Analysing Biomechanical Response Curves and How Statistics Expose Physiology

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I. INTRODUCTION

The viscoelastic nature of biological tissue may be explored through the study of creep response. The ideal method for statistically comparing lumbar spine creep response for various loading regimes, especially considering the entire load duration, is unclear. Current methods determine statistical difference in overall creep, but do not provide detail on how responses may differ [1-3]. This study explores multiple statistical methods for comparison of creep response between cyclic and static loading of lumbar spinal units. Herein, statistical approaches are identified to compare creep responses, allowing for determination of when responses may differ and what this may suggest about the underlying physiology. Presented statistical methods can be applied to various biomechanical behaviour curves.

II. METHODS

Experimental Testing

Porcine lumbar functional spinal units (FSUs) were tested in combined flexion compression loading. Four FSUs underwent cyclic loading and five underwent static loading, for a total of nine test specimens. Total applied peak stress was consistent at 4.15 MPa between the two loading regimes. The cyclic loading regime was modeled after measured lumbar accelerations of high-speed watercraft occupants [4]. The cyclic loading regime consisted of a 1 Hz sinusoidal compression wave with an offset 1 Hz flexion ramp. Flexion angle varied between 0° and 6° for cyclic tests. The static loading regime held flexion and compression constant throughout the tests. The static flexion angle was set to 5° based on a previous study that produced an equivalent creep response in static loading conditions as the cyclic loading creep response [5]. FSUs were paired by spine, such that one FSU from a spine underwent cyclic loading and the other one or two FSUs underwent static loading. FSUs were cyclically loaded until suspected endplate failure. FSUs undergoing static testing were loaded for at least the same duration as the paired cyclic test. Engineering strain was calculated from the distance between endplates adjacent to the intervertebral disc (IVD) obtained from pretest micro-CT scans. Normalised displacement-time data were used to define strain-time histories for statistical analyses.

Statistical Approach

One non-parametric (Kolmogorov-Smirnov (K-S) test) and two parametric (ANCOVA and combined ANOVA with linear regression) statistical methods were used to compare the mechanical responses between cyclic and static loading. The non-parametric test did not require any further manipulation of data to compare the distributions. Parametric tests relied on least squares regression, and creep response is nonlinear; thus, data were linearised using the Hill equation before parametric analysis. ANCOVA had a response variable of linearised strain and factors of regression phase and loading regime. Time in the log domain was the covariate. Additionally, ANOVA was used in combination with linear regression to assess slope differences among the groups. Linear regression captured the slopes of the data in each regression phase (from linearisation), and then ANOVA allowed for the comparison of slopes among groups. Global testing was first carried out. Then, if interaction terms showed significance, the data were subdivided, and lower-order analysis was carried out. Results from statistical methods were compared. Significance was assumed at $p<0.05$ for all statistical methods.

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III. INITIAL FINDINGS

All statistical methods found significant differences in curvature of the creep response between cyclic and static loading. Statistical difference in the K-S test is determined by two variables: the test statistic and the critical value. When the test statistic is greater than the critical value, the two distributions are statistically different. The K-S test resulted in a difference in the overall distributions of the loading regimes accounting for the entire test duration (test statistic: 0.274 > critical value: 0.074). Data linearisation for parametric analyses did not result in linear Hill plots but resulted in Hill plots with multiple phases (Fig. 1). Due to this, the curvature of the data was used to define start and end points for each phase objectively. Data were analysed based on the linear phases. Global ANCOVA found a statistical difference between loading regime and regression phase ($p<0.001$). A significant difference was seen between loading regimes for both linear phases using ANCOVA when data were divided by linear regression phase ($p<0.001$ for both phases). Also, a significant difference in slopes of linear regression phases was found with global ANOVA ($p<0.005$). Subdividing by regression phase, ANOVA resulted in significant differences between loading regimes: $p<0.04$ for the first phase and $p<0.007$ for the second phase.

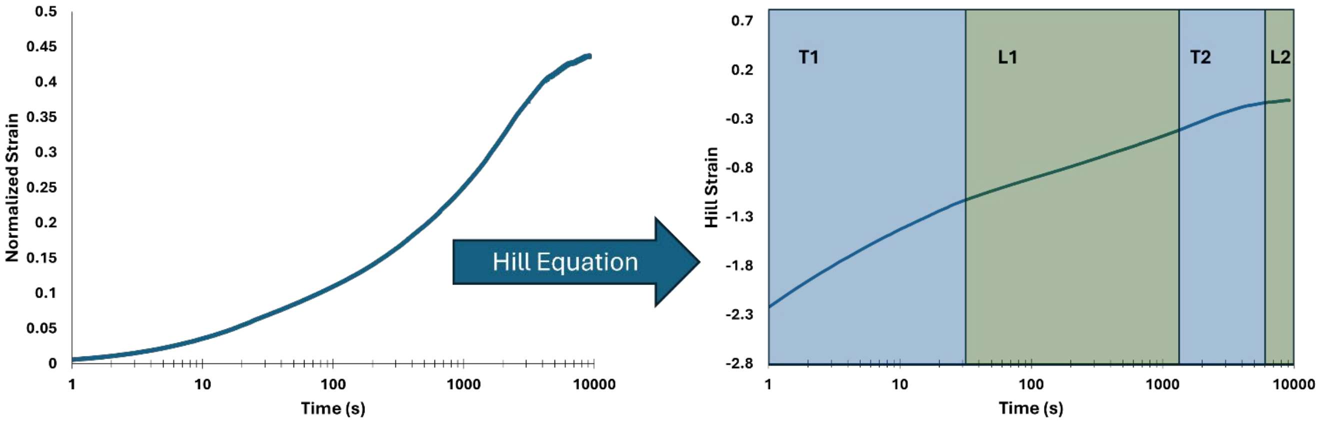

Fig. 1. Representative plot of creep from a single statically loaded FSU test. After linearising data with the Hill equation, the data show multiple phases. The plot is divided into two transition phases (blue, T1 and T2) and two linear phases (green, L1 and L2). Linear phases were used in ANCOVA and ANOVA with linear regression.

IV. DISCUSSION

We compared the curvature of the creep responses and how curvature changed over the test duration. The K-S test showed a difference between loading regimes without requiring additional data manipulation. However, the K-S test did not provide details on how or when curvature differs. After data linearisation, both ANCOVA and ANOVA showed differences in curvature during linear phases. The robustness of the results from ANCOVA, with high degrees-of-freedom, was supported by similar findings from ANOVA, despite its lower degrees-of-freedom. While yielding comparable findings, each method offers distinct insights into the nature and location of observed differences. The statistical approach used depends on the desired level of information from the data.

Linearisation of data captured an underlying phasic trend in the data. Comparison of the different phases not only provides statistical comparison but may also provide insight into how physiology changes during creep. These phases likely relate to the fluid flow and biphasic viscoelasticity of the IVD. Further analysis of these phases is important for understanding injury progression as the transition between phases may indicate a shift in the interaction between different structural and fluid components of the IVD during creep. One such shift is the flow of water out of the nucleus in an overloaded environment. Recent work from our lab suggests that the visualisation of fluid flow from the nucleus pulposus into the annulus fibers may be possible using micro-CT [6]. Future research will combine the investigation of phasic creep response with dynamic imaging to clarify the impact of water flow in the IVD on creep response. This study demonstrates the use of statistical approaches to compare creep response and highlights the potential of statistical methods to offer insights into physiology.

V. REFERENCES

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