FEASIBILITY OF BONE-LIKE PROSTHESES USING A PARAMETRIC TRABECULAR BONE MODEL AND DEM SIMULATIONS

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Introduction

To avoid stress shielding for titanium alloy prostheses, lattices can be used to reduce the apparent stiffness [1]. However, these lattices do not consider the physiological geometric anisotropy of the surrounding bone, which prevents optimal stress distribution. In this study, we numerically investigate the feasibility of biocompatible titanium alloy prostheses allowing osteointegration while respecting the geometric anisotropy of the bone, using a parametric model.

Materials and methods

Trabecular bone samples

From scanner images of 163 samples of bovine femoral trabecular bone, the preferred orientations of plates and rods were computed [2].

Parametric model

A parametric model was used to randomly generate cubic samples of synthetic bone, using a bone volume fraction (BV/TV) and the calculated preferred orientations as input data.

Discrete Element Method (DEM) simulation

The generated samples were used as computational domains in compression DEM simulations. The BV/TV was adjusted in the parametric model to maintain an apparent elastic modulus for bone and titanium alloys constitutive properties (Table 1), keeping the main orientations. The classical Ti-6Al-4V alloy was used, as well as a low modulus Ti-33Nb-4Sn alloy [3].

Constitutive Material	Density ($\mathrm{Kg.m^{-3}}$)	Young's modulus (Gpa)
Bone	1800	5
Ti-6Al-4V	4400	110
Ti-33Nb-4Sn	4400	36

Table 1: Constitutive properties of bone and titanium alloys.

Feasibility area

The pore size obtained for the generated structures in alloys ($Tb.Sp_{Ti}$) was then plotted against the BV/TV of the bone sample (BV/TV_{Bone}), to estimate the range of physiological volume fraction required for a biocompatible material to be used while maintaining the elastic properties of the sample.

Results

The $\boldsymbol{Tb.Sp_{Ti}}$ as a function of the $\boldsymbol{BV/TV_{Bone}}$ for the 163 bone samples is shown in Figure 1 (A). Two synthetic structures are also illustrated in Figure 1 (B).

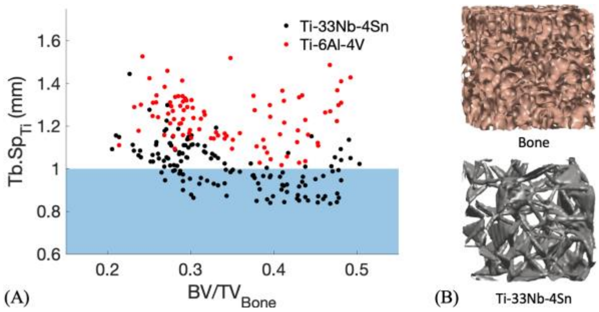

Figure 1: (A) Feasibility area for both titanium alloys. The blue zone corresponds to pore sizes below 1000 μm. (B) Synthetic samples with the same anisotropy directions and same elastic properties but different constitutive materials. The BV/TV are 0.5 and 0.1 respectively.

Discussion

A pore size limit of 1000 µm allows cell proliferation on the implant, its vascularization and the movement of waste and nutrients [1]. The large difference in elastic modulus between bone and Ti-6Al-4V makes it impossible to obtain samples with a pore size below 1000 µm. Recent research to propose low Young's modulus titanium alloys allows however to generate samples of same modulus and required pore size. Figure 1 (A) can then be used to map the compatible bone areas according to their bone volume fraction to go from the generated samples to complete prostheses (between 0.3 and 0.5 approximately, which corresponds to dense areas in the femur). This study is limited to the elastic behavior, but the post-rupture and fatigue behavior of the samples should be analyzed. However, it illustrates the feasibility of structures maintaining physiological elastic properties and anisotropy directions, using a biocompatible alloy.

References

[1] Wang et al., MSEC, 2021.
[2] Rogalski et al., Structmat, 2020.
[3] Guo et al., Sci Rep, 2015.