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Failure properties and strain distribution analysis of meniscal attachments

Diego F. Villegas, Jason A. Maes, Sarah D. Magee, Tammy L. Haut Donahue*

Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, MI, USA

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Abstract

The menisci are frequently injured due to both degeneration and traumatic tearing. 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. Therefore, the objectives of the current study were to (1) determine the failure properties of the meniscal horn attachments, and (2) determine the strain distribution over their surfaces. Eight bovine knee joints were used to study the mechanical response of the meniscal attachments. Three meniscal attachments from one knee of each animal were tested in uniaxial tension at 2%/s to determine the load deformation response. During the tests, the samples were marked and local strain distributions were determined with a video extensometer. The linear modulus of the medial anterior attachment (154 ± 134 MPa) was significantly less than both the medial posterior (248 ± 179 MPa, $p = 0.0111$) and the lateral anterior attachment (281 ± 214 MPa, $p = 0.0007$). Likewise, the ultimate strain for the medial anterior attachments ($13.5 \pm 8.8\%$) was significantly less than the medial posterior ($23 \pm 13\%$, $p < 0.0001$) and the lateral anterior attachment ($20.3 \pm 11.1\%$, $p = 0.0033$). There were no significant differences in the structural properties or ultimate stress between the meniscal attachments ($p > 0.05$). No significant differences in ultimate strain or moduli across the surface of the attachments were noted. Based on the data obtained, a meniscal replacement would need different moduli for each of the different attachments. However, the attachments appear to be homogeneous.

Key Words: Meniscus; Knee; Material properties; Meniscal replacement

1. Introduction

The menisci perform a variety of functions within the knee, but their most prevalent role is in weight bearing and load transmission across the knee joint (Morrison, 1970; Walker and Erkman, 1975; Shrive et al., 1978; Ghosh and Taylor, 1987; Renstrom and Johnson, 1990; Ahmed, 1992; Messner and Gao, 1998). The menisci are able to carry out this function due to their structural shape and firm attachment to the tibia (Shrive et al., 1978; Fithian et al., 1990; Renstrom and Johnson, 1990; Gao et al., 1998; Messner and Gao, 1998). When a meniscus is injured, two options are available to repair the damaged meniscus: surgical repair of the meniscal tear or a partial or full menisectomy (Ghadially et al., 1986; DeHaven, 1992; Newman et al., 1993; Asik and Sener, 2002). In the latter case, the procedure has been shown to lead to degeneration of the articular cartilage of the knee (Allen et al., 1984; McBride and Reid, 1988; Moon et al., 1988; Messner, 1999; Rodeo, 2001; Wyland et al., 2002). Therefore, if the meniscus must be removed, a sound option for its replacement must be readily available that can duplicate its biomechanical function.

While the material properties of meniscal tissue have previously been studied, meniscal attachments have received little attention. It has been shown that the meniscal attachments are important for restoring functionality to the knee (Chen et al., 1996; Goertzen et al., 1996; Paletta et al., 1997; Alhalki et al., 1999; Rodeo, 2001; Sekaran et al., 2002; Haut Donahue et al., 2003). Therefore, their time-dependent and failure properties need to be determined. We have already obtained the time-dependent properties of the meniscal attachments and found no

*Corresponding author. Tel.: +1 906 487 2078; fax: +1 906 487 2822.
E-mail address: thdonahu@mtu.edu (T.L. Haut Donahue).

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significant differences in creep or stress relaxation properties between the anterior and posterior attachments of the medial meniscus. However, there were significant differences in creep parameters between the lateral anterior attachment and the medial attachments (Maes and Haut Donahue, 2006). One other study has documented the peak failure loads of rabbit meniscal attachments with no values provided for the material properties (Goertzen et al., 1996). Therefore, study of the attachment mechanisms must be conducted to further the development of a successful meniscal replacement. The objectives of the present study are to (1) determine the failure properties of the meniscal horn attachments, and (2) determine the strain distribution over their surfaces.

2. Methods

2.1. Specimen preparation

Eight bovine stifle (knee) joints with an age range between 15 and 30 months were obtained from a slaughterhouse and frozen at −20 °C until the day of testing. From each animal, either the right knee or the left knee was randomly chosen for inclusion in the study. No attempt was made to study the differences between contralateral knees. On the day of testing, specimens were thawed at room temperature and disarticulated. All tissues were removed leaving only the proximal tibia with the menisci and their attachments intact. The attachments were cut leaving approximately 7 mm of the central third of the attachment intact. The tibia was cut around the insertion sites of the attachments leaving small bone blocks fastened to the meniscal horns. The bone blocks were potted within a custom fixture using commercially available fibre-strand body filler 6371 (The Martin Senour Company, Cleveland, Ohio) and left for approximately 15 min to set. A similar set-up has been used to test patellar tendons (Haut and Powlison, 1990; Haut and Haut, 1997) (Fig. 1). The menisci and attachments were kept moistened with saturated gauze throughout the preparation. The attachments were oriented physiologically within the fixture to replicate in situ loading conditions by aligning their collagen fibers parallel to the loading axis of the fixture.

After the filler had set, the fixture with the potted specimen inside was placed in a servo-hydraulic uniaxial materials testing machine (Model 8872, Instron Corp., Canton, Massachusetts). A custom designed "cryo-grip", which supplied liquid nitrogen into the back of the clamp to freeze the portion of the meniscus within the grip, was built to grasp the meniscal tissue (Riemersa and Schamhardt, 1982; Sharkey et al., 1995; Maes and Haut Donahue, 2006). A universal joint assured that uniaxial tension was applied to the test specimens.

The cross-sectional area of the attachments was measured at the midpoint of the attachment using an area micrometer and did not appear to change along the length of the attachment (Ellis, 1969; Allard et al., 1979). The lengths of the specimens were measured using digital calipers from the insertion into the tibia to the transition between the ligamentous attachment and the meniscal tissue. The medial anterior attachment (MA), medial posterior attachment (MP), and lateral anterior attachment (LA) were tested. In contrast to the human knee where all four meniscal horn attachments insert into the tibia, the posterior attachment of the lateral meniscus in the bovine knee inserts into the femur and thus was not included in the current study.

2.2. Mechanical testing

Each attachment was preconditioned for 10 cycles at 10 mm/min, between 0% and 3% of the gauge length using a sine wave. Immediately following preconditioning, a pull to failure test was performed. The pull to failure tests were conducted at 2%/s for all three attachments (Lam et al., 1995; Quapp and Weiss, 1998; Haut Donahue et al., 2001).

During the tests, the load, displacement, and time were recorded at 10 Hz using the system software (Wavemaker, INSTRON Corp., Canton, Massachusetts). As detailed below, markers were applied to the surface of the attachments and a charge-coupled video camera was used to record the pull to failure test and determine the strain distribution over the specimen surface. After preconditioning and pull to failure testing was performed on

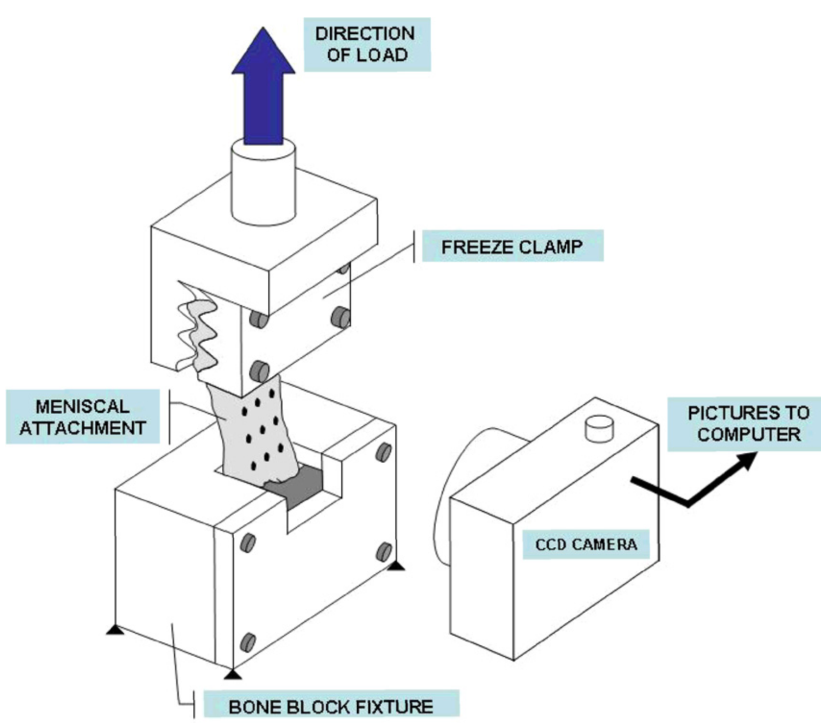

Fig. 1. Schematic of test set-up for meniscal attachments. A uniaxial tensile test was conducted at 2%/s using a hydraulic testing system.