INTRODUCTION

Aging and disease result in microstructural (such as increase in intracortical porosity) and material level changes (such as alterations in bone’s collagen and mineral) in the bone. However, the relative influence of these changes on bone fracture is unknown. In this study, we report the development and application of a micro-computed tomography (µCT) based finite element approach that allows to determine the effects of intracortical porosity on bone fracture. More importantly, this approach separates the effects of intracortical porosity from the other material level changes and can be used for non-invasively predicting bone fracture during preclinical trials and with aging and disease.

METHODS

Previously tested compact tension specimens from human tibia (19- and 81-year-old) were scanned using µCT (vivaCT 40, Scanco Medical AG) with a 21 µm resolution (Fig. 1a). After reconstruction, the voxel size was increased ten times in all directions. The porosity of the specimens was computed using the µCT software at 21 µm voxel resolution. The rescaled images of the compact tension specimens were converted to ABAQUS finite element meshes by representing each voxel as a finite element (Fig. 1b). The meshes of the compact tension specimens were modified by inserting three-dimensional cohesive elements in the path of the crack growth (Fig. 1c, and 2a,b). Cohesive elements follow a traction-crack opening displacement relationship (Fig. 1c). Traction-δu) are represented as surface elements with zero thickness and are compatible with solid elements (Fig. 3b). The cohesive model parameters, Gc and σc, used in the simulations were obtained from the experimental results reported in the literature for human cortical bone [1,2].

Finite element simulations were carried out using the same cohesive parameters for both specimens as well as using reduced cohesive parameters from the literature [1,2] to account for the other age-related changes in addition to porosity. The load and crack growth data computed in the simulations were used to calculate the crack growth resistance (Kc) at various crack lengths. For each donor, Kc was plotted as a function of crack extension to obtain the resulting slope by linear regression.

RESULTS

µCT scans showed that the 19-year-old specimen had 1% whereas 81-year-old specimen had 5% intracortical porosity. Consistent with previous studies [3], the finite element simulations showed increasing stress intensity factor with increasing crack growth. The simulations carried out using the same cohesive parameters for the young and the old specimens showed a 6% decrease in initiation toughness with a 4% increase in porosity (Fig. 4). On the other hand, propagation fracture toughness decreased by 62% with a 4% increase in porosity (Fig. 5). The difference between the 19- and 81-year-old specimens became more pronounced when the age-related effects due to the material properties (i.e. cohesive model parameters) were introduced in the simulations. The initiation and propagation toughness decreased by 51% and 83%, respectively (Fig. 4, 5), with the combined effect of 4% increase in porosity and decrease in the cohesive properties reflecting other age-related changes in bone.

DISCUSSION

This study demonstrates a novel application combining cohesive finite element modeling with advanced imaging for non-invasively determining the fracture toughness of human cortical bone. In contrast to experimental fracture mechanics, the computational method presented here is capable of decoupling the effects of microstructural and material level changes on the fracture toughness of bone.

Our results demonstrate that the intracortical porosity is a significant contributor to the fracture toughness of the bone. In contrast to initiation toughness, the toughening mechanism, represented by R-curve, was more dramatically altered by the presence of increased intracortical porosity and was not effective in the old bone with extensive porosity. The reduction in the fracture toughness of the bone became even more pronounced when the effect of other age-related changes was introduced in the simulations.

This novel computational method can be used to develop finite element models for preclinical trials that utilize advanced imaging for determining the effects of antiresorptive (such as bisphosphonates) and anabolic (such as PTH) treatments on fracture risk. Additionally, the high resolution peripheral CT (XtremeCT, Scanco Medical AG) developed for human in vivo measurements provides a resolution (41 μm) that can capture intracortical porosity and introduces the possibility of applying the method presented here to patient specific studies.


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