The effect of a centralization procedure for extruded lateral meniscus on load distribution in porcine knee joints at different flexion angles

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Abstract

Background: Meniscal extrusion results in loss of the ability to resist hoop strain and biomechanical overload on the joint articular surface. A centralization technique has been developed to overcome these problems. In this study, we analyzed the biomechanics of the extruded and centralized lateral meniscus (LM) in porcine knee joints at different flexion angles.

Methods: Porcine knee joints (n=8) were set in the universal tester and each knee was tested under the following states: 1) intact; 2) extrusion—meniscal extrusion was created by resecting the posterior root of the LM and posterior synovial capsule; and 3) centralization—centralization was performed by two anchors inserted in the lateral tibial plateau. Deviation distance of the meniscus, contact pressure, and contact area in the anterior LM, middle LM, posterior LM, and the contact pressure of the tibial cartilage were evaluated with an axial compressive force of 200 N at knee flexion angles of 30°, 45°, 60°, and 90°.

Results: The deviation distance of LM significantly increased in extrusion but was restored to the intact status after centralization at all angles. Both the contact pressure and area significantly decreased in extrusion and were restored after centralization close to the intact status in the anterior and middle LM; in the posterior LM, however, decreased contact pressure and area were not restored after centralization. The contact pressure of the tibial cartilage increased significantly in extrusion but decreased close to the intact status after centralization.

Conclusions: This centralization procedure could reduce extrusion of the LM and restore the load-distributing function of the anterior-middle LM. However, the procedure itself could not restore hoop function in cases where the defect lies in the posterior LM.

Background

Meniscal extrusion induces dysfunction of load distribution, one of the most important functions of the meniscus [1–3]. It is caused by the disruption of the meniscus hoop function and is often observed after meniscectomy [1, 4], meniscus root tears [5], and with aging [6–8]. Meniscal extrusion initiates osteoarthritis (OA) and accompanies its progression [9–11]. Restoring the lost function caused by meniscus extrusion can delay OA progression.

A centralization technique has been developed to reduce meniscal extrusion; the capsule attached to the meniscus is sutured to the edge of the tibial plateau using suture anchors [12]. Arthroscopic centralization of the extruded lateral meniscus (LM) improved clinical outcomes at two-year follow-up [12]. It also increased the radiographic lateral joint space width on standing at the 45° flexion view at three months; this was maintained for two years [12].

The biomechanical effects of centralization have not been fully elucidated. Recently, biomechanical analysis of the centralization procedure for extruded LM with posterior root deficiency has been reported in a porcine model. Although this study showed that the centralization procedure restored the load distribution to a value closer to that of the normal knee joint [13], the experiment was performed only at 45° of knee flexion. The purpose of the current study was, therefore, to analyze the effects of the centralization procedure in porcine knee joints at different flexion angles, in order to further clarify biomechanical properties of the centralization procedure.

Methods

Materials

Eight fresh-frozen porcine right knee joints (Tokyo Shibaura Zouki, Tokyo, Japan) were used for the experiments. Joints with cartilage or meniscus injury were excluded. The lateral compartment was used for the analysis.

Mechanical settings

After removal of muscles from around the knee joint, the tibia was cut at 3 cm distal to the tibial plateau, parallel to the joint line. The femoral cut line was set at 7 cm proximal from the distal end and cutting was performed obliquely, to couple the knee joint with the tibia at 45° of the knee flexion angle. The femur and tibia were fixed in a custom universal tester using polymethyl methacrylate. The anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and medial collateral ligament were preserved, although a lateral collateral ligament was cut to insert the sensor seat for counterforce evaluation. The angle-changing device was placed between the knee and a universal testing machine (Fig. 1A), so that the knee flexion angles could be set at 30°, 45°, 60°, and 90° (Fig. 1B).

The experimental settings were as follows: 1) Intact; 2) Extrusion—meniscal extrusion was created by resecting a 1 cm width of the posterior root of the LM, as well as a 45° of the adjacent posterior synovial capsule from the posterior root attachment site, thereby precluding anatomical repair of the posterior root (Fig. 1C); and 3) Centralization—two soft anchors (1.4 mm JuggerKnot Soft Anchors, Zimmer Biomet, Warsaw, IN, USA) were inserted into the middle part of the lateral tibial plateau (the first anchor was inserted 1 cm anterior to the popliteal hiatus, the second 1 cm anterior to the first anchor), and the extruded meniscus was reduced to its original position (Fig. 1C). The sutures were passed through the border between the meniscus and the remaining capsule attached to the meniscus; they were then stabilized to the tibia using mattress sutures. For all angles, an axial compressive force of 200 N was applied in each setting [13].

Deviation distance of the lateral meniscus

Three spherical red plastic markers (3 mm diameter) were attached: the posterior marker at the center of the tibial attachment of the PCL; the lateral marker at the lateral edge of the LM in the posterior view; and the posterolateral marker at the point where the middle line of the other two points intersects the outer edge of the meniscus in the posterior view (Fig. 2A). The markers were placed prior to the resection conducted to create the meniscus extrusion model. After application of an axial compressive force of 200N, the LM was photographed in the posterior view and the distance between the posterior marker line and the posterolateral marker line measured to evaluate the meniscal extrusion (Fig. 2A).

Contact area and force measurements

A pressure mapping sensor system (Tekscan, Inc. South Boston, MA) was used to evaluate the distribution of load-bearing force on the lateral compartment. This instrument enabled electronic scanning to measure the real-time force and contact area. The sensor was placed on the femoral side of the lateral meniscus and the load distribution recorded during application of the loading force. Wrinkling of the film over time (due to the dry environment) was minimized by adding saline mist during the experiment. The measurements included contact area, maximum contact pressure, and average contact pressure. All data were analyzed using MATLAB® (MathWorks, MA, USA).

Statistical Analysis

Statistical analysis was performed using Prism 6 software (GraphPad Inc., La Jolla, CA, USA). The Friedman one-way non-parametric test and Dunn’s test were used as post hoc tests. A P value smaller than 0.05 was considered statistically significant. All data were reported as the average value and 95% confidence intervals (CI).

Results

The distance between the two markers significantly increased after extrusion at all flexion angles (Fig. 2B, C; Supplementary Table 1). Conversely, it significantly decreased after centralization at each flexion angle. In all settings, the distance between the two markers increased with the knee flexion angle, although there were no significant differences among the distances measured for each angle (Supplementary Table 1).

For load distribution analyses, the lateral compartment was divided into the anterior LM, the middle LM, the posterior LM, and the tibial cartilage areas (Fig. 3A). For each angle, according to the representative images (Fig. 3B), the load was concentrated on the tibial cartilage after extrusion and redistributed to the anterior and middle LM after centralization.

The average contact pressure in the anterior and middle LM significantly decreased after extrusion and increased after centralization; this was true for each flexion angle except in the anterior LM at 30° and the middle LM at both 30° and 90° (Fig. 4, Supplementary Table 2). On the other hand, extrusion significantly decreased the average contact pressure in the posterior LM but centralization did not fully restore it; this was also true for each flexion angle. In the anterior LM, the average contact pressure at 45° significantly decreased at 90° in the intact setting; conversely, in the posterior LM, the average contact pressure at 30°

significantly increased at 60° and 90° in the centralization setting. In the tibial cartilage, extrusion significantly increased the average contact pressure at 45°, 60°, and 90°, whereas centralization significantly decreased it at 90°(Fig. 5, Supplementary Table 3).

The contact area significantly decreased after extrusion at each flexion angle in the anterior, middle, and posterior LM (Fig. 6, Supplementary Table 4). Contrarily, it significantly increased after centralization at each flexion angle in the anterior and middle LM, whereas centralization did not fully recover the contact area in the posterior LM. In all settings, the contact area in the anterior LM appeared to decrease with the knee flexion angle, although there were no significant differences among the areas measured for each angle (Supplementary Table 4). Also, in all settings, the contact area in the posterior LM appeared to increase with knee flexion angle, although there were no significant differences.

Discussion

In this study, the biomechanics of the extruded and centralized LM were analyzed in porcine knee joints at different flexion angles. In the anterior and middle LM, both the contact pressure and area decreased in extrusion, increasing close to the intact status after the centralization procedure. In this model, the effectiveness of centralization to restore the lost function of the meniscus has been demonstrated in the anterior and middle LM.

Although the deviation distance of the LM, which increased in extrusion, was restored to the intact status in centralization at all angles, the contact pressure and area, decreased in extrusion, were not fully restored in the posterior LM, even after centralization. This was possibly because a 1 cm width of the posterior root deficiency was left untreated. These results suggest that hoop function should also be reconstructed, if possible, in order to fully restore the load distribution function of the posterior LM. Even so, centralization decreased the contact pressure in the tibial cartilage, and this effect became more obvious as the flexion angle became larger.

A previous study reported the biomechanical effects of centralization in a similar model, but this study was performed only at 45° of knee flexion [13]. In the current study, the analyses were performed in porcine knee joints at 30°, 45°, 60°, and 90° of flexion. Although significant differences of contact area and contact pressure at different angles were not detected, the following trends were observed: Contact area and contact pressure in the anterior and middle LM reached their maxima at 30°, 45°, and 60°, while those at the posterior LM reached theirs at 90°.

The distances between the two markers increased with knee flexion angle in each setting, although no significances were found. This can be explained from the results of the current study; the load distribution moved posteriorly as the flexion angle increased. A previous magnetic resonance imaging (MRI) study also supports our results, showing that the lateral femoral condyle and LM consistently displayed a marked posterior translation [12].

To our knowledge, previous reports of biomechanical analysis for the centralization of the extruded meniscus are limited. Nakamura et al. evaluated the effects of knee biomechanics with an irreparable lateral meniscus defect using the centralization procedure in an ACL-reconstructed porcine knee; they reported that using arthroscopic centralization for the capsular support of the middle segment of the lateral meniscus improved the residual rotational laxity of the ACL-reconstructed knee accompanied with lateral meniscus dysfunction due to massive meniscal defect[14]. Daney et al., in the only other report apart from ours [13], measured meniscal extrusion and tibiofemoral contact mechanics at the medial compartment in human cadaveric knees [15]. The anatomic transtibial pull-out root repair and the anatomic transtibial pull-out root repair with centralization suture techniques best restored contact mechanics of the knee and meniscal extrusion when compared with root tear and nonanatomic repair states. However, the degree of extrusion increased as the knee was flexed to 90°. Their study differs from ours in terms of using human knees, examining the inner compartment, and performing the centralization with pullout techniques; both studies, however, showed the effectiveness of centralization.

In this porcine biomechanical experiment, the limitation causing most concern is that we could not completely mimic the physiological flexion movements of porcine knees in our mechanical setting. We also cut the lateral collateral ligament to insert a sensor from the lateral side, which might have affected the results. Furthermore, we inserted a pressure mapping sensor between the femoral cartilage and the LM, rather than between the LM and the tibial cartilage, as this would have impaired the load-distribution measurements for the entire tibial cartilage. However, the knee joint was stabilized and the loading force applied in the vertical direction; the comparison of evaluated values under intact, extrusion, and centralization settings at each flexion angle will therefore provide important information.

Conclusions

The centralization procedure could reduce extrusion of the LM and restore the load distribution function of the anterior-middle LM in a porcine model. However, the procedure itself could not restore hoop function in cases with a defect of the posterior LM.

List Of Abbreviations

OA: Osteoarthritis

LM: Lateral meniscus

ACL: Anterior cruciate ligament

PCL: Posterior cruciate ligament

CI: Confidence intervals

MRI: Magnetic resonance imaging

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Competing interests

We have no conflict of interest in this study.

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Authors’ contributions

RK: Data collection and draft writing. HKo: Conception, manuscript editing, and critical advice. NO: Study design, data analysis, and critical advice, and final approval of the article. JM: Mechanical setting and interpretation of data. YK: Interpretation of data. MM: Data collection. HKa: Data interpretation. IS: Conception and design, manuscript writing.

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Figures

Fig. 1

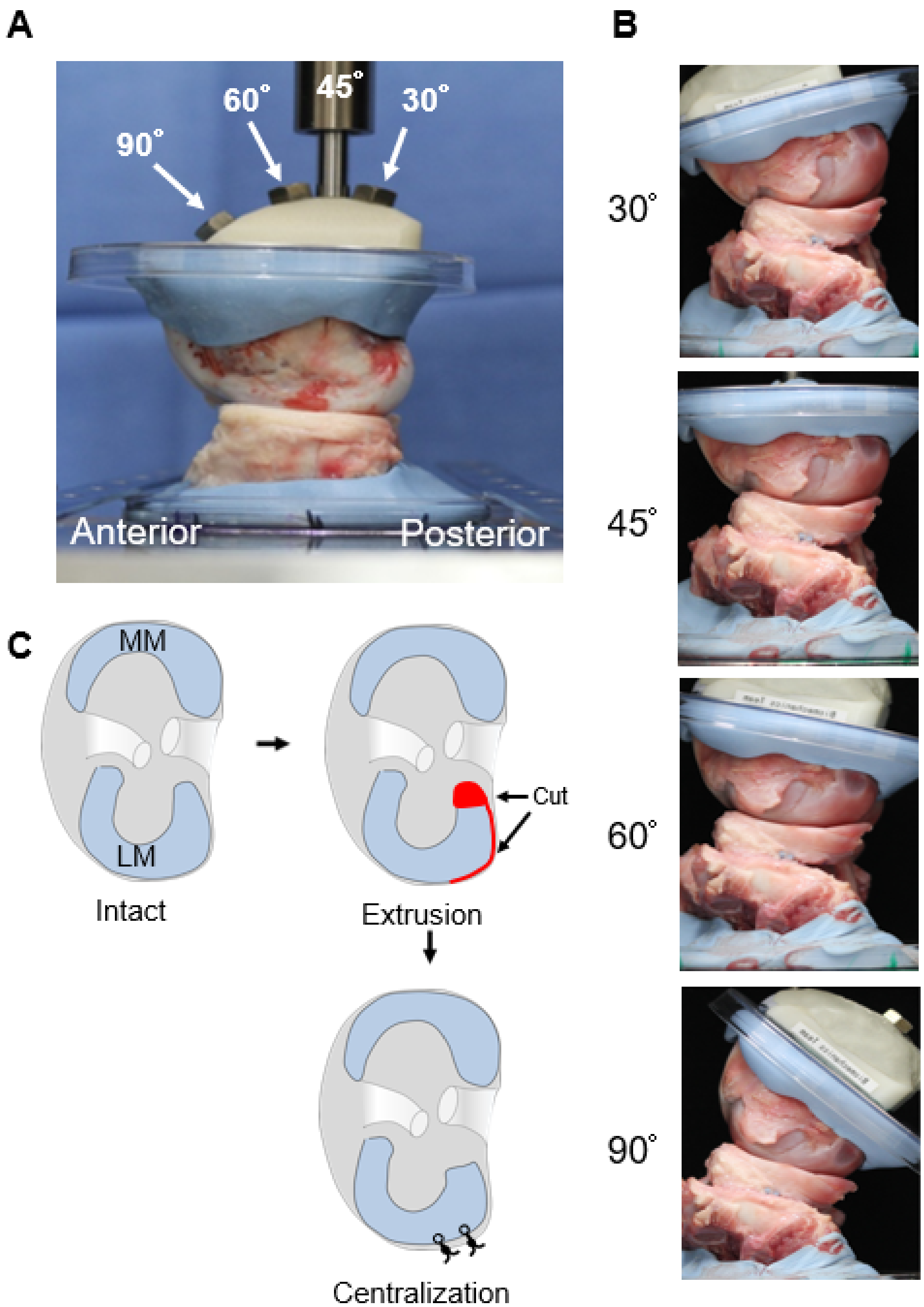

Figure 1

Experimental settings. A, Angle changing device set at 45°. B, Intact porcine knees viewed laterally, set at 30°, 45°, 60°,and 90° flexion. C, Scheme for extrusion and centralization. LM, lateral meniscus; MM, medial meniscus.

Fig. 2

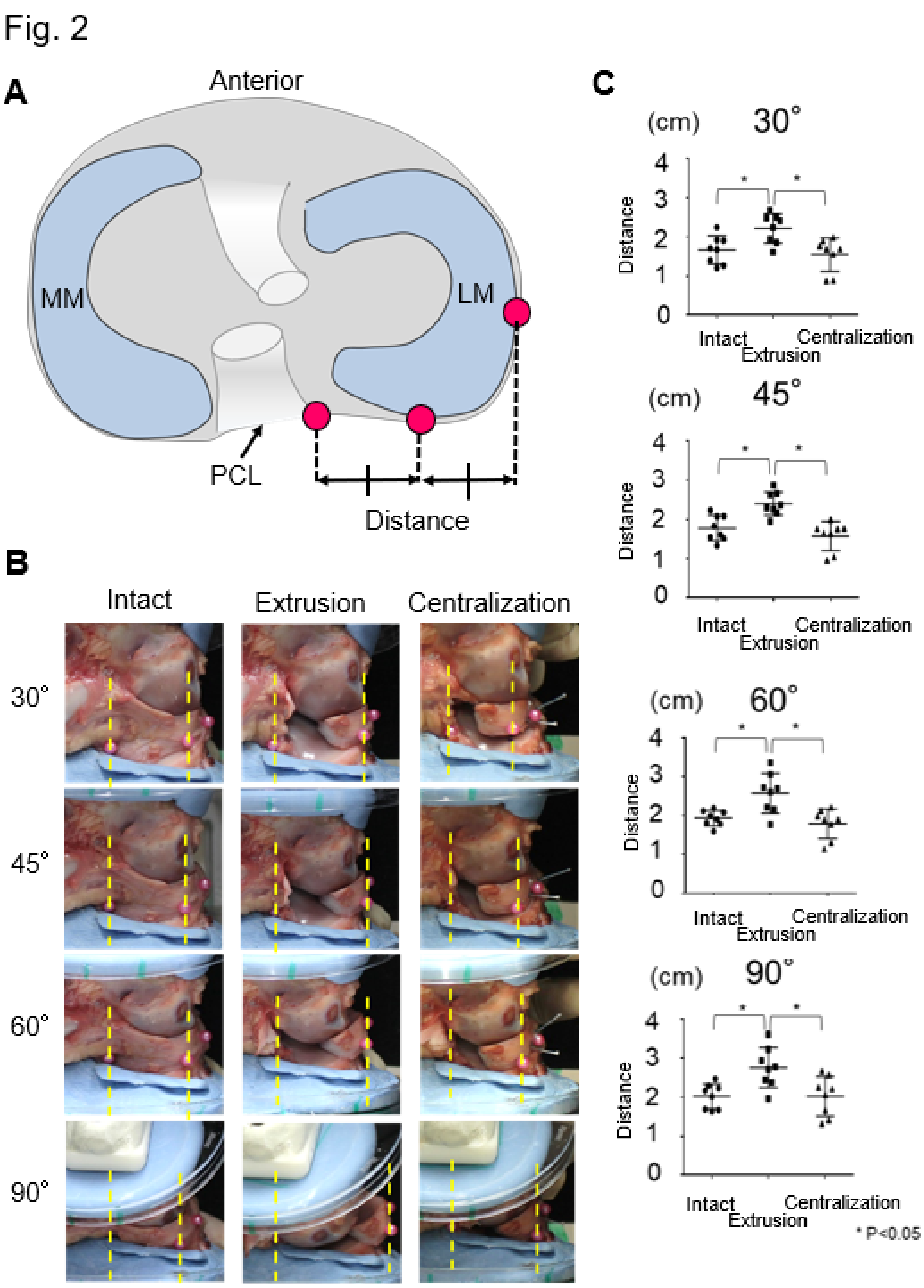

Figure 2

LM deviation distance with an axial compressive force of 200 N. A, Marker locations. PCL, posterior cruciate ligament. B, Knee viewed posteriorly. C, Quantitative analysis of inter-line distances. Each bar represents the average with 95% CI (n=8). (*P<0.05)

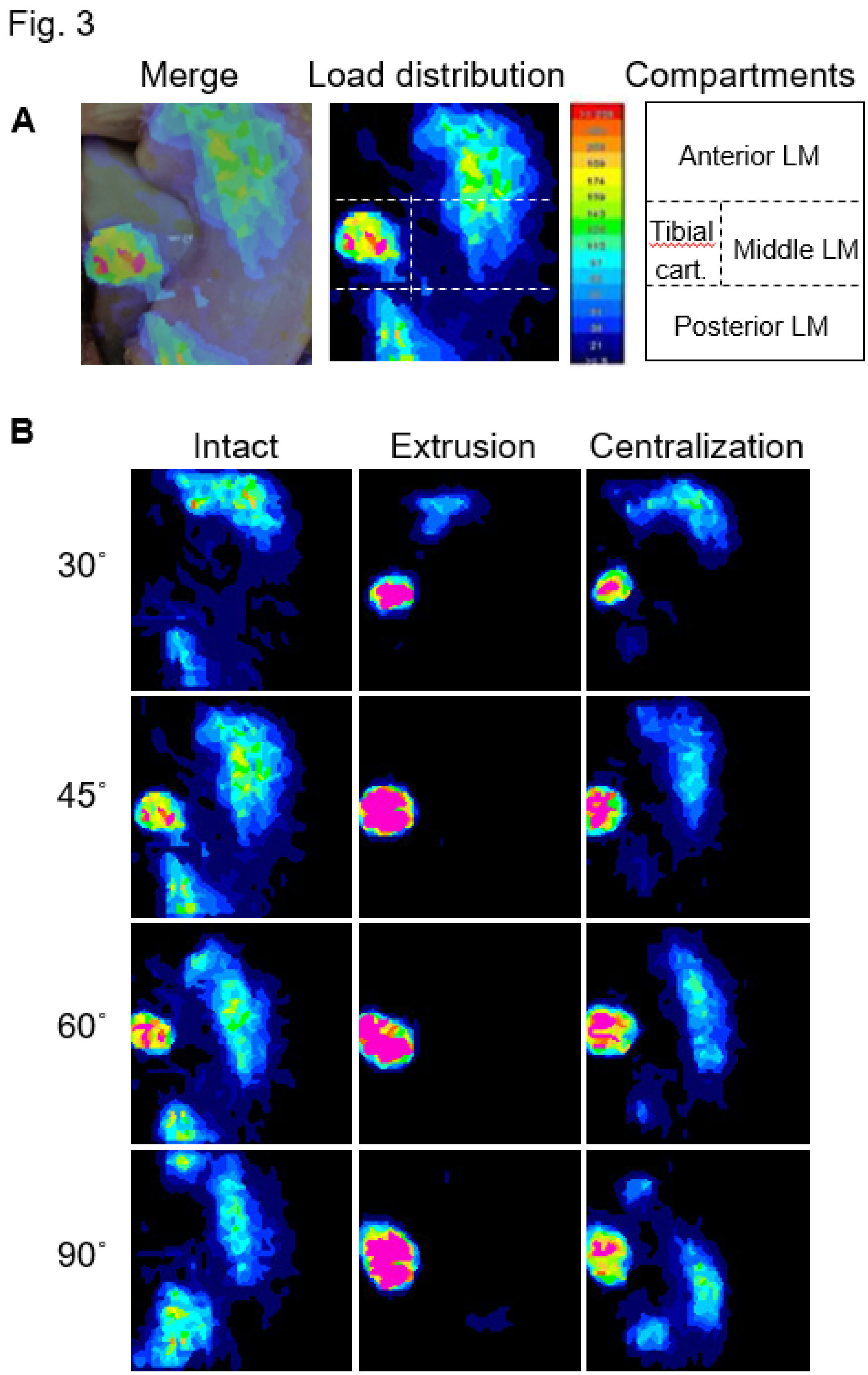

Figure 3

Load distribution analyzed with a pressure mapping sensor system. A, Tibial cartilage with LM; superposed image of load distribution and macro picture, lateral tibial surface divided into four compartments. B, Representative load distribution, axial compressive force 200 N.

Fig.4

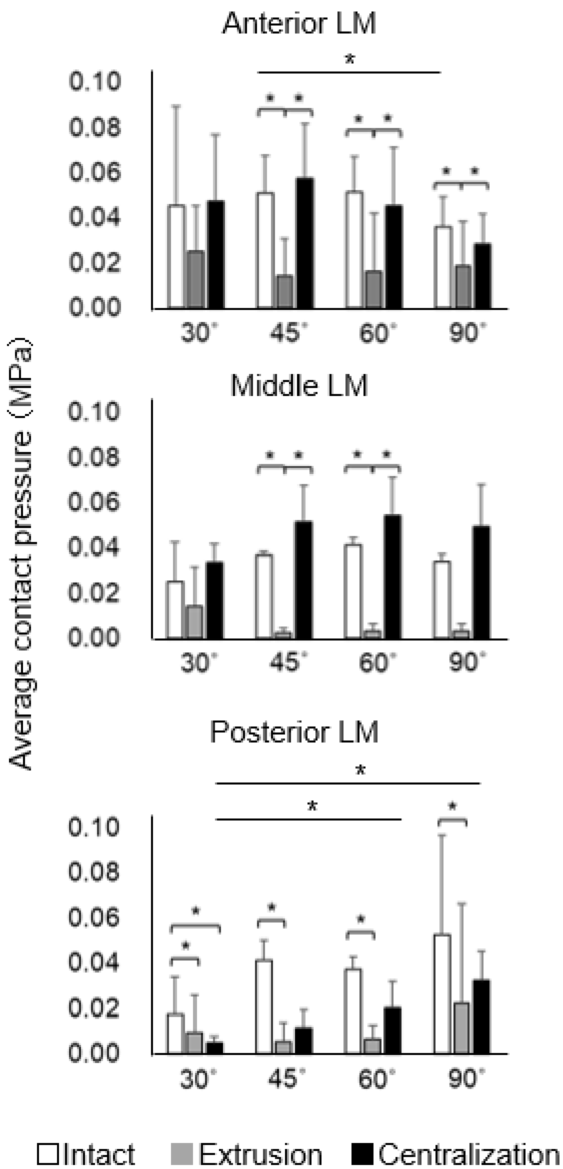

Figure 4

Quantitative analyses of average contact pressure on the anterior, middle, and posterior LM. The average values with 95% CI are shown (n=8). (*P<0.05)

Fig. 5

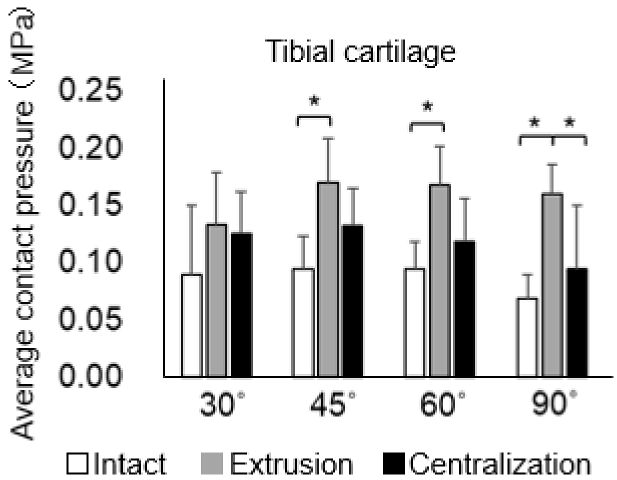

Figure 5

Quantitative analyses of average contact pressure on the lateral tibial cartilage. The average values with 95% CI are shown (n=8). (*P<0.05)

Fig. 6

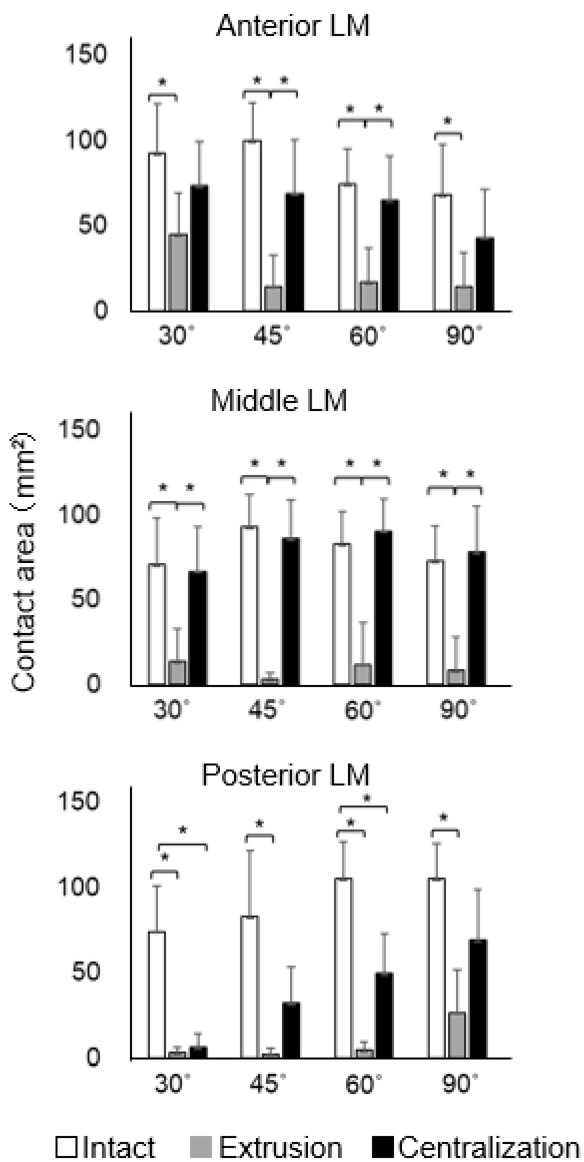

Figure 6

Quantitative analyses of contact area in the anterior, middle, and posterior LM. The average values with 95% CI are shown (n=8). (*P<0.05)

Supplementary Files

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- KubotaBMCMSDSupTable20191118.docx