Introduction

Assessing the quality of meniscus repair, replacement, and even tissue-engineering approaches requires knowledge of normal meniscus material properties. These properties, including aggregate modulus (stiffness of the solid matrix, $H_s$), permeability (ease of fluid flow through the matrix, $k$), and compressive strain at equilibrium ($\varepsilon_{eq}$), are stress-dependent as defined by biphasic theory [1], but this has not been explored experimentally in this tissue. A suitable animal model is also needed to research repair and replacement strategies, but studies comparing animal to human menisci have been limited [2]. In addition, proper controls are needed to investigate various treatments, but spatial variations in meniscal material properties complicate this effort.

Therefore, normal porcine and human menisci were tested in confined compression under three contact stresses (0.066, 0.196, 0.326 MPa) to 1) evaluate material property variation due to applied compressive stress, 2) determine species-related differences in material properties, and 3) ascertain whether repeated testing might permit intra-specimen controls to be used. The specific hypotheses to be tested were that 1) $H_s$ and $\varepsilon_{eq}$ would increase proportionally with increasing applied stress while $k$ would decrease due to pore size reduction upon tissue compaction, 2) porcine and human meniscal material properties would not differ, and 3) repeated testing in confined compression would not alter material properties.

Methods

Cylindrical specimens (3.0 mm dia, 1–2 mm thick) were obtained from medial and lateral menisci procured from five pairs of porcine knees (male and female mixed breed, skeletal immature 3–4 month old) and five unembalmed human knees (two right, three left) from four donors (all males, age 27–82 years, mean 61.8). Three specimens, each from a different location (anterior, middle, and posterior), were obtained from each meniscus. Each specimen was tested in uniaxial confined compression in specially designed testing systems under one of three compressive stresses until equilibrium displacement was reached. Porcine specimens were allowed to recover to at least 80% of their original height and were then re-tested in confined compression under conditions identical to those of the initial test. Porcine and human menisci also demonstrate similar material properties over a range of applied loads, which is important in identifying a suitable animal model for use in future meniscus research since healthy human menisci are scarce and animals are necessary for in vivo repair studies. One of the most useful findings from this study is that repeated testing in confined compression had no effect on porcine meniscal material properties. This allows a specimen to serve as its own control, eliminating the need to account for property variation with experimental results of 1.74 ± 0.19 (porcine) and 1.99 ± 0.79 x10^-4 m/Ns (human). Porcine and human menisci also demonstrate similar stress-dependent permeability relationship found in the current study using the stress of Joshi et al. [2] yields porcine and human values of 1.52 and 2.36 x10^-15 m/Ns, respectively, which correspond well to their experimental results of $1.74 \pm 0.19$ (porcine) and $1.99 \pm 0.79$ x10^-15 m/Ns (human).

Results

Porcine meniscus

The level of applied compressive stress had a significant effect on all material properties. Aggregate modulus increased with increasing stress across all levels ($p<0.001$; Fig. 1). Permeability decreased as stress increased from 0.066 to 0.196 MPa ($p>0.01$; Fig. 2) and further decreased in specimens subjected to a second confined compression test as stress increased to 0.326 MPa ($p<0.001$). Equilibrium strain increased with increasing stress from 0.066 to 0.326 MPa ($p<0.015$). Mean specimen height was significantly reduced by 9.2% and 12.1% for specimens tested at the 0.196 and 0.326 MPa level, respectively, to initial testing ($p<0.001$). However, subsequent testing in confined compression did not significantly alter $H_s$ ($p>0.61$; Fig. 1), $k$ ($p>0.13$; Fig. 2), or $\varepsilon_{eq}$ ($p>0.55$) at any stress level.

Human meniscus

As with porcine menisci, applied stress affected all material properties. Aggregate modulus increased with stress across all levels ($p<0.001$; Fig. 1). Permeability decreased as stress increased from 0.066 to 0.196 MPa ($p<0.001$; Fig. 2), but was unchanged by increasing stress to 0.326 MPa ($p>0.52$). Equilibrium strain increased with applied stress ($p<0.007$). In comparing human meniscal material properties to those of porcine, no differences were detected between the species for any material property at any stress level ($p>0.075$).

Discussion

Establishing the load-dependent behavior of meniscal material properties is essential for constructing mathematical models to predict dynamic tissue behavior and allows for comparisons between experiments that use different testing conditions. For instance, solving the stress-dependent permeability relationship found in the current study using the stress of Joshi et al. [2] yields porcine and human values of 1.52 and 2.36 x10^-15 m/Ns, respectively, which correspond well to their experimental results of $1.74 \pm 0.19$ (porcine) and $1.99 \pm 0.79$ x10^-15 m/Ns (human). Porcine and human menisci also demonstrate similar material properties over a range of applied loads, which is important in identifying a suitable animal model for use in future meniscus research since healthy human menisci are scarce and animals are necessary for in vivo repair studies. One of the most useful findings from this study is that repeated testing in confined compression had no effect on porcine meniscal material properties. This allows a specimen to serve as its own control, eliminating the need to account for property variation with location and thereby reducing subject numbers to result in a more efficient experimental design.

References


Listing for additional author affiliation

**University of Cincinnati, Cincinnati, OH

*** Stress Engineering Services, Inc., Mason, OH