Viscoelastic Recovery of the Human Intervertebral Disc is Much Slower than Creep

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INTRODUCTION:

Intervertebral disc hydration strongly influences its mechanical behavior, [1] including the time-dependent viscoelastic properties. Disc hydration is controlled by fluid flow into and out of the disc, which is continually re-balancing under externally applied load (fluid outflow) and internal osmotic pressure (fluid inflow). Although several creep studies have been performed to quantify the loading response, there still remain questions regarding the time course and pathways for fluid motion. [2, 3] Moreover, the recovery response following unloading has not been quantified, although the recovery time has been suggested to be greater than the loading time. [3-6] Quantifying both the loading and recovery response is critical for understanding the disc function, degeneration, diurnal loading, fluid flow equilibrium, and nutrition. **The objective of this study was to measure the creep and unloaded recovery behavior of human lumbar motion segments and quantify these responses using a viscoelastic model.** We hypothesize that the time for the disc to recover its initial disc height will occur at a slower rate than the height loss during creep loading.

METHODS:

Human lumbar spines were acquired from an IRB approved protocol (n=12, 25-76 years). Bone-disc-bone motion segments were prepared from the L2-L3 level. Samples were potted in bone cement and allowed to hydrate overnight prior to mechanical testing. A 20N preload was applied to the samples to ensure contact with the loading platen. A creep load of 1000N was rapidly applied in 1.5s and held for 4 hours. The sample was then rapidly unloaded to the 20N preload and allowed to recover to its original disc height for up to 24 hours. Force and displacement values were recorded during creep loading and recovery.

The creep and recovery response was curvefit (lsqcurvefit, Matlab Inc.) to a 7 parameter model composed of three Voigt Solids and a spring in series:

$$d(t)=\sum_{i=1-3}\frac{L}{S_i}\left(1-e^{-\frac{t*S_i}{\eta_i}}\right)+\frac{L}{S_4}$$

Model parameters S_i and η_i represent the elastic and viscoelastic damping coefficients, respectively. L, d and t represent the applied load, displacement and time, respectively. Time constants were defined as η/S. The superposition principle was used to incorporate the creep loading history when modeling the recovery behavior of the sample. The percent of recovery was calculated from the experimental data as the displacement during recovery divided by the displacement during creep. The equilibrium displacement was determined by the model parameters at $t = \infty$, where the viscous effects have dissipated. The time to reach equilibrium was defined at 99% of the equilibrium displacement. A paired t-test was used to compare the creep and recovery time constants and amplitudes. Significance was set at $p \leq 0.05$.

RESULTS:

The model fit the experimental data very well ($R^2 = 0.997$; Fig 1). Equilibrium was predicted at 13.5 hours for creep (displacement 3.27 ± 0.66 mm) and at 42 hours for recovery (displacement 2.46 ± 0.33 mm); 0.8 mm of displacement was predicted to be unrecoverable. The experimental data did not reach equilibrium during testing (Fig 1): creep reach 88 ± 4% of equilibrium displacement and recovery reached 95 ± 3%. The samples only recovered 70 ± 16% (range = 49 – 98%) of the disc height loss during creep, with only two samples reaching their initial disc height value (grade = 1.8 for both).

The seven-parameter model produced three time constants; the first was on the order of 2 seconds, while the other two were on the order of minutes and hours. Since the 2 sec time constant was similar to the 1.5 sec ramp time, it was assumed to be part of the initial elastic response and added to L/S_4. This effectively reduced the model to a 5-parameter model with an initial elastic response and two exponential responses over a short time (minutes) and a long time (hours). The creep elastic response (1.31 ± 0.44 mm) was 3X the recovery elastic response (0.46 ± 0.11 mm; $p < 0.0001$; Fig 2). The amplitude of the creep short response (0.44 ± 0.25 mm) was 45% greater than the recovery short response (0.30 ± 0.09 mm; p=0.04; Fig 2). The amplitude of the long response was not different between creep and recovery, and was 46% of the total creep deformation and 64% of recovery deformation. The short time constant for recovery was 8X longer than creep; the long time constant was 3X longer for recovery (p<0.001; Fig 3).

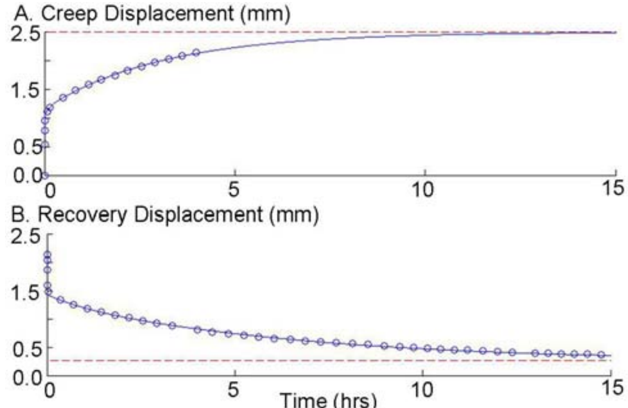

Fig 1: Representative figure of the A) Creep & B) Recovery behavior. Equilibrium displacement and experimental data (not all data points shown) is denoted by the dotted red line and circles, respectively.

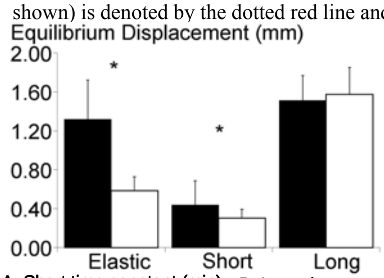

Fig 2: Equilibrium displacements of the elastic, short and long response for creep (black) and recovery (white). * p < 0.04.

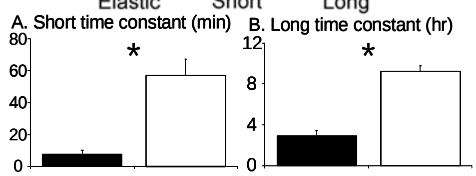

Fig 3: A) Short & B) long time constants for creep (black) and recovery (white). * p < 0.0001.

DISCUSSION:

This study quantified the creep and recovery response of human lumbar motion segments. The creep equilibrium time in this study is comparable to previous experimental measurements of 15 hours to creep equilibrium; [7, 8] these are the first data for recovery equilibrium. The model predicted that the disc would reach recovery equilibrium after 42 hours, which is three times longer than the equilibrium time under creep load (13.5hrs). This suggests that pressurization from applied load causes fluid to flow out of the disc at a greater rate than passive diffusion of water into the disc during recovery. The pathway of fluid flow (i.e. flow via the endplate or AF) during the short and long time response remains unknown. Furthermore, the disc generally did not reach its initial disc height even at equilibrium state. This may be explained by a state of super-hydration of the sample by allowing overnight hydration at 0N rather than the preload of 20N.

The disc has been suggested to recover disc height *in vivo* during 8 hours of bed rest. [4] However, the long time constant reported here does not support full recovery within 8 hours. This observation suggests that *in vivo* the disc is in a ***steady state*** condition, not an ***equilibrium*** one. The observation for increases in disc height following space flight and bed rest support this contention. [9, 10] In conclusion, the recovery of disc height *in vitro* is significantly slower than the disc height loss.

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REFERENCES: [1] Costi+ Spine: 33(16) 2008; [2] Ayotte+ JOR: 19(6) 2001; [3] van der Veen+ J Biomech: 40(10) 2007; [4] Adams+ Spine: 12(2) 1987; [5] Tyrell+ Spine: 10(2) 1985; [6] O'Connell+ 54th ORS 2008; [7] Burns+ J Biomech: 17(2) 1984; [8] Masuoka+ Spine: 32(18) 2007; [9] Park CO Yonsei Med J: 38(1) 1997; [10] Wing PC+ Orthop Clin North Am: 22(2) 1991