

Additive manufacturing of mechanomimetic bone structures

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Abstract. Bone is a complex composite structure consisting of hard and soft components distributed in 3-dimensional space. The evaluation of the bone organisation to produce a suitable data set that can be realised in a physical manufacturing process promises potentially significant applications such as in prosthetics. Critically, high fidelity translation of the bone structure into a synthetic output can give an accurate copy of the bone's mechanical properties, giving a 'mechanomimetic' bone structure. A workflow employing x-ray microtomography (XRT) to image bone followed by the construction of a digital model and subsequent multi-material additive manufacturing is presented here. A number of compact bone structures are considered to evaluate the complex synergies between soft tissue regions, mineralised hard tissue regions and their organization. Mechanical testing of manufactured and their corresponding bone structures are finally used to evaluate mechanomimetic effectiveness.

Introduction

Bone is a prevalent example of a mineralized tissue demonstrating considerable mechanical performance, including resistant to compression and relatively high toughness [1], using hard mineral apatite and a range of softer materials mostly consisting of collagen. A number of disease states and conditions exist that compromise the mechanical integrity of bone, and healthcare therefore requires effective replacement of bone material that is able to provide suitable mechanical function.

The replacement of bone material broadly follows two pathways of either employing biomaterials to allow bone regeneration [2] or using engineering structures to replace significant volumes of the whole bone [3]. Additive layer manufacturing, commonly referred to as three-dimensional (3D) printing, shows significant potential in producing the complexity required for replacing large bone volumes, especially due to the more recent availability of multi-jetting technology to provide composite structures [4].

Experimental

Samples from the mid-diaphysis of bovine bone femura were cored by removing cylinders from the host. The cored samples were extracted from an extensively remodelled mature bovine bone showing a significant number of secondary osteons and immature bovine bone with a considerable lack of remodelling limiting the number of secondary osteons. An x-ray microscope (Versa 520, Carl Zeiss Ltd., USA) was used to image the bone samples and produce tomographic reconstructions of the bone material, with emphasis on distinguishing the hard and soft phases, as well as porosity. Data was segmented and iso-surfaces produced from the different phases using meshing procedures (MeshLab v1.3.3., Ita.) to give a digital model of the bone structures. The resultant steps from the XRT through to the meshing is shown in Figure 1 below.

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Fig. 1. Representation of the workflow from (left) the XRT of a compact bone sample through to the meshing step (middle). Compositional changes is shown (right) for secondary osteonal regions within the bulk.

Additive manufactured samples were outputted from the digital model using an inkjet based 3D printer (ProJet 5500X, 3D Systems, USA) that allowed the deposition of multiple materials. The hardest material was used for the secondary bone regions (VisiJet CR-WT, 3D Systems, USA) and a series of increasingly softer matrix materials (VisiJet RWT-FBK 100, VisiJet RWT-FBK 250 and VisiJet RWT-FBK 500, 3D Systems, USA) were used as the primary bone material. The materials were chosen from the range available commercially for use in the 3D printer. The printer was operated in XHD mode with a highest 0.013 mm spatial resolution in the z-axis. Resultant manufactured samples and their parent bone samples were mechanically tested to failure in compression. Stress-Strain behaviour for the manufactured and corresponding bone samples were compared to evaluate the effectiveness of the 3D printer in producing mechanical properties that tend towards those of the bone.

Conclusion

Compact bone samples were imaged using XRT, digital models developed and outputted using a multi-material additive manufacturing process. Mechanical properties of the manufactured bone-like structures were compared to the parent structures to understand the effectiveness of the workflow in providing mechanomimetic bone.

References

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