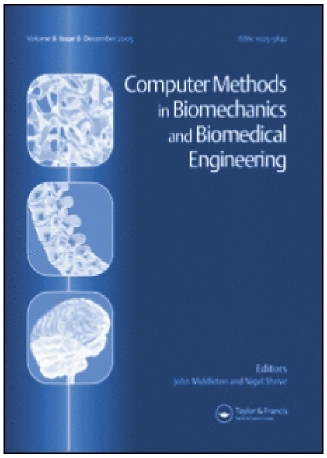

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Influence of nanoindentation test direction on the elastic properties of human cortical bone lamellae

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1. Introduction

The development of nanoindentation technique by Oliver and Pharr (1992) allowed investigations of cortical bone mechanical properties at the lamellar scale. Hardness and Young's modulus of interstitial lamellae were found higher than osteon lamellae properties (Rho *et al.* 1998, Zysset *et al.* 1999) and, within one osteon, an increase of properties was observed from the periphery to the centre of osteon (Rho *et al.* 1999) but not confirmed by another study (Hengsberger *et al.* 2002). Those previous investigations were performed in the longitudinal direction of cortical bone. Only one study performed on one human tibia sample by Fan *et al.* 2002 enlightened the influence of indentation direction on mechanical properties at the lamellae scale.

The present study intended to investigate the influence of the direction of nanoindentation tests on the elastic properties of cortical bone.

2. Materials and methods

Two cortical bone samples ($5 \times 4 \times 4$ mm) were cut from lateral and medial side of a human femur (70 years). Three faces (faces 1–3) perpendicular respectively to radial, tangential and longitudinal axes of the femur were polished and dried at room temperature. On each sample face, interstitial bone and osteon lamellae were identified using ESEM images (Philips XL30 ESEM-FEG, Royal Philips Electronics, the Netherlands). According to grey level, two osteon types were taken in consideration: "black" osteons and "white" osteons.

On each face, nanoindentation tests were performed on two different locations for interstitial, "white" and "black" osteon lamellae. For osteon structure, two lamellae were investigated: one lamella near to canal and one near to the periphery. On face 1 and 2, tests were performed on both side of the Haversian canal. Nanoindentation tests were performed at 2000 nm depth with a XP nanoindenteur (MTS System Corp., USA) using a pyramidal Berkovich tip and the continuous stiffness measurement (CSM) technique. Thanks to the CSM technique and in order to assess the properties within bone lamellae, Young's moduli were assessed from 600 to 1000 nm depth.

Statistical tests were performed with non parametrical Mann and Whitney tests ($p = 0.05$).

3. Results

On ESEM images, both "black" and "White" osteons have been observed on face 1 and 3 of medial and lateral samples but only "white" osteons on face 2.

Generally speaking, Young's modulus values were found higher for interstitial lamellae than for osteon lamellae (figure 1). Moreover, interstitial lamellae values were found higher in the longitudinal direction than in transversal directions for both medial and lateral samples ($p < 0.05$). Young's modulus values in radial and tangential directions were found different for lateral sample ($p < 0.05$) but not for medial sample ($p > 0.05$).

Results obtained for osteons in both medial and lateral samples showed the heterogeneity of osteon lamellae: Young's modulus values were found smaller for "black" osteons than for "white" osteons ($p < 0.05$). No significant difference was observed between inner and outer lamellae ($p > 0.05$). Nanoindentation test direction seemed to have an influence on Young's modulus values of osteon lamellae but this influence remained weak and non systematic.

4. Conclusion

This study enlightened the influence of nanoindentation test direction on the elastic properties measured. Interstitial

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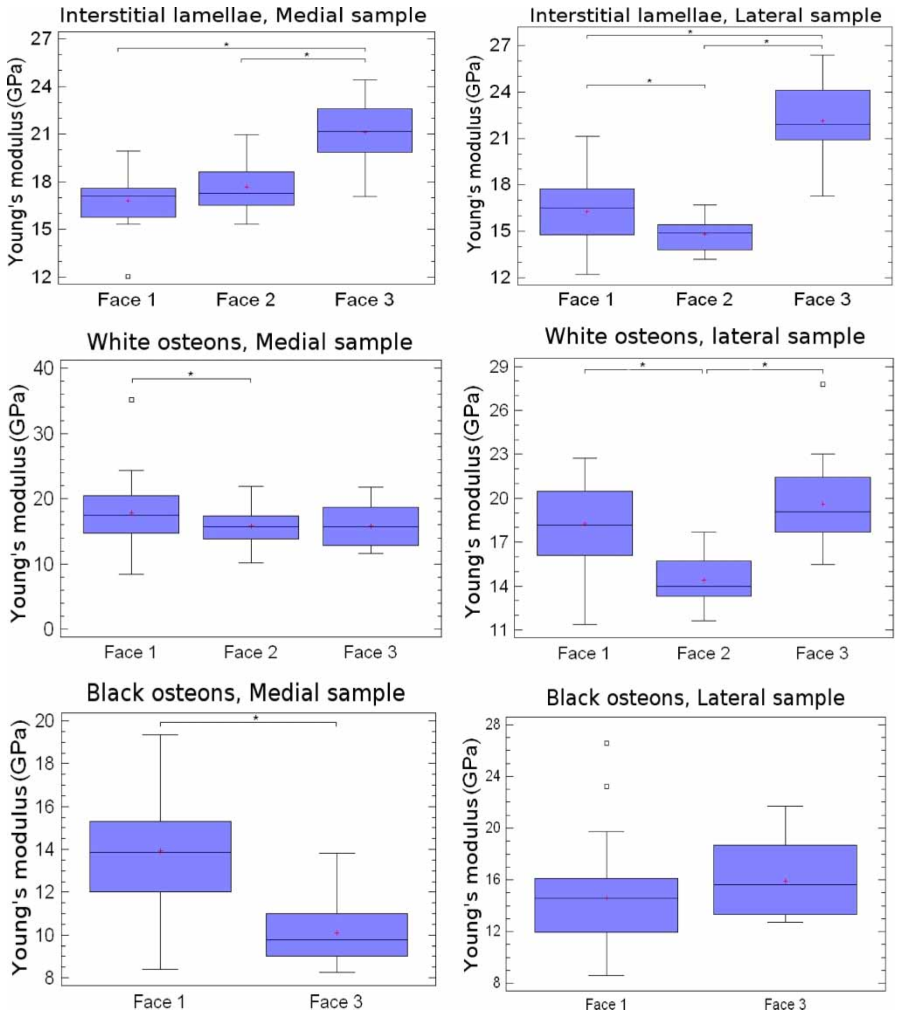

Figure 1. Young's modulus values obtained for interstitial, white and black osteons on medial and lateral samples (*significant difference $p < 0.05$).

lamellae were found stiffer than osteon lamellae and exhibited higher values in the longitudinal direction than in the transversal ones. Osteon lamellae exhibited a strong heterogeneity of elastic properties according to osteon type but a weak one according to direction test.

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