PARAMETRIC ANALYSIS OF GEOMETRIC VARIANCE IN ARTICULAR CARTILAGE SAMPLE BIOMECHANICS USING FINITE ELEMENT

Viktor Jönsson (1), Gustavo A. Orozco (1), Lorenzo Grassi (1), Hanna Isaksson (1)

1. Department of Biomedical Engineering, Lund University, Sweden

Introduction

Osteoarthritis (OA) affects joint mechanics through e.g., degeneration of cartilage and subchondral bone. However, the mechanisms behind how the biomechanical properties change with OA are not fully understood. Experimentally, the variability in force response between different samples during mechanical testing is generally large, even when comparing multiple samples from the same knee. Such a high variability can hide key information during OA progression over time. Traditionally, the samples used in unconfined compression are assumed to be perfectly cylindrical. Ongoing work using in situ mechanical testing and synchrotron phase-contrast micro-tomography shows that the samples are not always perfectly cylindrical. In this study, we aim to quantify the influence of different geometric imperfections on cylindrical samples for the biomechanical properties of cartilage during unconfined compression using Finite Element (FE) modeling.

Methods

Based on experimental unconfined compression (2x15% strain, 1%/s), stress relaxation data from multiple bovine knee cartilage cylindrical samples from a single specimen was used to determine the fibril-reinforced poro-visco-hyperelastic (FRPVE) material parameters [1]. For this, a "geometrically ideal" average cartilage sample FE model was created in Abaqus.

Based on the tomography images (n= 34 samples), three geometric imperfections were identified: missing cartilage areas at the base, remnants of calcified cartilage at the base and an uneven top of the sample (Fig. 1A). The imperfections were assumed to behave like planes intersecting the ideal sample; the height and angle for each plane were measured (Fig. 1B). To quantify the influence of the imperfections, a 3-level Design of experiment (DOE) were designed with the levels based on the experimental mean +/- std. The DOE included 8 factors for creating the geometric imperfections that were simulated in 45 different combinations determined by the statistical software JMP. The outcome parameters were equilibrium forces, peak forces and relaxation times on each of the two stress-relaxation steps. The influence of the imperfections was calculated using 2-way ANOVA.

Results

The fitted FRPVE parameters were (E_m=0.27MPa, ν=0.22, E_0=4.3MPa, E_ε=315MPa, k_0=0.01mm^4/(Ns) M_k=6.2). For the DOE results, the top angle contributed the most to the variation (25-50% of variability) in the equilibrium forces. The peak forces were affected almost equally by the top angle and the missing areas of cartilage (ca 25%) while relaxation times were most affected by the height of the remaining calcified cartilage (ca 30%).

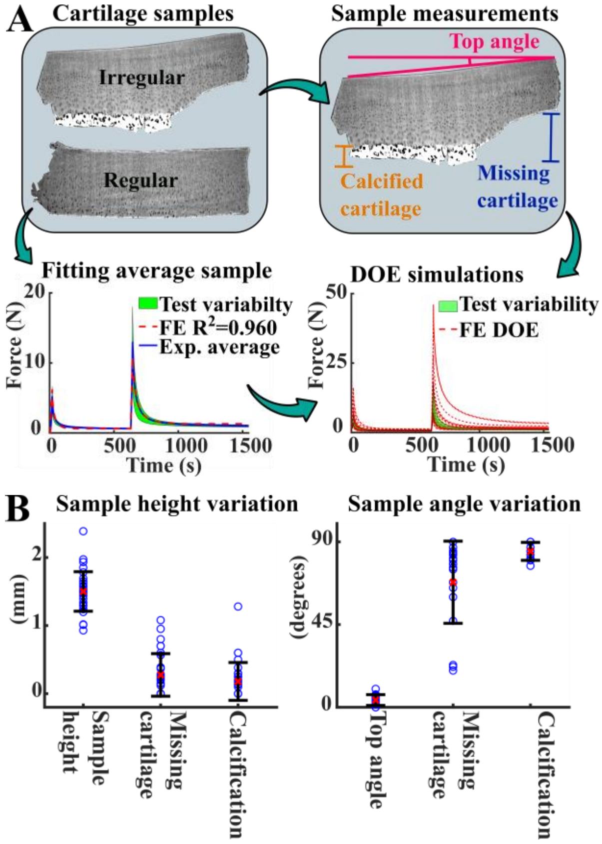

Fig. 1 A) Workflow with measurements of multiple samples and fitting average sample. DOE simulations showing different reaction forces. B) Variation of experimentally measured factors.

Discussion

Based on our results, geometric variation of the samples due to small imperfections have an impact on the cartilage biomechanical response. This suggests that more rigorous sample preparation should be considered to minimize the imperfections. Also, this study can help to distinguish among the variability from sample preparation, uncertainties in mechanical testing and the inherent heterogeneity of cartilage tissue properties.

References

1. Wilson et al. Journal of biomechanics, 37,3 (2004): 357-66

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