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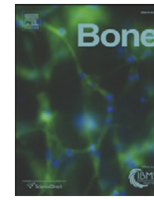

Original Full Length Article

# Shear deformation and fracture of human cortical bone

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ABSTRACT

Bone can be viewed as a nano-fibrous composite with complex hierarchical structures. Its deformation and fracture behaviors depend on both the local structure and the type of stress applied. In contrast to the extensive studies on bone fracture under compression and tension, there is a lack of knowledge on the fracture process under shear, a stress state often exists in hip fracture. This study investigated the mechanical behavior of human cortical bone under shear, with the focus on the relation between the fracture pattern and the microstructure. Iosipescu shear tests were performed on notched rectangular bar specimens made from human cortical bone. They were prepared at different angles (i.e. 0°, 30°, 60° and 90°) with respect to the long axis of the femoral shaft. The results showed that human cortical bone behaved as an anisotropic material under shear with the highest shear strength (~50 MPa) obtained when shearing perpendicular to the Haversian systems or secondary osteons. Digital image correlation (DIC) analysis found that shear strain concentration bands had a close association with long bone axis with an average deviation of 11.8° to 18.5°. The fracture pattern was also greatly affected by the structure with the crack path generally following the direction of the long axes of osteons. More importantly, we observed unique peripheral arc-shaped microcracks within osteons, using laser scanning confocal microscopy (LSCM). They were generally long cracks that developed within a lamella without crossing the boundaries. This microcracking pattern clearly differed from that created under either compressive or tensile stress: these arc-shaped microcracks tended to be located away from the Haversian canals in early-stage damaged osteons, with ~70% developing in the outer third osteonal wall. Further study by second harmonic generation (SHG) and two-photon excitation fluorescence (TPEF) microscopy revealed a strong influence of the organization of collagen fibrils on shear microcracking. This study concluded that shear-induced microcracking of human cortical bone follows a unique pattern that is governed by the lamellar structure of the osteons.
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## Introduction

Bone fracture, especially hip fracture is a serious and costly public health problem. Approximately 1.5 million hip fractures occur each year worldwide, and the prevalence increases to 2.6 million by 2025 and a staggering 4.5 million by 2050 [1]. Hip fractures are also associated with huge economic burden and increased risk of death, with 8.4% to 36% mortality within 1 year after the fracture incident [2]. From a materials point of view, hip fracture is the combined result of a fragile bone structure and the complicated stress state of tension, compression, and shear caused by external impacts. It is essential to better understand how bone fractures under different stress states and how this relates to bone's hierarchical structures as a means to improve clinical risk assessment and to contribute to the development of solutions to prevent hip fracture.

Prior to fracture, human cortical bone exhibits significant inelastic deformation, an important characteristic that directly contributes to bone's high resistance to fracture [3]. Inelastic deformation is accompanied by the formation and development of microcracks [3,4]. The pattern of microcracks strongly depends on the local stress. In tension, densely distributed wavy microcracks form roughly normal to the direction of the stress with crack length around 2–10 μm [4–6]. In contrast, compressive microcracks are straight and relatively longer; forming a typical cross-hatched pattern, orienting at approximately 27°–40° to the long axis of the bone [3,7–9]. If such a specific relation between the microcracking pattern and the applied stress is confirmed for all stress states, one could potentially use the microcracks as "finger prints" to reconstruct the at-fracture stress state of a complicated clinical hip fracture. Most previous studies of bone failure at the material level have focused on tension and compression while far fewer studies have focused on shear-induced microcracking [10–12], despite the fact that buckling-induced shear between lamellae is likely to be involved in femoral neck fractures [13,14]. Ascenzi and Bonucci were among the earliest to investigate the shear properties of single osteons [15]. Their

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work on single osteons under compression [16] showed that the microcracks created by compression-induced shear formed an angle of roughly 30°–35° with the long axis of the osteon. With detailed electron microscopic study, they have found circular cracks in the osteons having alternating fiber orientations in adjacent layers [17]. Later torsional studies showed that damage appeared within interstitial bone, Haversian systems, and along cement lines [18,19]. However, since torsional tests generate non-uniform shear in the specimens, they are not suitable for studying bone tissue behavior in pure shear mode [20,21]. More importantly, how shear induces microcracks within or between lamellae at the cortical bone level is still unknown. Our previous study on human cortical bone under compression revealed a clear sub-lamellar cross-hatched pattern, indicating an interfibrillar cracking nature [22]. We thus hypothesized that human cortical bone under shear deformed through intralamellar and interfibril microcracking.

Therefore, the purpose of this study was to investigate the shear-induced deformation and microcracking processes in human cortical bone and their relationship with bone's hierarchical structures, especially the collagen fibril orientation. Our specific objectives were to: 1. identify unique microcracking pattern under shear; 2. quantitatively define the shear-induced microcracks in osteons at the osteonal-interstitial level; and 3. specifically link the shear-induced microcracks to the lamellar structure at the micro-level.

## Materials and methods

### *Study design and general approach*

We conducted mechanical testing followed by microscopic examination on the transversal plane (i.e. perpendicular to the long axes of osteons) to address our objectives. Specifically, we combined Iosipescu shear tests (ASTM standard D 5379) with digital image correlation (DIC) for in-plane strain analysis, and fluorescence staining and laser scanning confocal microscopy (LSCM) for microcrack imaging. To access the interactions between bone's hierarchical structures and microcracking and deformation processes, we integrated second harmonic generation (SHG) [23] and two-photon excitation fluorescence (TPEF) [24] imaging techniques to relate the unique microcracking pattern to bone structures at the sub-lamellar level. Although SHG and TPEF have been used for biological and medical imaging for almost two decades, their potential has not yet been fully explored for imaging bone and microcracking [25]. We provide more detailed methods below.

### *Specimens preparation*

We obtained eight freshly frozen human cadaver femurs (six males, two females, age range: 62–79) without reported metabolic bone tissue conditions from LifeLegacy Foundation. All bone tissues were kept frozen at −20 °C until specimen preparation. The study was approved by the Clinical Research Ethics Review Board at the University of British Columbia.

Twenty-nine specimens in total were subjected to shear testing (ten 0°, nine 30°, five 60° and five 90° orientation, respectively). The shear specimens were obtained from the cortex of the diaphysis region. Two cuts, each perpendicular to the femoral shaft's long axis, were made at 27% and 48% from the proximal end of each femur with a band saw. The medial quadrant of each bone cylinder thus obtained was then sectioned into four different orientation bar specimens (Fig. 1), i.e. oriented at 0°, 30°, 60° and 90° to the long bone axis, and thus the long axes of majority osteons, by a low speed diamond saw (IsoMet 1000, Buehler Ltd, ON, Canada). The four sides of each specimen aligned either parallel or normal to the periosteal surfaces of femoral shaft. Rough machining was performed using a mini-milling machine (Sherline, model 5400, Vista, CA, USA). The specimens were subsequently manually grounded, using a series of carbide grinding papers (Buehler Buehler Ltd, ON, Canada), and polished with diamond suspension starting with 6 μm and ending with 1 μm (Leco Co., St. Joseph, MI, USA). The final specimens were 20 mm long, 5 mm wide and 3 mm thick, with the front and back surfaces (20 mm × 5 mm) parallel to the periosteal surface of femoral shaft. By following the ASTM standard (ASTM D5379/D5379M) [26], two 90° V-shaped notches, approximately 22% of the depth of the specimen total width, were made with a razor

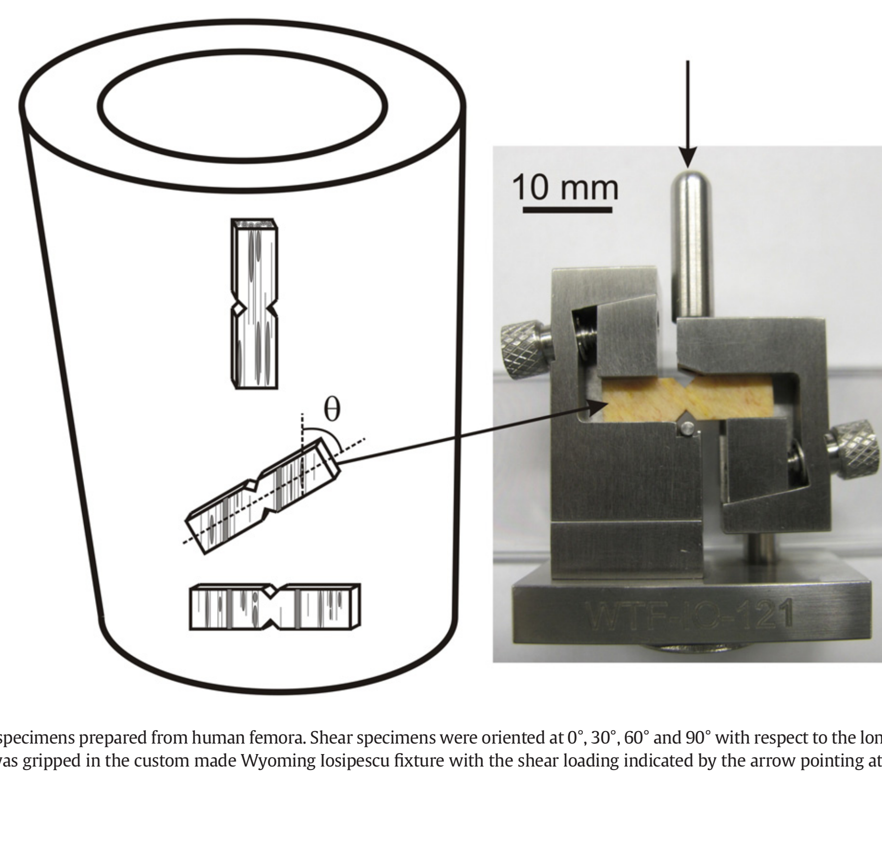


**Fig. 1.** Schematic illustration of specimens prepared from human femora. Shear specimens were oriented at 0°, 30°, 60° and 90° with respect to the long axis of femora, which is indicated by the gray lines. A specimen was gripped in the custom made Wyoming Iosipescu fixture with the shear loading indicated by the arrow pointing at the top of the rod.

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