Changes in Joint Contact Mechanics in a Large Quadrupedal Animal Model After Partial Meniscectomy and a Focal Cartilage Injury

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Acute mechanical damage and the resulting joint contact abnormalities are central to the initiation and progression of post-traumatic osteoarthritis (PTOA). Study of PTOA is typically performed in vivo with replicate animals using artificially induced injury features. The goal of this work was to measure changes in a joint contact stress in the knee of a large quadruped after creation of a clinically realistic overload injury and a focal cartilage defect. Whole-joint overload was achieved by excising a 5-mm

wedge of the anterior medial meniscus. Focal cartilage defects were created using a custom pneumatic impact gun specifically developed and mechanically characterized for this work. To evaluate the effect of these injuries on joint contact mechanics, Tekscan (Tekscan, Inc., South Boston, MA) measurements were obtained pre-operatively, postmeniscectomy, and postimpact (1.2-J) in a nonrandomized group of axially loaded cadaveric sheep knees. Postmeniscectomy, peak contact stress in the medial compartment is increased by 71% ($p=0.03$) and contact area is decreased by 35% ($p=0.001$); the center of pressure (CoP) shifted toward the cruciate ligaments in both the medial ($p=0.004$) and lateral ($p=0.03$) compartments. The creation of a cartilage defect did not significantly change any aspect of contact mechanics measured in the meniscectomized knee. This work characterizes the mechanical environment present in a quadrupedal animal knee joint after two methods to reproducibly induce joint injury features that lead to PTOA.

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Introduction

Osteoarthritis (OA) is painful degeneration of a joint and a leading cause of disability worldwide. Significant numbers of OA cases arise following joint injury and are termed PTOA [1]. Injuries associated with the development of PTOA include fractures ranging from mild, single-fragment rotational-type fractures to severely comminuted intra-articular fractures and soft tissue injuries ranging from mild ligament sprains to severe ligament ruptures [2–4]. Regardless of the mechanism of the original injury, it is ongoing abnormal joint mechanics after a traumatic injury, which play a key role in the development of PTOA [1,5–8]. Even in joints in which overall stability has been restored after injury, such as a knee following anterior cruciate ligament (ACL) reconstruction, abnormal joint contact mechanics can persist [9–12].

Focal cartilage defects are a common feature of the types of traumatic joint injuries known to contribute to the development of PTOA [13]. For example, in the knee, these focal lesions are frequently found with concomitant meniscal injury after an ACL rupture [14]. Such lesions disrupt the smooth continuity of the articular surface, potentially putting the nearby intact tissue at risk for compensatory overloading and eventual cartilage breakdown. Likewise, loss of an intact meniscus can cause widespread overload of the weight-bearing articular cartilage [15]. Changes in contact mechanics from both types of injury potentially contribute to PTOA, but the interplay between a focal defect and whole-joint overload remains unclear.

Studies relating cartilage overload to PTOA can be most systematically conducted using animal models. These models almost universally feature quadrupeds which have knees that function in higher degrees of flexion and with less rotational freedom than human knees [16]. In order to apply the findings of animal models of PTOA progression and cartilage repair to the treatment of human subjects, a thorough understanding of these differences in joint mechanics is required. The goal of this work was to determine the knee joint contact mechanics in a common orthopedic animal model (sheep) with both a focal cartilage defect and with whole-joint load changes. As it is challenging to mimic the exact mechanisms of human knee injury in animals [17,18], a new device to create a well-controlled, reproducible focal cartilage impact defect was developed and mechanically characterized, and changes in whole-joint contact mechanics were induced surgically via meniscal disruption.

Methods

Impact Gun Development. To create reproducible focal cartilage defects for study, the severity of which can be controlled, we developed a cartilage impact gun by modifying a

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Fig. 1 The cartilage impact gun featuring (a) the impact rod in a loaded position and (b) a conical spike on the impact rod face

commercially available pneumatic stapler (SureBonder Model 9600, Wauconda, IL). In a conventional use, this stapler relies on an air pressure pulse to accelerate a ram that in turn drives a common staple. We modified it to drive a 35-mm long nonporous stainless steel rod with a diameter of 6 mm (Fig. 1). The previous work has shown this diameter impact face to be sufficiently large to prevent rim stress concentrations and shearing of the cartilage from the subchondral bone during impact [19,20]. To ensure that contact pressure at the gun–cartilage interface is consistent prior to impact delivery, the trigger will not engage until resistance from a spring-loaded pin at the rod–gun interface has been overcome (Fig. 1(a)). A 1-mm long, 30-deg conical spike machined into the impact rod face (Fig. 1(b)) prevents the impact face from slipping along the cartilage surface. When the trigger is pulled, the impact face is driven against the cartilage surface by an air pressure pulse.

Calibration of the device was accomplished through benchtop tests using rigid polyurethane foam blocks (density = 0.32 g/cm³). The homogeneous material properties of this material facilitated accurate and precise calibration of impact energy with gun pressure. During the first test, seven replicate impacts at air pressures of 30, 40, 50, and 60 pounds per square inch (psi) were delivered to the foam blocks manually using the impact gun. A digital caliper was used to measure the indentation depth of each trial. Mean indentation depth was calculated for each air pressure, and a linear equation was fit to the plot of mean impact depth versus applied air pressure. In the second test, an MTS 810 servohydraulic material testing system (MTS Systems Corporation, Eden Prairie, MN) was used to drive the impact rod to depths of 1.0, 1.5, 2.0, and 2.5 mm under displacement control (0.1 s per trial; four trials of each depth). An axial load cell measured force during each trial. Impact energy was calculated by integrating the curve produced by plotting force versus impact rod displacement, and a second linear equation was fit to a plot of impact energy versus impact depth. Substitution of the impact depth versus air pressure equation into the impact energy versus impact depth equation yielded an equation describing impact energy (J) as a function of impact gun air pressure (psi).

Contact Stress Measurement. The knees of nine skeletally mature sheep (mean mass 92 kg) euthanized for other IACUC-approved studies at our institution were harvested and frozen for subsequent mechanical measurement of changes in joint contact stresses associated with a surgically induced partial meniscectomy and a focal cartilage defect. Prior to testing, each specimen was

thawed for 24 h at room temperature and dissected free of overlying muscles and other soft tissues while leaving the joint capsules intact. The proximal femur and distal tibial shafts were potted in polymethylmethacrylate (PMMA) so as to maintain the joint at 60 deg of knee flexion, the angle at which peak loading occurs in the sheep gait cycle [21].

Immediately prior to testing, the joint capsule was incised both anteriorly and posteriorly and a calibrated contact pressure sensor (a bisected Tekscan model 5033, South Boston, MA with a resolution of 72 sensels per square centimeter) was inserted into the medial and lateral compartments of the knee, proximal to the menisci (Fig. 2(a)) [22–24]. The free ends of the sensor were secured to the posterior proximal femur with screws to prevent sensor shifting during testing. The joints were then set one at a time in a custom axial loading fixture mounted into an MTS 810 system. The loading fixture permitted knee varus/valgus and internal/external rotation of the tibia but was otherwise constrained.

Fig. 2 (a) Photographs of an intact knee specimen (top) and following partial meniscectomy (bottom). The 5-mm wedge of meniscus to be excised has been marked. The Tekscan sensor has been positioned to cover the main weight-bearing portions of the medial and lateral compartments. (b) Tekscan stress maps for an intact knee specimen (top) and the same specimen following partial meniscectomy (bottom).

Table 1 Average (± 1 standard deviation) measurements of peak stress, contact area, and center of pressure (CoP) shift in each compartment

Compartment	Measure	Pre-op	Post-apm ^a	<i>P</i> -value (versus pre-op) ^b	Post-impact	<i>P</i> -value (versus post-apm ^a) ^b
Medial	Peak stress (MPa)	4.9 $\pm$ 2.4	8.4 $\pm$ 3.4	0.03	10 $\pm$ 5.4	0.5
	Contact area (mm ²)	252 $\pm$ 32.5	163 $\pm$ 66.5	0.001	156 $\pm$ 57.2	0.9
	AP CoP shift (mm) ^c		-0.52 $\pm$ 1.5	0.7	-0.45 $\pm$ 1.3	0.8
	Cruciate/collateral CoP shift (mm) ^d		2.6 $\pm$ 0.89	0.0040	-0.19 $\pm$ 0.43	0.8
Lateral	Peak stress (MPa)	6.8 $\pm$ 1.7	7.7 $\pm$ 2.7	0.5	6.3 $\pm$ 2.9	0.4
	Contact area (mm ²)	240 $\pm$ 24.1	226 $\pm$ 21.5	0.1	212 $\pm$ 32.3	0.5
	AP CoP shift (mm) ^c		-0.24 $\pm$ 0.37	0.9	0.066 $\pm$ 0.39	1.0
	Cruciate/collateral CoP shift (mm) ^d		1.2 $\pm$ 0.68	0.03	0.036 $\pm$ 0.58	1.0

^aapm, anterior partial meniscectomy.

^bCoP shift *p*-values calculated from position, not shift.

^cPositive indicates a posterior CoP shift, and negative indicates an anterior CoP shift.

^dPositive indicates a CoP shift toward the cruciate ligaments; negative indicates a CoP shift toward the collateral ligaments.

Note: Statistically significant results are marked in bold.

To simulate peak load during normal sheep gait, a ramp load of 900 N (equivalent to twice the average sheep body weight [21]) was applied at a rate of 100 N per second. With the 900-N load applied, the Tekscan sensor recorded baseline intact knee contact pressure simultaneously in the medial and lateral compartments (Fig. 2(b)). To alter joint loading via partial meniscectomy, the 900-N load was removed and a 5-mm wedge was excised from the anterior horn of the medial meniscus, taking care to preserve the adjacent cartilage and sensor. The 900-N load was then reapplied and a second Tekscan recording was taken. The specimen and loading fixture were then removed from the MTS for creation of the focal cartilage lesion. Taking care to prevent movement of the Tekscan sensor, the specimen was flexed to 100 deg to expose the weight-bearing cartilage surface of the medial femoral condyle. The impact gun was manually positioned normal to the articular cartilage surface, and a 1.2 J impact was delivered. The knee was then extended to its original position and replaced in the MTS, and a final cycle of loading and contact pressure recording occurred.

Raw Tekscan data and sensor calibration curves were loaded into a custom MATLAB (The Mathworks, Natick, MA) program for analysis. Peak contact stress, contact area, total load recovery, and center of pressure (CoP) were calculated for the medial and lateral compartments in the intact, overloaded, and focal defect conditions.

Results

Statistically significant increases in peak contact stress ($\sim 171\%$ increase) and decreases in contact area ($\sim 35\%$ decrease) were observed in the medial compartment after partial meniscectomy (Table 1). These results are consistent with the work of Lewinski et al., in which the peak contact stress increased by an average of 260.4% and contact area was reduced by 55% compared to controls in a study of fully meniscectomized sheep knees [22]. Although the shift in the location of the CoP in the anteroposterior direction failed to achieve statistical significance, there was a significant shift of the CoP toward the middle of the joint in both compartments after partial meniscectomy.

The impactation gun was able to deliver repeatable, well controlled impacts as indicated by small standard deviations in the penetration depths obtained during testing using the polyurethane foam (SD = 0.09 mm at 30 psi; SD = 0.11 mm at 40 psi; SD = 0.08 mm at 50 psi; SD = 0.11 mm at 60 psi). Linear fits to impact depth versus air pressure (impact gun testing) and impact energy versus impact depth (MTS testing) demonstrated excellent correlations ($R^2 = 0.99$ and $R^2 = 1.0$, respectively), again indicating consistency. Substitution of the linear fit equation relating impact depth to air pressure into the equation relating impact energy to impact depth yielded the relationship between impact energy and air pressure

$$\text{Energy} = 0.0288 \times \text{Air pressure} - 0.566 \quad (1)$$

Fig. 3 (Top row) Axial view of four 1.2-J cartilage impacts. (Bottom row) Corresponding sagittal views following the bisection of the impact site. Specimens were photographed under equivalent lighting conditions and positioning. India ink has been used to emphasize cartilage damage.

When the impact gun was used to deliver a 1.2-J impact to the sheep knee articular cartilage, it consistently created a cartilage lesion without damaging the subchondral bone (Fig. 3). However, despite the consistent impact and similar cartilage damage, the addition of a focal cartilage defect did not significantly change contact stress, contact area, or the location of the CoP in the weight-bearing articular cartilage of the overloaded knee (Table 1). The area of impacted cartilage was 28.3 mm^2 , representing $\sim 11\%$ of the cartilage contact area in the medial compartment of a normal sheep knee (series mean = 252 mm^2 , $\text{SD} = 32.5 \text{ mm}^2$). Following partial meniscectomy, this same area represents $\sim 23\%$ of the medial cartilage contact area (series mean = 163 mm^2 , $\text{SD} = 66.5 \text{ mm}^2$). Stress measurements for each individual specimen can be found in the Supplemental Data, which is available under the “Supplemental Materials” tab for this paper on the ASME Digital Collection.

Discussion

Characterizing the mechanical changes that result from joint trauma is essential to the development of an understanding of how mechanics contribute to the development of PTOA. Both the whole-joint overload induced by partial meniscectomy and the focal cartilage defects created by the impact gun developed in this work are consistent with injuries attributed to the onset of PTOA.

In contrast to other types of blunt impact devices, the impact gun is a portable and maneuverable hand-held instrument. Although other examples of handheld, spring-loaded cartilage impact devices are present in the literature [19,25], our pneumatic device presents a novel approach with a number of critical advantages. First, minimal recoil during impact ensures that the gun is held steady and that energy is delivered to the tissue and not dissipated by the device itself. Second, injury severity is simply and reliably modulated by gauge pressure. Both features ensured the resultant focal defects were highly consistent. The rigid foam used to calibrate the impact gun was not representative of its intended use on cartilage, rather it was specifically chosen for its homogeneous material properties. This ensured that impact reproducibility could be evaluated independently of interspecimen variability prior to using the device on cartilage.

The lack of significant changes in contact stress after impacts was somewhat unexpected; however, our finding was consistent with the previous work which found the biomechanical effect of rim stress concentration to be insignificant for defects of 10-mm or less in diameter [26]. In addition, while previous work featured full-thickness osteochondral lesions devoid of tissue inside the defect [20], our work has created a full-thickness cartilage injury (Fig. 3), wherein the tissue remaining within the defect following impact may limit the presentation of immediate changes in contact stress. Finally, as noted previously, the defect size was a relatively small ($\sim 11\%$ for intact, $\sim 23\%$ postmeniscectomy) percent of compartmental contact area. These factors, as well as increased contact stresses following partial meniscectomy, may have contributed to the negligible findings that followed defect creation. Given the ample evidence supporting deleterious effects of impact trauma on cartilage health [27,28], it is perhaps more likely that mechanical changes associated with this type of focal defect are related to increased friction between the disrupted and healthy articular surfaces during joint movement rather than a focal overloading. A study of forces in the joint during dynamic simulation through a full gait cycle would be necessary to fully understand such effects.

In conclusion, disruption of the meniscus in a quadrupedal animal knee increased and shifted peak contact stresses on the articular surface, whereas addition of a focal cartilage defect had little additional effect on joint contact mechanics. The joint overload and focal articular cartilage injuries mechanically characterized here have numerous applications, including a longitudinal study of PTOA development after joint injury and evaluation of a

variety of biochemical and surgical treatment options for cartilage defects.

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