FEA Simulation of Parametric Trabecular Bone Scaffolds

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INTRODUCTION: Bone scaffolds are used to treat bone defects, but these procedures have been reported to result in complications involving elevated implant failure rates and delayed bone healing [1] indicating a need for continued research and development of these devices. Trabecular bone scaffolds are most commonly used at the hip, wrist, and spine. Bioactive ceramic materials such as beta tricalcium phosphate (β-TCP) have been emerging as viable material for bone scaffolds. β-TCP has been proven to be an effective material for integration into human bones as it slowly disintegrates and becomes one with the existing environment due to its great similarity to the mineral structure of human bone [2]. Manufacturing processes of β-TCP are an important determinant of micro-structural and bulk properties. Particularly, the sintering temperature of injection-molded β-TCP scaffolds has significant effects on mechanical properties, pore size, and porosity. Sintering β-TCP at temperatures of 950°C, 1050°C, and 1150°C found the lowest sintering temperature resulted in the greatest pore size, lowest material density, and lowest apparent elastic modulus [3]. Computational modeling such as Finite Element Analysis (FEA) offers a precise and flexible approach for comparing the mechanical behaviour of different scaffold designs in a timely and economical manner. Parametrizing trabecular bone scaffold models and FEA allow many parameters to be changed simultaneously for iterative analyses, improving time-efficiency and design solutions. Therefore, the purpose of this study was to demonstrate a parametric method for structural analyses of a bone β-TCP scaffold sintered at 950°C, 1050°C, and 1150°C and simulate the mechanical response to compressive loading on the scaffold.

METHODS: A parametric model of a β-TCP scaffold was built in SOLIDWORKS 2019 such that different dimensional parameters could be changed easily with automatic updating of FEA results. Based off a previously tested scaffold as the preliminary design [3], a scaffold was built with six parallel beams stacked in ten orthogonal layers (Fig 1). The assembled scaffold consisted of ten alternating beams stacked in the Z direction and six beams separated by five pores in the X and Y directions for the XZ and YZ planes, respectively. The XZ "default" dimensions for the width (R), height (S), and X-pore width (T) of beams were set as 0.65 mm, 0.65 mm, and 0.22 mm, respectively. Similarly, the YZ "default" dimensions for the width (M), height (N), and Y-pore width (O) of beams were set as 0.65 mm, 0.65 mm, and 0.22 mm, respectively. This resulted in assembled scaffold dimensions of 5.00 mm, 5.00 mm, and 6.50 mm for the X, Y, and Z lengths, respectively. The assembled scaffold dimensions were calculated, and the CAD model was automatically generated, given the parameters: beam dimensions, as well as the number of columns, A, and rows, B. All variables (R, S, T, M, N, O, A, B) were assigned through an input file (Excel spreadsheet) and can be easily modified. Elastic moduli of 44.28 GPa, 87.76 GPa, and 73.84 GPa were assigned to the 950°C, 1050°C, and 1150°C scaffolds respectively [3]. A Poisson's ratio of 0.3 was used for all three scaffolds. To evaluate the scaffold parameters at each temperature, the principal stresses, displacements, and strains were computed at all nodes of the models with FEA using SOLIDWORKS 2019. The resulting tensile principal strain was predicted for a uniform displacement of -10 μm in the Z-direction, on the outer surface of the top six beams. All displacements of the outer surface of the bottom six beams were fixed.

RESULTS: For the geometry of the 950°C sintered scaffold a maximum principal strain of 2463 με was measured at a node on the top row of the XZ plane beam (Figure 1). The scaffold geometry sintered at 1050°C experienced larger strains of 2729 με for the maximum principal strain occurring at the bottom beam in the YZ plane. The 1150°C scaffold resulted in a maximum principal strain of 2778 με at the bottom YZ plane beam. The structural stiffnesses and porosities of the 950°C, 1050°C, and 1150°C scaffolds were calculated to be 24.70 N/μm and 40.98%, 47.70 N/μm and 39.57%, and 43.30 N/μm and 36.49%, respectively.

DISCUSSION: The results showed that strain increased as the sintering temperature increased. Of particular interest are the low (blue) and high (red) strain regions for the transversely and axially oriented beams. The analysis performed is limited due to differences between the model and the actual scaffolds that were not captured. Therefore, experimental validation of the models was not possible. For instance, the simulated model simulated sixty identical, perfectly bonded beams, but the real scaffolds had varying dimensions for each beam and compliant interfaces. Since the interface between the beam layers was not accounted for in the model, the structural stiffness of the scaffold was over-predicted in comparison to the tested scaffolds [3]. This study demonstrated the potential of such parametric FEAs for providing an efficient method to iterate with local strain distribution predictions within the structure that are difficult to measure in an experiment.

CLINICAL RELEVANCE: This study demonstrates an efficient simulation tool that has utility in pre-clinical design and analysis of bone scaffolds. This method demonstrates the relationship between bone scaffold material properties, microstructure and bulk properties which are key to the implant's success.

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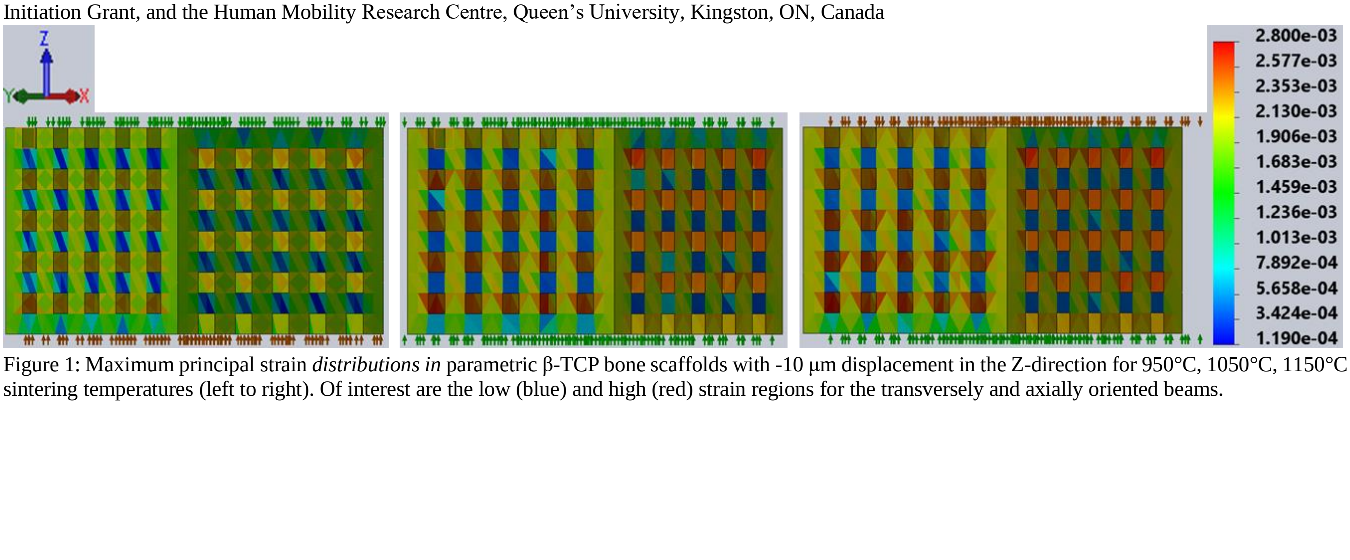

Figure 1: Maximum principal strain *distributions in* parametric β-TCP bone scaffolds with -10 μm displacement in the Z-direction for 950°C, 1050°C, 1150°C sintering temperatures (left to right). Of interest are the low (blue) and high (red) strain regions for the transversely and axially oriented beams.