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Journal of Biomechanics 41 (2008) 1236–1242

JOURNAL OF BIOMECHANICS

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Impact-induced osteochondral fracture in the tibial plateau

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Accepted 21 January 2008

Abstract

In this study, human tibia plateaus with the meniscus removed were impacted on various regions of the plateau surface via a drop test using a 5 mm indenter. Osteochondral blocks containing the failure site were then extracted, chemically fixed, dehydrated, gold-particle coated, and sent for X-ray micro-CT imaging to obtain 3-D image reconstructions of the cartilage and underlying bone. Cartilage failure upon impact appeared to be characteristically brittle in nature. Impacted cartilage from the region not protected by the meniscus showed a relatively large cavernous disruption with microcrack propagation extending radially into the subchondral bone, while impacted cartilage from beneath the meniscus showed less dramatic surface disruption and with no underlying bone failure.

Keywords: Cartilage mechanics; Fracture; Bone; Failure; Micro-CT

1. Introduction

The goal of many previous studies in cartilage mechanics has been to determine the critical limits of the joint in load bearing, this in relation to the mechanical overloading of the cartilage–bone system that occurs in trauma and injury (Patwari et al., 2001). It has been of particular interest to determine the mechanical limits of cartilage under impact loading, where it was found that the stresses that cause fissures and laceration in articular cartilage ranged from 11 to 36 MPa (Repo and Finlay, 1977; Torzilli et al., 1999; Haut, 1989; Obeid et al., 1994, Kerin et al., 2003, Verteramo and Seedhom, 2007, Wilson et al., 2003; Atkinson et al., 1998). Such a variation in these stresses may likely be attributable to differences in cartilage thickness, stain rate, the species of animal from which the sample was taken (Burgin and Aspden, 2007; Jeffrey and Aspden, 2006; Flachsmann et al., 2005), and even the cartilage split-line direction (Kamalanathan and Broom, 1993). Such is the challenge presented to the cartilage researcher.

The complexities increase when considering that the cartilage failure from impact loading may or may not cause an associated disruption of the underlying osteochondral junction and bone. Yet arguably, it is this underlying region that is hypothesized to be crucial, such that, if damaged, it is believed to lead to the direct development of posttraumatic osteoarthritis (Buckwalter and Mankin, 1998; Thambyah, 2005). Thus, if posttraumatic osteoarthritis results from high strain rate loading in the articular surface, with accompanying damage to the underlying osteochondral junction, then the relevant research questions should include: (1) just how mechanically protective is the intact articular cartilage of the osteochondral junction during impact loading; and (2) can an insidious fracture in the osteochondral region occur without significant damage to the overlying articular cartilage following the impact?

The second question above refers to subfracture impact loads of the articular cartilage and the development of microcracks in the underlying bone. The information for this type of fracture has been less available, and this is largely due to difficulties in detecting and ascertaining when these microcracks have occurred. However, the significance of such microfractures comes from the large body of work that show its purported role to the

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0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2008.01.033

consequential development of osteoarthritis (Burr and Radin, 2003; Norrdin et al., 1998; Radin and Rose, 1986).

In the present study, we investigate the failure mechanisms of cartilage-on-bone as a result of a single blunt impact load delivered by a free-falling rigid mass to the tibial plateau. The tibial plateau is chosen as the study model as previous work has shown that the cartilage and bone mechanical properties vary significantly between regions covered by the meniscus and that not covered (Yao and Seedhom, 1993; Thambyah et al., 2006). These studies showed that while the uncovered regions of cartilage appeared intact, their mechanical properties were deficient and significantly inferior to the adjacent cartilage covered by the meniscus. This model thus provides an intact cartilage continuum consisting of two different protective abilities.

For the impact test, the mechanical response of the cartilage-on-bone to drop-load is analysed through the measured resistive force, stiffness and failure load. Further, by first chemically fixing and then gold-coating the tissue, an evaluation of the impacted cartilage–bone structure is carried out using X-ray micro-computer tomography (micro-CT), in which *both* the cartilage articular surface and deeper bone may be visualized together following 3-D image reconstruction.

2. Materials and methods

2.1. Specimens

A total of six human tibia specimens were obtained. Careful gross examination was performed to include only knees that had no obvious injury or damage to the articular cartilage. The knees came from three separate fresh-frozen male cadavers with age at death ranging from 62 to 70 years old.

The specimens were obtained from bodies that had been donated to scientific and medical research, under the administrative control of the Health Science Authority of Singapore. These cadavers were available following a period of at least 6 weeks and no longer than 2 months after death. All tests were carried out on the fully thawed knees within a month of storage at −20 °C.

The tibial plateau specimens measured an average length and breadth of 84.3 ± 6.0 and 63.7 ± 6.1 mm, respectively. The mean articular cartilage thickness was estimated by measuring directly on the sawn sample, following the impact tests.

2.2. Impact test

An impact load was delivered to the tibial plateau by a free-falling 0.26 kg mass in the form of a cylindrical mild steel rod, 105 mm long, with a 20 mm diameter, to which was attached a 25 mm indenter of 5 mm diameter. The previous works of Atkinson et al. (1998) and Fukuda et al. (2000) were considered in determining the method of applying the impact load, and the indenter formed the end of the impactor with its gradually hemispherical tip, similar to a previous design aimed at preventing damage caused by sharp edges (Scott and Athanasiou, 2006).

A piezoelectric accelerometer was mounted on top of the impactor and was connected to a signal conditioner. The acceleration signal was recorded continuously by a digital storage oscilloscope. The impactor, guided by a cylindrical tube, fell from a height of 300 mm onto the target.

The tibial plateau target was continuous with its shortened (to about 150 mm) tibia shaft potted in cement within a steel holder. The holder was held within a lockable steel ball-joint, which allowed the necessary adjustment before each test to ensure that the impact trajectory was perpendicular to the articular surface of the tibial plateau.

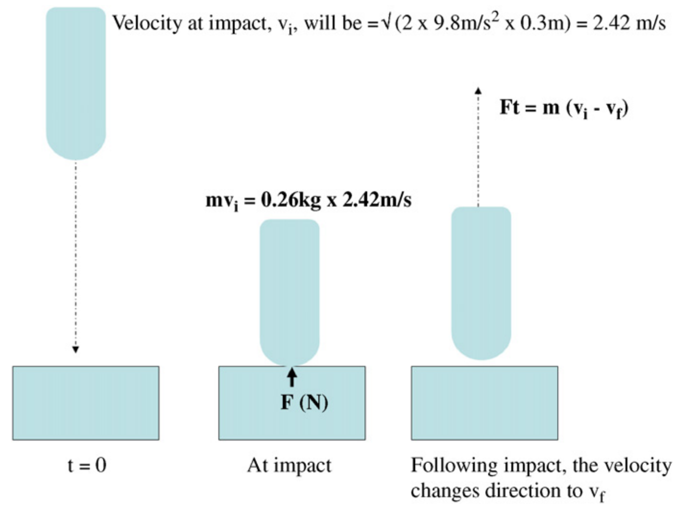

Fig. 1. Schematic showing how straight-line motion equations was used to calculate the initial velocity, v_i, from which, together with the force-time data, the final velocity, v_f, is derived using conservation of momentum and impulse.

Preliminary tests were conducted on ovine tibiae to eliminate or reduce dynamic effects in the apparatus, optimize filtering and signal conditioning, and confirm the experimental protocol for the present study. The dimensions and mass of the impactor used in the present study were further confirmed in the pilot tests to ascertain the appropriate impactor shape, mass, size and drop height to induce an appropriate fissure. In these earlier tests, a high-speed camera was used to capture the moment of impact [Ovine Cartilage Video[1]].

The meniscus was removed by careful dissection. Two regions of interest on the human tibial plateau samples were identified. The uncovered or non-meniscus protected region I, and the covered or meniscus protected region II. On the tibia, the regions were demarcated using waterproof permanent ink. The loads were applied sequentially to the medial and lateral sides, beginning with the unprotected regions first. Each impact site was selected to be sufficiently distant from the others so that there would not be any mutual influence. Throughout the test, the tibial surface was kept moist by squeezing gauze saturated with physiological saline over the surface.

The following data were obtained from each impact test: peak reaction force (N), and time at peak force (seconds), from which impulse (force × time) or change in momentum was calculated, and by dividing by the mass of the impactor the change in the velocity was obtained (Fig. 1) to attempt to quantify the extent of force dissipation in the collision. From integrating twice the acceleration–time data to yield displacement values (mm) and plotting with force (N), the instantaneous compressive stiffness (N/mm) was derived from the gradient of the linear rise in the force–displacement curve.

2.3. Micro-CT (and SEM)

To obtain high-resolution visualization of both the cartilage surface and underlying bone with X-ray micro-CT, a tissue preparation protocol, similar to that used for scanning electron microscopy (SEM), was used. Six medial–lateral osteochondral cubes measuring approximately 10 mm × 10 mm × 10 mm, each from an impact site, were extracted from the impacted tibia plateau using an oscillating saw. Each cube was fixed by immersion in 3% glutaraldehyde for 4 h at 4 °C. The samples were then

[1]Supplementary Website material. Filename: *ovine.avi*