent study suggests that its strength is similar to anterior cruciate ligament [4]. PCL is reported to reduce posterior displacement of the tibia by 89% [2]. Meniscus is important in maintaining the stability of knee joint and flexibility of normal physiological functions [5]. Seedhom [6] found that the meniscus bears 40 to 60% of the load of knee joint. When extended, the average loading area of normal tibiofemoral joint is 20.13 cm^2, and when flexed, the area is 11.60 cm^2. After resection of meniscus, the areas are 12 cm^2 and 6 cm^2, respectively [7]. Thambyah [8] confirmed that the meniscus at extension position bears 50-70% of the knee joint load, and 90% of the load at 90° flexion. Although there are some studies regarding the secondary injury resulted from PCL injury, such as injury in meniscus and articular cartilage, the results of these studies are mostly based on animal experiments or clinical observations. Questions remain unanswered as how much PCL injury would impact the biomechanic characteristics of lateral meniscus? And how each part of the lateral meniscus shares the stress when PCL is ruptured in different ways? So far, very little has been reported on the biomechanic effect of complete or partial PCL rupture on different parts of lateral meniscus using fresh normal human knee joints. A better understanding of the biomechanic effect of PCL ruptures, either complete or partial, on different parts of lateral meniscus will provide information for effective prevention and treatment of lateral meniscus injury, and for prevention of osteoarthritis.

Two kinds of methods are usually used for determination of pressure in the knee joint, namely the direct methods [8] and indirect methods [9]. In recent years, more and more studies use the finite element method to investigate the biomechanics characteristics of the knee joint using reconstruction and ideal geometry models without considering the contact characteristics in the friction between the friction joints [10]. The practical applicability of these results needs to be further verified. In this study, we used a home-made micro-strain gauge with the sensitive gate whose size is only 1 mm × 1 mm with resistance strain gauge area of 3.5 mm × 3 mm. The reduced gauge area minimizes the effect of the material properties on measurement. Furthermore, the gau-ge was attached to the side of lateral meniscus, making no impact on the integrity of the meniscus structure. The direction of the strain gauge was set in the same direction as that of the load. All these measures were taken to ensure accurate and realistic measurements of mechanical properties.

The knee loads and flexion angles used in this study were set to simulate the daily knee activities. According to the "2000 national physique monitoring report" [11], the load of single knee is about 200 N, which was then used as the lowest load in the test. The load at center of the knee joint can be as high as 2 to 3 times of body weight during human activities and in daily activities, the maximum PCL stress should be less than that limit. Therefore, 1000 N (two times of body weight) was selected as the upper load. For the flexion angles, 0, 30, 60 and 90° were selected to represent the flexion angles at standing, normal walking, maximum walking and fast running, respectively.

Our measurements show that at normal knee position, the stresses in the anterior horn, caudomedial part and posterior horn of lateral meniscus were negative, being compressive strain. When flexed for 30° or deeper, the stresses in the anterior horn and caudomedial part became positive, being tension strain, while the stresses in the posterior horn remained negative. The changes in the strain is likely due to the fact that the lateral meniscus and femoral condyle can move on tibial plateau as the knee flexes. Studies have shown that after flexed for 20°, meniscus begins to shift posteriorly, and the posterior meniscus is sandwiched between the femoral condyle and tibial plateau when the knee is flexed to 90° [12]. We found that at 0° of flexion, the stresses in the anterior horn, caudomedial part and posterior horn were all negative. At loads of 200 N and 400 N, the stresses in the anterior horn and caudomedial part were greater in completely transected and PMB groups than in intact and ALB groups. Furthermore, no significant difference in the stresses was found between intact and ALB groups, indicating that complete or partial rupture of PCL will result in unchanged or increased stresses in anterior horn and caudomedial part. On the hand, Transection of PCL and PMB generated negative reduction of the stresses in the posterior horn as compared with intact and ALB groups. Meanwhile, no significant difference in the strain was seen between intact and ALB groups, suggesting that complete or partial rupture of PCL will not reduce or slight reduce the pressure in posterior horn. At the loads of 600 to 1000 N, the absolute stresses in the anterior horn and caudomedial part were completely transected > PMB > ALB > intact groups, while in the posterior horn, the order reversed. These results indicate that either complete or partial rupture of PCL will lead to increased pressure in the anterior horn and caudomedial part, and reduced pressure in the posterior horn. This phenomenon may be resulted from the restricted posterior shifting of tibia by PCL at 0° of knee flexion. When PCL is completely or partially ruptured, knee joint will become instable axially and shift posteriorly to redistribute the load, leading to increased strain in the anterior horn and caudomedial part, and reduced strain in the posterior horn. When the knee was flexed to 30-90°, the stresses in the anterior horn and caudomedial part became negative in completely transected and ALB groups and positive in intact and PMB groups, indicating that there is no pressure in the anterior horn and caudomedial part when PCL is intact or PMB is ruptured and the two parts are pressed when PCL and ALB are ruptured, as shown by the changes in the stresses from positive (tension strain) to negative (compressive strain). For the posterior horn, the pressure was compressive when PCL was intact or PMB was ruptured. The pressure became tensile when PCL and ALB were transected. No significant change or slight reduction in the stresses was observed in the posterior horn when PMB was transected as compared to intact PCL. These data indicate that at these flexion angles (30-90°), when PCL is completely or partially rupture, the pressure is mainly on the anterior horn and caudomedial part, not on the posterior horn, where the compression remains unchanged or reduce to zero. These findings are consistent with previous studies [13]. This is because PCL ends at lateral midline on the posterior tibia plateau and its rupture will result in posterior or mild posterior and extroversive subluxation of tibia, leading to pulling, twisting and longitudinal crack of the anterior horn by femoral condyle [14]. In addition, the lateral meniscus has larger activity range than the medial meniscus does but the smallest elasticity. Therefore, it is prone to injury [13]. In short, our results suggest that complete or partial PCL rupture can cause dramatic change in the biomechanical properties of lateral meniscus during knee flexion process, leading to possible meniscus injury, particularly in the anterior horn and caudomedial part, while the posterior horn is less affected.

In this study, PCL is divided into anterior lateral and posteromedial bundles. Our data obtained at flexion angle of 0° and knee load of less than 400 N indicate that the stresses in completely transected PCL and PMB groups were similar, indicating that at this flexion position PMB stabilizes the joint. When the knee load was over 400 N, there were differences in the stresses in different groups. This may be resulted from that the possibility that the heaver load used in the experiment is over the mechanic bearing limit of PMB, resulting in loss of its stabilizing function for the knee joint. The stresses in PMB group were different from these of PCL completely transected group, implying that at heavier loads, some of the ALB are involved in stabilizing the joint. Data obtained at the flexion of 30° suggest that at the angle ALB is responsible for stabilizing the joint at the load of less than 400 N. Once ALB is transected, the instability of the joint is the same as if PCL is transected. However, when the load was heavier than 600 N, the stresses were different in each group. This may be due to the loss of joint-stabilizing function that ALB has due to overloading. The stresses of ALB group was smaller than those of completely PCL transected group, suggesting that some of PMB are involved in stabilizing the joint. At the flexion angles of 60 and 90°, remarkable differences in the stresses were seen between groups at the same loads, and the absolute stresses were greater in completely transected group than in ALB and intact group, and than in PMB group. We speculate that when flexed to these degrees, ALB and PMB are both responsible for stabilizing the joint. These findings are also in line with the anatomic results [15]. Lio et al [15] found that there are fiber bundles in ALB and PMB with typical functions. These fiber bundles are most important in stabilizing posterior shift of tibia and have the widest range of tension during the knee flexion. These fiber bundles are called the functional bundles [15]. The combined action of the functional bundles in ALB and PMB is shown to be enough to maintain the posterior stability of tibia during the knee joint activity. Therefore, PCL reconstruction should not be simplify based on anatomical structure and mechanical properties of ligament, but more on the functional reconstruction of PCL bundles in dynamic joint environment. The results of our study show that the mechanical properties of ALB and PMB are different in different knee motions and that partial rupture of PCL would also result in dramatic change in the biomechanical properties of lateral meniscus during the knee flexion and extension process, leading to potential injury. These findings further suggest that it is necessary to reconstruct the functional bundles in ALB and PMB after PCL rupture. Of course, more studies are needed to confirm the suggestion.

PCL is an important structure to maintain the stability of knee joint. Once ruptured, compensatory mechanisms are initiated in the structures such as meniscus to maintain the normal function of the knee joint. PCL injury can cause abnormal stress in meniscal tissue, resulting in meniscus injury, particularly in the anterior horn and caudomedial part body. Long-term meniscus injury can cause osteoarthritis in knee joint [16]. Therefore, it is highly desirable to reconstruct the double functional bundles in case of PCL rupture to restore the stability of knee joint, reduce the degeneration of meniscus and slow down osteoarthritis. The findings from our study reveal the impact of complete or partial PCL rupture on lateral meniscus and will be of great importance for prevention of the secondary injury after PCL injury and planning of PCL reconstruction.

Conclusion

Data from our study show that complete transection of PCL will impact the stresses in the anterior horn, caudomedial part and posterior horn of lateral meniscus at various knee flexion and loads. At 200 and 400 N, the stresses in ALB group at 0° and PMB group at 30° are the same as in intact group for all the three parts, and the stresses are different when the loads increase to 600 and 800 N. At all loads, transection of ALB and PMB affects the stresses in the anterior horn, caudomedial part and posterior horn at the flexion angles of 30-90° and 0-90°, respectively.

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Disclosure of conflict of interest

None.

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