Microstructure influence on the local mechanical properties of human trabecular bone: insights for biomimetic scaffold for bone repair

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Abstract

Background

Bone tissue is a highly dynamic tissue that undergoes remodeling throughout life and has the capacity for self-healing. However, this capacity becomes limited when bone lesions are extensive. One promising strategy for bone repair is to associate mimetic bone scaffolds, bone progenitor cells and soluble factors to create an environment suitable for the cells to proliferate and differentiate. Scaffolds are hence the essential component as they provide support for the cells and promote vessel and nerve growth. Bone allografts extracted from human donors are promising scaffolds. These scaffolds provide both the chemical and biochemical environment, and also local mechanical properties felt by the bone cells. In fact, trabecular bone porosity is well known to be an important determinant of macroscopic mechanical properties such as the apparent Young's modulus and permeability. On the contrary, the relationship between trabecular bone microarchitecture and mechanical conditions at the microscopic scale, i.e., the trabeculae level is still poorly understood. This information is essential for designing biomimetic scaffolds that provide a suitable environment for cells to resembles the in vivo environment.

Materials and methods

Twenty-nine trabecular bone allografts harvested from human femoral heads obtained from a tissue bank were included in the present study. These samples were devitalized and defatted, and cut into cylindrical shapes with a diameter of 6.9 mm and a height of 10 mm. X-ray computed tomography were used to obtain the 3D images and a representative cylindrical volume was chosen for each sample to reconstruct the 3D numerical model and to calculate the microarchitectural parameters such as bone volume fraction and degree of anisotropy. Finite element analysis (FEA) and computational fluid dynamics (CFD), respectively were used to determine the trabecular mechanical response and the wall shear stress, respectively. The correlation between the microarchitectural parameters and the mechanical properties at both apparent and local scales were investigated.

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Results

From the FEA results, it was found out that the apparent Young's modulus is linearly correlated with the porosity of the scaffold; however, the average axial strain, the average axial stress and the average strain energy density were more correlated with the plate-and-rod composition, determined by the ellipsoid factor (EF), and the degree of anisotropy (DA) of the trabecular structure. A new parameter DAEF was obtained from these two parameters that can well predict the micromechanical properties. From the CFD results, it was found out that the permeability and the average wall shear stress of the scaffold were well predicted by the porosity of the scaffold. The results also show that surface curvature plays a significant role in wall shear stress on a local scale.

Conclusion

Studying their relationship between the microarchitecture of scaffolds and the local mechanical properties of human trabecular bone will help the design of 3D synthetic substitutes. In the present study, a new parameter DAEF derived from the plate-and-rod composition and the degree of anisotropy can well predict the mechanical properties under compression. On the other hand, the surface curvature will influence the level of local wall shear stress under fluid flow while the porosity determine the average wall shear stress level at macroscopic scale. As a result, these microarchitectural parameters need to be taken into account for future biomimetic scaffold design for bone repair, in order to recreate a mechanical environment suitable for the cells to proliferate and differentiate.

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References

1. Xiong Z, Rouquier L, Chappard C, Bachy M, Huang X, Potier E, Bensidhoum M, Hoc T. A New Microarchitecture-Based Parameter to Predict the Micromechanical Properties of Bone Allografts. *Materials.* 2023; 16(9):3349. https://doi.org/10.3390/ma16093349
2. Xiong Z, Rouquier L, Huang X, Potier E, Bensidhoum M, Hoc T. Porosity and surface curvature effects on the permeability and wall shear stress of trabecular bone: Guidelines for biomimetic scaffolds for bone repair. Comput Biol Med. 2024 Jul;177:108630. doi: 10.1016/j.compbiomed.2024.108630.