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Research paper

The effect of strain rate on fracture toughness of human cortical bone: A finite element study

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ABSTRACT

Evaluating the mechanical response of bone under high loading rates is crucial to understanding fractures in traumatic accidents or falls. In the current study, a computational approach based on cohesive finite element modeling was employed to evaluate the effect of strain rate on fracture toughness of human cortical bone. Two-dimensional compact tension specimen models were simulated to evaluate the change in initiation and propagation fracture toughness with increasing strain rate (range: 0.08–18 s^{-1}). In addition, the effect of porosity in combination with strain rate was assessed using three-dimensional models of micro-computed tomography-based compact tension specimens. The simulation results showed that bone's resistance against the propagation of a crack decreased sharply with increase in strain rates up to 1 s^{-1} and attained an almost constant value for strain rates larger than 1 s^{-1}. On the other hand, initiation fracture toughness exhibited a more gradual decrease throughout the strain rates. There was a significant positive correlation between the experimentally measured number of microcracks and the fracture toughness found in the simulations. Furthermore, the simulation results showed that the amount of porosity did not affect the way initiation fracture toughness decreased with increasing strain rates, whereas it exacerbated the same strain rate effect when propagation fracture toughness was considered. These results suggest that strain rates associated with falls lead to a dramatic reduction in bone's resistance against crack propagation. The compromised fracture resistance of bone at loads exceeding normal activities indicates a sharp reduction and/or absence of toughening mechanisms in bone during high strain conditions associated with traumatic fracture.

1. Introduction

Bone is subject to a wide range of strain rates during daily activities such as walking (0.004 s^{-1}) (Lanyon et al., 1975), strenuous activities such as sprinting and downhill running (0.05 s^{-1}) (Burr et al., 1996) or traumatic fracture events such as accidents or falls (25 s^{-1}) (Hansen et al., 2008). Previous studies showed that the mechanical response of

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bone, including its modulus of elasticity, yield stress and strain, and ultimate stress and strain vary with the loading rate (McElhaney and Byars, 1965; Crowninshield and Pope, 1974; Saha and Hayes, 1974; Currey, 1975; Saha and Hayes, 1976; Wright and Hayes, 1976; Robertson and Smith, 1978; Evans et al., 1992; Hansen et al., 2008; Zioupos et al., 2008).

A comprehensive understanding of traumatic fractures requires an investigation of the bone's resistance to fracture initiation and propagation under a variety of low and high strain rates. Most of the fracture toughness measurements reported in the literature under varying strain rates, however, corresponded to quasi-static conditions and reported only on fracture initiation. For example, using quasi-static conditions, some of the earlier studies done on bovine or equine bone reported an increase in initiation fracture resistance measured as energy absorption or critical stress intensity factor with increasing strain rates up to a certain level after which a decrease was observed (Piekarski, 1970; Crowninshield and Pope, 1974; Robertson and Smith, 1978; Behiri and Bonfield, 1980, 1984; Evans et al., 1992). More recent investigations also reported similar trends where fracture toughness in bovine and equine bone (Adharapurapu et al., 2006; Charoenphan and Polchai, 2007; Kulin et al., 2008, 2010, 2011) and energy to fracture in human cortical bone (Zioupos et al., 2008) decreased with increasing strain rate. The only study that measured the propagation toughness at a high strain rate reported the loading rate effects on the *R*-curve behavior of equine cortical bone (Kulin et al., 2010). This study showed that although the bone exhibited increasing fracture toughness with crack propagation under both quasi-static and dynamic loading, the propagation toughness was lower in the dynamic loading compared to the quasi-static case. Furthermore, the reduction in the propagation toughness was more pronounced compared to the reduction in initiation toughness (Kulin et al., 2010).

It is well known that the energy absorption during the fracture of a bone depends critically onto whether the fracture is stable (high energy) or unstable (low energy) with the fracture scenario mostly passing from a state of (i) diffuse widespread microcracking damage, to (ii) a localized stable crack growth, to (iii) an unstable growth of a crack front (Zioupos, 1998). The degree to which bone is brittle or tough depends on its ability to avoid a ductile to brittle transition for as long as possible during the deformation between stages (i + ii) and (iii). With regard to strain rate effects in particular the key to bone's brittleness is the strain and damage localization early on in the process, which leads to low post-yield strains and low energy absorption to failure between stages (i) and (ii) (Zioupos et al., 2008). Crack growth behavior in stages (ii) and (iii) under different strain rates has been investigated by Charoenphan and Polchai (2007) who showed that the stress intensity factor in bovine bone increased with crack growth up to the point of unstable crack growth, after which the values started to decrease. In addition to experimental studies on cortical bone, finite element models incorporating varying strain rates have been also developed to predict the experimental measurements of energy release rate in cortical bone (Charoenphan and Polchai, 2007), and the effect of variation of architecture and strain rates on trabecular bone fracture behavior (Tomar, 2008).

The review of the literature shows that the experimental studies in the literature mostly reported the measurement of initiation fracture toughness or energy to fracture but did not focus on propagation fracture toughness with the exception of one study (Kulin et al., 2010). Initiation and propagation toughness represent different fracture processes in bone (Vashishth, 2004). Bone exhibits increasing fracture toughness with crack propagation following crack initiation (Vashishth et al., 1997; Nalla et al., 2005). Physiological everyday loading inherently leads to the creation of in-vivo microcracks about 50–100 µm long, which accumulate with age increasing in number and density due to the fact that the human body is less able to repair them in later life (Schaffler et al., 1995; Norman and Wang, 1997; Zioupos, 2001). Such observations indicate that the propagation toughness is the critical measure of toughness that evaluates the crack growth resistance in bone, and this has to encompass relevant conditions such as variable strain rate of loading, aging, increasing porosity and so forth.

The overall goal of the current study is to develop a computational approach that evaluates the effect of strain rate on both initiation and propagation toughness of human cortical bone. The experimental study (Kulin et al., 2010) conducted on propagation toughness measurement only focused on two strain rates that represent quasi-static and dynamic loading and did not investigate a wide range of strain rates. Furthermore, the experiments were carried out using equine cortical bone. The current study will provide additional information on the response of human cortical bone under various strain rates ranging between 0.08–18 s^{-1}. The computational method used in this study is cohesive finite element modeling which has been applied and validated previously in other applications (Ural and Vashishth, 2006b, 2007a,b). Unlike experimental studies, the use of a computational approach enables controlled evaluation of the effects of a single parameter on the fracture response of bone. This feature of computational modeling ensures that there are no additional confounding factors (such as those present in an experimental approach i.e inter- and intra-donor variation) included in the evaluation. In the current study, using two-dimensional simulations of compact tension specimen geometry, we varied the strain rate while keeping the same specimen geometry, material properties and microstructure to determine the effects of strain rate on the initiation and propagation fracture toughness of human cortical bone. The measured fracture toughness values were tested for correlations with the amount of microdamage that bone accumulates in a diffuse/microcracking manner when tested over a range of strain rates in the absence of a major notch (Zioupos et al., 2008). Furthermore, using three-dimensional models of micro-computed tomography-based compact tension specimens (which provided realistic structures with fine micro detail) the effect of porosity was also assessed in combination with strain rate to determine the influence of microstructure on fracture behavior under varying strain rates. This aims to improve our current understanding of fall-related fractures in the elderly.

In summary, the current study focuses on determining (a) the variation of initiation and propagation fracture toughness with strain rate (b) the correlation of microcracking