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# Penetration of cutting tool into cortical bone: Experimental and numerical investigation of anisotropic mechanical behaviour

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ABSTRACT

An anisotropic mechanical behaviour of cortical bone and its intrinsic hierarchical microstructure act as protective mechanisms to prevent catastrophic failure due to natural loading conditions; however, they increase the extent of complexity of a penetration process in the case of orthopaedic surgery. Experimental results available in literature provide only limited information about processes in the vicinity of a tool–bone interaction zone. Also, available numerical models the bone-cutting process do not account for material anisotropy or the effect of damage mechanisms. In this study, both experimental and numerical studies were conducted to address these issues and to elucidate the effect of anisotropic mechanical behaviour of cortical bone tissue on penetration of a sharp cutting tool. First, a set of tool-penetration experiments was performed in directions parallel and perpendicular to bone axis. Also, these experiments included bone samples cut from four different cortices to evaluate the effect of spatial variability and material anisotropy on the penetration processes. Distinct deformation and damage mechanisms linked to different microstructure orientations were captured using a micro-lens high-speed camera. Then, a novel hybrid FE model employing a smoothed-particle-hydrodynamic domain embedded into a continuum FE one was developed based on the experimental configuration to characterise the anisotropic deformation and damage behaviour of cortical bone under a penetration process. The results of our study revealed a clear anisotropic material behaviour of the studied cortical bone tissue and the influence of the underlying microstructure. The proposed FE model reflected adequately the experimental results and demonstrated the need for the use of the anisotropic and damage material model to analyse cutting of the cortical-bone tissue.

## 1. Introduction

Penetration of a sharp tool into bone tissue is required in many clinical procedures, such as orthopaedic surgery, bone implant and repair operations. The success of bone-cutting surgery depends largely on precision of the operation and the extent of damage it causes to the surrounding tissues. An excessive force, generated by a sharp surgical tool or an implant device, can lead to formation of micro-cracks and fracture (Ebacher et al., 2012; Launey et al., 2010), and, ultimately, cause permanent damage to the adjacent area of cortical bone tissue that, in turn, can delay postoperative recovery of patients (Wazen et al., 2013). Therefore, information on deformation behaviour of cortical bone under penetration of a sharp tool is essential to understand the interaction process at tool–bone interface; this can improve the control of a surgical instrument to minimise damage caused to surrounding bone tissues. Previous bone-cutting experiments (Giraud et al., 1991; Itoh et al., 1983; Jacobs et al., 1974; Krause, 1987; Plaskos et al., 2003; Wiggins and Malkin, 1978) focused on characterisation of cutting parameters such as cutting forces, speed and depth of cut, whereas information with regard to the full-field deformation process in bone tissue was very limited, especially for the un-cut region (the remaining bone tissue). Measurements of forces generated during bone drilling reported in (Alam et al., 2011; Jacob et al., 1976; Wiggins and Malkin, 1976) suggested that they depended greatly on the drilling direction with respect to the bone's main axis due to high anisotropy of the cortical bone tissue. Furthermore, Sugita and co-authors (Sugita and Mitsuishi, 2009; Sugita et al., 2009) proposed a new cutting method based on the characteristics of crack propagation in cortical bone, indicating a fundamental difference between cutting of cortical bone tissue and metals.

From the modelling perspective, only a few models are available in literature to address issues related to bone penetration (Davidson and James, 2003; Sezek et al., 2012; Basiaga et al., 2011; Alam et al., 2009a; Kasiri et al., 2010). Despite these attempts, there is still no adequate model that can fully describe the material's anisotropy and damage behaviour under conditions of the tool-penetration process.

The challenges of creating such a comprehensive model can be partially associated with two reasons: the intricate mechanical

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behaviour of cortical bone and numerical difficulties linked to simulation of the penetration process due to large deformations. Although our understanding of the deformation and damage behaviours of cortical bone has progressed significantly in recent years (Abdel-Wahab et al., 2010; Li et al., 2012, 2013a), there have not yet resulted in a sophisticated bone-cutting model. Modelling techniques such as unzipping, re-meshing and element-deletion, which are employed to tackle the numerical difficulties associated with large deformation and formation of new surfaces, have all encountered various issues and criticisms in modelling of cutting. In recent years, the development of meshless FE algorithms has greatly assisted modelling of large-deformation processes, especially in machining (Limido et al., 2007). Smoothed particle hydrodynamics (SPH) is one of meshless techniques that have been implemented to simulate machining processes (Heinstein and Segalman, 1997; Limido et al., 2007). Similar to other particle-based interpretations, such as those described in Iliescu et al. (2010) and Ambati et al. (2011), SPH provides much better stability and accuracy for modelling of cutting processes thanks to its meshless nature and Lagrangian formulation (Limido et al., 2007).

Therefore, the focus of this study is on elucidating the anisotropic deformation and damage behaviours in cortical bone, which have been overlooked previously in modelling of penetration/cutting. Both experimental and numerical approaches were conducted in this study. The penetration test was chosen due to the requirement of smaller specimens, its simplicity and repeatability. It is also fundamentally similar to that of single-edge-cutting test (and with simpler kinematics). The newly developed SPH model was validated employing results of the penetration tests, and, for the first time, it provides insight into full-field deformation and fracture processes in the vicinity of the tool–bone interaction zone.

## 2. Materials and methods

### 2.1. Experimental analysis

Specimens of cortical bone used in this study were excised from mid-diaphysis of a fresh bovine femur obtained from a local butchery shop. A total number of 40 rectangular specimens with dimensions of 30 mm × 3 mm × 3 mm (length × width × thickness) were prepared for two orientations: parallel and perpendicular to the bone′s main axis (Fig. 1b), using a low-speed band saw and then a diamond-coated precision blade (Isomet Low-Speed Saw, Buehler) under water irrigation. The specimens were further categorised into four groups according to their anatomic quadrants, namely, *anterior*, *posterior*, *medial* and *lateral* in order to reduce inconsistency caused by material variability across different regions (Li et al., 2013a). Penetration tests were performed using Instron MicroTester 5848 with a 2 kN load cell. The specimens were kept hydrated in saline solution prior to the experiments and then glued to the testing base. Four penetrations were made for each cutting direction: perpendicular to osteons (L–C and L–R planes, Fig. 1a) and along them (C–L and C–R planes) using a standard sharp cutting tool under quasi-static loading conditions (displacement rate of 1.8 mm/min). A high-speed camera (Fastcam SA-3, Photron) equipped with a micro-lens (AF Micro-Nikkor 105 mm f/2.8D, Nikon, 5000–7500 fps) was employed to capture the deformation process at micro-scale.

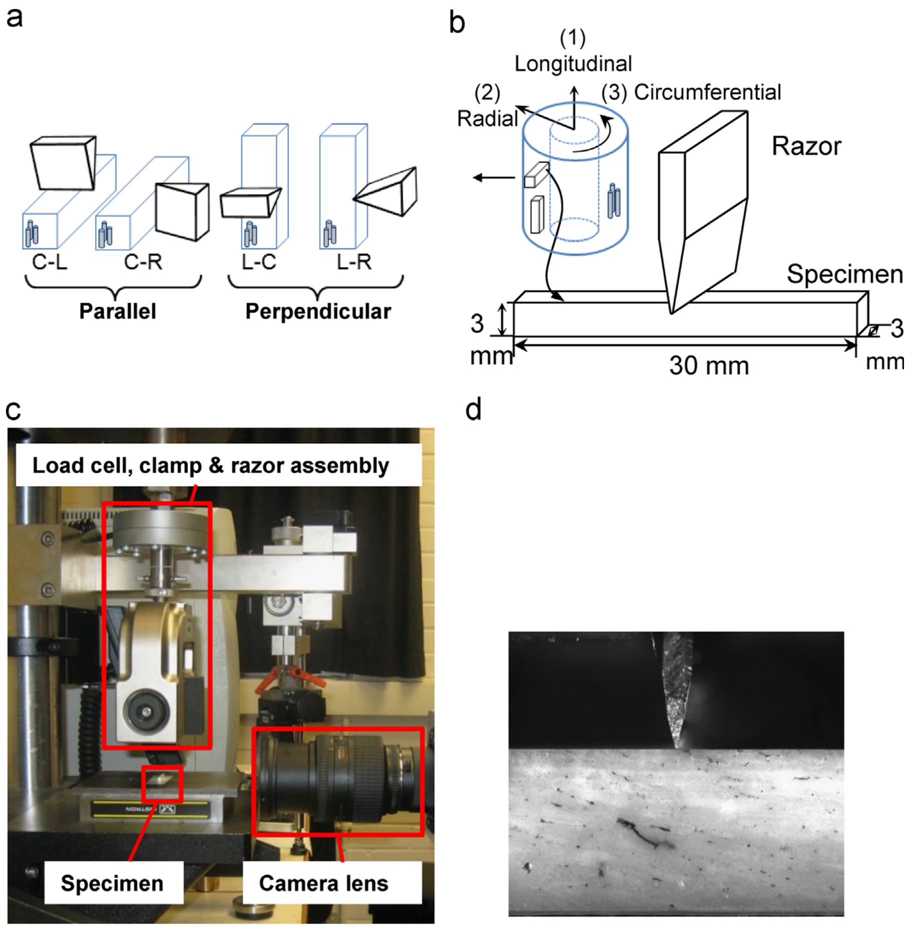

**Fig. 1.** (a) Notation of penetration directions according to ASTM E399 standard (the first letter refers to normal direction, while the second letter refers to the plane of motion, i.e. C–L means penetration direction perpendicular to circumferential direction and parallel to the longitudinal axis); (b) schematic of specimen preparation and cutting configuration; (c) setup for cutting experiments mounted on Instron MicroTester 5848; (c) superimposed image of razor and cortical-bone specimen taken with high-speed camera (Fastcam SA-3, Photron).