Clinical Biomechanics 24 (2009) 577–582

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Osteochondral microdamage from valgus bending of the human knee

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ARTICLE INFO

Article history:
Received 6 November 2008
Accepted 6 May 2009

Keywords:
Anterior cruciate ligament rupture
Osteoarthritis
Bone bruise
Knee injury
Valgus bending
Tibiofemoral compression

ABSTRACT

Background: Valgus bending of the knee is promoted as an anterior cruciate ligament injury mechanism and is associated with a characteristic “footprint” of bone bruising. The hypothesis of this study was that during ligamentous failure caused by valgus bending of the knee, high tibiofemoral contact pressures induce acute osteochondral microdamage.
Methods: Four knee pairs were loaded in valgus bending until gross injury with or without a tibiofemoral compression pre-load. The peak valgus moment and resultant motions of the knee joint were recorded. Pressure sensitive film documented the magnitude and location of tibiofemoral contact. Cartilage fissures were documented on the tibial plateau, and microcracks in subchondral bone were documented from micro-computed tomography scans.
Findings: Injuries were to the anterior cruciate ligament in three knees and the medial collateral ligament in seven knees. The mean (standard deviation) peak bending moment at failure was 107 (64) N m. Valgus bending produced regions of contact on the lateral tibial plateau with average maximum pressures of approximately 30 (8) MPa. Cartilage fissures and subchondral bone microcracks were observed in these regions of high contact pressure.
Interpretation: Combined valgus bending and tibiofemoral compression produce slightly higher contact pressures, but do not alter the gross injury pattern from isolated valgus bending experiments. Athletes who sustain a severe valgus knee bending moment, may be at risk of acute osteochondral damage especially if the loading mechanism occurs with a significant tibiofemoral compression component.

1. Introduction

The knee is one of the most frequently injured joints in the human body, accounting for 19–23% of all injuries (Hootman et al., 2002). That percentage is even higher in the athletic population with the most common injury classification being internal knee trauma (Majewski et al., 2006). Epidemiological studies have shown there are over 80,000 anterior cruciate ligament (ACL) tears in the USA each year, with a total cost of more than $1 billion (Griffin et al., 2000). The medial collateral ligament (MCL) is frequently injured as well, both individually and in combination with the ACL (Majewski et al., 2006; Viskontas et al., 2008).

An additional complication of an acute knee injury is a significantly increased risk of developing post-traumatic osteoarthritis (OA) (Felson, 2004). Between 50% and 70% of patients with a complete ACL rupture and associated injuries have radiological changes consistent with chronic joint disease after 12–20 years (von Porat et al., 2004). Post-traumatic OA development in patients with ligament tears may be caused by acute damage to the articular cartilage and subchondral bone due to excessive compressive forces generated in the joint at the moment of injury (Fang et al., 2001; Frobell et al., 2008). In over 80% of ACL cases and 50% of MCL cases, there is a characteristic osteochondral lesion in the tibial plateau and/or the femoral condyle (Atkinson et al., 2008). Geographic bone bruises, in particular, are also a sign of cartilage softening, fissuring or overt chondral fracture in regions overlying bone bruises (Vellet et al., 1991; Johnson et al., 1998). Osteochondral microdamage that is a “footprint” of the pattern of the joint contact at the moment of ACL injury (Sanders et al., 2000; Viskontas et al., 2008) has been confirmed during isolated TF compression experiments in cadaver knees (Meyer et al., 2008a). Meyer et al. (2008a) also validate that these “footprints” are specific to the mechanism of ACL injury by comparing the TF contact pressures produced by TF compression, internal tibial torsion and more recently, hyperextension loading mechanisms (Meyer et al., 2008b).

Valgus bending of the knee is one of the most commonly referenced loading mechanisms for ACL rupture in athletes. This type of motion is described in over 60% of non-skiing ACL injuries (Boden et al., 2000). In basketball, approximately 37% of non-contact ACL injuries were termed “valgus collapse” (Krosshaug et al., 2007). Valgus bending of the knee is affected by many types of external forces, and associated with other motions of the joint. Specifically, there is a strong coupling between valgus bending and axial tibial

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doi:10.1016/j.clinbiomech.2009.05.006

rotation (Inoue et al., 1987; Matsumoto et al., 2001). In experiments that allow motion in five out of the six possible degrees of freedom (all except knee flexion/extension), ACL sectioning significantly increases valgus laxity, while MCL sectioning does not (Inoue et al., 1987). The estimated force in the ACL is highest at 30° of knee flexion for a 10 N m valgus bending moment (Fukuda et al., 2003). Other biomechanical studies, however, have shown significantly more restraint from the MCL than the ACL during valgus bending (Seering et al., 1980; Shapiro et al., 1991). Although valgus bending is frequently identified in video analysis of ACL injuries in sports, it is not clear if this motion induces the injury or occurs as a result of the ACL being torn (Olsen et al., 2004).

Few studies have documented the forces or relative joint displacements at failure levels under controlled loading of the knee joint. The objective of the current study was to apply failure level valgus bending moments to the knee and document the soft tissue injuries and osteochondral microdamage that occur during this event. The study was designed to measure the contact pressure occurring in the knee joint during failure level valgus bending moments. Additionally, in the current study valgus bending and TF compression were combined to better simulate an off balance jump landing. It was hypothesized that valgus bending would result in ligament failure and that during gross ligamentous injury to the knee valgus loads would generate high contact pressures in the lateral plateau causing acute osteochondral microdamages. These damaged regions may have the potential for development of post-traumatic OA, even after surgical reconstruction of the ligamentous injury.

2. Methods

Valgus bending experiments were conducted on paired TF joints from four male cadavers with an average age of 40 (15) years, where () indicates the standard deviation of the mean throughout the manuscript. The joints were procured through University sources (see "Acknowledgements"), stored at −20 °C and thawed to room temperature for 24 h prior to testing. The joints were sectioned approximately 15 cm proximal and distal to the center of the knee. The skin and muscle tissues were removed leaving the knee joint capsule and collateral ligaments intact. The femur and tibia shafts were cleaned with 70% alcohol and potted in cylindrical aluminum sleeves with room temperature curing epoxy (Fibre Strand, Martin Senour Corp., Cleveland, OH, USA). One side was randomly selected for isolated valgus bending experiments, while the opposite limb was used for combined loading experiments with a valgus bending moment and a TF compression pre-load. Valgus moments were applied via four-point bending, with the moment applied to the potting cups (Fig. 1). The femoral cup was mounted on an *XY* translational table to allow anterior/posterior and proximal/distal motion. These motions were recorded with linear encoders (Model #X00Z01A, Renishaw, Hofman Estates, IL, USA). The flexion angle was fixed at 30°, while internal/external rotation of the femur was unconstrained and recorded with a rotary encoder (Model #RCH25D-6000, Renco Encoders Inc., Goleta, CA, USA). The tibia rotation was fixed in all directions of motion except the applied valgus bending.

A hydraulic materials testing machine with a linear actuator (Models 312.21 and 204.52, MTS Corp., Eden Prairie, MN, USA) was used to apply the bending moment with a 2 Hz haversine waveform and a time to peak of 250 milliseconds (ms). Valgus bending was applied to the knee joint through the four-point bending moment arm via repeated, increasing magnitudes of actuator displacement (in 5 mm increments) until gross ligamentous injury. In the combined valgus bending and TF compression experiments the TF compression pre-load was applied immediately before each valgus bending test by hand using a lever arm that was connected to the femoral fixture through extension springs. Two springs (Part # 9630K33, McMaster-Carr, Atlanta, GA, USA) with a stiffness of 161 N/cm each were arranged in parallel and displaced 7 cm from their nominal spring length in order to produce approximately two times body weight (BW) of TF compression in the first three specimens. In the last specimen, four springs were used to produce approximately 4 BW of TF compression.

Valgus rotation and relative translation between the femur and tibia were also measured using a six camera Vicon motion system (Oxford Metrics Ltd., Oxford, UK) with a capture volume of 50 cm × 40 cm × 30 cm. The valgus rotation was measured about the fixed (global) medial/lateral coordinate axis defined during setup of the Vicon system. Reflective markers were attached to the femur and tibia fixtures and four marker arrays were screwed into each bone. For the current study, the valgus angle and internal femur rotation were measured at the time corresponding to the peak moment. The anterior–posterior relative motion between the tibia and femur were analyzed only during the application of the compressive pre-load. The accuracy of the Vicon system was assessed by comparing the femur rotation and displacement measured by the linear encoders with the motion captured by the Vicon system. Differences in displacement were noted to be less than 0.3 mm.

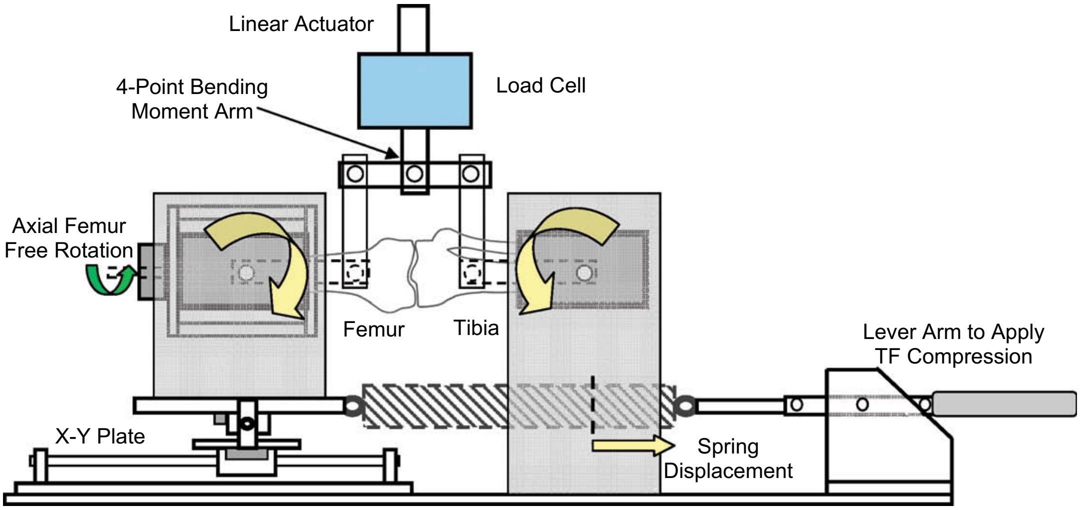

Fig. 1. Knee specimen, potted and attached to the valgus bending test fixture.