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The micro-mechanics of cortical shell removal in the human vertebral body

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Abstract

An improved understanding of the biomechanical role of the vertebral cortical shell with respect to the trabecular bone may improve diagnosis of osteoporosis and provide insight into the effects of disease, aging, and drug treatments. In this study, we present results from finite element simulations of removal of the shell from the vertebral body and the associated mechanical effects in terms of overall change in vertebral structural stiffness and of the tissue-level stresses. Specimen-specific micro-mechanical finite element models of thirteen vertebrae were generated from micro-CT scans with 60-μm voxel size. An algorithm was developed to automatically isolate the thin (and discontinuous) shell and the images were converted into finite element models by mapping each image voxel into a finite element. After removal of the endplates, compressive loading conditions were applied and linear elastic analyses were run for three cases – with and without the shell, and shell-only models. The models contained up to 13.6 million elements and were solved using a maximum of 144 CPUs in parallel, 300 GB memory, and a custom code with a parallel mesh partitioner and algebraic multigrid solver. Results indicated that the shell was on average, 0.38 ± 0.06 mm thick, accounted for 21–39% of the overall bone mass, but accounted for 38–68% of the overall vertebral stiffness. Examination of the tissue-level stresses indicated that this disproportionately large mechanical effect of shell removal was due in part to unloading of the remaining peripheral trabeculae adjacent to the shell. Stress paths were also preferentially within vertically-aligned bone: the cortical shell and vertically-aligned trabeculae. Taken together, these results demonstrate two important roles of the thin vertebral cortical shell: it can carry significant load by virtue of representing a large proportion of the vertically-aligned bone tissue within the vertebra, and, as a shell, it also maximizes the load carrying capacity of the trabecular centrum, particularly around the periphery.

Keywords: Spine biomechanics; Micro-mechanics; Cortical shell; Finite element analysis; Vertebral body; Trabecular bone

1. Introduction

The human lumbar and thoracic vertebrae are major load-bearing bones within the spinal column that consist primarily of highly porous trabecular bone, surrounded by a thin cortical shell. The mechanical integrity of the vertebra is a critical factor in the etiology of age-related osteoporotic fractures and in the support structure for a variety of orthopaedic implants such as pedicle screws and intervertebral disc replacements. An improved understanding of the biomechanical role of the vertebral cortical shell with respect to the trabecular bone may improve diagnosis of osteoporosis and provide insight into the effects of disease,

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aging, and drug treatments. It may also provide a basis for mechanistic validation of finite element models used for fracture risk prediction [7,11,14,16] and for improved design of spinal implants.

Since the cortical shell is a thin, discontinuous and porous structure, it has been difficult to characterize its mechanical contribution to the overall strength of the vertebral body. While some studies have concluded that the cortical shell takes over 40% of the load [14,23,31], others have concluded that it takes less than 15% [17,26]. The major shortcoming of the experimental studies is controlling the removal process of the shell: if too much is removed, it may induce damage to the trabecular centrum, if too little is removed, the effect of the shell is underestimated. Since the shell is on the order of 0.25–0.4 mm thick [9,22,25,30], it is difficult to remove it in a precise fashion. Continuum-level finite element models [5,7,11,14,16,26] suffer from a simplistic modeling of the shell and its interaction with the trabecular centrum, although these analyses have provided unique insight. For example, it has been shown that the load taken by the shell depends on the location along the superior–inferior axis [5,14,26], as well as the applied boundary conditions [14].

With recent advances in micro-computed tomography (micro-CT) and parallel supercomputer technologies, it is now possible to obtain high-resolution scans of whole bones at a spatial resolution on the order of 50–100 μm and analyze the micro-mechanics of the bones using image-specific finite element analysis at this spatial resolution. Studies using this technique have provided unique insight into the mechanical effects of osteoporosis at the proximal femur [29] and the vertebral body [10,13]. Analyses on the vertebra have shown that the average load fraction taken by the vertebral cortical shell is 0.45 across vertebrae [10], maximum at the mid-section [10,13] and that with osteoporosis, the trabecular micro-structure becomes less resistant to non-habitual loads [13]. Despite these studies, there remains an incomplete understanding of the mechanisms by which the shell contributes to the load-carrying capacity of the vertebra.

As part of an overall effort to understand the micro-mechanics of the human vertebral body, including the specific load sharing role of the cortical shell [10], our goal in this study was to investigate the biomechanical effects of removal of the shell from the vertebral body. Our first objective was to develop an automated technique to digitally identify the geometrically complex cortical shell using micro-CT scans of a series of human vertebral bodies and using this, calculate mean values of shell thickness and the shell's contribution to the total bone mass. Our second objective was to create and analyze three micro-finite element models of each vertebral body: (1) the whole vertebral body; (2) the trabecular centrum alone, having virtually removed the shell from the vertebra; and (3) the isolated cortical shell itself. Data were then analyzed to determine the effects of shell removal and the dependence of these effects, if any, on the density and stiffness of the vertebral body. This study is unique in its precise isolation of the cortical shell and its focus on the micro-mechanics of shell removal.

2. Methods

Thirteen T-10 vertebral bodies obtained from female human cadavers (age range: 54–87 years, 74.6 ± 9.4 years) were scanned at 30-μm voxel size using micro-CT (SCANCO 80, SCANCO Medical AG, Bassersdorf, Switzerland). The voxel size was increased to 60 μm using region averaging to reduce the CPU time required to analyze the resulting finite element models. Next, both superior and inferior cortical endplates were removed from the vertebral body. This was done to facilitate easier application of uniform compressive boundary conditions on the superior and inferior surfaces, a protocol that has also been used in experiments on cadaver vertebrae [19].

A custom program was developed within commercial image processing software (IDL, Research Systems Inc., Boulder, CO) to analyze the morphology of the shell. This program was designed to accomplish three tasks: (1) identify the cortical shell; (2) measure its thickness; and (3) measure its percentage contribution to total bone tissue within the vertebral body. The micro-CT scan data at 60-μm voxel size were analyzed one layer at a time starting at the inferior surface and then proceeding in the superior direction. Each slice of the vertebral body was first divided into four quadrants. Each of these four sections was processed in the same manner. Within each quadrant, the outer edge of the cortical shell was defined as the first filled voxel (i.e., bone tissue) on a line originating from the edge of the image layer (horizontal or vertical depending on the quadrant being processed). The inner edge of the shell was defined as the first empty voxel (i.e., space) after a series of filled voxels along the line. At this point it is important to note that two scenarios can lead to inaccuracies in the cortical shell identification (Fig. 1). The first is the possibility of trabeculae being adjacent to the shell that would artificially increase the thickness of the shell at that location. The second is that the discontinuities in the cortical shell can cause the algorithm to enter the trabecular centrum and count internal trabeculae as part of the shell. Therefore, the program used moving averages and various checks to ensure that these two cases were properly handled during the identification of the cortical shell. The moving average was used to identify sudden increases in shell thickness. Further, if the first filled voxel along the search line was far from the current calculated position of the shell it was ignored. This method allowed us to identify discontinuities in the shell. In order to model the porous nature of the shell, any bone encountered within an average pore size of 180 μm [25] of the outer structure of the shell was identified as part of the shell. The accuracy of our algorithms was verified by visually comparing original scan layers and the identified cortical shell.