INTRODUCTION

Bone fracture is a major concern for elderly because the toughness of aged bone becomes more susceptible to impact load.\(^6\) It has been well documented that the post-yield behavior of bone determines the major part of the toughness of bone.\(^3,4\) As a natural composite material, bone primarily comprises a hard mineral phase (mainly hydroxyapatite crystals) and a more compliant collagenous matrix (90% type I collagen).\(^5\) From composite materials perspectives, the biomechanical properties of bone may be the function of the quality and spatial arrangement of its constituents. Some of previous studies have suggested that microcrack accumulation is a major mechanisms in energy absorption during the post-yield deformation of bone.\(^2,7-9,11-13\) On the other hand, some studies indicate that the age-related changes in the collagen network may contribute significantly to the toughness of bone.\([\text{Wang, 2001 \#101} ; \text{Wang, 2002 \#244} ; \text{Zioupos, 1999 \#253}]\) Moreover, in a recent study Thomason et al. reported that a recoverable bond in the collagen molecules may contribute to the energy dissipation in the post-yield deformation of bone.\(^10\) To elucidate the role of collagen in the post-yield deformation of bone, we proposed in this study that the microdamage accumulation leads to the surface energy dissipation during the post-yield deformation of bone, whereas the degradation and deformation in the collagen network are the major mechanisms in the inelastic and viscoelastic energy consumption.

ANALYTICAL TREATMENT

Figure 1 shows a typical strain-stress curve of bone in monotonic testing schemes. From the curve, the initial elastic modulus \(E_0\) can be determined by estimating the slope of the linear portion of the curve AB. The yield point \(\sigma_y\) separates the elastic and post-yield deformation of bone. After yielding, bone begins to show permanent deformation, which is characterized by a residue strain, \(\varepsilon_p\). During the post-yield deformation (from B to C), bone loses its stiffness significantly \(E_1\). However, bone exhibits a significant viscoelastic behavior after yielding in terms of an unloaded and reloaded hysteresis. The toughness of bone \(U_T\) is usually defined as the area under the strain-stress curve (shaded area of ABCE). Hence, \(U_T\) can be divided into three components: the elastic energy (the area under unload curve-CED), viscoelastic energy \((i.e., \text{the hysteresis area of CDC})\), and the plastic energy by the permanent deformation of bone \((i.e., \text{the area of ABCD})\). In this study, we propose that: 1) the decreased elastic modulus with increasing post-yielded deformation of bone is due to microcrack accumulation because elastic modulus of bone is dominated by the mineral phase; 2) the irreversible energy consumption is induced by the denatured collagen around the microcracks; and 3) the viscoelastic behavior of bone during the post-yield deformation is contributed by the reversible collagen deformation.

Figure 2 shows a schematic representation of the model of the above assumptions. As shown in this figure, there would be two types of microdamages: microcracks (on the order of microns) and the nano...
fracture (around 26%).

began to increase (approximately 18%) and more than doubled at the similar to the control specimens (unloaded). After yielding, %DC deformation region, the amount of denatured collagen (about 12%) is increased with the extent of post-yield deformation. In the elastic deformation region, the amount of denatured collagen (about 12%) is similar to the control specimens (unloaded). After yielding, %DC began to increase (approximately 18%) and more than doubled at the fracture (around 26%).

SUMMARY
This study proposed that the post-yield behavior of bone most likely involves three distinct mechanisms: microcrack formation, denaturation of collagen, and recoverable collagen deformation (viscoelasticity). By distinguishing different paths of energy dissipation during post-yield deformation of bone, one can study changes in both the collagen and mineral phases that may contribute to the decreased toughness of aged or disease bone tissues.

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