INTRODUCTION

More than 1 million procedures for the total or partial removal of the meniscus are performed in the United States and Europe each year. Damage to the meniscus can destabilize the knee and predispose the joint to further degenerative changes. As such, great interest exists in developing implants for the treatment of meniscal tears.

Previous studies showed promising results in the regeneration of tissue in meniscal lesions in dogs using degradable porous polymer scaffolds [1,2]. In spite of the important role of the meniscus as an articular load-bearing surface, little information is available on the mechanical behavior of the resultant meniscal tissues.

Frictional properties may be particularly important, since the meniscus articulates against articular cartilage during the gait cycle. Specifically, boundary mode frictional properties of this neo-tissue are of great interest, because these conditions produce the highest friction coefficient (μ) and are thus most likely to induce damage to the apposing tissue. Therefore, we sought to quantify the boundary mode friction coefficient of engineered meniscal repair tissue in sheep over the course of 1 year.

METHODS

All animal studies were carried out under the guidelines of the Institutional Animal Care and Use Committees at the Hospital for Special Surgery and Colorado State University. Briefly, fourteen healthy, skeletally mature sheep underwent longitudinal resection of the medial section of the meniscus. The lesion was replaced with an engineered polyurethane foam [1] that was sutured to adjacent meniscal tissue. Right knees only were implanted and left knees were left intact as controls. Joints were allowed full range of motion; all sheep were allowed to walk normally as soon as possible.

Animals were sacrificed at 3, 6, and 12 months, and the menisci removed for evaluation. Operated knees and contralateral knees were dissected, and 4 mm cores taken with a biopsy punch. Samples were cored from the scaffold region, from the anterior and posterior horns adjacent to the scaffold, and from the contralateral intact knee. Cores were immediately frozen, then thawed and cut to 2 mm thickness just prior to testing.

For friction testing, samples were divided into three groups: meniscal samples cored from the scaffold region (SC), native meniscus adjacent to the implanted scaffolds of the right knee (AJ) shown in Figure 1, and native meniscus from the contralateral intact knee (CL). The scaffold constructs and native tissue controls were tested in a custom friction apparatus previously described [4]. In brief, the linearly oscillating friction apparatus placed a normal strain on the tissue and regulated the relative speed between samples and a glass articulating surface. A custom biaxial load cell simultaneously measured the normal and frictional shear loads on the sample. The resulting equilibrium friction coefficient (μ_eq, the ratio of the normal load to the shear load when the engineered sample has fully relaxed from the applied normal strain) was calculated via a Matlab code. During testing, tissue samples were submerged in a lubricant bath of either PBS with complete protease inhibitor or equine synovial fluid (ESF). A Stribeck surface [4] was created to determine the entraining speeds and normal strains to produce boundary mode lubrication for native meniscus lubricated with PBS. Friction coefficient, μ, was measured over a range of entraining speeds from 0.2 mm/s to 30 mm/s and normal strains from 10% to 40%. The region of speed/strain space that yielded relatively invariant μ was considered boundary lubrication.

All data are presented as mean ± standard deviation. The effect of lubricant, location and implantation time on μ_eq was determined using two factor analysis of variance (ANOVA).

RESULTS

Both native meniscus tissue and scaffold implants exhibited frictional behavior well described by Stribeck surfaces [4], with distinct regions of boundary and mixed lubrication modes in PBS for CL native meniscus (Fig. 2a) and scaffolds (Fig 2b). The boundary mode friction coefficient (μ_eq) was similar for adjacent (AJ) and contralateral (CL) tissue, ranging from 0.11 ± 0.03 in ESF to 0.33 ± 0.11 in PBS (Fig. 3). As described previously [5], the friction coefficient of the unimplanted scaffold (SC) was 3-4 fold higher than CL or AJ tissue (p<0.05).

Boundary mode μ_eq for SC implants decreased with time, Fig. 3. By 3 months μ_eq was 0.11 in ESF, similar to AJ and CL tissue, but μ_eq was 0.45 in PBS, which was significantly higher than AJ and CL tissue (p<0.05). At 6 and 12 months, μ_eq of SC implants was ~0.15 in PBS and ~0.35 in PBS, and were not statistically different from CL and AJ tissue.

DISCUSSION

In this study, boundary mode μ_eq was measured for repair tissue formed in scaffolds implanted in meniscal defects in sheep over the course of one year. The μ_eq of engineered meniscus improved with time and was similar to native tissue after 6 months. Tissue ingrowth into the polyurethane scaffold [6] likely caused improvement in the frictional performance of the scaffold. The similarity of μ_eq of CL and AJ samples indicates that the frictional behavior of the native meniscus adjacent to the implants was not adversely affected by scaffold placement.

The region of boundary mode friction behavior was broader for SC samples at 3 months as shown by the larger region of constant μ_eq in Figure 1b, likely due to higher permeability of this early repair tissue into porous scaffolds is an important strategy for improving mechanical performance in meniscal repair.

REFERENCES


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