

Characterization and Three-Dimensional Modeling of the Lamellar Architecture within Bone Osteons

Auteur : Lakhel, Ahmed

Promoteur(s) : Ruffoni, Davide

Faculté : Faculté des Sciences appliquées

Diplôme : Master en ingénieur civil biomédical, à finalité spécialisée

Année académique : 2024-2025

URI/URL : <http://hdl.handle.net/2268.2/23338>

Avertissement à l'attention des usagers :

Tous les documents placés en accès ouvert sur le site le site MatheO sont protégés par le droit d'auteur. Conformément aux principes énoncés par la "Budapest Open Access Initiative"(BOAI, 2002), l'utilisateur du site peut lire, télécharger, copier, transmettre, imprimer, chercher ou faire un lien vers le texte intégral de ces documents, les disséquer pour les indexer, s'en servir de données pour un logiciel, ou s'en servir à toute autre fin légale (ou prévue par la réglementation relative au droit d'auteur). Toute utilisation du document à des fins commerciales est strictement interdite.

Par ailleurs, l'utilisateur s'engage à respecter les droits moraux de l'auteur, principalement le droit à l'intégrité de l'oeuvre et le droit de paternité et ce dans toute utilisation que l'utilisateur entreprend. Ainsi, à titre d'exemple, lorsqu'il reproduira un document par extrait ou dans son intégralité, l'utilisateur citera de manière complète les sources telles que mentionnées ci-dessus. Toute utilisation non explicitement autorisée ci-avant (telle que par exemple, la modification du document ou son résumé) nécessite l'autorisation préalable et expresse des auteurs ou de leurs ayants droit.

MASTER'S THESIS: CHARACTERIZATION AND THREE-DIMENSIONAL MODELING OF THE LAMELLAR ARCHITECTURE WITHIN BONE OSTEONS

AHMED LAKHEL

MASTER SCIENCE OF BIOMEDICAL ENGINEERING - ACADEMIC YEAR 2024/2025

SUPERVISOR: DAVIDE RUFFONI

Abstract

Bone strength is a crucial concept in biomechanics and clinical practice. For bone to withstand significant loads without fracturing, it must exhibit high mechanical resistance. This resistance is the result of the combination of three essential factors: bone mass, geometry, and intrinsic quality.

Bone mineral density (BMD) is considered as an indirect clinical indicator of bone strength. Although this measurement accounts for a significant part of the mechanical performance of bone, it remains insufficient on its own to accurately predict the risk of fracture. Other determining aspects, such as bone microarchitecture, remain insufficiently explored and deserve further investigation in ongoing research.

In this context, this thesis presents an innovative approach to investigate bone architecture at the micrometer length scale. The focus is placed on the morphology of the lamellae forming cortical bone osteons combining experiments and mathematical modeling. To achieve this, images acquired with second harmonic generation (SHG) microscopy of three osteons from a bone sample collected from the femur midshaft of a 56-year-old patient were processed using a series of rigorous methods, detailed throughout this report.

Firstly, the lamellar morphology is analyzed and characterized based on the raw images of each osteon. Although these images correspond to transverse sections, we were able to reconstruct the lamellae in several longitudinal planes of the osteon, where they appear in the form of relatively straight lines. This observation motivated the fitting of linear regressions to derive a first mathematical representation of these structures. This representation allowed us to extract relevant morphological features and revealed that lamellae have a conical geometry when observed in three dimensions, thereby challenging the cylindrical model that has long been accepted in the literature.

Secondly, a protocol was developed to reconstruct the imaged osteons as individual mathematical objects, allowing for simple and coherent interpretation. Although SHG microscopy provides high-contrast images, the resulting signal remains complex and can clearly be simplified. To achieve this, we proposed a series of steps aimed at reducing the SHG signal to a unit-thickness object which exhibits smoother appearance. Specifically, following post-processing that included binarization, the images were skeletonized. Given the quite circular geometry of the lamellae, transforming the images into polar coordinates proved useful for fitting smoothing splines along the lamellae. This initial reconstruction, performed manually, was limited to three transverse slices per osteon. Then, it became necessary to develop a method for estimating the lamellar structure across all other slices, based both on the reconstructions from the three reference slices and on the linear regressions obtained from the first part of this work. Ultimately, we demonstrated that, overall, the proposed protocol is relatively robust and provides a reliable approximation of the raw SHG signal.

This work is not limited to a detailed exploration of cortical bone microarchitecture; it also paves the way to a wide range of research opportunities. In particular, the simplified model of lamellae that we propose appears promising for being superimposed onto images of the lacuno-canalicular network and osteocytes, with the aim of gaining more insight into the interactions involved between these structures that coexist within bone tissue, and whose formation results from successive temporal episodes. For instance, our model could be used to estimate the number of canaliculi crossing a lamella formed at time t , and an adjacent, more internal lamella formed at time $t + 1$, thereby enabling a temporal assessment of cortical bone development.