Confined and Unconfined Creep: A Comparative Study of Swine Cartilage and PVA Hydrogels

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Introduction: Studies have shown that Polyvinyl alcohol (PVA) can be made into biocompatible, lubricous, and tough hydrogels that can survive the loading environment in joints, making them ideal biomaterials for cartilage replacement therapy. Due to the nature of skeletal loading, creep is one of the more physiologically relevant means to quantify mechanical properties of artificial cartilage constructs. Creep is investigated either in a confined setting, as is the case with a hydrogel osteochondral plug that is replacing a focal cartilage defect, or in an unconfined setting, as with an interpostional device that is replacing a damaged meniscus. Under a 3-parameter biphasic viscoelastic Kelvin-Voight model [1], creep behavior can be described in terms of the immediate elastic response of the cartilage matrix, and the time-dependent viscoelastic response due to fluid pressurization within the cartilage. The theoretical elastic and viscoelastic values of various PVA hydrogels and swine cartilage under confined and unconfined conditions were compared to experimental data.

Materials and Methods: Hydrogels were made by dissolving 25wt% Polyvinyl alcohol (PVA) in de-ionized (DI) water at 90°C, with either 1.25wt% Polyacrylic acid (PVA-PAA), 28wt% Polyethylene glycol (PVA-PEG), or 15wt% Polyacrylamide (PVA-PAAm). The resulting hydrogels were dehydrated in PEG, annealed, and then hydrated in DI water. A non-annealed PVA-PEG (control PVA) hydrogel was prepared as a control. Harvesting of cartilage: The 6mm articular cartilage samples were harvested from the lateral trochlear grooves of three young Yorkshire swines shortly after euthanasia. Creep: Custom creep testers were used to load samples to 3.5MPa compressive stress for 1hr followed by rapid decrease to 0.35MPa for 1hr in 40°C DI water. The elastic and viscoelastic components of the total creep strain and total recovery was reported. A porous ceramic well was used to radially confine the samples for the duration of the confined creep tests. Modeling: The resulting creep strain data was retrofitted to a 3-parameter Kelvin-Voight model to determine elastic spring constants (K_I,K_P,K_R), and viscoelastic damping coefficient (η). The primary and secondary time constants (1° τ, 2° τ), the time it took to reach 63.2% and 86.5% of the total creep strain (TCS), respectively, were also calculated.

Results: PVA-only hydrogels showed the least amount of creep (Figure2). No hydrogel or cartilage samples recovered to their initial dimensions in the allotted relaxation time. The elastic strain was more pronounced when the hydrogels were unconfined. In general we observed higher creep strain with increasing EWC. As shown in Table1, the confined and unconfined 1° τ for lower EWC hydrogels (PVA, PVA-PAA) were similar but higher EWC hydrogels had higher 1° τ when confined. The 2° τ for unconfined hydrogel creep was also much lower than when confined. Swine cartilage's 1° τ and 2° τ, however, were similar independent of confinement.

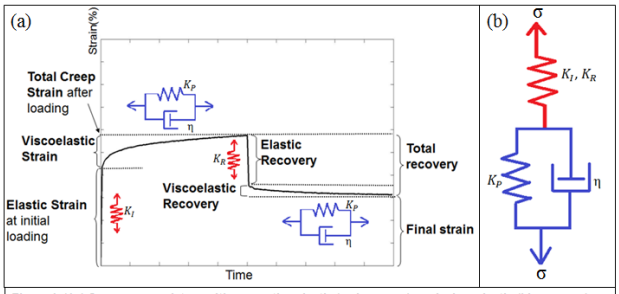

Figure1. (1a) Creep nomenclature with respective elastic (red: K_I, K_R) and viscoelastic (blue: η, K_P) components. (1b) Final 3-parameter Kelvin-Voight model.

Discussion: The purpose of this study was to develop an experimental and analytical method to investigate the confined and unconfined creep behavior of articular cartilage, PVA-only, and PVA-based hydrogels. PVA-based hydrogels had a secondary polymer such as non-ionic PAAm or ionic PAA in an attempt to mimic the functional groups in cartilage. The significant differences between the PVA-only hydrogels and the PVA-PAA, PVA-PEG, and PVA-PAAm hydrogels is probably due to the varying degrees of crystallinity of PVA in these different gel networks [2]. While the total creep resistance of the PVA-PAAm and PVA-PAA hydrogels was less than that of PVA, their higher EWC allowed them to have a viscoelastic response [2] similar to swine cartilage creep behavior, as was evident both experimentally and analytically. All hydrogel creep strains were proportional to EWC but significantly more so when unconfined, contrary to cartilage behavior. K_R values were expectedly higher than K_I for all hydrogels and cartilage due to the non-recovered total creep strains. We hypothesize that unconfined creep is higher than confined creep because

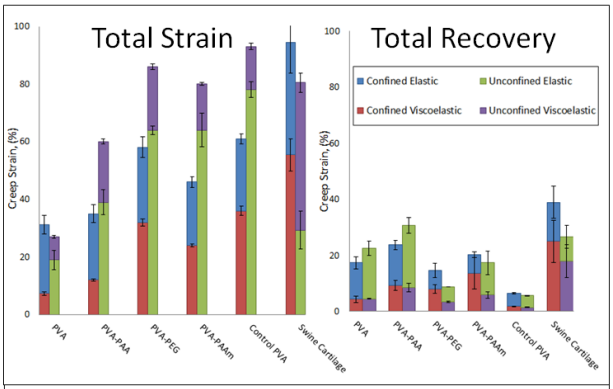

Figure 2. Creep and recovery strains broken into their elastic and viscoelastic components. The hydrogels are listed in order of increasing EWC from left to right.

the unconfined scenario allows for radial deformation, whereas the confined creep is primarily due to water loss. Our model efficiently simplified complex viscoelastic creep behaviors of cartilage and hydrogels alike into a tangible set of numerical constants.

References: [1] Ateshian GA *et al.*, J.Biomechanics. 1997; 30: 1157-64 [2] Bodugoz-Senturk H *et al.*, Biomaterials. 2009; 30: 589-96.