Strain-Based Interpretation of Lumbar Endplate Injury Risk Incorporating Creep Loading and Recovery Behavior

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I. INTRODUCTION

Exposure to repetitive mechanical loading is associated with the development of low back pain (LBP), particularly in military and occupational environments with limited recovery [1–2]. Cyclic combined flexion-compression loading can produce lumbar endplate fracture, and injury risk curves have been developed to estimate fracture probability [3]. Lumbar spine creep loading and recovery behavior are characterised by strain-time responses while injury risk models are a function of peak stress and loading duration. This mismatch limits interpretation of how specific loading and rest/recovery schedules influence cumulative injury risk. This study reinterprets an existing cyclic lumbar endplate injury risk curve in terms of strain and integrates it with modeled creep loading and recovery behavior enabling direct comparison between mechanical response and injury onset. We hypothesise that injury is governed primarily by strain and that incomplete recovery permits progressive strain accumulation toward failure.

II. METHODS

To understand how recovery relates to injury risk in the lumbar spine two main steps were performed. First, injury risk was redefined from a stress-based metric into a strain-based metric. Secondly, the strain-based injury risk was used in conjunction with a model of lumbar creep loading and recovery to evaluate the relationship between loading-recovery cycles and injury onset. The approach for each step is described below.

Strain-based Injury Risk Analysis

Previously published stress-based injury risk data from 20 porcine lumbar functional spinal units (FSUs) subjected to cyclic combined flexion-compression loading were reanalysed in terms of strain [3] (Fig. 1). Twelve tests resulted in failure (endplate fracture) and eight did not. For the reanalysis, engineering strain was calculated from displacement-time data relative to initial endplate-to-endplate height (Fig. 1B). Endplate-to-endplate height was calculated as the mean distance between adjacent endplates, including the disc and both endplates, from nine measurements obtained from pretest microCT images across three coronal slices at anterior, middle, and posterior positions. The same censoring was used for the strain-based analysis as was used in the original stress-based analysis. For fractured specimens, injury was interval-censored between the strain at the end of primary creep and the strain at the displacement-time fracture point. Tests without fracture were treated as right-censored using the strain at the end of primary creep. Binary logistic regression assessed whether injury occurrence depended on strain alone or on interactions between variables. Survival analysis was conducted using the Turnbull estimator for arbitrarily censored data, with strain as the time-to-event variable.

Integration of Injury Risk with Modeled Loading and Recovery Behavior

The strain-based injury risk was then integrated with a previously developed viscoelastic model to evaluate how loading-recovery cycles relate to injury risk. Simulated strain-time histories were generated using a quasilinear viscoelastic (QLV) model of porcine lumbar FSUs under cyclic combined loading and included a subsequent minimally loaded recovery phase which permitted strain recovery. Simulations were performed at 1 MPa peak stress for one hour of cyclic combined loading followed by varying recovery durations. Accumulated strain across repeated loading-recovery cycles was evaluated relative to the strain-based injury interval.

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III. INITIAL FINDINGS

Binary logistic regression resulted in complete separation, indicating that strain alone classified injury status. These findings support strain, inherently dependent on applied stress and loading duration, as a governing predictor for endplate fracture under cyclic combined loading. Nonparametric survival analysis using the Turnbull estimator identified a single strain interval [0.38, 0.49] associated with injury onset (Fig. 1C). The 95% confidence limits coincided with this interval. Under cyclic combined loading at 1 MPa for 1 hour, QLV model predictions showed approximately 0.07 strain accumulation during loading. This magnitude is more than five times lower than the lower bound of the injurious strain interval (0.38), indicating that a single loading cycle did not cause endplate fracture. With full recovery (100%) between cycles, the model predicted strain returned to baseline before subsequent loading and no strain accumulation occurred with repeated cycles. When the recovery model was limited to 95%, a residual strain of approximately 0.003 remained after each cycle and accumulated progressively. The model indicated that the lower bound of the injurious strain interval would be reached after approximately 127 loading-recovery cycles (~127 days assuming one cycle per day). These results demonstrate the strong influence of recovery on cumulative injury risk.

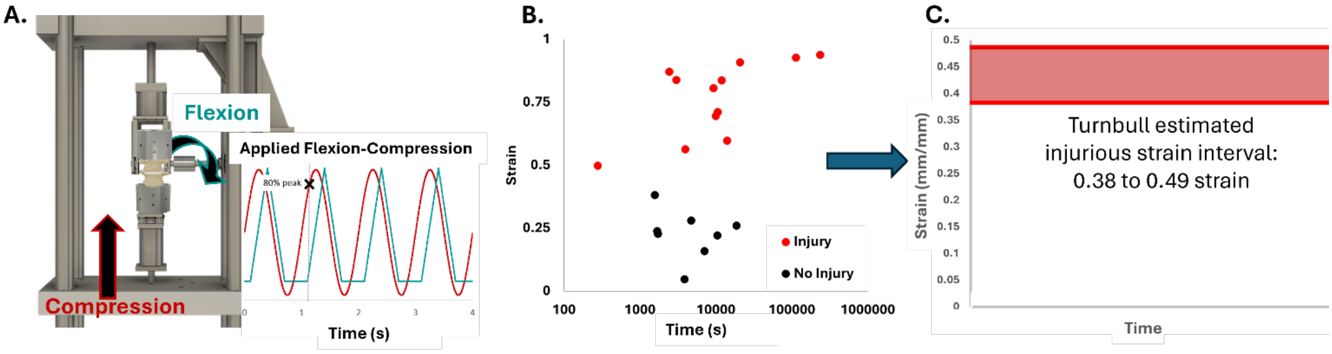

Fig. 1: Development of a strain-based lumbar endplate injury criterion. (A). Cyclic combined flexion-compression loading of porcine lumbar FSUs. (B). Previously published injury data [3] expressed in terms of strain, with injured (red) and non-injured (black) specimens. (C). Turnbull-estimated injurious strain interval (0.38–0.49 strain).

IV. DISCUSSION

This study demonstrates that lumbar endplate fracture under cyclic combined flexion-compression loading is governed by strain magnitude. Redefining injury risk in terms of strain identified an injurious interval [0.38, 0.49], enabling direct comparison between creep loading and recovery behavior and injury probability. Traditional stress-duration injury curves assume continuous exposure and do not account for recovery between loading cycles. The present results show that recovery impacts whether strain accumulates toward failure. When full recovery occurs between cycles, cumulative strain does not increase despite repeated loading. In contrast, incomplete recovery produces small residual strains that progressively accumulate, eventually reaching the injurious strain interval even though each individual loading cycle remains well below the failure threshold. The analysis was based on porcine FSUs, and absolute strain thresholds may differ in humans. Additionally, simulated loading schedules assumed consistent daily exposure and linear accumulation of residual strain. Further work is needed to validate the integration of the strain-based injury risk metric with the QLV model. Nevertheless, the mechanistic relationship between incomplete recovery and cumulative strain progression is expected to persist across species and loading conditions. These findings have implications for military and occupational environments characterised by repetitive spinal loading and limited rest. Schedules that restrict recovery time may accelerate strain accumulation and reduce time to injury, whereas sufficient recovery intervals may mitigate long-term risk.

V. REFERENCES

[1] Adams M, Acupunct Med, 2004.

[2] Fatoye F *et al.* ,Rheumatol Int., 2019.

[3] Morino C *et al.* , Ann Biomed Eng, 2024.