MULTISCALE MODELLING OF BONE BIOMECHANICS - THE STRUCTURAL ROLES OF MINERAL AND ORGANIC CONSTITUENTS
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Background

Bone is a naturally occurring composite material whose constituent phases are hierarchically organized to provide a structure that exhibits high stiffness and excellent resistance to fracture [1]. At the tissue-scale and above, there are now well-established structure-property relationships that provide good approximations of biomechanical performance through, most commonly, power-law relationships that relate tissue mineral density to elastic properties ($E \propto \rho^{\alpha}$) However, below the tissue-level, the individual role of the constituents becomes prominent and more advanced theoretical and computational models are required to describe the mechanical response [2], [3]. While these models have provided excellent insight into sub-tissue biomechanics in the elastic regime, the prediction of damage and failure processes at this scale becomes extremely challenging. In particular, lamellar bone is composed of mineralised collagen fibrils that are embedded within an extra-fibrillar matrix comprised of hydroxyapatite minerals and non-collagenous proteins. Each of these constituent components exhibit drastically different mechanical behaviour and there remains some uncertainty on the precise arrangement of these constituents at lower length scales. This talk will provide a perspective on the structural roles of mineral, collagen and non-collagenous protein constituents by presenting our current understanding of bone biomechanics at small length scales, with quantitative insight provided by a range of recent multiscale models that we have developed in this area [3-9].

Recent Advances

Building on previous experimental observations, we have developed both finite element [3, 4, 7] and coarse-grained molecular dynamics [5, 6, 8, 9] models to investigate the roles of mineral, collagen and non-collagen proteins on the sub-tissue mechanical properties. These have investigated the relative roles of intra- and extra-fibrillar mineral on tissue biomechanics, demonstrating that the extra-fibrillar mineral is the phase that makes the primary contribution to tissue stiffness [4]. While the extra-fibrillar matrix is a key determinant of elastic properties, we provide evidence that intra-fibrillar mineralisation is essential in providing mineralised collagen fibrils both high strength and ductility [5]. Furthermore, these results show that mineralised collagen fibrils have fracture strains that are far higher than tissue-level fracture strains. These properties enable mineralised collagen fibrils to provide extrinsic toughening to crack propagation at this scale [6, 7], through mechanisms such as fibre bridging. Finally, we investigate the structural roles of non-collagenous proteins [7-8] and have predicted their

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significant potential to dissipate energy at mineral interfaces in the tissue. In agreement with experimental observations [10], these components likely play a critical role in the onset and evolution of damage at constituent interfaces at lower length scales. Together, these models show that subtle changes in constituent properties and/or arrangement can have a drastic impact on higher-level tissue performance.

Future directions

Our recent computational work has provided quantitative insight on the relative contributions of tissue constituents on bone biomechanics. However, significant challenges still remain. Such computational models are generally limited to an individual length scale, where it assumed that a characteristic representative volume element (RVE) can be defined. However, the definition of model parameters within these representations (both geometric and material) is extremely difficult, and computational models of this type remain "conceptual", rather than being truly predictive. Future directions in this area require closer collaboration with the state-of-the-art experimental efforts in this area, to better define structural, compositional and mechanical properties of constituents at lower length scales.

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