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Medial meniscus grafting restores normal tibiofemoral contact pressures

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Abstract

Background Tissue excision in the setting of a meniscal tear has been shown to dramatically increase peak contact stresses in the affected tibiofemoral joint compartment, leading to the development of degenerative changes and osteoarthritis.

Purpose/hypothesis The current in vitro study utilized a porcine model to evaluate the effectiveness of segmental medial meniscal grafting following partial meniscectomy. The study hypothesis was that the procedure would normalize medial tibofemoral joint compartment pressure magnitudes, areas, and locations relative to an intact meniscus.

Study design Controlled laboratory study.

Methods Using pressure film, medial tibiofemoral joint compartment peak, and mean pressure magnitudes, peak pressure location and peak pressure area were determined using 12 potted, fresh frozen, porcine knee specimens. Data were collected at three different knee flexion angles (90°, 45°, and 0°) for three conditions: intact medial meniscus, following resection of the central third of the medial meniscus, and following segmental medial meniscal grafting. For each condition, the potted femur was positioned horizontally in a bench vise clamp, while a 20 pound (88.96 N) axial compression force was manually applied for a 60 s duration by the primary investigator through the base of the potted tibia using a digital force gauge.

Results Loss of the central 1/3 of the medial meniscus resulted in significant increases in the mean and peak pressures of the medial tibiofemoral joint compartment and decreased peak pressure area. Segmental meniscal grafting of the central third defect closely recreated the contact pressures and loading areas of the native, intact medial meniscus.

Conclusion From a static, time zero biomechanical perspective, segmental medial meniscus grafting of a partially meniscectomized knee restored mean pressure, peak pressure, and mean peak contact pressure areas of the medial tibiofemoral joint compartment back to levels observed in the intact medial meniscus at different knee flexion angles. In-vivo analysis under dynamic conditions is necessary to verify the healing efficacy and ability of the healed segmental medial meniscal allograft to provide long-term knee joint homeostasis when confronted with dynamic shear, rotatory, and combined, higher magnitude physiologic loading forces.

Keywords Meniscectomy · Meniscus allograft · Biomechanics

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Introduction

Weight-bearing load distribution by intact menisci is essential to normal knee kinematics and protection of tibiofemoral joint articular cartilage [1–4]. Excision of tissue in the setting of a meniscal tear has been shown to dramatically increase peak articular cartilage contact stresses in the affected tibiofemoral joint compartment, leading to degenerative changes and osteoarthritis [5, 6]. Since the late 1940s when Fairbank [7] described the radiographic changes that developed following meniscus excision, numerous studies have documented the poor clinical outcomes that occur subsequent to meniscectomy [8, 9].

Although the current approaches to meniscal tear surgery have focused on preservation and repair rather than resection whenever possible, certain tear types remain problematic [10, 11]. Radial tears extending to the meniscocapsular junction disrupts the circumferential collagen fibers. This prevents the normal resistance to the hoop stresses that occur during weight-bearing activities [11]. While a number of techniques have been developed to repair radial meniscus tears, healing rates and clinical outcomes are highly variable [6, 12, 13]. When a radial tear is deemed irreparable, partial meniscectomy has been the mainstay of surgical treatment, aiming to preserve meniscal tissue adjacent to the tear site.

While partial meniscectomy in the setting of an extensive radial meniscus tear often provides short-term symptomatic relief, the long-term impact on the articular cartilage in the affected tibiofemoral joint compartment remains a major concern. In a cadaveric study evaluating the effect of serial medial meniscectomy on tibiofemoral contact mechanics, Lee et al. [14] reported that despite the presence of residual meniscal tissue, when partial meniscectomy was performed for a radial tear, weight-bearing knee mechanics were equivalent to that observed following total meniscectomy. To prevent partial meniscectomy-induced knee osteoarthritis, greater attention needs to be placed on restoring normal biomechanical forces following radial tear meniscal repair.

Basic science and biomechanical support for meniscal allograft transplantation began appearing in the orthopaedic surgery literature in the early 1990s [8, 15]. With promising biomechanical data, authors investigated the utility of meniscal transplantation in animal models [3].

While the need for a segmental meniscal graft in the setting of a previous partial meniscectomy is well-established, how segmental meniscus grafting might benefit patients who have undergone partial meniscectomy for a significant radial tear is currently unknown. Standard meniscal allograft transplantation for this patient population would require removal of a considerable amount of normal meniscal tissue, which is undesirable. The potential for implanting a segmental meniscal allograft in this setting is logical and desirable provided that the sutured allograft can heal both to the peripheral capsuloligamentous tissue and also to the posterior and anterior remnant junctions, ultimately incorporating the native meniscus as healing progresses. The purpose of this in vitro study using a porcine knee model was to evaluate the effectiveness of segmental medial meniscal grafting following partial meniscectomy with respect to its ability to restore normal tibiofemoral contact pressures compared to partial meniscectomy. We hypothesized that segmental medial meniscal grafting would normalize medial compartment pressure magnitudes, areas, and locations to the levels and locations observed in an intact, normal meniscus.

Methods

Twelve, whole, fresh frozen porcine knees were carefully dissected of soft tissue without compromising anterior cruciate, posterior cruciate, or lateral collateral ligament function and without having to perform an osteotomy. This enabled sufficient access to the medial tibiofemoral joint compartment for all study procedures without adversely influencing knee kinematics (Fig. 1). Precise dissection of the anteromedial menisco-tibial coronary ligaments was performed to allow for the passage of a high-density polyethylene template beneath the medial meniscus, which facilitated the collection of medial tibiofemoral joint compartmental pressure data (Fig. 2). This 5 cm × 2.5 cm template with a slight proximal taper ensured sufficient clearance for pressure film insertion.

Pressure data were collected using Fuji Prescale Ultra Low Film (Fuji, Sensor Products, Madison, NJ) and pressure magnitude was determined using the standardized Fuji pressure comparison chart. Following dissection, the femur and tibia of each knee specimen were potted in a 3-inch

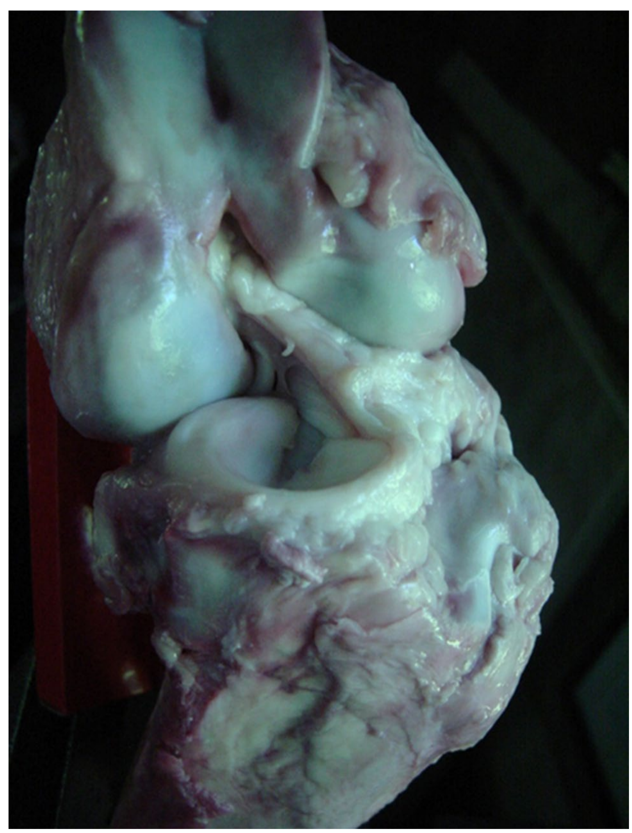

Fig. 1 Whole porcine knees were carefully dissected without compromising anterior cruciate, posterior cruciate, and lateral collateral ligament function. This enabled sufficient access to the medial tibiofemoral compartment for all study procedures, without adversely influencing knee biomechanics

Fig. 2 Dissection of the anteromedial menisco-tibial "coronary" ligaments enabled passage of a high-density polyethylene template beneath the medial meniscus

diameter PVC tube using a fiberglass filler compound. Each potted femur was then positioned horizontally in a bench vise clamp. After knee flexion angle confirmation using a handheld goniometer, a 20 pound (88.96 N) axial compression force was manually applied through the base of the potted tibia by the primary investigator at a loading rate of approximately 22.2 N/s using a digital force gauge (FGV-100XY, Shimpo Force Gauge). The axial compressive load was maintained for 60 s at each test position. Axial compression force loading data (1000 Hz) were collected and stored (TorriemonUSB software). Data were collected with the knee positioned at 90° flexion, 45° flexion, and 0° flexion as confirmed using a handheld goniometer. To control for possible order effects, the testing order was alternated, such that the initial test angle changed from 90° to 0° knee flexion for every two specimens.

Three conditions were evaluated for each of the 12 knees: (a) intact medial meniscus, which served as the control; (b) partial medial meniscectomy in which the central 1/3 of the medial meniscus was removed; and (c) segmental medial meniscal grafting, in which the previously removed meniscal tissue served as the graft that was used to repair the defect. Thus, each knee was successively taken through axial compression load testing and data collection at 0° knee flexion, 45° knee flexion, and 90° knee flexion for each test condition. This resulted in nine data points for each knee (3 meniscus conditions × 3 flexion angles). Following completion of each axial compression loading cycle, the pressure film was carefully removed and assessed for mean and peak pressure magnitude, peak pressure location, and peak pressure area. Peak pressure area was calculated by a summation of peak pressure rectangular region process from each film, magnified by a factor of 10 for ease of measurement using an electronic digital caliper (#47257, Cen Tech, Harbor Freight Tools, CA). Calculated area values were then divided by 10 for true area determination [16]. The specimens were carefully examined after each test condition to ensure that meniscus and surrounding tissue integrity was maintained. In addition, room temperature and relative humidity were recorded prior to each data collection (70–73 °F, 50–60% relative humidity) to maintain uniformity.

Meniscectomy procedure

The central third of the medial meniscus was resected using a #11 scalpel simulating the typical partial meniscectomy performed for a radial tear extending 90% to the meniscocapsular junction (Fig. 3). The meniscal tissue was excised as a single unit to allow for later grafting.

Meniscus grafting procedure

The meniscus grafting procedure was performed using a double-loaded 2.0 Ethibond suture meniscal repair system (ConMed Linvatec, Largo, FL) and a standard meniscus repair technique. The resected medial meniscal tissue obtained from the simulated partial meniscectomy test condition was used as a segmental graft. This graft was secured into the defect using two vertical mattress sutures at the periphery and one horizontal mattress suture at the anterior and posterior junctions. Four sutures were used to repair the segmental defect, which resulted in a robust repair construct (Fig. 3).

Statistical analysis

Kolmogorov–Smirnov testing revealed that group data for mean and peak pressure did not display a normal distribution. Although area measurements did display a normal distribution, non-parametric statistical analysis was used for all group comparisons. A series of Kruskal–Wallis tests were used to compare groups by condition (intact, partial meniscectomy, and meniscal grafting) and knee flexion angle (90°, 45°, and 0°). Post-hoc Mann–Whitney *U* tests were then used to delineate the exact location of statistically significant group differences. An alpha level of $p < 0.05$ was selected to indicate statistical significance. Statistical analysis was performed using SPSS, v. 21.0 software (IBM, Armonk, NY, USA).

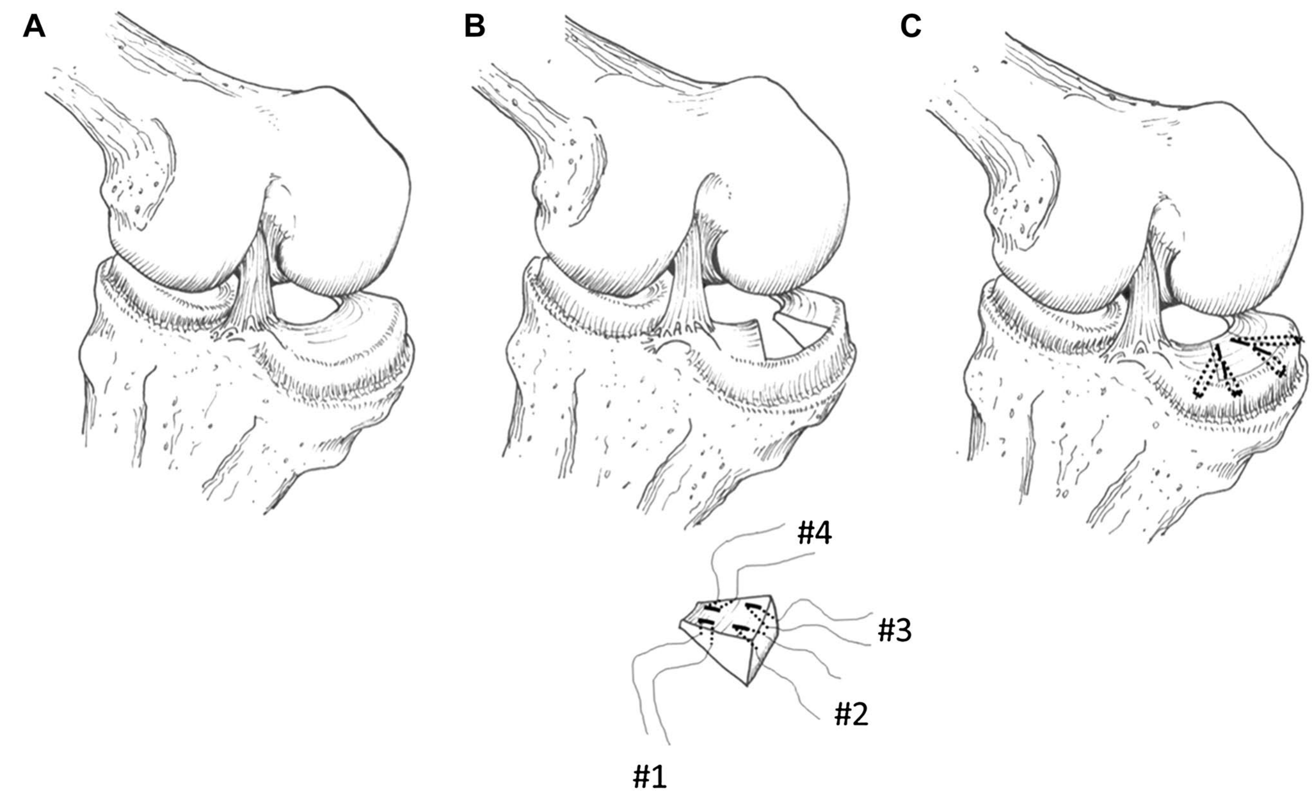

Fig. 3 Intact medial meniscus (**a**); after removal of the central 1/3rd of the medial meniscus leaving the knee joint capsule intact (**b**) (preserving the resected portion for subsequent segmental medial meniscus grafting with numbered suture order); and following segmental medial meniscus grafting (**c**)

Results

The location of peak and mean medial tibiofemoral joint compartment knee pressure was consistently in the posterior third of the pressure film at 90° knee flexion, in the middle third at 45° knee flexion, and in the anterior third at 0° knee flexion for the intact medial meniscus condition. Furthermore, partial medial meniscectomy and subsequent medial meniscus segmental grafting did not change these pressure locations. Pooled results for all three testing conditions showed that knee flexion angle changes did not result in statistically significant differences for mean pressure, peak pressure or peak pressure area values (Table 1).

A meniscectomy involving the central 1/3 of the medial meniscus resulted in significant ($p < 0.05$) increases in the pooled mean and peak pressure of the medial tibiofemoral joint compartment in knees at 0°, 45°, and 90° knee flexion compared to knees with an intact meniscus, or following segmental medial meniscus grafting (Fig. 4; Table 2). The loss of the central 1/3 of the medial meniscus also resulted in significant ($p < 0.05$) decreases in the peak pressure area, which was restored to intact meniscus levels by the segmental grafting procedure (Table 2). There were no repair failures observed in this study.

Discussion

The growing understanding of the importance of normal meniscus function has made preservation of paramount importance [1, 8, 9, 17]. Similar to other biomechanical studies, we have shown that segmental meniscal loss from a partial meniscectomy creates altered tibiofemoral compartmental pressures [14, 18]. Of greater importance is that we have shown that

Table 1 Knee flexion angle condition results (mean, 95% confidence intervals) for mean pressure, peak pressure, and peak pressure area

Variable	Angle 1 (90°)	Angle 2 (45°)	Angle 3 (0°)	*p*
Mean pressure (PSI)	56.2 (53.4–59.1)	54.7 (52.4–56.9)	55.3 (52.4–58.2)	0.65
Peak pressure (PSI)	74.0 (69.3–78.7)	77.4 (72.8–82.0)	75.4 (71.2–79.5)	0.79
Peak pressure area (mm^2)	26.6 (22.7–30.5)	22.6 (18.9–26.2)	25.8 (21.8–29.8)	0.34

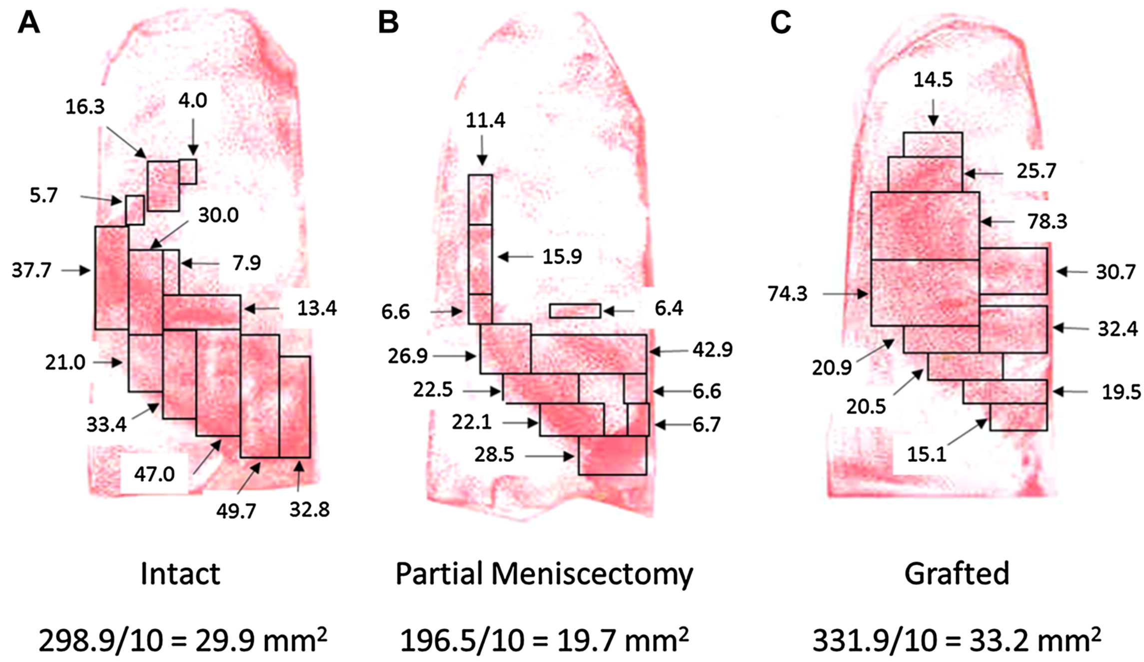

Fig. 4 Representative medial tibiofemoral joint pressure film sample under intact (**a**), 1/3rd central medial meniscectomy (**b**) and segmentally grafted conditions (**c**) at 0° knee flexion. The partial medial meniscectomy condition displayed *a* > 40% reduction in peak pressure surface area

Table 2 Group condition results (mean, 95% confidence intervals) for mean pressure, peak pressure, and peak pressure area

Variable	Group 1 (intact)	Group 2 (partial meniscectomy)	Group 3 (segmental meniscus graft)	*P*
Mean pressure (PSI)	53.9 (51.4–56.6)	60.1 (56.9–62.2)[a]	52.6 (50.4–54.8)	Overall < 0.0001; post-hoc Mann Whitney "*U*" test Group 1 (*P* = 0.004), Group 3 < Group 2 (*P* < 0.0001)[a]
Peak pressure (PSI)	71.4 (67.0–75.8)	83.2 (78.8–87.5)[a]	72.3 (68.6–75.9)	Overall < 0.0001; post-hoc Mann Whitney "*U*" test Group 1 (*P* < 0.0001), Group 3 < Group 2 (*P* < 0.0001)[a]
Peak pressure area (mm^2)	30.7 (27.1–34.2)	16.7 (14.4–19.0)[a]	27.7 (23.8–31.5)	< 0.0001; Post-hoc Mann Whitney "*U*" test Group 1 (*P* < 0.0001), Group 3 > Group 2 (*P* < 0.0001)[a]

PSI pounds/square inch

[a]Indicates statistically significant difference compared to intact condition

segmental medial meniscus grafting restored peak and mean medial tibiofemoral joint compartment pressure magnitudes, peak pressure areas, and peak pressure locations, to those of an intact, normal meniscus. These findings confirmed the study hypothesis.

A recent study by Walker et al. [19] highlighted the importance of the medial meniscus by showing that it distributes a majority (58%) of the loads transmitted in the medial tibiofemoral joint compartment, while the uncovered articular cartilage transmits the remaining 42%. In addition, Arno et al. [18] and Lee et al. [14] have shown that partial medial meniscectomy alter knee biomechanics by changing anterior–posterior stability, laxity, contact area, and peak contact stresses. These changes have the potential to increase articular cartilage injury risk in the meniscectomized knee leading to osteoarthritis. Therefore, there has been a trend towards repairing more meniscus tears, including at least attempting to repair complex radial and root tears.

Meniscal allograft transplantation has proven to be a good option following total meniscectomy [20]; however, it is not an option after partial meniscectomy [15, 21]. Commercially available scaffolds have been used with some success for patient treatment following partial meniscectomy of irreparable meniscal tears [22–25]. Even though satisfactory outcomes have been reported following use of these scaffolds, currently, no high-quality, level I studies support their use [24–27]. In this current study, we have shown that segmental medial meniscus grafting restored mean and peak pressures, as well as peak pressure area in the medial tibiofemoral joint compartment back to levels comparable to those observed in normal, intact meniscus.

Although further study is needed, the current findings raise the possibility of using a transplanted segmental meniscus allograft to treat patients who present with a significant meniscal defect following partial meniscectomy for treatment of an irreparable meniscus tear. However, in contrast to complete meniscal allograft transplantation, an added challenge of segmental meniscus grafting is that healing must occur not just at the capsular periphery, but also at the anterior and posterior meniscus tissue remnants. Further in-vivo research is needed to determine if a segmental meniscus allograft is capable of healing to the remnant meniscal tissue. The prospect of being able to offer patients another option to restore meniscus-mediated chondroprotection is exciting.

This study has several strengths including the use of a validated model to test the meniscus repair, good sample size, maintenance of consistent test conditions, and taking measures to reduce any bias that could arise from potential test order effects. This study also has several limitations inherent to biomechanical studies. Only a limited amount of porcine specimens were tested, and a direct axial compression load was applied that differed from physiologic loading conditions. Although the porcine model is frequently used to simulate human articular cartilage and meniscus conditions, further study using a cadaveric model and more physiologic loading conditions are needed to determine how well this repair can maintain meniscal and medial tibiofemoral joint compartment articular surface homeostasis under dynamic shear, rotary, or combined knee forces [8, 14, 18, 19, 28, 29]. Finally, this study only examined segmental medial meniscal repair at time zero. Future studies are needed to evaluate repair integrity and medial tibiofemoral joint pressure distributions during and after dynamic, progressive magnitude cyclical loading conditions. Despite these limitations, study results clearly revealed that segmental meniscus grafting was able to restore mean pressure, peak pressure, and peak contact pressure areas of the medial tibiofemoral joint compartment back to levels found in the intact medial meniscus at different knee flexion angles. Segmental medial meniscus grafting may provide the knee surgeon with an effective method to delay, reduce, or prevent medial tibiofemoral compartment degenerative changes following partial meniscectomy of a complex tear. Future in-vivo studies are needed to verify segmental medial meniscal allograft healing and chondroprotective effects.

Conclusion

From a static, time zero biomechanical perspective, segmental medial meniscus grafting of a partially meniscectomized knee restored mean pressure, peak pressure, and mean peak contact pressure areas of the medial tibiofemoral joint compartment back to levels observed in the intact medial meniscus at different knee flexion angles. In-vivo analysis under dynamic conditions is necessary to verify the healing efficacy and ability of the healed segmental medial meniscal allograft to provide long-term knee joint homeostasis when confronted with dynamic shear, rotatory, and combined, higher magnitude physiologic loading forces.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest. Dr. DC and Dr. ES are consultants for the Joint Restoration Foundation.

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Ethical approval This article does not contain any human participants. In vitro porcine specimens used for study purposes were obtained from a local abattoir.

Informed consent Not applicable.

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