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Research Paper

Study of indentation of a sample equine bone using finite element simulation and single cycle reference point indentation

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ABSTRACT

In an attempt to study the mechanical behavior of bone under indentation, methods of analyses and experimental validations have been developed, with a selected test material. The test material chosen is from an equine cortical bone. Stress–strain relationships are first obtained from conventional mechanical property tests. A finite element simulation procedure is developed for indentation analyses. The simulation results are experimentally validated by determining (1) the maximum depth of indentation with a single cycle type of reference point indentation, and (2) the profile and depth of the unloaded, permanent indentation with atomic force microscopy. The advantage of incorporating in the simulation a yield criterion calibrated by tested mechanical properties, with different values in tension and compression, is demonstrated. In addition, the benefit of including damage through a reduction in Young's modulus is shown in predicting the permanent indentation after unloading and recovery. The expected differences in response between two indenter tips with different sharpness are predicted and experimentally observed. Results show predicted indentation depths agree with experimental data. Thus, finite element simulation methods with experimental validation, and with damage approximation by a reduction of Young's modulus, may provide a good approach for analysis of indentation of cortical bone. These methods reveal that multiple factors affect measured indentation depth and that the shape of the permanent indentation contains useful information about bone material properties. Only further work can determine if these methods or extensions to these methods can give useful insights into bone pathology, for example the bone fragility of thoroughbred racehorses.

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Introduction

In large mammals such as humans or horses, bone health is an important topic given the critical role it plays in life. From human athletes or racehorses at risk of fracture, to medical professionals performing surgery or those investigating the influence of disease such as osteoporosis, determining the health of bone is an objective highly relevant to the health and quality of lives.

Bone is the main load bearing organ of vertebrate animals, making it a specific point of interest since the dawn of modern medicine. Bone can be classified into two main types, cortical (or compact) and trabecular (or spongy). Cortical bone takes the brunt of the forces involved in structural loading, and therefore will be the focus of study here, at the characteristic Haversian, or osteonal level. Cortical bone is a biological hierarchical composite material, with different structural configurations corresponding to different scales of length, as seen in Fig. 1.

The measurement and testing of cortical bone properties have been researched for decades, with a variety of approaches. Conventional mechanical testing such as axial loading in tension and compression, and beam bending in three or four-point load setups have been explored extensively (Currey, 2002, 1999, 1990; Burstein et al., 1972; An and Draughn, 2000; Simkin and Robin, 1973; Reilly and Burstein, 1975). Various indentation methods have been used as well, ranging from macro scale methods such as Vickers and Rockwell, to using Berkovich indenters with an atomic force microscope or nanoindentor. Most of these tests are performed at quasi-static to low loading rates. Additionally, mineral density and chemical composition investigations have been performed, with various correlations being made to elastic properties (Mullins et al., 2009; Zhang et al., 2010, 2008; Rho et al., 1998; Zysset, 2009; Hoc et al., 2006; Mercer et al., 2006; Tai et al., 2006).

One significant complication in testing properties of bone is the question of in- or ex-vivo. This is a large barrier for testing of bone. Inside a living animal, bone is hydrated and constantly undergoing cellular driven microstructural processes. Over the years many investigators have made advances in non-invasive in-vivo testing of bone properties. In particular, x-ray based methods have been extensively developed and are used for testing bone mineral density and tissue composition (Mazess et al., 1990). Another non-invasive technique used is that of ultra-sound measurements, widely studied and generally focused on density and elastic modulus (Jeffcott et al., 1987), but also used to investigate other properties, for example, correlation with failure strength in equine cortical bone (Glade et al., 1986).

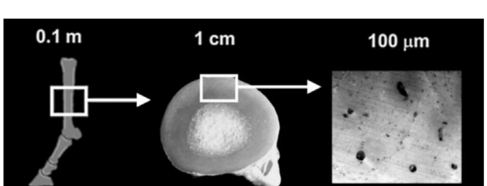

Fig. 1 – Depiction of the configuration of bone at various scales of length.

Recently, another minimally-invasive in-vivo technique is receiving attention in the medical community, called reference point indentation (RPI) developed by two of the present authors (Bridges et al., 2012; Gallant et al., 2012). A new handheld reference point indentation instrument, the Osteoprobe®, utilizes a single rapid, dynamic, indentation, with maximum indentation distance being the primary variable (Randall et al., 2013). A focus on dynamic indentation is used since most naturally occurring large deformation events occur in bone under impact or rapid loading, such as a sports injury or in a transportation accident. Due to indentation's inherent connection to hardness, pressure and strength, this avenue of testing bone tissue has gained interest as a simple method to test bone quality in a quantitative way. There is growing clinical and laboratory evidence that bone response can reveal critical information about bone health as a whole, with important implications for fracture risk (Farr et al., 2014; Zhang et al., 2010; Rho et al., 1998; Zysset, 2009).

The goal of the current study was to examine indentation of equine cortical bone, with finite element analysis and experimental validation. Material was obtained from the third metacarpal of a thoroughbred donor, and stress–strain relationships of a cortical bone sample were first obtained from conventional mechanical property tests. A finite element simulation procedure was developed for indentation analyses, incorporating a yield criterion in the simulation calibrated by tested mechanical properties, with different values in tension and compression. Experimental validation of the simulation procedure, using material from the same bone sample, was performed by determining the maximum depth of indentation with single cycle reference point indentation, and the profile and depth of the unloaded, permanent indentation with atomic force microscopy. Refinement of the finite element procedure by introduction of a type of damage through reduction of Young's modulus was added to further increase accuracy in simulating the profile and depth of the unloaded, permanent indentation, post recovery. Utility of the validated simulation procedure was demonstrated through prediction of differing responses between two tips of indenters with varying sharpness with experimental validation. This study details the development of a finite element procedure which uses a Drucker–Prager yield criterion, calibrated through mechanical testing of the same material sample used in experimental validation, and with simple Young's modulus reduction to address damage, to simulate the response of cortical bone under a single cycle type of reference point indentation. Concluding remarks are made as to the insights gained with regard to the mechanical properties and behaviors of the equine cortical bone.

Materials and methods

Mechanical testing

Four-point bending and axial compression tests were performed on cortical bone samples using an instrumented MTS 810 Universal Test machine. Bone tissue was provided by