Finite element analysis of nanoindentation across bone interfaces and effects on the measured mechanical properties

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The microscopic structure of cortical bone reveals a complex architecture composed of osteons that contributes to bone fracture resistance. Osteons are formed from concentric lamellae that protect blood vessels at the center. Osteons are bordered by a tiny layer called cement line. Biologically, the cement lines are more mineralized than the surrounding bone and rich in osteopontin, a non collagenous protein. Their thickness varies between 1 and 5 μm and they appear during the remodeling of bone tissue, separating the new bone from the old. These thin structures play a predominant role in biomechanics by effectively dissipating energy, by deviating or stopping microcracks, thus increasing the bone's resistance to fracture. Despite their importance, the mechanical behavior of cement lines remains poorly understood.

Local mechanical properties of cement line can be investigated by experimental techniques such as nanoindentation. However, the interpretation of the nanoindentation results is challenging as the cement lines are surrounded by osteon and interstitial bone, and they are very thin. Nanoindentation techniques face experimental limitations due to the size of the probed surface, which may be larger than the extremely fine dimension of the cement lines. Therefore, simulations can be used to better understand indentation results. The main objective of this master's thesis is to explore these local mechanical properties at bone interfaces through nanoindentation simulations conducted by the finite element method. This study determines the impact of the bone internal interfaces on local mechanical responses, evaluating the variability of indentation measurements induced by the positioning of the indenter, and thus proposes recommendations for supporting a better interpretation of experimental data.

Initially, pilot tests were conducted using the ANSYS Workbench software, where the model size, mesh sensitivity, and other simulation parameters were examined. The comparison of the results from two-dimensional and three-dimensional simulations showed an underestimation of measurements in two-dimensional modeling. Keeping this in mind, 2D models could still be used to perform parametric studies, especially for comparing relative properties and not absolute values.

The thesis was structured in two main phases. Initially, the material properties of 3 bone regions of different mineral content and age were analyzed. A spatial resolved analysis was performed, and it demonstrated a significant local influence of bone interfaces, causing substantial deviations in the measured tissue modulus with respect to the nominal value for a position in the middle of the cement line, with this deviation increasing as the indenter approached interfaces with surrounding tissues, thus highlighting the importance of the placement of the indenter tip within the cement line. Subsequently, the inclination of these bone interfaces was explored to assess its impact on the measured mechanical behavior. This confirmed that the sample sectioning process is of great importance in the reliability of the results.

In conclusion, thin bone interfaces have shown a significant influence on the mechanical properties that can be measured experimentally, suggesting several improvements in data interpretation. One possible improvement is the use of backscattered electron imaging post-nanoindentation to determine the exact position of the indents and to consider only those falling in the middle of the cement line, hence reducing the influence of surrounding tissues. This study has also opened new research perspectives, including the exploration of the influence of porosity, the study of surface roughness induced by polishing, and the direction of collagen fibers.

Keywords: Nanoindentation, Finite Element Methods, Cement Line, Interface, Osteonal Bone, Interstitial Bone, Effective Young's Modulus.