VALIDATED, HIGH-RESOLUTION, NON-LINEAR, EXPLICIT FINITE ELEMENT MODELS FOR SIMULATING SCREW PUSH-IN STRENGTH

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Introduction

Bone screws are widely used in orthopaedic applications, but screw loosening is still a major concern [1]. Finite element (FE) models have been extensively used to predict the mechanical response of orthopaedic screws with the goal of improving screw design. However, studies in the past had to compromise between modelling the trabecular structure at a high resolution vs. sophistication in terms of mechanical properties and/or boundary conditions. This typically resulted in systematic differences being reported between experimental and FE model generated pull- or push-out stiffness and strength results [2]. The aim of our work is to overcome the limitations of previous studies by utilizing explicit FE solvers that allow for modelling some of the complex mechanical interactions at play in bone-screw constructs at a micro level resolution. We validated our model against previously published experimental results from push-in tests [3].

Methods

The trabecular bone geometry of the samples was segmented from µCT images using Fiji (ImageJ 1.53t, NIH). The µCT images were resampled to a lower resolution (from 20 to 80 µm), followed by a direct voxel-to-8 node hexahedral element conversion, using an in-house MATLAB code. The screw geometries were digitally inserted into the FE model by removing bone voxels where bone and screw overlapped. The models were solved using Abaqus explicit solver (ABAQUS 2021, Dassault Systemes). FE models with different degree of sophistication were compared to the experimental results: (i) bonded contact between bone and screw elements with linear elastic (LE) bone properties (E=8.4 GPa); (ii) same as (i) but with non-linear bone properties (CDP=concrete damage plasticity) and element deletion at 35% post-ultimate strain; (iii) sliding bone-screw contact (μ=0.3) and LE bone properties; (iv) and sliding bone-screw contact with CDP bone properties. The boundary conditions are shown in Figure 1 (a). The FE models were solved on a computer cluster with 128 GB ram and 64 CPUs.

Results

The FE models solved over 15h of wall-time on average. The maximum principal strain field of different models are shown in Figure 1, and the corresponding force-displacement curves are shown in Figure 2 (a). The fracture was found to be limited to near the threads in the case of friction contact, and for bonded contact only after trabecular fracture (CDP element deletion), similarly to previous experimental results [4], rather than the far field propagation found in previous linear models [2]. The frictional contact decreased the push-in stiffness from 8357 N/mm to 3947 N/mm, which better matches the 3876 N/mm found in the experimental result (Figure 2 (a)). The numerical model considering contact and material nonlinearity (model iv) matched the experimental results of different bone samples within 15% error in terms of stiffness, strength, and displacement at failure (Figure 2 (b)).

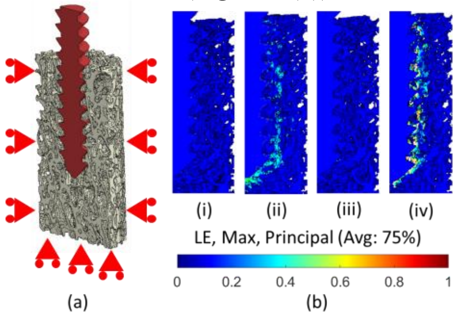

Figure 1: (a) Boundary conditions of the push-in simulation; (b) Max principal strain field of different models (model i-iv) .

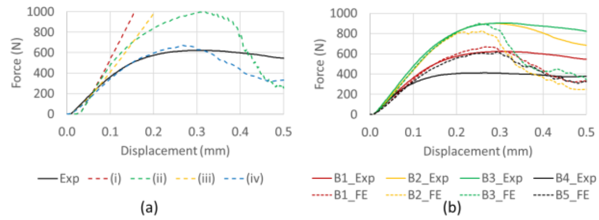

Figure 2: Force-displacement curves of numerical (dash) and experimental (solid) results [3]; (a) Mechanical responses of different models vs experiment; (b) Experimental and numerical (model iv) results of different bone samples.

Conclusion

Non-linear friction contact and a CDP bone model can reduce the stiffness of numerical push-in simulations, and reproduce the experimental results within small error (15 %) for different bone samples. Friction contact and/or element deletion also limit the strain field to near the threads, which was observed experimentally [4].

References

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Acknowledgements

The authors are grateful for support from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 812765. The authors extend their gratitude to the authors of Steiner J.A. et al [3] that contributed experimental data to the study.