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Research paper

Strain-rate sensitivity of the lateral collateral ligament of the knee

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ABSTRACT

The material properties of ligaments are not well characterized at rates of deformation that occur during high-speed injuries. The aim of this study was to measure the material properties of lateral collateral ligament of the porcine stifle joint in a uniaxial tension model through strain rates in the range from 0.01 to 100/s. Failure strain, tensile modulus and failure stress were calculated. Across the range of strain rates, tensile modulus increased from 288 to 905 MPa and failure stress increased from 39.9 to 77.3 MPa. The strain-rate sensitivity of the material properties decreased as deformation rates increased, and reached a limit at approximately 1/s, beyond which there was no further significant change. In addition, time resolved microfocus small angle X-ray scattering was used to measure the effective fibril modulus (stress/fibril strain) and fibril to tissue strain ratio. The nanoscale data suggest that the contribution of the collagen fibrils towards the observed tissue-level deformation of ligaments diminishes as the loading rate increases. These findings help to predict the patterns of limb injuries that occur at different speeds and improve computational models used to assess and develop mitigation technology.

1. Introduction

Human ligament injuries are common and can cause significant morbidity and long-term disablement (Gelber et al., 2000). The EUROCOST reference group estimate the incidence of knee ligament injuries at 0.04% population/year with associated treatment costs alone at an average of €1727 per injury (Polinder et al., 2005). The types of joint injuries that occur may vary according to health, age, sex, anatomy, mechanism of trauma and rate of loading (Ytterstad, 1996). Prevention of significant joint injuries requires us to understand why different patterns of injury may occur with

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different traumatic mechanisms and rates of loading. Computational modelling of joint injuries is one method that may be useful to help predict different patterns of injury and assess mitigation technologies. However, reliable biomechanical measurements of the connective tissues of joints are required if the models are to be accurate and useful.

Ligaments are visco-elastic materials made of collagen fibres, which change in strength and stiffness relative to their rate of loading (Yannas and Olson, 1972; Tipton et al., 1967). Tensile modulus and failure stress are useful measurements to compare the material properties of different ligaments. These material properties are important input parameters to computational models of human joint injuries. Previous laboratory studies have found that the tensile modulus and failure stress of ligaments both increase as the rate of loading increases (Danto and Woo, 1993; Yamamoto et al., 2003; Yamamoto and Hayashi, 1998; Ng et al., 2004). However, many of the previous studies have focused on the failure characteristics at quasi-static loading rates or assessed only a few different loading rates (Danto and Woo, 1993; Noyes et al., 1974; Crowninshield and Pope, 1976; Kennedy et al., 1976).

This strain-rate dependent material behaviour of ligament tissue cannot be understood without considering the hierarchical nature of the structure. Small angle X-ray diffraction (SAXD) has been performed previously on collagenous tissues such as tendons, bones and cartilage in an attempt to quantify the viscoelastic properties of the tissues at a fibrillar level and utilize them to explain their typical macroscopic behaviour (Fratzl et al., 1997; Gupta et al., 2010; Puxkandl et al., 2002). Fratzl et al. (1997) proposed a simple model explaining why the ratio of fibril-to-tissue strain increases with strain rate in the quasi-static range. They suggest that the proteoglycan-rich matrix becomes stiffer due to an increase of the viscous component as strain rate increases. Unfortunately, the maximum strain rate at which they tested was 0.001/s and so their observations are not adequate to demonstrate or explain potential changes in strength and modulus at strain rates experienced at injury.

Whilst work at slow rates is useful to understand behaviour in normal joint function and to choose replacement grafts, the application of these results to high-speed injury modelling may not be valid; significant error may occur if low strain-rate material properties are applied to simulations of traumatic injury. The limitations of previous work are likely to be caused by the technical difficulties of measuring stress and strain at rates that simulate high-speed injuries, such as motor vehicle collisions or battlefield injuries due to blast (Nagasaka et al., 2003; Ramasamy et al., 2011).

The aim of this study was to investigate the material properties of ligaments in a uniaxial tension model at strain rates in the range from 0.01 to 100/s. A porcine stifle joint ligament experimental model was designed to simulate the strain rates that may occur during a full range of different human knee ligament loading. The hypothesis was formulated that the strain-rate sensitive material properties of a ligament would diminish as strain rate increased. Studying ligament properties over a large order of magnitude of strain rates also provides an insight into the different structural explanations for their visco elasticity. Furthermore, time resolved synchrotron small angle X-ray scattering on human ligaments was used to investigate the deformation mechanisms at the nanoscale in an attempt to explain the strain-rate dependent behaviour of ligaments.

2. Methods

2.1. *Specimen preparation*

Ligaments of the porcine stifle joint were selected because of their similarity in morphology, size, structure, material properties and physiological loading to the human knee joint (Xerogeanes et al., 1998). Sixty porcine hind limbs were delivered to the laboratory on the day of slaughter from a local abattoir. Excess muscle bulk was removed from the limbs, which were then stored at −20 °C. All limbs were utilized within one month of slaughter to minimize any potential deterioration in their mechanical properties (Masouros et al., 2009). All limbs were from healthy female large-white pigs, aged between 9 and 12 months. The demographics of the pigs were controlled to limit the physiological variation in material properties, which is known to occur between sexes, age groups, pig breeds and in unhealthy subjects (Germscheid et al., 2011; Noyes and Grood, 1976).

Each hind limb was thawed at room temperature on the day of testing. The lateral collateral ligament (LCL) of the porcine stifle joint was isolated by removing skin, muscle, other joint ligaments and tibia, thus leaving the femur, LCL and fibula intact. A hand saw was used to cut a $15 \times 15 \times 25$ mm^3 bone block around the femoral attachment of the LCL. A similar bone block was created with the fibula by removing its rounded proximal margin and dividing it transversely at 40 mm in length. A thin longitudinal round segment of ligament was isolated along the posterior margin of each LCL, such that each ligament's fascicles were easily aligned, similar in length and would reliably fail in its mid-substance. The unwanted anterior segment was removed by separating the ligament via blunt dissection in line with the fascicles, and divided transversely both proximally and distally when the fascicles could no longer be easily separated; thus ensuring no structural damage. This created a test specimen with a long thin middle section of a relatively constant cross-sectional area, with a broad anchor at either end made of the bone blocks and fibrocartilage transition zone (Fig. 1).

Cross-sectional area was measured using a previously validated technique for use in soft tissues (Goodship and Birch, 2005). Each specimen was held under 1 N of tension and the mid-substance of the ligament was cast in a quick-setting, stiff alginate paste (Blueprint® cremix, Dentsply DeTrey, Germany). The solid alginate paste was cut perpendicular to the long axis of the construct after removal of the ligament. Digital photographs were taken of the cut sections of alginate paste at three different sites. Each photograph was converted into binary code, based on whether or not each pixel contained an image of the ligament cast. The number of pixels in each photograph was counted using a custom computer code (MatLAB, MathWorks Inc., Natick, MA, USA). The cross-sectional area was calculated by comparing the