Analytical Modelling of Human Trabecular Bone Viscoelastic Response to Compressive Loads

Brian Kunath[1], Sylvana Garcia-Rodriguez[2], Roshni Rainbow[1], Heidi-Lynn Ploeg[1]
[1]Dept. of Mechanical and Materials Engineering, Queen's University, Kingston, ON, Canada, [2]Dept. of Radiology, University of Wisconsin, Madison, USA
Email: 14bak3@queensu.ca

Disclosures: Brian Kunath (N), Sylvana Garcia-Rodriguez (N), Roshni Rainbow (N), Heidi-Lynn Ploeg (N)

INTRODUCTION: The mechanical behaviour of trabecular bone has been shown to be time-dependent when subject to different strains and strain rates, where strain is the stress-induced deformation relative to the material's initial dimension. This time-dependent behaviour, commonly known as viscoelasticity, can play a significant role at the bone-implant interface when considering aspects such as orthopaedic implant loosening and implant fits [1, 2]. Several studies have previously explored modelling the relaxation response and creep response of trabecular bone using analytical models and finite element models (FEMs) to quantify the viscoelastic response in terms of stress and strain; however, these studies were limited to testing cadaveric bovine bone at room temperature [1, 2]. Addressing these limitations can provide a better understanding of how bone reacts to implant placements and designs. Additionally, it can improve quantifying strain during mechanical testing, allowing for a better understanding of the viscoelastic response of bone. Therefore, the objective of this study was to fit analytical models to experimental relaxation data of human trabecular bone and quantify the viscoelastic response.

METHODS: 5 mm x 10 mm cylindrical (height x diameter) trabecular bone samples (n = 76) were sliced, cored, and milled from human femoral heads obtained from seven patients (five female; ages varying between 66 to 87 years) who underwent hip replacement surgery. This study was approved by the Queen's University Research Ethics Board and patient written consent was provided. Bone cores were individually tested in an *ex vivo* bioreactor chamber at room temperature. Samples were subjected to five compressive loads in the following order, 11 µm, 15 µm, 19 µm, 23 µm, and 27 µm, for one minute using a ZETOS piezoelectric custom loading system with a 20-minute recovery period between compressions. Prior to compressions, samples were pre-loaded to 10 N for 5 seconds. Time, force, and piezoelectric actuator (PZA) expansion were measured using a load cell and strain gauges on the PZA. The PZA expansion was converted to compressive deformation of the bone core. Bone specimen stress with respect to time was found from the measured force normalized to cross-sectional area. To quantify sample viscoelasticity, analytical models were fit to the experimental stress versus time data for 7 bone core samples using the corresponding relaxation modulus: Maxwell, 3-parameter solid, 4-parameter solid, and generalized Kelvin-Voigt, also known as a Prony series model [1]. Model fitting was performed in MATLAB 2019b by minimizing the residual sum of squares between the experimental stress data and each analytical relaxation model. Comparisons were made between the experimental data and models with a one-way ANOVA ($\alpha = 0.05$).

RESULTS: Experimental data showed a nonlinear response typical of viscoelastic materials. For each sample, there was no significant differences in comparing the experimental results and those obtained from all of the analytical models, although the Maxwell model produced a linear fit to the data (Figure 1a). Among the models used, a 3-term Prony series of the generalized Kelvin-Voigt model was observed to consistently provide the least difference compared to the experimental data for the different compressive loads (Figure 1b). Nonetheless, an underestimation of stress was observed at the final stage for over 50% of samples when using this analytical model.

DISCUSSION: The results demonstrated that modelling relaxation data with analytical models can help characterize the viscoelastic behaviour of trabecular bone. There was no statistically significant difference between any of the models with respect to the experimental data, including the Maxwell model, which could be attributed to the noise within the experimental data. The 3-term Prony model resulted in the best fit for the experimental data. Further research would enrich this study to explore the underestimation that was observed at the final stages of relaxation for over 50% of the tests. Samples were tested at room temperature instead of 37°C, which is one limitation of this study since viscoelastic properties are temperature dependent. Other limitations include the testing of cadaveric instead of viable bone, and experimental data noise, which could have affected model accuracy. Future work will investigate viable bone and non-linear viscoelastic models such as Schapery's nonlinear constitutive model or the Boltzmann superposition integral. Comparison of analytical models with FEM could further develop these methods and provide more accurate means for quantifying the viscoelastic response of trabecular bone.

SIGNIFICANCE/CLINICAL RELEVANCE: The significance of this study is that it aims to provide a more accurate characterization method of trabecular bone viscoelasticity and to help orthopaedic researchers better understand the impact of implant design and placement on bone mechanical behaviour.

REFERENCES:

[1] Manda, et. al., *Biomech Model Mechanobiol,* 15 (6) :1631, 2016. [2] Manda, et. al., *Biomech Model Mechanobiol,* 16 (1) :173, 2017.

ACKNOWLEDGEMENTS: We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC), Ploeg's Research Initiation Grant, and the Human Mobility Research Centre, Queen's University, Kingston, ON, Canada

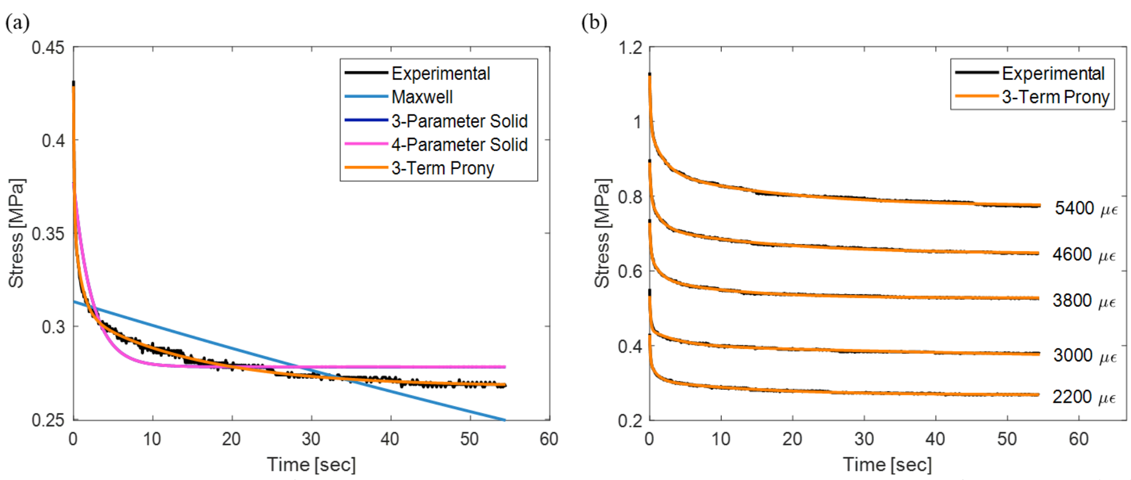

Figure 1 (a) Relaxation response of a representative trabecular bone core and the analytical viscoelastic models for the 2200 µε load. (b) Comparison of the experimental relaxation response at each strain level with the generalized Kelvin-Voigt 3-term Prony series model.