Use of Digital Image Correlation to Investigate the Influence of Rate on Vertebral Body Response

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I. INTRODUCTION

Vertebrae exhibit rate dependent behaviour with a stiffer response observed at higher displacement rates [1-3]. Therefore, if loading vertebrae at a rate typical of an injury scenario, less displacement is expected than if the bone is loaded at a quasistatic (QS) rate. However, this has not been quantified using full-field measurements which are possible using digital image correlation (DIC), an optical, non-contact method to measure displacement based on video images collected during deformation.

We propose using DIC to measure displacement and strain on cadaveric vertebral bodies at a QS and dynamic loading rate with a repeated measures design. We hypothesise that at a higher impact rate, the displacements at a given force will be lower, and that the displacement patterns at one rate will be predictive of the displacement patterns at another rate. Similarly, we predict lower strain magnitudes with increasing rates and that the strain magnitudes at the lower rate will be predictive of the strain magnitudes at the higher rate. Quantifying these differences in vertebral body compression experiments for loading at slow and fast rates can be used to validate computational models and to better understand injury to vertebral bodies as a result of high-speed loading.

II. METHODS

Fresh-frozen human cadaveric lumbar vertebrae (n = 9) were used. Soft tissue and the posterior elements were removed. The bone was potted in polymethylmethacrylate (PMMA) to create parallel surfaces for loading. For the DIC, the bones were painted white and speckled with black paint using an airbrush. Images of the anterior surface during loading were captured with two high speed cameras (V12.1, Vision Research, Wayne, NJ) (Figure 1). The forces and moments were collected with a six-axis load cell below the specimen.

For the QS loading, the bone was loaded in a materials testing system (Instron, Norwood, MA, USA) at a rate of 0.05 mm/s. The image resolution was 1280 x 800 pixels, and images were collected at 100 frames/s. For the dynamic loading, a custom built impactor rig (mass = 0.96 kg) was attached to a drop rail and the impactor was released from a height of 10 cm above the superior PMMA resulting in an average velocity of 1.37 m/s. For the fast loading, the image resolution was 800 x 600 pixels, and images were collected at 10,000 frames/s.

The images were processed using commercial DIC software (Strainmaster, LaVision Inc., Germany) to obtain the 3D displacement and strain on the anterior surface of the bone. The DIC surfaces from the two loading rates were aligned to each other and comparisons of the measurements were made on a point-by-point basis for the same location on the bone.

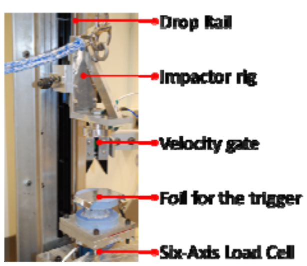

Figure 1. Test setup used to impact the vertebral body for the dynamic test.

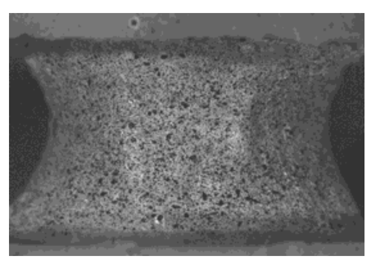

Figure 2. Image from high-speed video of vertebral body painted with speckle pattern for DIC analysis

III. INITIAL FINDINGS

The patterns of DIC strain on the anterior surface were compared for an applied force of 1000 N. Regressions were used to compare the displacement or strain at the dynamic rate vs. the measurement for the QS rate at the same bone location (Figure 3 and Figure 4).

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Specimen 4 was excluded from analysis because the displacements were below the noise threshold of the DIC. For the displacements, points below the unity line would indicate less displacement at the higher rate; for the strain, points above the unity line would indicate less strain at the higher rate.

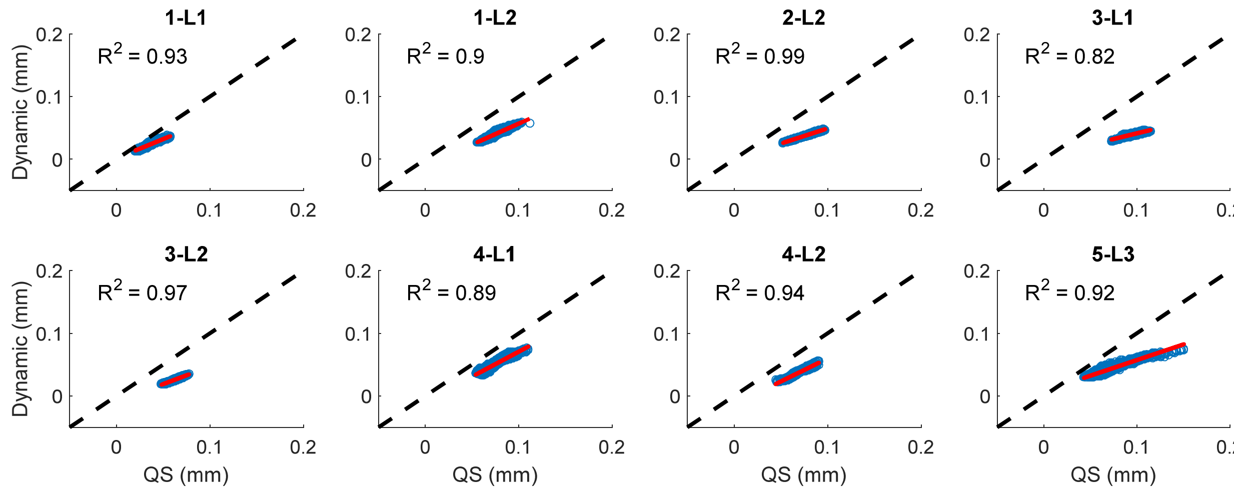

Figure 3. Point-by-point comparison of the DIC-measured displacements on the anterior surface for the QS (horizontal-axis) and dynamic (vertical-axis) tests at an axial force of 1000 N, relative to a preload of 300 N. The solid line is the linear fit of the regression and the dashed line is unity.

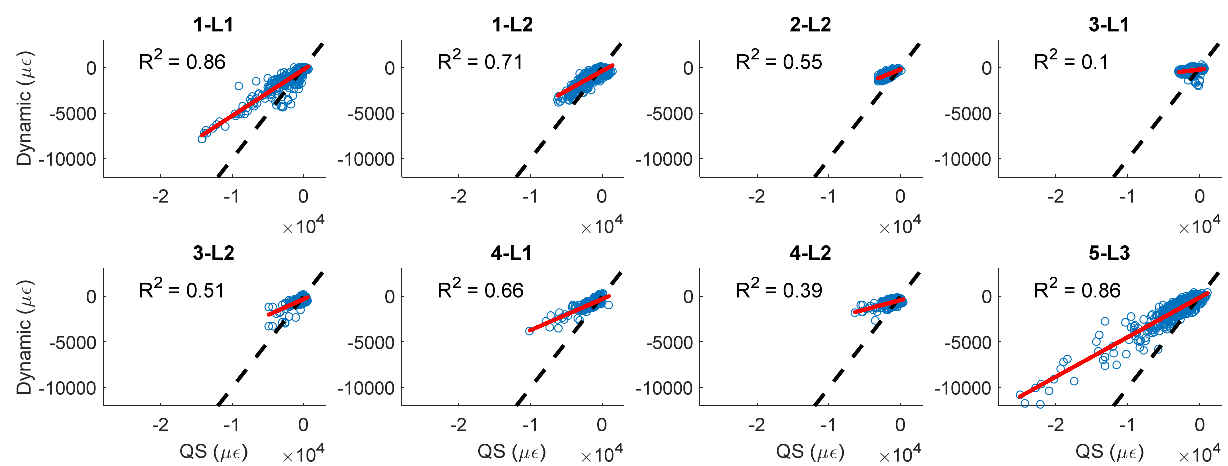

Figure 4. Point-by-point comparison of the DIC-measured minimum principal strains on the anterior surface for the QS (horizontal-axis) and dynamic (vertical-axis) tests at an axial force of 1000 N, relative to a preload of 300 N. The solid line is the linear fit of the regression and the dashed line is unity.

IV. DISCUSSION

Generally, less displacement was measured at a given force for the dynamic loading. Similarly, less strain was measured for the dynamic loading compared to the QS loading. These results support the hypothesis that the bone would deform less at higher impact velocities. The coefficients of determination show that the displacements at lower velocities are generally predictive of the strain patterns at higher impact velocities (R^2 = 0.82 to 0.99). For the strains, the coefficients of determination had a larger range (R^2 = 0.10 to 0.86). For both the displacements and strains, the goodness of fit varied between specimens. Quantifying the displacements and strains on vertebral bodies at different impact rates can be used to validate computational models and can provide more insights about bone failure due to high-speed loading.

V. REFERENCES

[1] Ochia RS, et al. J Biomech, 2003.
[2] Stemper BD, et al. J Mech Behav Biomed Mater, 2015.
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