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Comparative biomechanical analysis of human and caprine knee articular cartilage

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ABSTRACT

Background: The goat is one of the most commonly used preclinical models for focal defect repair and regeneration. While the biomechanics of the human knee has been studied extensively, less is known about the biomechanics of the caprine knee. Differences between human and caprine knees have not been quantified and their significance is largely unknown.
Methods: We conducted a biomechanical analysis of the differences in goat and human knees to assess the validity of these preclinical in vivo models.
Results: CT and MRI scans revealed several differences in articular geometry: the caprine tibial plateaux were more convex and the menisci were significantly thicker and covered a larger proportion of the tibial articular surface. Caprine cartilage thickness was consistently thinner, while elastic modulus on indentation testing was consistently stiffer than human cartilage measured at eight different articular locations. Contact area and pressure were measured with electronic pressure sensors under loads normalized by multiples of body weight and at knee flexion angles reported for walking. The highest peaks in contact pressure were measured in the patellofemoral joint in goat and human knees. Peak contact pressure measured at 2 times body weight at the goat tibiofemoral joint at 70° flexion was significantly higher than for any other condition at the human tibiofemoral joint.
Conclusion: These differences in contact conditions might explain the lower quality of local repair reported for caprine femoral condylar defects relative to trochlear defects. Further comparative analysis, including biologic response, is necessary to determine the extent to which the goat knee reproduces clinical conditions.

1. Introduction

Repair of cartilage lesions is extremely important because of the poor intrinsic repair capacity of articular cartilage. Chondral lesions are significantly more prevalent than previously believed, with full-thickness lesions found in approximately 20% of knee arthroscopies and located most commonly in the medial femoral condyle [1–4]. Progression of partial-thickness and initially asymptomatic cartilage defects has been documented with detectable reduction in cartilage volume occurring over as little as two years [5].

Despite the various treatment options available for full-thickness chondral and osteochondral lesions, long-term clinical results are not consistently successful [6]. Surgical options can be classified into repair, regeneration, and replacement. Examples of repair are microfracture and abrasion arthroplasty. Autologous chondrocyte implantation (ACI) is an example of inducing regeneration; while osteochondral grafting replaces the lost tissue with mature bone and cartilage [7]. Repair results in tissue, which is typically fibrocartilaginous and regeneration, can generate cartilage that is hyaline in nature. However, in both cases several weeks are required for the injected cells to regenerate tissue, and clinical recovery is slower than with osteochondral grafting [8]. Osteochondral grafting immediately replaces the lesion with native hyaline articular cartilage [9]; however, there are issues with integration with host tissue and donor-site morbidity. A clear need therefore exists for more effective and longer-term treatment of cartilage lesions.

Preclinical evaluation using animal models is generally required to assess the new techniques and technologies for cartilage defect repair and regeneration before clinical application. Numerous animal models, ranging from small (e.g., rodents and rabbits) to larger animals (e.g., goats and horses), have been used successfully to investigate the safety and efficacy of different cartilage repair regimen [10]. However, each model presents its own advantages and disadvantages as a surrogate for humans, largely due to the intrinsic physiological, anatomical, and biomechanical characteristics of the joint [10,11].

The goat is one of the most commonly used models for focal defect repair and regeneration. It has been used to evaluate a wide range of surgical techniques and technologies, including microfracture [12], metal implant [13,14], osteochondral allografts and autografts [15–17], tissue-engineered products [18–20], and biologics [21–25].

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There are several advantages to using goats in cartilage repair research [10,11]. The thickness of the articular cartilage typically ranges from 0.8 to 2.0 mm, allowing the opportunity to create partial- and full-thickness defects. The joint anatomy is similar to human. Larger focal defects (>6 mm in diameter) have limited intrinsic healing capacity, closely resembling the clinical observation in patients [26]. In addition, it is possible to assess the progress of the repair and outcome by using arthroscopy and MR imaging [12,27].

In goats, focal defects have been created on the medial and lateral femoral condyles and on the trochlear groove. The anatomic location of the defect appears to affect the repair response. Osteochondral defects in the condyle healed significantly better than those in the trochlear groove when treated with synthetic implants [28]. In chondral defects repaired with bone marrow stimulation, the defects on the groove generated better repair tissue [29,30]. This difference in repair response was attributed to differences in mechanical loading, subchondral bone density and structure, thickness of the calcified cartilage, and exposure to the synovial environment.

While the biomechanics of the human knee has been studied extensively, less is known about the biomechanics of the goat knee. At the present time, the goat knee is one of the most popular models for preclinical evaluation of cartilage repair. Several obvious and subtle differences exist between human and goat knees. However, these differences have not been quantified and their significance is largely unknown. This study is an initial biomechanical assessment of the differences in goat and human knees to support informed assessment of the validity of these preclinical in vivo models.

2. Methods

2.1. Specimens

Goat knees (N = 5, males) were obtained from Thomas Morris Inc, Reisterstown, MD. Human cadaver knees (N = 4, males) were obtained from Anatomy Gifts Registry, Hanover, MD. Demographics and grade of cartilage degeneration are provided in Table 1. High-resolution axial CT (Fig. 1), MRI scans (Fig. 2), and digital photographs (Fig. 3) were obtained from human and goat knees. Fig. 1 shows geometry extracted from the CT scan image data of one representative goat knee and one representative human knee.

2.2. Contact pressure and area measurements

Human and goat knees were mounted using custom adapters on a multiaxial testing machine (Fig. 4A, Force 5, AMTI, Watertown, MA). Human knees were tested at 0° and 30° flexion, goat knees were tested at 50°, 60° and 70°. These flexion angles covered the ranges of knee flexion reported during the weight-bearing phase of human and sheep knees [31]. The tibia was free to translate in the mediolateral direction and to rotate about its anteroposterior axis. The patella was free to translate in the mediolateral direction and to rotate about its superoinferior axis, which reduced the variability in contact pressure measurements induced by small errors in alignment. Sheep knee contact forces calculated during walking peaked at an average of 2.1 ×BW (times bodyweight) [31]. We have measured human knee contact forces and reported a similar value (2.2 ×BW) for walking (note normalization by bodyweight) [32]. We therefore chose to apply static loads across the articular surfaces of the femorotibial and patellofemoral joints at 0.25 ×BW, 1 ×BW, and 2 ×BW. A calibrated pressure sensor (Tekscan, South Boston, MA) was used to measure contact stresses and contact area.

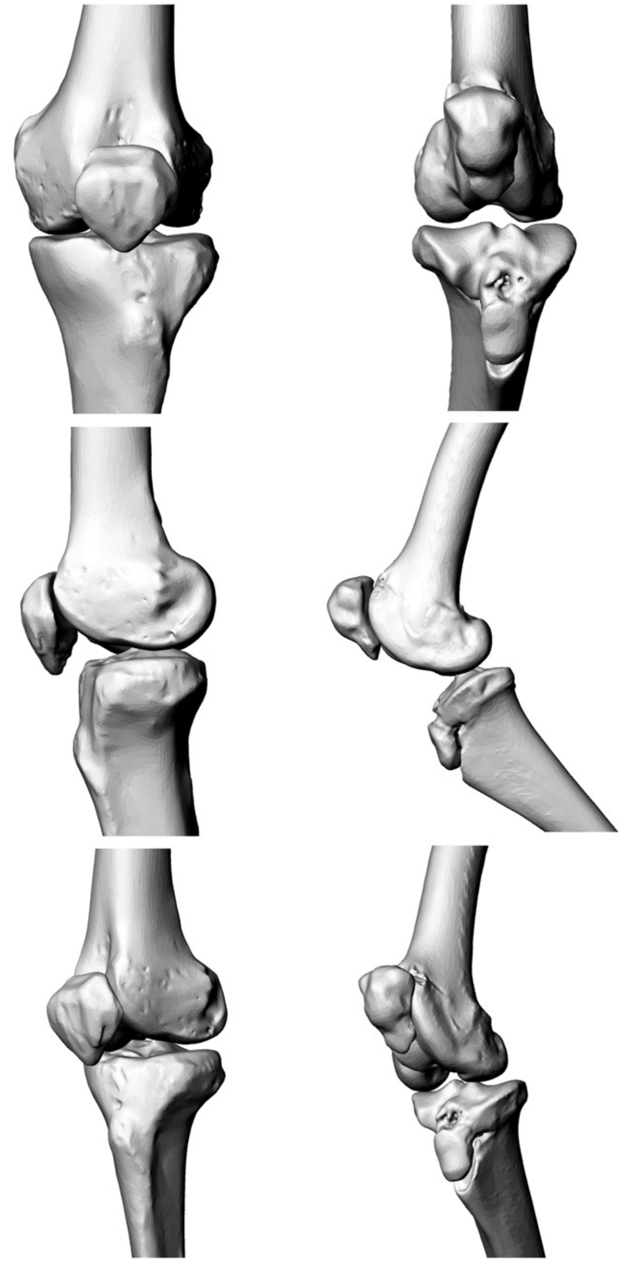

Fig. 1. CT scans of human (left) and goat (right) knees were segmented and reconstructed to obtain the geometry of the bones. Top: anterior view; middle: lateral view; bottom: oblique view.

Table 1
Human and goat specimen demographics.

Species	Age range (years)	Body weight (kg)	Grade of osteoarthritis
Human	52–83	56.8–63.6	Gr II
Goat	1.5–2	50.5–52.7	Gr 1

2.3. Cartilage thickness

A total of eight cartilage contact regions of human and goat knees were identified and were tested for each knee: lateral and medial aspects of patella, trochlea, femoral condyle, and tibial plateau. Osteochondral cores (5-mm diameter) were obtained from each cartilage contact region. The thickness of the cartilage at four equally spaced circumferential locations was measured and averaged.

2.4. Indentation testing

Each of the eight test sites was subjected to indentation testing to obtain force–displacement data. Using a custom bench top apparatus