Mechanical Characterization of UHMWPE-PVA Fibrous Composites For Meniscal Replacement

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Statement of Purpose: The meniscus is a C-shaped fibro-cartilage disc and is the most commonly injured tissue in the knee. The current treatment of choice for an unrepairable meniscal tear is a partial meniscectomy; however, this is known to lead to joint degeneration.[1] The meniscus is capable of handling significant loads, with a tensile modulus in the range of 3-295 MPa and a compression modulus of 0.22 MPa.[2] A fiber reinforced polymer-based synthetic meniscus allows tailoring of the mechanical properties and molding of the implant to the size and shape of the native cartilage. Specifically, the research outlined in this paper focuses on the use of a poly(vinyl alcohol) (PVA) hydrogel, a known biocompatible material that can be synthesized to mimic the properties of soft tissue,[3] reinforced with ultra high molecular weight polyethylene (UHMWPE) fibers. The purpose of this study was to evaluate the composite mechanically and determine its suitability as a meniscal replacement.

Methods: Physically cross-linked PVA hydrogels were synthesized using freeze-thaw cycles with UHMWPE fibers added for reinforcement. Composites were synthesized using a manual fiber lay-up technique. Compressive and tensile modulus were determined for various compositions and synthesis parameters of the PVA hydrogels and/or composites. Microstructure and crystallinity analysis were performed to lend insight into the processes occurring during freeze-thaw cycling and their relationship with modulus. The swelling response was characterized using a poly(ethylene glycol) (PEG) based osmotic solution to model the swelling pressure of the knee *in vitro.* For composite materials, a limited swelling response is desired to prevent interfacial failure.

Human cadaveric knee studies were performed using a gait simulator to compare contact pressures on the tibial plateau during gait for an UHMWPE-PVA composite to an intact meniscus, no meniscus, and an allograft.

Results: The compressive modulus of PVA hydrogels varied between 0.0012 and 0.85 MPa, similar to aggregate compressive modulus values reported for the meniscus[2], with increasing values occurring at higher freeze-thaw cycles and polymer concentrations.

An investigation of PVA crystallinity showed significant increases occurring through the first 3 freeze-thaw cycles; however, changes were noted in modulus through the first 6 cycles. Microstructure analysis shows ripening of the PVA pore structure, where areas of high concentration of PVA form, through 6 cycles.

UHMWPE fiber reinforcement was added to the PVA hydrogel in order to increase hydrogel tensile modulus. UHMWPE-PVA composites demonstrated improved tensile properties, with a modulus of 0.23 ± 0.02 MPa without any reinforcement to 258.1 ± 40.1 MPa at 29 vol% UHMWPE. This corresponds to the tensile modulus range reported of the native meniscus, 3-295 MPa.[2]

Swelling response determined in a PEG based osmotic solution showed sample equilibration after 14 days with equilibrium water content dependent on initial polymer concentration. Limited swelling was observed to occur between 30 and 35 wt% PVA. No dependence was found between freeze-thaw cycles and equilibrium water content as shown in Figure 1.

Human cadaveric knee studies showed improved contact pressures on the tibial plateau during gait for the UHMWPE-PVA composites compared to a meniscectomy. However, results were not comparable to an intact meniscus.

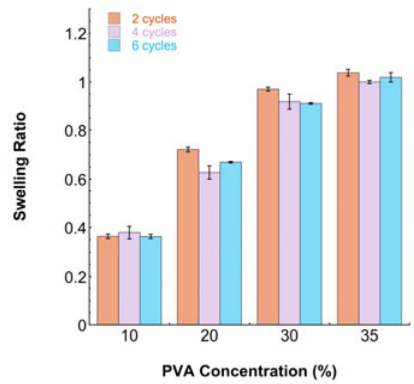

Figure 1. Swelling ratio (weight/initial weight) as a function of polymer concentration and freeze-thaw cycles.

Conclusions: An investigation of hydrogel and composite tensile and compressive modulus indicates fiber-reinforced PVA hydrogels could replicate the unique anisotropic modulus distribution present in the native meniscus. Additionally, analysis of the changes in crystallinity and microstructure of PVA with cycling indicate the presence of multiple mechanisms, cross-linking and ripening of the PVA structure, as causes for increasing hydrogel modulus with freeze-thaw cycling. Swelling ratio was shown to be entirely dependent on initial polymer concentration. This allows the tailoring of PVA modulus and swelling ratio through modulation of polymer concentration and freeze-thaw cycles to achieve a specific swelling ratio and compressive modulus.

Preliminary human cadaveric gait simulations of this implant show promise; however, future work will need to focus on mimicking meniscal behavior through precise design of the composite material.

References:

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