INTRODUCTION: Thirty percent of the total annual trauma charges from automobile collisions are for lower extremity injuries1. Annual costs of treatment, lost work time, and rehabilitation for these injuries are approximately $21.5 billion2. The knee is injured in approximately 10% of the automobile collisions studied each year. Fractures of the patella, tibial plateau, and femoral condyles combine to represent approximately 25% of severe knee injuries, while tendon and ligament injuries account for another 25% of these injuries. Knee impacts on the tibia contribute the majority of posterior tibial translation and rupture of the posterior cruciate ligament. The anterior cruciate ligament (ACL) can also be damaged by hyperextension of the knee, as the unbelted occupant contacts the windshield. These soft tissue injuries can often be overlooked in the emergency room, as higher priority is placed on bone fractures and life-threatening injuries3. Large compression loads can also be measured in the tibia for the unbelted and belted, as well as airbag restrained occupant during a collision. The hypothesis of the current study was that under excessive tibiofemoral compressive loads the tibia would translate anteriorly to rupture the ACL prior to gross fracture of bone. And, that in these experiments occult microcracks of bone would be generated within the femoral condyles and/or the tibial plateau.

METHODS: Experiments were conducted on 6 pairs of human knee joints from cadavers aged 74.3 ± 10.5 years. The limbs were stored at −20°C for 1–2 years prior to the experiments. One knee from each subject pair was randomly selected and thawed at 27°C for 24 hours prior to sectioning the joint approximately 15 cm proximal and distal to the knee. The femoral and tibial shafts were cleaned with 70% alcohol and potted in cylindrical aluminum sleeves with room temperature curing epoxy. The specimens were flexed 90° and loaded with a single cycle, 20 Hz load input. A 6–8 N pre-load was applied to the tibia before each experiment. The input axial load on the tibia was then incremented by 500 N in repeated tests on each specimen using a servo-hydraulic testing machine. A rotary encoder was used to measure internal-external rotation of the tibia/fibula with respect to the femur. The anterior surface of the femur was supported on a bed of epox. The femur was secured to an x-y translational plate that traveled on linear bearings. The plate allowed the femur to move in the anterior-posterior and medial-lateral directions relative to the tibia during axial compressive loading of the TF joint via the plate. Linear encoders were attached to the plate to record motion of the femur relative to the tibia/fibula. Low and medium range pressure sensitive film (Prescale, Fuji Film Ltd., Tokyo, Japan) was stacked and sealed in packets. The film was inserted between the menisci and the femoral condyles in the medial and lateral compartments of the TF joint. The experiment was repeated with increasing load intensity until a catastrophic injury was noted in the joint. The joints were then immersed in 10% buffered formalin for a minimum of 14 days and decalcified in 20% formic acid for approximately 3–4 weeks. The tibial plateau and femoral condyles were grossly sectioned into medial and lateral tissue blocks for processing by standard paraffin methods. The 10μm thick sections were stained with Safranin O-Fast Green and mounted on slides for light microscopy to identify occult microcracks underlying articular cartilage in the joint. Five response variables were recorded: the TF joint compressive load, the actuator position, the anterior-posterior translation of the femur relative to the tibia, the medial-lateral translation of the femur relative to the tibia, and the internal-external rotation of the tibia relative to the femur. The input loads and the corresponding joint responses (axial tibial translation, tibial rotation, medial-lateral femur translation and posterior femur translation) from the six joints were combined to create average response curves. Paired t-tests were performed on the pressure film data to evaluate differences between medial and lateral TF contact pressures and contact areas. Significant statistical differences were reported for p < 0.05.

RESULTS: Tibiofemoral (TF) compressive loading of these isolated human knees resulted in proximal motion of the tibia/fibula and internal rotation of the tibia/fibula with respect to the femur. The femur also translated posteriorly (Figure 1) and medially with respect to the tibia/fibula. Five of six experiments resulted in an isolated substance tear of the ACL at 6.0±3.2kN. One joint failed by fracture of the tibial plateau. ACL rupture occurred at 6.0±4.0mm of posterior translation of the femur, 9.0±7.0° of internal tibial rotation and 4.0±1.5mm of medial femur translation with respect to the tibia. In ACL injury experiments the TF contact pressure in the medial compartment (21.9±3.5MPa) significantly exceeded that in the lateral compartment (15.0±1.4MPa). Furthermore, the medial compartment contact area (193±63.9mm2) significantly exceeded that recorded in the lateral compartment (41±54.9mm2). These data help explain the appearance of horizontal-oriented occult microcracks in the medial compartment of the femoral condyle in 3 of 5 ACL-injured cases (Figure 2A). In 3 of 5 cases (2 of the above 3 cases) vertical-oriented occult microcracks were noted bilaterally under the tibial plateau (Figure 2B).

DISCUSSION: The current study showed that isolated ACL ruptures under excessive TF joint compression were associated with posterior-medial translation of the femur with respect to the tibia, and internal rotation of the tibia with respect to the femur. Earlier studies, by others, show anterior translation of the tibia under TF joint compression in the flexed knee is due to a 10°-15° posterior inclination of the human tibial plateau4,5. Experimental constraint of anterior tibial translation mitigates rupture of the ACL prior to fracture of the femoral condyles or tibial plateau6. During these failure experiments the average contact forces generated in the medial compartment of the TF joint significantly exceeded those in the lateral compartment. Correspondingly, histological sections from ACL-injured specimens showed occult microcracks near the tendifmark in the medial femoral condyle and the zone of calcified cartilage for both compartments of the tibial plateau. These occult microcracks may be precursors to gross bone fracture, and provide a histological basis for MRI-identified “geographic bone bruises” seen in the automotive trauma patient7. Occult geographic sub-cortical femoral and tibial fractures are also associated with early degradative changes in overlying cartilage, that may be a precursor to a frank osteoarthritis8,9. The long-term consequences of these injuries, especially in the automobile trauma patient, are currently unknown.

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