Comparing Human and Porcine Lumbar Spinal Unit Primary Creep in Combined Loading with a Viscoelastic Model

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INTRODUCTION: Lower back pain (LBP) is a prevalent disorder among adults, yet its etiology is poorly understood. Epidemiology suggests development of LBP may be associated with repetitive combined bending-compression loading of the lumbar spine, such as the conditions experienced by high-speed watercraft or helicopter operators. Characterizing the behavior of the lumbar spine under these conditions is both essential and highly relevant to mitigating LBP. To achieve this, it is crucial to characterize the lumbar spine's mechanical dynamic response in terms of viscoelasticity that models the influence of loading history and time-dependency on spinal response. However, the viscoelastic properties of the lumbar spine under cyclic combined loading remain unknown, highlighting a gap in current research. This study uses a mathematical model to compare the initial mechanical responses of human and porcine lumbar functional spinal units subject to repeated flexion-compression loading, leveraging the commonly used porcine lumbar spine as an animal surrogate for its human counterpart. Focusing specifically on the differences in primary creep behavior between human and porcine surrogates, we aspire to enhance our understanding of lumbar spine injury predisposition, thereby improving the evaluation of porcine surrogates as a suitable model for the human counterpart. This comparison seeks to provide orthopedic professionals with insight that can contribute to refining comprehension of lumbar spine mechanics and potentially inform clinical considerations related to lower back health.

METHODS: Fifteen porcine and nine human functional spinal units (FSU), consisting of two lumbar vertebrae and an intervertebral disc, were exposed to cyclic compression at 1 Hz and offset cyclic flexion using a biaxial test apparatus. Each FSU was subject to flexion from 0° to 6° while the maximum compressive load applied ranged from 600N to 2600N depending on the specimen. *In vivo* conditions were approximated by loading in an environmental chamber supplying body temperature and 100% humidity. Distance between endplates and average endplate cross-sectional area were measured prior to testing from high-resolution computed tomography (MicroCT) images. Anthropometry was used with force and displacement data to derive stress and strain for a primary creep model. Displacement data were filtered with an 8th order phaseless low-pass Butterworth filter with a 0.1 Hz cutoff frequency to smooth data oscillations for slope assessment. The model assumed quasilinear viscoelasticity (QLV) with separable time-dependent (creep) and load-dependent (instantaneous elastic) responses. The creep response was estimated based on a generalized Kelvin-Voigt model with two time constants (β_1, β_2) and three associated creep coefficients (J_1, J_2, J_0), which represent the short-time, long-time, and non-transient response contributions to the overall creep. The nonlinear instantaneous elastic response was modeled using a Fung exponential form with two instantaneous elastic parameters (A, B). Values for each parameter were determined using an arbitrary time history integration of the history integral that minimized the sum of squares error (SSE). Time constants were iteratively optimized so that they were consistent across each test. Creep and instantaneous elastic parameters were independently optimized for each test. Statistical comparisons between parameters and subject characteristics were made using analysis of variance (ANOVA).

RESULTS: Mechanical tests were performed on 24 specimens, comprising twelve porcine and four human lumbar spines. The conclusion of primary creep was identified through an inflection in displacement time history, with test durations averaging 380±230 seconds for modeling analysis. The creep model consistently exhibited a strong fit with experimental data, yielding a mean R^2 of 0.990±0.012. Optimized time constants were determined for each species, resulting in similar timescales between species with β_1 values of 7s for human and 24s for porcine specimens, as well as β_2 values of 311s for human and 593s for porcine specimens. Creep coefficients J_1 and J_2 are significantly different ($p<0.05$) between species where $J_{1,human}$= 0.34±0.04, $J_{1,porcine}$= 0.20±0.03, $J_{2,human}$= 0.16±0.04, and $J_{2,porcine}$= 0.30±0.03 (Figure 1), while the non-transient creep coefficients did not have a significant difference ($J_{0,human}$ = 0.50±1E-3, $J_{0,porcine}$ = 0.50±4E-5). The instantaneous elastic response curves also exhibited significant differences, as depicted in Figure 2.

DISCUSSION: This quasilinear viscoelastic creep model accurately fits strain values to experimental data with time and stress input for both human and porcine specimens (R^2=0.990±0.012). The dominant non-transient creep coefficient J_0 contributes 50% of the creep response to both species. Notably, the short strain-rate coefficient J_1 plays a larger role than J_2 in human models, while the reverse is true for porcine models, suggesting different time frames for creep behavior. The human instantaneous elastic response curve shows smaller strain values than the porcine instantaneous elastic response curve when at equivalent stress values. Thus, the human FSU model exhibits stiffer load-dependent creep on a shorter time scale compared to the porcine FSU. This analysis was performed for combined flexion-compression loading at 1 Hz frequency. These results are not necessarily applicable to frequencies outside the current testing parameters nor other loading conditions such as extension or tension. Overall, this study suggests effective representation of primary creep in both the human and porcine lumbar spine subject to cyclic flexion-compression using a generalized Kelvin-Voight quasilinear viscoelastic model and demonstrates significant creep differences between the two species that should be considered when using porcine surrogates.

SIGNIFICANCE/CLINICAL RELEVANCE: This study established a primary creep model for human and porcine lumbar spines subject to cyclic flexion-compression loading, capable of predicting lumbar displacements from an input load and arbitrary time history. These results improve our understanding of the viscoelastic creep response of the lumbar spine, how human and porcine lumbar spines differ under combined loading, and will inform injury prediction modeling in future efforts by biomedical engineers and orthopedic specialists.

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IMAGES AND TABLES:

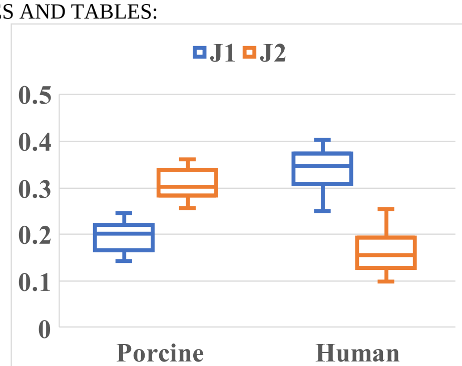

Figure 1: Comparison of short and fast strain-rate creep constants.

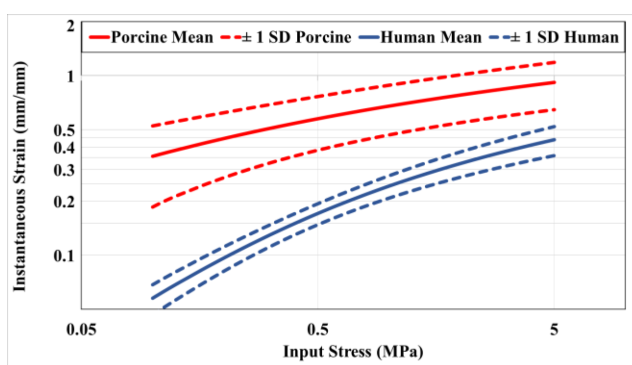

Figure 2: Comparison of instantaneous elastic response curves with arbitrary stress input.