Assessment of Stiffness Variability in Thoracic Vertebrae: Implications for Surgical Treatment of Compression Fractures

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INTRODUCTION: Vertebral compression fractures are a common clinical condition affecting millions annually. Surgical procedures used in treatment, such as vertebroplasty and kyphoplasty, have been found to induce biomechanical alterations, creating a stiffness mismatch between the treated and intact adjacent vertebrae, ultimately leading to failure of these adjacent vertebrae. Information on the stiffness and other factors must be evaluated to restore the failed vertebrae to physiologic conditions. The main objective of this study is to assess the stiffness of human vertebrae and their variability along the spine.

METHODS: Specimen-specific finite element models (FEM) of cadaveric thoracic vertebral bodies were developed from Computed Tomography (CT) imaging of 10 subjects, 5 men and 5 women. Through the process of CT image segmentation, rendering, generation of the finite element mesh from the 3D model, material property assignment, application of boundary conditions, and finally, FEM simulation, anterior wedge-shaped compression fractures were induced (Figure 1). Vertebral stiffness was evaluated using the slope of the fitting line of the initial portion of the load-displacement curve. The stiffness load variability along the spine was obtained by averaging the values for each vertebra across all datasets.

RESULTS: The stiffness in the lower thoracic spine (59,650 ± 2,299 N/mm) was statistically more significant than that in the middle (51,307 ± 8,154 N/mm) and upper thoracic spines (37,237 ± 1,148 N/mm). The middle thoracic spine had statistically higher stiffness than the upper thoracic spine. Specifically, T11 had the highest mean stiffness (62,885 ± 8,339 N/mm), while T1 had the lowest (35,991 ± 5,642 N/mm) (Figure 2).

DISCUSSION: Our primary finding is that the average stiffness in the upper thoracic spine is 73% of the stiffness in the mid-thoracic spine and 62% of the stiffness in the lower thoracic spine. Moreover, it increases within all three regions, particularly in the middle one. Conversely, the average failure load increases by nearly 3000 N from the upper to the mid-thoracic and from the mid-thoracic to the lower thoracic region. This study does recognize certain limitations such as the approximate nature of FEM which may be impacted further as complexity increases. Furthermore, this study did not utilize soft tissues which could potentially affect the results in vivo. Despite this, our study has several advantages; for instance, the reliable material characteristics applied to the elements of the model, derived directly from the CT images, allowed us to account for vertebral bone heterogeneity and accurately reproduce the mechanical response of vertebrae. The surface-based FEM created a realistic and smooth surface of the entire vertebra using tetrahedral elements, unlike voxel-based FEMs, which can generate artificial stress raisers.

SIGNFIGANCE: Vertebral stiffness and strength represent essential predictors of future fractures. With the increasing rates of osteoporosis and related compression fractures, this information has potential implications for evaluating the risks of compression fractures and improving our current surgical procedures, such as vertebroplasty and kyphoplasty.

IMAGES AND TABLES:

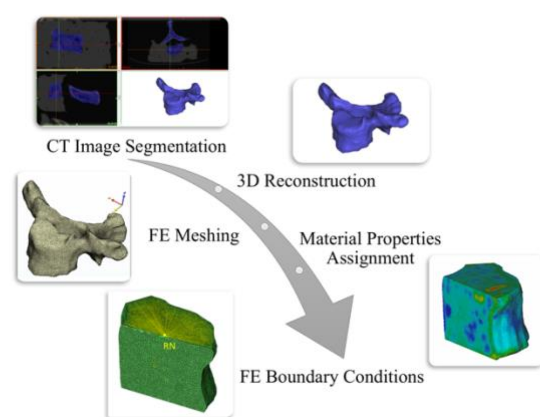

Figure 1. Sequence of steps used in CT-based finite element analysis (CT/FEA) of thoracic stiffness

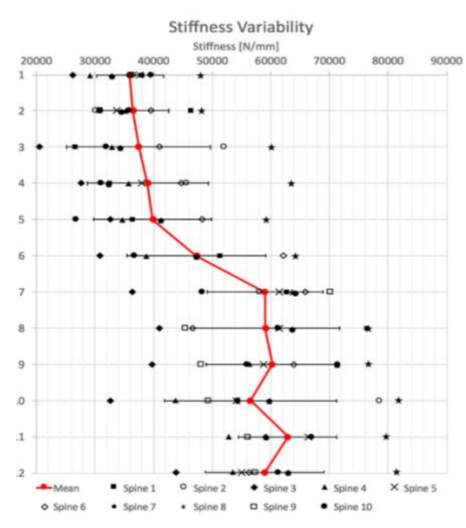

Figure 2. Stiffness data points and average values over the ten datasets, along the thoracic spine. Error bars represent ± one standard deviation