OSTEOINDUCTIVE SCAFFOLD DESIGN: DIGITAL OPTIMISATION AND PREVENTION OF OVER-SPECIALISATION

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Background

There is a compelling argument in favour of designing bone tissue engineering (BTE) scaffolds that can promote bone formation by carefully stimulating the mechanotransduction processes of osteogenic cells. However, current BTE techniques often fail to accurately predict, control and understand the local mechanical environment within the scaffold. Research has shown that scaffold design parameters, such as stiffness, pore size and pore shape are crucial for tissue growth [1], but most designs still neglect the considerable heterogeneity and inter-subject variability of native bone architecture. Furthermore, scaffold design typically relies on trial and error methods, which are costly and time-consuming. In this study we developed a digital parametric design tool that automatically generates heterogeneous scaffold structures with optimised local mechanical properties and porosity for user-specified objectives. We established a proof-of-concept for this novel tool via evaluation of the computational models and procedures, fabrication through a light-based 3D printing method, and characterisation of the 3D printed designs.

Methods

The design tool was implemented in C# as a plugin to the 3D modelling software Rhinoceros 3D and its algorithmic modelling platform Grasshopper. This plugin supports automatic cellular topology generation within arbitrary closed shapes and optimisation of individual strut thicknesses to meet both local strain and porosity targets under a specified load case, building on a heuristic strain-based optimisation algorithm derived by the authors [2]. The capabilities of this design framework were assessed *in-silico* and *in-vitro* for uniaxial compression by comparing the resulting optimized designs with controls, defined as homogeneous scaffolds with same outer shape and same mass as the optimized designs. Finite Element (FE) analyses were run in Abaqus to simulate material (stable stress) and structural (buckling) scaffold failure. Finally, designed models were manufactured in a photocurable acrylic resin using direct light processing, and mechanically tested under compression loading. The influence of added material or stochastic noise in geometry definition, onto structural failure was studied.

Results

All 3D printed scaffolds had good resolution. The optimised scaffolds presented higher stiffness and material failure loads under compression compared to controls. In contrast, the optimised scaffolds presented a lower structural failure load compared to controls.
The FE models accurately predicted stiffness and failure load of the samples. Additionally, the models were able to accurately predict global buckling deformation under compression (Figure 1). The optimised scaffolds presented a substantially narrower strain range around the set target compared to controls.

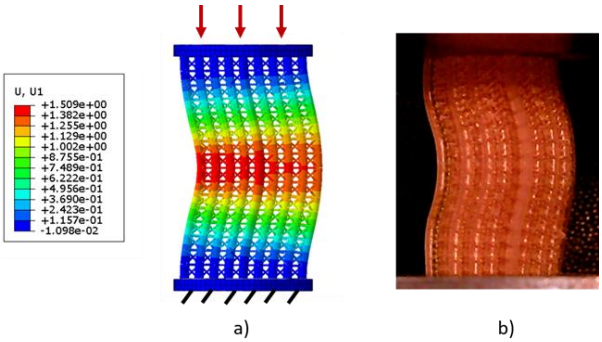

Figure 1: (a) In-silico and (b) in-vitro buckling of a cylindrical lattice scaffold under vertical compression. Colour scales refer to lateral displacement (mm).

Addition of material in the transverse direction, as well as introduction of stochastic noise in the optimised scaffold geometry definition, increased the structural failure load while maintaining high porosity.

Conclusion

We developed and evaluated a scaffold design tool that automatically generates heterogeneous geometries tailored to user-defined deformation targets for stimulating bone cells. This tool is publicly available (link in Acknowledgements). The results showed that design optimisation based solely on stable material deformation analysis produces geometries that are more susceptible to structural failure than the non-specialized controls. However, the design optimisation framework presented here allows for the integration of mitigation features to prevent these risks of 'over-specialisation'.

References

1. Hollister SJ, Nature Materials, 4, 2005.
2. Phillips ATM, et al., International Biomechanics, 2, 2015.

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