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Different effects of the lateral meniscus complete radial tear on the load distribution and transmission functions depending on the tear site

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Abstract

Purpose To compare the effect of the lateral meniscus (LM) complete radial tear at different tear sites on the load distribution and transmission functions.

Methods A compressive load of 300 N was applied to the intact porcine knees ($n = 30$) at 15°, 30°, 60°, 90°, and 120° of flexion. The LM complete radial tears were created at the middle portion (group M), the posterior portion (group P), or the posterior root (group R) ($n = 10$, each group), and the same loading procedure was followed. Finally, the recorded three-dimensional paths were reproduced on the LM-removed knees. The peak contact pressure (contact area) in the lateral compartment and the calculated in situ force of the LM under the principle of superposition were compared among the four groups (intact, group M, group P, and group R).

Results At all the flexion angles, the peak contact pressure (contact area) was significantly higher (lower) after creating the LM complete radial tear as compared to that in the intact state ($p < 0.01$). At 120° of flexion, group R represented the highest peak contact pressure (lowest contact area), followed by group P and group M ($p < 0.05$). The results of the in situ force carried by the LM were similar to those of the tibiofemoral contact mechanics.

Conclusion The detrimental effect of the LM complete radial tear on the load distribution and transmission functions was greatest in the posterior root tear, followed by the posterior portion tear and the middle portion tear in the deep-flexed position. Complete radial tars of the meniscus, especially at the posterior root, should be repaired to restore the biomechanical function.

Keywords Meniscus · Lateral meniscus · Radial tear · Load distribution · Contact pressure · Contact area · Load transmission · In situ force · Compressive load · Knee

Abbreviations

DOF Degree of freedom
LM Lateral meniscus
3D Three-dimensional
UFS Universal force/moment sensor

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Introduction

The menisci are interposed in the tibiofemoral joint, which has low congruity, and cover approximately 60% and 80% of the medial and lateral tibial plateaus, respectively [10, 27]. As interposition of the menisci increases the joint congruity, an external compressive load is distributed on the tibiofemoral contact surface [34, 40]. The ultrastructure as well as the morphology of the meniscus also contribute to the biomechanical function. The extra-cellular matrix forming

the meniscus is mainly composed of type I collagen fibers, which are predominantly aligned circumferentially [32]. The circumferential fibers are organized by radial tie-fiber sheets and are inserted directly into the bone at the firm attachments (meniscal roots) [2, 3]. The collagen hoop structure serves to transfer a compressive load into a circumferential tensile load; consequently, most of the load onto the tibiofemoral joint is transmitted through the menisci [35, 38]. The load distribution and transmission functions are pivotal roles of the meniscus for cartilage protection and joint preservation [14].

Radial tear of the meniscus disrupts the integrity of the circumferential collagen fibers and has a detrimental effect on the load distribution and transmission functions [7, 8]. The lateral meniscus (LM) complete radial tear drastically deteriorated the biomechanical function, although partial tear of radial width did not affect the tibiofemoral contact mechanics in the lateral compartment or the in situ force carried by the LM [28, 37]. In the clinical settings, radial tears of the meniscus can be observed at various locations; however, the effect of the tear site on the deterioration of the load distribution and transmission functions remains unclear [9, 36]. The meniscus complete radial tear at different tear sites may cause different impacts on the load distribution and transmission functions. Understanding the association between the radial tear location of the meniscus and the degradation of the biomechanical function must be helpful to estimate the adverse effect on the tibiofemoral joint or decide the appropriate treatment strategies in clinical practice.

The purpose of this study was to compare the effect of the LM complete radial tear at different tear sites on the load distribution and transmission functions using a porcine knee model. It was hypothesized that the detrimental effect of the LM complete radial tear on the load distribution and transmission functions would differ among different tear sites.

Materials and methods

Thirty fresh-frozen porcine knees, which were obtained from a local butcher, were used in this study. The institutional review board of the Osaka University Hospital reviewed the study protocol and determined that this study did not require oversight. The mean age and weight of specimens were 24 weeks (range 23–25 weeks) and 120 kg (range 115–125 kg), respectively. It was verified that the size of the tibial joint surface was relatively uniform and its transverse diameter was approximately 48 mm [29]. Knees with an apparent injury to the ligaments, menisci, or articular cartilage were excluded. Each knee was thawed at room temperature for 24 h before testing. All the muscles except for the popliteus were removed, while the patella, the patellar tendon, the collateral ligaments, and the capsule around the knee were carefully left intact. The femur and the tibia were both cut at a distance of 13 cm from the joint line, and both ends were potted and fixed in cylindrical molds of acrylic resin (Ostron II; GC, Tokyo). The fibula was cut 4-cm distal from the proximal tibiofibular joint and was fixed in the anatomic position with acrylic resin.

Robotic system

A 6-degree of freedom (DOF) robotic system (FRS-2010; Technology Service Ltd., Nagano) was utilized in this study. The system consists of a velocity-control 6-DOF (3 translational-axis and 3 rotational-axis) manipulator with a universal force/moment sensor (UFS) (SI-660-60; ATI Industrial Automation, Apex, NC) and a control computer (Windows XP; Microsoft, Redmond, WA) linked with a high-speed motion network (Mechatrolink-II; Yaskawa Electric, Fukuoka) [15, 17, 18]. The manipulator is composed of the upper and lower driving mechanisms, and the UFS is attached to the upper mechanism. The upper mechanism is linked to two translational-axis actuators (SGDS-01F12A; Yaskawa Electric) and three rotational-axis actuators (HA-800B-3A; Harmonic Drive Systems, Tokyo), while the lower mechanism is linked to 1 translational-axis actuator. All the actuators are powered by alternating-current servomotors. The data about both the position of and the force/moment acting on the knee joint are acquired via the UFS, and the control computer operates the program in a graphical language programming environment (LabView 8.6.1; National Instruments, Austin, TX) to control the position and the force/moment.

This system can manipulate the physiological three-dimensional (3D) motion of the knee joint by calculating and applying the 3D path to eliminate the force/moment on the knee joint except for the operator's intended direction. The manipulator has a position accuracy of less than ± 0.015 mm in translation and $\pm 0.01°$ in rotation; the clamp-to-clamp stiffness is more than 450 ± 180 N/mm in translation and 110 ± 30 Nm/° in rotation [11]. The frequency of data acquisition, kinematic and kinetic calculation, and motion of actuators is 20 Hz. The tibial and femoral cylindrical molded ends were connected firmly to the upper and lower driving mechanisms of the manipulator, respectively, with custom-designed aluminum clamps. A knee joint coordinate system developed by Grood and Suntay [20] was introduced, and a 3D digitizer (MicroScribe-3Dx; Immersion, San Jose, CA) was utilized to aim the femoral insertions of both the medial and lateral collateral ligaments (resolution, 0.13 mm; accuracy, 0.23 mm).
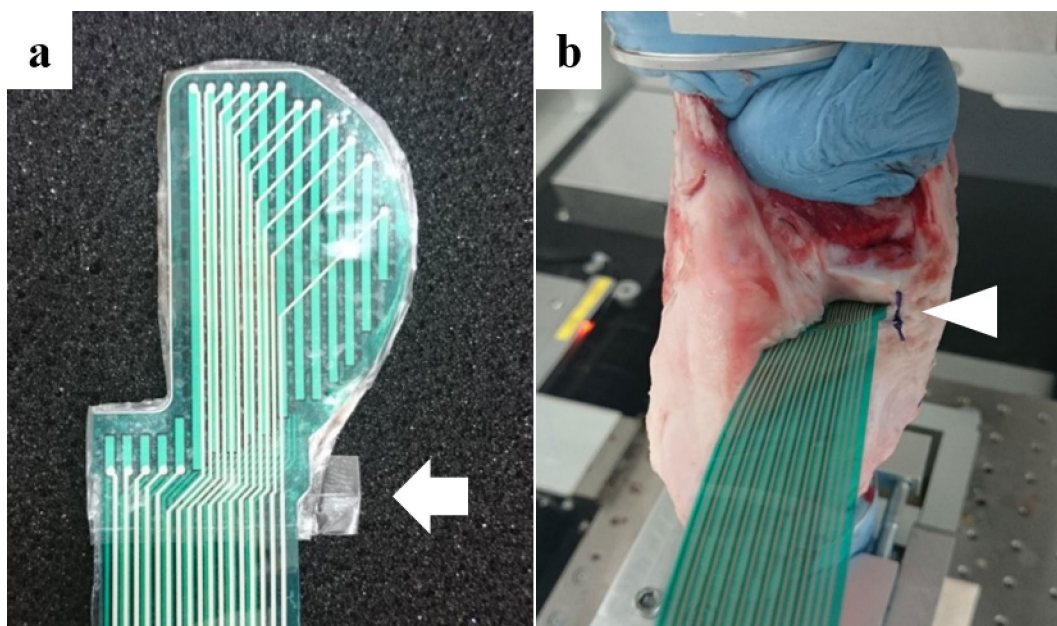
Pressure film sensor

A thin electronic pressure film sensor with a thickness of 0.2 mm (K-Scan system model 4011; Tekscan, Boston, MA) was utilized to measure the tibiofemoral contact mechanics (pressure and area) in real time (sampling frequency: 100 Hz) [5, 12]. The pressure film sensor was made up of 404 sensels (based on 26×22 grid of sensels with 2-mm square). The sensor was used after cutting in half and was initially calibrated in a dry environment following the instructions of the manufacturer. To prevent the diminishing of the load output over time due to exposure to liquid [22], both the upper and lower surfaces of the sensor were coated with 0.01 mm-thick polyurethane plastic film (Eleban film; Hakuzo Medical, Osaka) creating a small tab beside the sensor as in the previous report [41] (Fig. 1a). A 20-mm-long horizontal incision was created on the capsule between the anterior portion of the LM and the anterior edge of the lateral tibial plateau. The pressure film sensor was inserted between the LM and the tibial articular surface through the capsular incision and was fixed by sewing the capsule including the tab using a 3-0 polyester suture (Fig. 1b).

Testing protocol

At the beginning of the examination, three cycles of flexion–extension motion between 15° and 120° of flexion with a continuous compressive load of 20 N were applied

to the intact knees to exclude the influence of creep behavior in viscoelastic soft tissues. First, an axial compressive load of 300 N was applied to the intact knees at 15°, 30°, 60°, 90°, and 120° of flexion, respectively. A compressive load of 300 N was employed, because the amount was approximately equivalent to a quarter of the porcine weight and is considered as the load imposed on the tibiofemoral joint in the static standing position. The tibiofemoral contact pressure and area in the lateral compartment were recorded via the pressure film sensor, while the 3D path of the tibia relative to the femur (P_i) and the force/moment acting on the knee joint (F_i) were recorded via the UFS.

Next, the porcine knees were divided into three groups of ten knees each, and the LM complete radial tears were created at the middle portion (group M), the posterior portion (group P), or the posterior root (group R) using a scalpel from the extra-knee joint. The locations of complete radial tears were the midpoint between the anterior and posterior roots in group M, the midpoint between the group M point and the posterior root in group P, and the meniscal insertions of both the posterior root and the meniscofemoral ligament in group R (Fig. 2). Subsequently, the same loading procedure was followed by the knees in all the three groups. The tibiofemoral contact pressure and area in the lateral compartment were again recorded via the pressure film sensor, while the 3D path (P_{rt}) and the force/moment (F_{rt}) on the knee joint were also recorded via the UFS.

Fig. 1 **a** Electronic pressure film sensor. Both the upper and lower surfaces of the sensor were coated with 0.01 mm-thick polyurethane plastic film creating a small tab beside the sensor (white arrow). **b** Insertion of the pressure film sensor between the LM and the tibial articular surface. The sensor was fixed by sewing the capsule including the tab using a 3-0 polyester suture (white arrow head). *LM* lateral meniscus
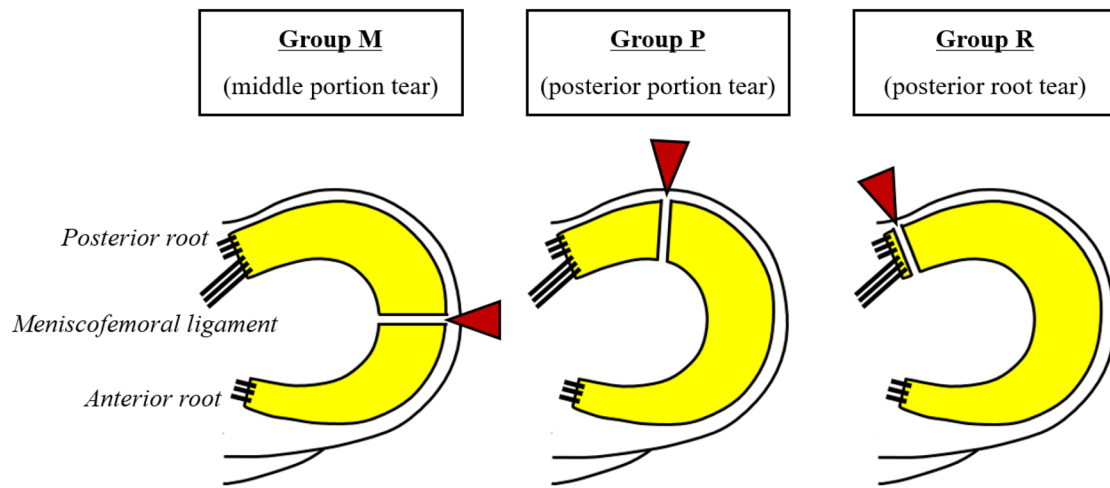
Fig. 2 Sites of the LM complete radial tear. The locations of complete radial tears were the midpoint between the anterior and posterior roots in group M, the midpoint between the group M point and the posterior root in group P, and the meniscal insertions of the both posterior root and the meniscofemoral ligament in group R (red arrow head). *LM* lateral meniscus

Finally, the pressure film sensor was extracted from all the knees through the capsular incision by cutting the suture on the capsule and tab. Then, the LM was totally removed by resecting the anterior and posterior roots, the meniscofemoral ligament, and the connective fibers to the surrounding capsule using a scalpel. Then, the previously recorded 3D paths in the intact knees and the knees with the LM complete radial tear (P_i and P_{rt}) were sequentially reproduced on the LM-removed knees recording the force/moment on the knee joint (F_i' and F_{rt}'). This process was conducted to calculate the in situ force carried by the LM under 300 N of axial compressive load (Fig. 3).

Data acquisition

The peak contact pressure and the contact area in the lateral compartment under 300 N of axial compressive load were automatically calculated from the sensor output data by an exclusive analyzing software (I-Scan system ver. 5.2; Tekscan, Boston, MA). The peak contact pressure was defined as the average pressure of the area with

Fig. 3 Testing protocol and data acquisition. *The in situ force carried by the LM was calculated under the four meniscal conditions (intact, group M, group P, and group R) based on the principle of superposition and compared among the four groups. *LM* lateral meniscus, *RT* radial tear, *3D* three-dimensional

2×2 sensels which showed the highest net load. The peak contact pressure and the contact area in the lateral compartment were compared among the intact ($n = 30$), group M ($n = 10$), group P ($n = 10$), and group R ($n = 10$). The in situ force carried by the LM was calculated under the four meniscal conditions (intact, group M, group P, and group R) as the difference of the acquired force/moment vector between before (F_i and F_{rt}) and after (F_i' and F_{rt}') the removal of LM based on the principle of superposition [16, 18]. The in situ force carried by the LM under 300 N of axial compressive load was also compared among the four groups. The data at the third cycle were employed for all the assessments.

Statistical analysis

All statistical analyses were performed using the JMP software (JMP Pro version 13.1.0; SAS Institute, Cary, NC). Power analysis (power, 0.8; α, 0.05; estimated detectable difference, 167.2 for the peak contact pressure, 86.9 for the contact area, and 24.8 for the in situ force carried by the LM; estimated standard deviation, 80.8 for the peak contact pressure, 41.3 for the contact area; and 12.0 for the in situ force carried by the LM) indicated a sample size requirement of ten subjects in each group for valid comparisons. The null hypothesis of normal distribution of the acquired data was tested and denied with the Shapiro–Wilk test. Therefore, the Kruskal–Wallis test for one-way factorial analysis of variance by ranks and the Steel–Dwass test for post-hoc multiple comparison were used to compare non-parametric variables among the four groups; a p value < 0.05 were considered statistically significant.

Results

Peak contact pressure and contact area in the lateral compartment

The peak contact pressure was significantly higher and the contact area was significantly lower after creating the LM complete radial tear as compared to that in the intact state at all the flexion angles ($p < 0.01$). At 90° of flexion, the peak contact pressure and the contact area in group R were higher and lower, respectively, as compared to those in group M ($p < 0.05$). At 120° of flexion, group R represented the highest peak contact pressure and the lowest contact area, followed by group P and group M ($p < 0.05$) (Fig. 4).

In the intact knees, the tibiofemoral contact pressure was constantly well distributed in the lateral compartment. On the other hand, the contact pressure was concentrated at the central area in the knees after creating the LM complete radial tear. In addition, the concentrated part of the contact pressure seemed to have shifted more posteriorly in group R as compared to that in both groups M and P at 120° of flexion (Fig. 5).

In situ force carried by the LM

The in situ force carried by the intact LM under 300 N of axial compressive load ranged from 76 to 123 N. The in situ force carried by the LM was significantly decreased by 40–88% after creating the LM complete radial tear as compared to that in the intact state at all the flexion angles ($p < 0.01$). At 90° of flexion, the in situ force carried by the LM in group R was lower as compared to that in both groups
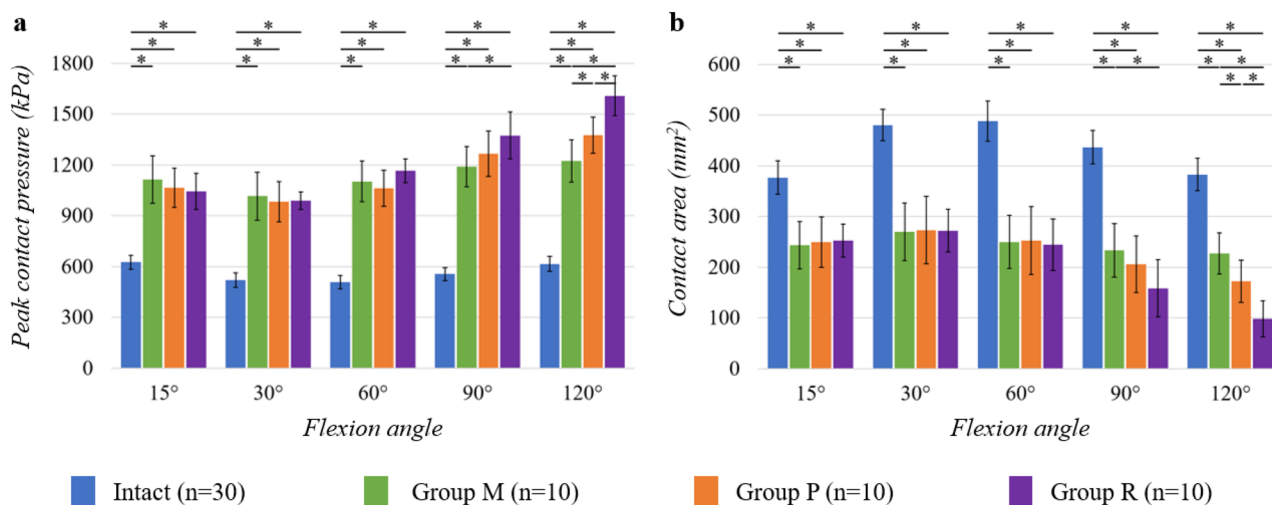
Fig. 4 Peak contact pressure (**a**) and contact area (**b**) in the lateral compartment. *Statistically significant difference ($p < 0.05$)

Fig. 5 Representative contact pressure maps in the lateral compartment for each group. The data were obtained from the electronic pressure film sensor (K-Scan system model 4011; Tekscan, MA, USA)
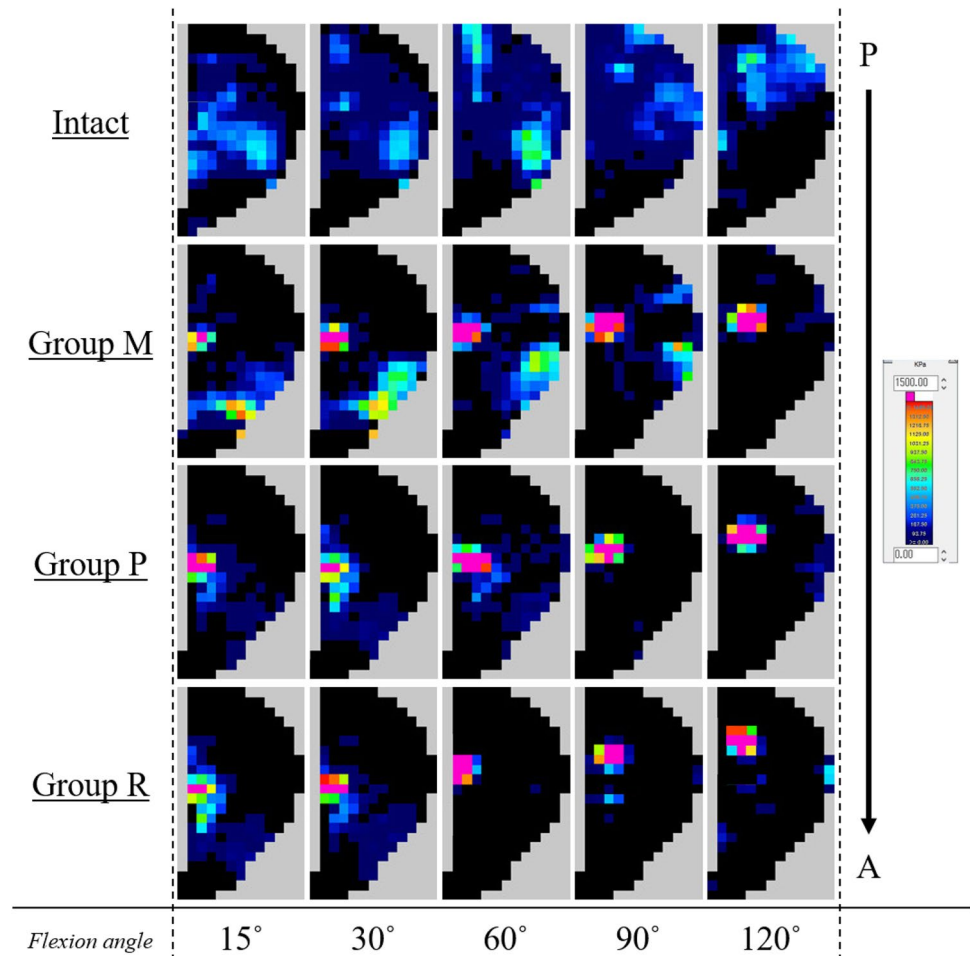
M and P ($p < 0.05$). At 120° of flexion, group R represented the lowest in situ force, followed by group P and group M ($p < 0.05$) (Table 1).

Discussion

The principal finding of this study was that the detrimental effect of the LM complete radial tear on the load distribution and transmission functions was greater as the tear site was closer to the LM posterior root in the deep-flexed position.

Table 1 The in situ force carried by the LM under 300 N of axial compressive load

Flexion angle	15°	30°	60°	90°	120°
Intact ($n = 30$)	123.2 ± 25.4	114.1 ± 24.4	106.0 ± 26.6	96.8 ± 28.5	75.6 ± 23.0
Group M ($n = 10$)	70.5 ± 11.1* (−42.8)	56.6 ± 14.9* (−50.4)	45.7 ± 17.7* (−56.9)	41.0 ± 14.6* (−57.6)	36.0 ± 11.0* (−52.4)
Group P ($n = 10$)	73.3 ± 13.2* (−40.5)	60.2 ± 10.5* (−47.2)	42.9 ± 10.3* (−59.6)	32.8 ± 8.7* (−66.1)	23.9 ± 9.1*,† (−68.3)
Group R ($n = 10$)	73.5 ± 12.5* (−40.3)	60.5 ± 15.4* (−47.0)	34.8 ± 16.2* (−67.2)	17.4 ± 7.3*,‡ (−82.0)	9.0 ± 7.1*,‡ (−88.1)

Mean ± standard deviation (N), (): percent decrease as compared to the value in the intact state (%)

LM lateral meniscus

*Significantly lower as compared to the value in the intact state ($p < 0.01$)

†Significantly lower as compared to the value in the group M ($p < 0.05$)

‡Significantly lower as compared to the value in both the groups M and P ($p < 0.05$)

The meniscus has a high tensile modulus in a circumferential direction close to that of the major knee ligaments [26] as it is primarily composed of dense circumferential collagen fibers [32]. In addition, the meniscus is also relatively stiff in a radial direction [26] because the circumferential fibers are organized by radial tie-fiber sheets as fascicles [2, 3]. Thus, the 3D configuration of the meniscus is substantially maintained under a compressive load onto the tibiofemoral joint, contributing to the load distribution [34, 40]. Moreover, the ultrastructure of the meniscal surface is analogous to that of the articular cartilage surface; this ensures that an external compressive load is efficiently transferred into an internal circumferential tensile load [4]. The meniscus transmits the tensile load through the well-organized circumferential collagen fascicles directly attached to the bones via the meniscal roots [3, 35, 38]. Complete radial tear of the meniscus absolutely disrupts the integrity of the circumferential collagen hoop structure, which is essential for the load distribution and transmission functions. Therefore, this study demonstrated that the LM complete radial tear, regardless of the tear site, drastically deteriorated the load distribution and transmission functions in accordance with the results of previous reports [28, 37].

The load distribution and transmission functions of the meniscus are also attributable to the firm attachments (meniscal roots) at the joint center. As far as the circumferential collagen fibers are anchored to the bones via the meniscal roots, the internal tensile load can be generated inside the collagen fibers. Accordingly, even when complete radial tear of the meniscus has occurred to the mid-substance, the meniscal portion being still stabilized by the roots can resist the extrusion and develop the biomechanical function [35]. Besides, Walker et al. [39] reported that a compressive load onto the tibiofemoral joint was applied mainly to the anterior portion of the meniscus in the extended position and to the posterior portion in the deep-flexed position. Therefore, in this study, the detrimental effect of the LM complete radial tear was not different among the three different tear sites in the extended position because the anterior portion of the LM remained intact in all the three groups. In contrast, in the deep-flexed position, the deterioration of the load distribution and transmission functions was greater as the tear site was closer to the posterior root due to the decrease of the meniscal portion being continued to the posterior root (Fig. 6). Actually, complete disruption of the medial meniscus posterior root [1] or the LM posterior root/
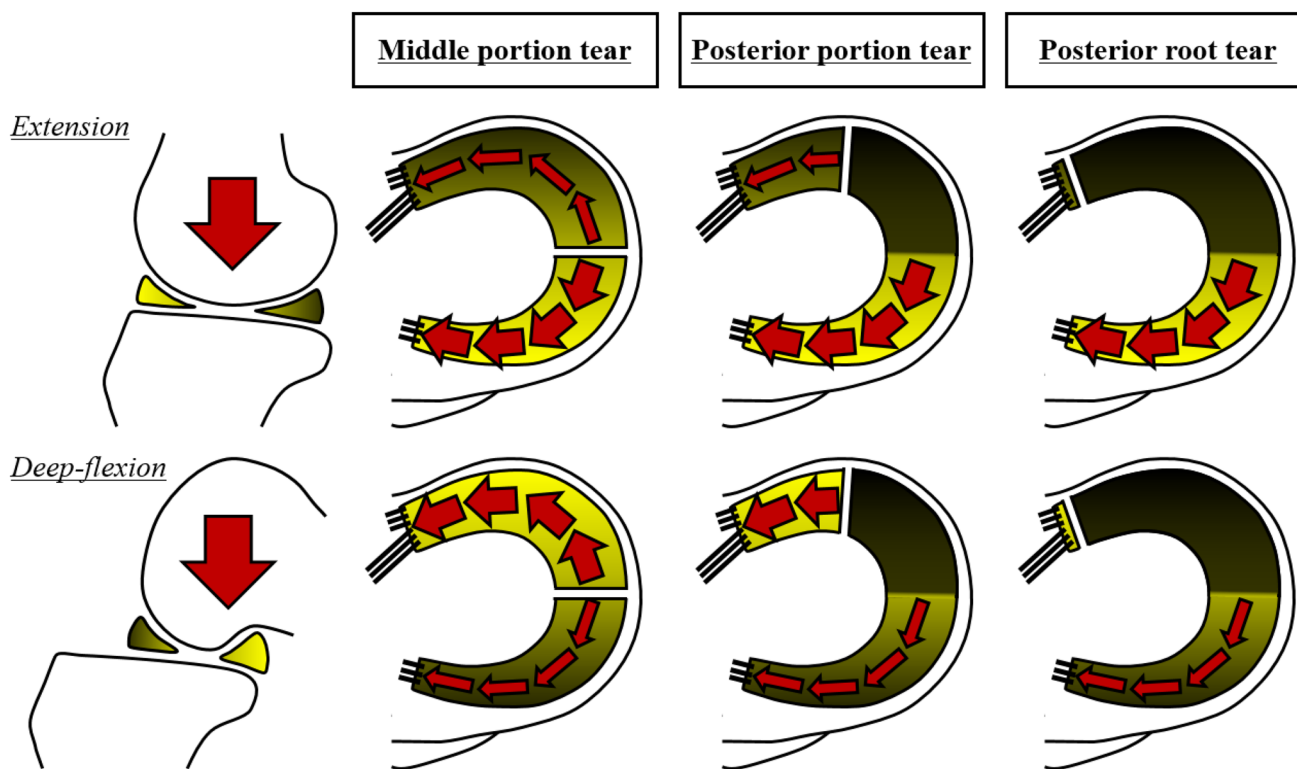
Fig. 6 Differences of the load distribution and transmission through the LM among the three different tear sites. A compressive load onto the tibiofemoral joint is applied mainly to the anterior portion of the meniscus in the extended position and the posterior portion in the deep-flexed position. The meniscal portion being still anchored to the bones by the meniscal roots can develop the load distribution and transmission functions against an external compressive load. The detrimental effect of the LM complete radial tear on the load distribution and transmission functions was greater as the tear site was closer to the posterior root in the deep-flexed position. *LM* lateral meniscus

meniscofemoral ligament [19] is associated with comparable deterioration of the load distribution function as observed after the corresponding total meniscectomy in the deep-flexed position.

Clinically, complete radial tears of the meniscus, especially at the posterior root, have increasingly recognized as a cause of development of knee osteoarthritis [6, 23, 24]. This study also demonstrated that the peak contact pressure in the lateral compartment was almost doubled and the in situ force carried by the LM was reduced by approximately half after cleating the LM complete radial tear as compared to the values in the intact state. However, radial tears of the meniscus, including the posterior root tears, have historically been treated with partial or total meniscectomy to achieve short-term benefit such as pain relief or alleviation of catching symptoms [30]. Biomechanical analyses have demonstrated that both inside-out and all-inside repairs to complete radial tears of the meniscus [28, 43], as well as in situ pull-out re-fixation to the complete posterior root tears [25, 31], improve the involved tibiofemoral contact mechanics to a level comparable to the intact state. Moreover, satisfactory clinical outcomes are achievable after those meniscus repairs during a short-term follow-up, and the progression of knee osteoarthritis seems to be prevented [13, 42]. Therefore, complete radial tears of the meniscus, especially the posterior root tears, should be repaired to restore the load distribution and transmission functions and prevent the progression of knee osteoarthritis.

This study had several limitations. First, a porcine knee model was utilized. As the porcine knee has steeper posterior tibial slope and stiffer meniscus compared to the human knee joint, the results in this study; the significant differences of the detrimental effect following the LM complete radial tear depending on the tear site in the deep-flexed position; may not be applicable to the human knee joint. Second, the in situ force carried by the LM was possibly overestimated because there might be interactive forces between the LM and the surrounding capsule. The calculated in situ force might not accurately reflect the actual force transmitted though the LM because of incomplete following of the assumptions required for the principle of superposition [21]. Third, the horizontal capsular incision to insert the pressure film sensor may have influenced the tibiofemoral contact mechanics or the in situ force carried by the LM. The knee joint kinematics might be altered by creating the capsular incision; however, the incision length was minimized and most of the capsule was carefully left intact. Finally, unlike the previous reports [19, 25, 33], the detrimental effect of complete radial tear was not compared with that of partial or total meniscectomy and the effect of meniscal repair was also not evaluated. Further investigations regarding these clinically relevant conditions need to be performed. However, the finding of this study would be useful to estimate the adverse effect of radial tear of the meniscus depending on the tear site or decide the appropriate treatment strategies in clinical practice.

Conclusions

The LM complete radial tear at different tear sites caused different detrimental effects on the load distribution and transmission functions and the effect was greatest in the posterior root tear, followed by the posterior portion tear and the middle portion tear in the deep-flexed position. As complete radial tears of the meniscus, especially at the posterior root, have a harmful impact on the load distribution and transmission functions, these tears should be repaired to restore the biomechanical function and prevent the progression of knee osteoarthritis.

Compliance with the ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The institutional review board of the Osaka University Hospital reviewed the study protocol and determined that this study did not require oversight.

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