THE MECHANICAL INTERPLAY BETWEEN BONE AND SCAFFOLD MICROSTRUCTURES – A COMPUTATIONAL ANALYSIS

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Introduction

Treatment of segmental bone defects is challenging in orthopaedic surgery. Bone scaffolds can be used to support bone regeneration. Autografts are bone samples taken from the same individual and requiring an additional surgery. Synthetic 3D printed scaffolds offer an alternative, with the possibility to tune scaffold microstructure. Given the high heterogeneity of bone and scaffold microstructures, the following questions arises: how does the insertion of a bone scaffold (autograft or 3D printed) impact the mechanical loading on the surrounding bone? To which extent can the mechanical interplay between the bone and the scaffold be tuned by controlling scaffold microstructure? To address these issues, we conducted a computational study in which a bone defect was generated, and different scaffolds were virtually implanted into a human radius.

Methods

The starting point of this work are micro-computed tomography (microCT) images of the radius and of the iliac crest of the same individual (53-year-old female). A trabecular bone defect (cube of 5 mm^3) at the distal radius was generated, and two bone scaffolds were considered: an autograft, derived from the microCT of the iliac crest, and a Triply Periodic Minimal Surface (TMPS) gyroid scaffold, having the same porosity as the autograft (Fig. 1). Only a distal portion of the radius (height of 2 cm) was modelled and loaded under uniaxial compression along the longitudinal direction. To make a comparison restricted to microarchitectures, we assigned identical material properties to the bone and the scaffolds (Young's modulus of 16 GPa and Poisson ratio of 0.3). The mechanical behaviour was solved using ParOSol [1], a parallel finite element solver for linear elastic analyses running on 36 cores on a NIC5 supercomputer. A region of interest (ROI) around the scaffold was chosen to evaluate the frequency distribution of von Mises stresses (Fig. 2a) in four different scenarios: intact bone, bone with the defect and bone with the scaffold and autograft.

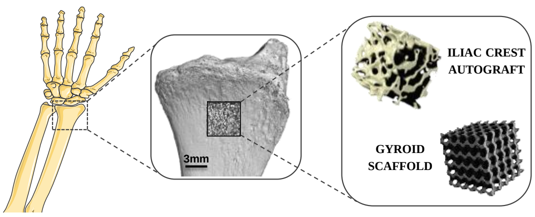

Fig. 1: Model for a trabecular bone defect in the distal radius, filled with an autograft or a gyroid scaffold.

Results

The bar plot in Fig. 2b represents the fraction of lowly and highly loaded elements in the ROI. When there is no defect, the fraction of lowly and highly stressed elements is comparable. Inclusion of the defect increased the fraction of lowly loaded elements, with almost no variation in the number of highly loaded elements. Conversely, insertion of the scaffold had an impact on both lowly and highly loaded regions: the fraction of elements lowly loaded increased (up to a factor of 2) while those highly loaded decreased (also by a factor of 2), compared to the intact bone. Despite the same porosity, autograft insertion led to a slightly higher fraction of lowly loaded bone elements than TPMS.

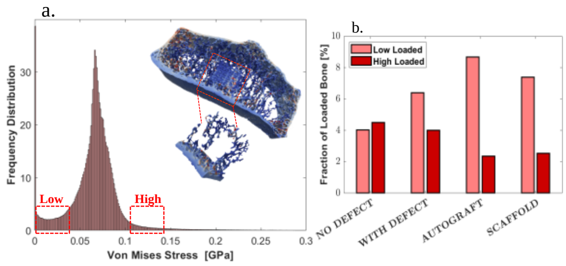

Fig. 2: a. Frequency distribution of von Mises stress in the ROI (inset), with low- and high-stress regions highlighted. b. Fraction of lowly and highly loaded elements.

Discussion

In this work we gained an initial understanding of the complex mechanical interplay between bone and scaffold microstructures. Contrary to what is expected around a defect in a monolithic material, we did not observe stress concentrations but trabecular unloading, as also found in other porous structures [2]. Scaffold insertion had an important stress shielding effect, coming from differences in the microstructure rather than in material properties, which should still be considered, as stiffer scaffolds can intensify the effect. Our approach may be also relevant in the mechanobiological contest to understand bone mechanical adaptation around scaffolds.

References

1. Flaig et al., Parallel Comput, 37: 846-854; 2011
2. Ruffoni et al., Phil Mag, 13: 1807-1818; 2010

Acknowledgements

This work was supported by the "ReBone" project, funded by the European Union's Horizon Europe program under the MSCA Doctoral Network (grant agreement no. 101119884). Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI).