Journal of Biomechanics 43 (2010) 463–468

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Geometry, time-dependent and failure properties of human meniscal attachments

Karen N. Hauch, Diego F. Villegas, Tammy L. Haut Donahue *

Department of Mechanical Engineering—Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA

ARTICLE INFO

Article history:
Accepted 29 September 2009

Keywords:
Meniscus
Knee
Horn attachments
Enthesis
Modulus
Material properties

ABSTRACT

Meniscectomies have been shown to lead to osteoarthritis and the success of meniscal replacements remains questionable. It has been suggested that the success of a meniscal replacement is dependent on several factors, one of which is the secure fixation and firm attachment of the replacement to the tibial plateau at the horn locations. To aid in the development of meniscal replacements, the objectives of the current study were to determine the time-dependent and failure properties of human meniscal attachments. In contrast to the time-dependent tests, during uniaxial failure testing a charge-coupled video camera was used to document the local strain and linear modulus distribution across the surface of the attachments. The lateral attachments were statistically smaller in cross-sectional area and longer than the medial attachments. The anterior attachments were statistically longer and had a smaller cross-sectional area than the posterior attachments. From the stress relaxation tests, the load and stress relaxation rates of the medial anterior attachment were statistically greater than the medial posterior attachment. There were no significant differences in the creep, structural properties or the ultimate stress between the different attachments. Ultimate strain varied between attachments, as well as along the length of the attachment. Ultimate strain in the meniscus region ($10.4 \pm 6.9\%$) and mid-substance region ($12.7 \pm 16.4\%$) was smaller than the bony insertion region ($32.2 \pm 21.5\%$). The lateral and anterior attachments were also found to have statistically greater strain than the medial and posterior attachments, respectively. The linear modulus was statistically weaker in the bony insertion region (69.7 ± 33.7 MPa) compared to the meniscus region (153 ± 123 MPa) and mid-substance region (195 ± 121 MPa). Overall the anterior attachments (169 ± 130 MPa) were also found to be statistically stronger than the posterior attachments (90.8 ± 64.9 MPa). These results can be used to help design tissue-engineered replacement menisci and their insertions and show the differences in material properties between attachments, as well as within an attachment.

1. Introduction

Menisci serve several important functions in the knee joint including load bearing and transmission across the joint (Walker and Erkman, 1975; Shrive et al., 1978; Radin et al., 1984). The geometry, composition, and firm attachment of the menisci to the tibial plateau allow it to bear and distribute load across the knee joint (Fithian et al., 1990; Renstrom and Johnson, 1990; Setton et al., 1999). Menisci are frequently injured and often treated by partial or total meniscectomy if the injury occurs in the avascular zone. Meniscectomies have been shown to lead to decreased contact areas, increased stress, and degeneration of articular cartilage (Baratz et al., 1986; Chen et al., 1996; Szomor et al., 2000; Zielinska and Haut Donahue, 2006). Therefore, meniscal replacements are under investigation. Effective meniscal replacements aim to restore the native contact mechanics of the knee. Factors affecting the function of meniscal replacements include: the method of fixation to the tibial plateau (Chen et al., 1996; Alhalki et al., 1999; Setton et al., 1999; Cole et al., 2003), the size, geometry and material properties of the replacement (Pollard et al., 1995; Setton et al., 1999).

Meniscal attachments are thought to be ligamentous and previous studies have characterized the time-dependent (Maes and Haut Donahue, 2006) and failure properties of bovine meniscal attachments (Villegas et al., 2007). Although these studies have provided more insight on meniscal attachments, one pitfall is that in the bovine knee the lateral posterior enthesis attaches to the femur unlike a tibial insertion in the human. The current study will expand the knowledge of the mechanical response of human meniscal horn attachments in order to aid in the development of more successful meniscal replacements. The objectives of the present study were to: (1) examine the stress relaxation and creep properties of human meniscal attachments, (2) determine the failure properties of human

* Corresponding author. Tel.: +906 487 2078; fax: +906 487 2822.
E-mail address: thdonahu@mtu.edu (T.L. Haut Donahue).

0021-9290/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2009.09.043

meniscal attachments, and (3) examine the local strain and linear modulus distribution across the surface of the attachments.

2. Materials and methods

2.1. Specimen preparation

Six human knees (51–67, average age 59 yr; 5 males, 1 female) were obtained from a national tissue bank and frozen (NDRI, Philadelphia, PA). The sample size used in this study was not large enough to study differences due to age or gender. Prior to testing, each knee was thawed at room temperature and dissected. A non-destructive method of accurately measuring the cross-sectional area of irregular shapes was used to measure the area (Race and Amis, 1996; Goodship and Birch, 2005). The length measurements were taken parallel to the collagen fibers at three locations: outer, middle, and inner (Fig. 1) and on both the proximal and distal surfaces of each attachment.

The tibia was potted in a steel tube and mounted in a custom-built 5 DOF fixture previously used (Maes and Haut Donahue, 2006). Meniscal attachments were loaded parallel to the collagen fiber orientation and tibial plateau, while bathed in 37 °C PBS using a servo-hydraulic uniaxial materials testing machine (Model 8872, Instron Corporation, Canton, MA) (Fig. 2). To ensure uniaxial tension and reduce slippage, a universal joint was used with a cryo-clamp. Care was taken to ensure that the zone of frozen tissue did not extend beyond the freeze clamp and the freeze line did not penetrate into the tissue being tested.

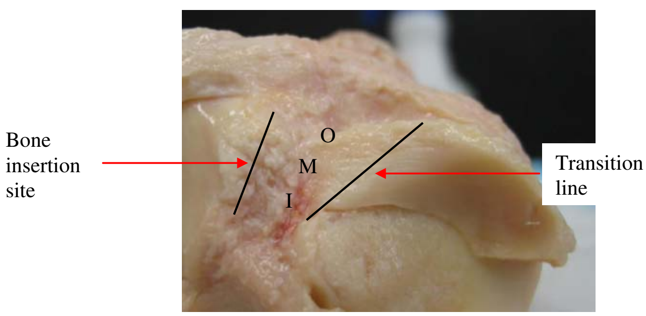

Fig. 1. Superior view of the lateral anterior (LA) attachment showing the transition from meniscus to attachment and the bone insertion site. Regions of length measurement are also labeled (outer—O, middle—M, inner—I).

The meniscus was gripped at the transition line between the meniscal tissue and attachment, while the tibia was held fixed. Each attachment was preconditioned for 10 cycles at 10 mm/min, between 0% and 3% of the gauge length using a sine wave (Maes and Haut Donahue, 2006). Each attachment of a given specimen was first tested for stress relaxation, followed by a recovery period (Maes and Haut Donahue, 2006) prior to a creep test. Lastly, following the creep test and a recovery period, each attachment was pulled to failure.

The stress relaxation test ramped to a deformation of 3% of the gauge length in 0.5 s and then held the deformation for 45 min (Hingorani et al., 2004). All four attachments were tested randomly from each specimen. The specimen was then placed at 4 °C and allowed to recover fully (Maes and Haut Donahue, 2006). The creep test ramped to the peak load determined from the stress relaxation test (Hingorani et al., 2004) in 0.5 s and was held for 45 min. Again, attachments were tested randomly and allowed to recover. The creep and stress relaxation rates were determined by plotting against the natural log of time and finding the slope using linear regression. One sample slipped from the grip during time-dependent testing, hence, that knee data was not included in the data analysis and results.

In order to increase the sample size for failure testing data, we tested 2 additional knees with an average age of 55, 1 female and 1 male. Testing of the additional knees was completed to ensure at least 5 samples of each attachment were tested. Not all sample sizes were equal to 8, however, since some samples slipped, errors with the data acquisition system occurred and some attachments failed at the grip interface. The pull to failure test ramped at a rate of $2\%\,s^{-1}$ (Lam et al., 1995; Quapp and Weiss, 1998). A 3×3 grid was created on the tissue surface, dividing the attachment into three horizontal regions and three longitudinal sections (Fig. 3). The meniscus (ME) region was defined as the upper region near the meniscus, the midsubstance (MI) was defined as the middle region of the attachment, and the bony insertion (BO) was defined as the lower region near the insertion into the bone. Longitudinally, the attachment was divided into outer, middle, and inner sections (Fig. 3). A charge-couple video camera (Model MicroPix M-1024 CCD camera, Ann Arbor, MI) recorded the motion of the markers. Pictures captured from the camera were analyzed using a custom-made processing program (MATLAB, version 7.4 (R2007a)) in order to calculate Green's strain (Villegas et al., 2007). Both structural and material properties were determined from the failure tests. To quantify the structural properties of the attachments the ultimate load (N), the ultimate elongation (mm), and the linear stiffness (N/mm) were determined. The linear stiffness was defined as the slope of the linear region of the load versus displacement plot and was determined using linear regression. To quantify the material properties of the attachments, the ultimate stress (MPa), the ultimate strain (%), and the linear modulus (MPa) were determined. The linear modulus was defined as the slope of the linear region of the stress versus strain plot using linear regression.

Averages and standard deviations were calculated for dimensional properties, stress relaxation and creep properties, structural properties, and ultimate stress for each of the four attachments and a one-way repeated measures analysis of

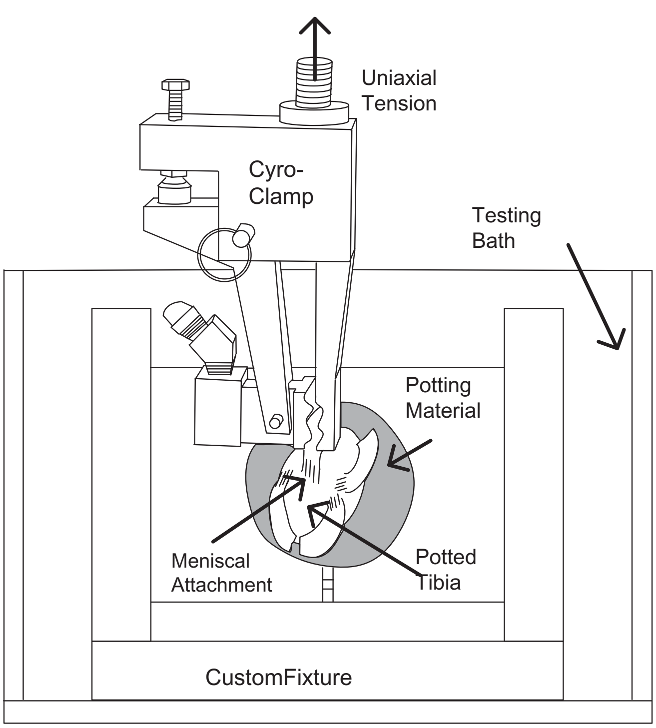

Fig. 2. Schematic of test set-up with fixture/bath assembly, clamp assembly, and loaded specimen.

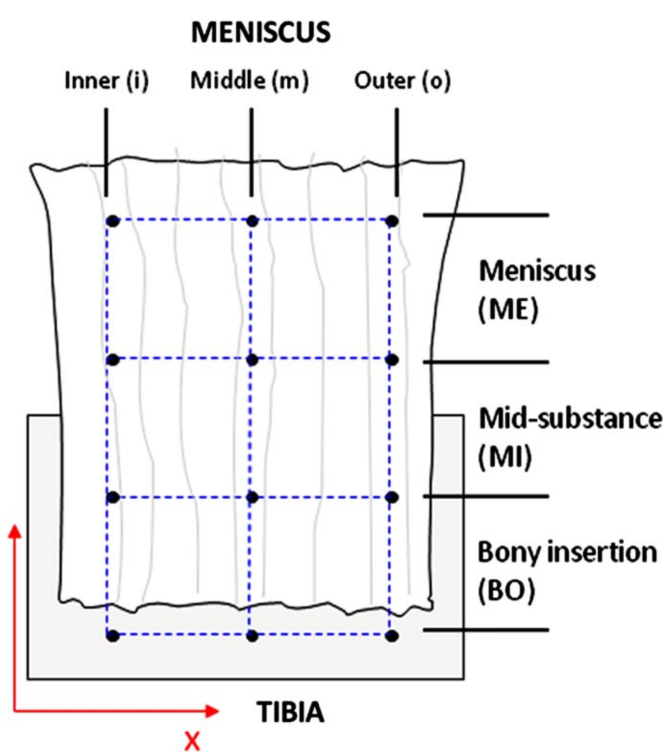

Fig. 3. Regions of meniscal attachment for strain analysis.