Title:
Vertebral Strength Prediction of a Patient-Specific Functional Spinal Unit – a Finite-Element Study

Authors:
D. Anitha, anitha@mymail.sutd.edu.sg, Singapore University of Technology and Design
Karupppasamy Subburaj, subburaj@sutd.edu.sg, Singapore University of Technology and Design
Thomas Baum, thomas-baum@gmx.de, Technical University of Munich

Keywords:
Finite Element Analyses, 3D Modelling, Spine Biomechanics, Vertebral Fracture, Bone Strength

DOI: 10.14733/cadconfP.2019.202-206

Introduction:
Osteoporotic vertebral fractures are increasingly common and are associated with an increased risk of subsequent fractures, loss of daily abilities and high mortality. Dual-energy X-ray absorptiometry (DXA) is limited by its inaccuracy in identifying patients with impending fractures. This is because DXA does not consider three-dimensional (3D) structural information of the spine. Due to the challenges involved in diagnosing fractures before they occur, patient-specific non-linear finite element (FE) analyses have shown potential in predicting bone strength non-invasively, enabling the possibility of early intervention. FE models of the isolated vertebral bodies alone provides limited information on the strength of the spine, as the intervertebral discs (IVDs) also influence the load applied to the spine. The purpose of this preliminary study is to first construct a patient-specific functional spinal unit (FSU) from multi-detector computed tomography (MDCT) images and compare the numerical failure load with the experimentally-obtained failure load and evaluate the accuracy of the FE analysis. Second, the numerical failure load of the FSU will be compared to the individual vertebra, without incorporating the IVDs, and the influence of IVDs will be evaluated.

Main Idea:

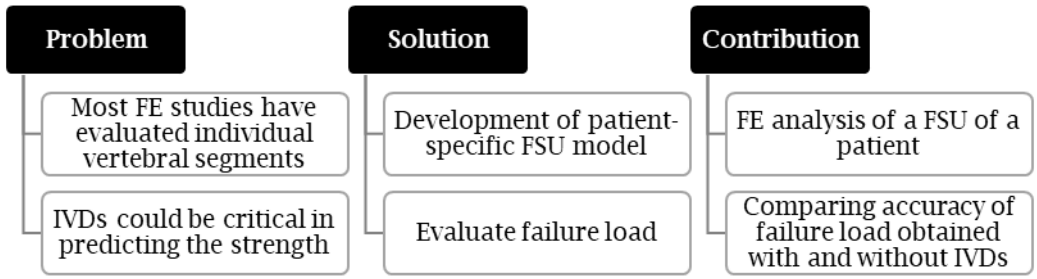

Fig. 1: Summary of the problems, solutions and contributions associated with this study.

The biomechanical study and analysis of the spine is paramount to understanding the mechanism involved behind osteoporotic vertebral fractures. Computational modelling using FE analysis has good potential in providing non-invasive insight in a patient-specific manner to aid clinicians in predicting and preventing these fractures before it is too late. While FE modelling has recently been widely

established in the prediction of bone strength and consequently fractures, challenges remain in the modelling of the spine. This is because the human spine is structurally-complex, consisting of multiple bone units, unlike long bones. Consequently. many FE studies have focused on modelling of vertebral segments in isolation from radiological scans in the prediction of various biomechanical properties [2-4],[10],[14]. Liebschener et al. showed that FE-predicted vertebral stiffness was comparable to experimentally-obtained stiffness and that FE analysis could be used as tool for evaluation of biomechanical properties and an indication of fracture [10]. A study done by Buckley and his group showed that quantitative computed tomography (QCT)-based FE-predicted strength measures correlated significantly with experimental strength and was better predictive of compressive strength than BMD [2].

OVFs are not just a result of the deterioration of the bone density and strength, but also a result of disc degeneration. Disc generation not only alleviates obvious clinical symptoms such as pain but also results in spinal instability, which in turn influences the structural strength of the spine. Consequently, FE analysis incorporating the IVDs could be critical in predicting the strength and impending fractures of the spine. However, running a whole spine analysis may be too ambitious in terms of the computational time and the implying need for whole spine CT scans, which will still not justify the non-invasive evaluation of this computational method.

Methodology

In this study, the functional spinal unit (FSU), comprising of a full T10 vertebral body between two IVDs and two half-T9 and T11 vertebral bodies, was obtained from a human cadaver spine (age = 98 years old; weight = 42 kg). MDCT imaging was first performed on the FSU, followed by in-vitro mechanical testing to obtain the experimental failure load (F_{exp}). The MDCT images were then imported into image processing software Mimics (Materialise NV, Harislee, Belgium) to do segmentation of the respective vertebral bodies and IVDs (Fig.1). Transversely isotropic elastic-plastic material properties were assigned to the vertebrae based on relations available in literature [5-9],[12]. The vertebrae were meshed in commercial software 3-Matic (Materialise NV, Harislee, Belgium) and exported for FE analysis with ABAQUS version 6.10 (Hibbitt, Karlsson, and Sorensen, Inc., Pawtucket, RI, USA). This non-linear FE analysis protocol for the vertebrae has been previously validated in our previous work [1].

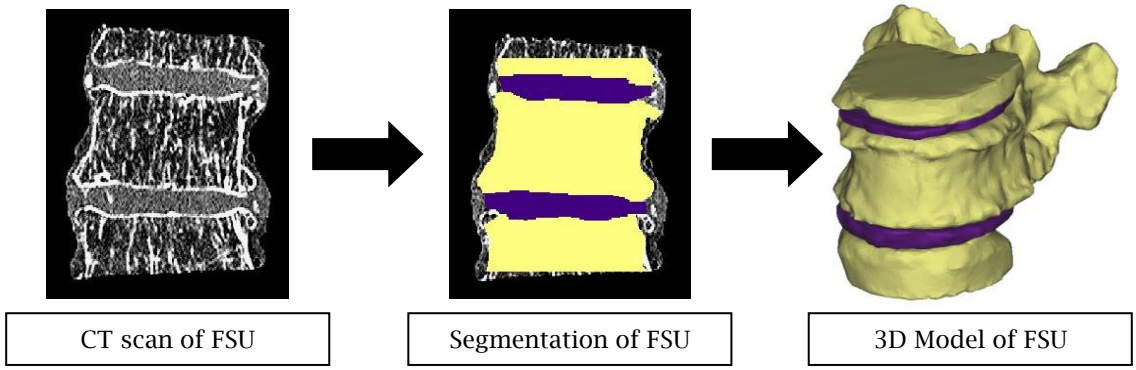

Fig. 2: Illustration of progression from image segmentation to 3D modelling of the FSU (left to right). (a) MDCT scan, (b) Segmentation masks of vertebral bodies and IVDs and (c) T9-T10-T111 FSU model.

On the other hand, the IVDs were exported as point cloud files into Solidworks (Dassault Systemes, Vélizy-Villacoublay, France) and exported as Parasolid files. In ABAQUS, the IVDs were first partitioned by centering an ellipse into annulus fibrosus (AF) and nucleus pulposus (NP), such that the NP represented approximately 30% of the total IVD volume [11],[13] (Fig. 2). Homogenous linear elastic

properties were assigned to the AF and cartilage endplates and the NP was defined as an incompressible fluid-filled cavity (ρ = 1.125g/cm^3). Cartilage endplates on top and bottom of the IVD were defined as a membrane. Hard contacts were used between vertebrae and respective contacting surfaces and tie constraints were applied between the interacting surfaces of the AF and NP. Displacement load was applied on the superior surface of T9 and the inferior surface of T11 was constrained in all directions. The peak of the force-displacement graph was assumed as the FE-predicted failure load (F_{FE}) of the FSU.

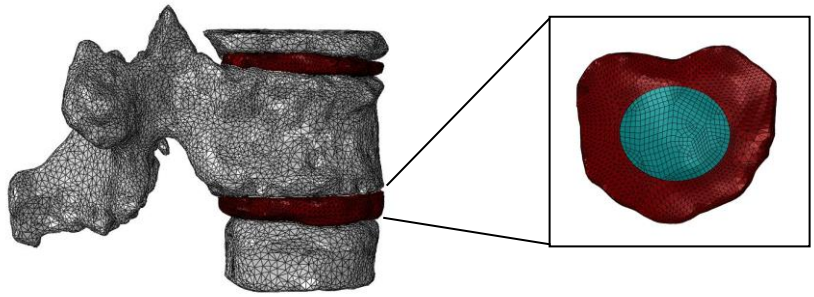

Fig. 3: Illustration of the bottom IVD divided into annulus fibrosus (outer red) and nucleus pulposus (inner green).

Results

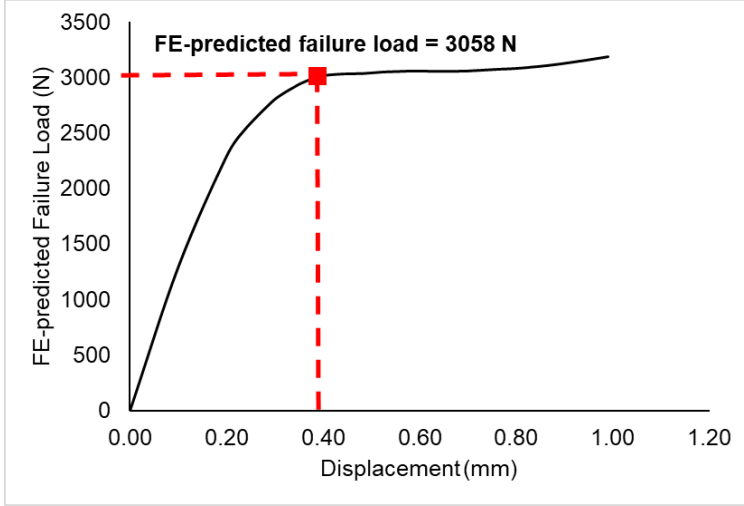

Fig. 4: Force-displacement curve produced by the FE analysis illustrating the peak force as the FE-predicted failure load.

F_{FE} obtained for the FSU FE model was 3058 N (Fig. 4) and it correlated well with F_{exp} (= 2950 N) with a difference of 3.7% (Table 1). However, F_{FE} obtained for the isolated T10 central vertebral segment alone (= 4222 N) deviated from Fexp by 43%. The post-processed model after FE analysis showing the

displacement distribution is illustrated below in Fig. 5. The incorporation of IVDs into the analyses had significant influence on the displacement distribution and consequently the failure load obtained as shown by the results.

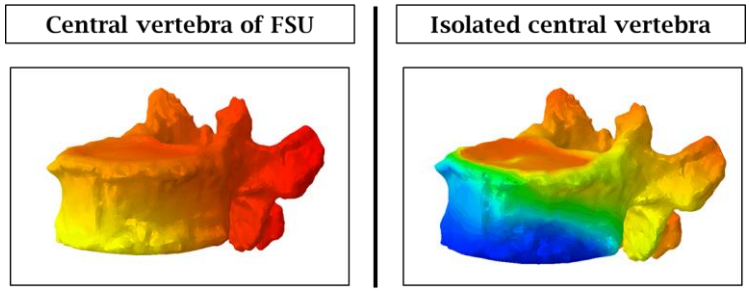

Fig. 5: Displacement distribution of central vertebra of the T9-T10-T11 FSU (left) and the isolated T10 central vertebral segment (right).

Conclusions:
To the best of our knowledge, this study is the first of its kind to determine the significance of IVD in FE analyses using failure load. The primary focus of this study was to develop patient-specific FSU FE models to validate predictions failure load from FE analysis and experimental testing. Our preliminary study demonstrated that the inclusion of IVDS was more accurate than analyzing the isolated central vertebral segment alone. Isolated vertebral bodies may not be able to accurately predict the compressive strength of the spine. IVDs may have a paramount role to play in the biomechanics of the spine. Vertebral strength prediction based on FE analyses should focus on FSUs that are at higher risk for fractures during diagnosis in the clinical scenario.

Acknowledgements:
This study has received funding by Deutsche Forschungsgemeinschaft (DFG) BA 4906/2-1 (TB), and TUM Faculty of Medicine KKF grant H01 (TB).

References:
[1] Anitha, D.; Subburaj, K.; Mei, K.; Kopp, F. K.; Foehr, P.; Noel. P. B.; Kirschke, J. S.; Baum, T.: Effects of dose reduction on bone strength prediction using finite element analysis, Scientific Reports, 6, 2016, 38441. https://doi.org/10.1038/srep38441
[2] Buckley, J. M.; Leang, D. C.; Keaveny, T. M.: Sensitivity of vertebral compressive strength to endplate loading distribution, Journal of Biomechanical Engineering, 128(5), 2006, 641-646. https://doi.org/10.1115/1.2241637
[3] Crawford, R. P.; Cann, C. E.; Keaveny, T. M.: Finite element models predict in vitro vertebral body compressive strength better than quantitative computed tomography, Bone, 33(4), 2003, 744-750. https://doi.org/10.1016/S8756-3282(03)00210-2
[4] Eswaran S. K.; Gupta, A.; Keaveny, T. M.: Locations of bone tissue at high risk of initial failure during compressive loading of the human vertebral body, Bone, 41(4), 2007, 733-739. https://doi.org/10.1016/j.bone.2007.05.017
[5] Goulet, R. W.; Goldstein, S. A.; Ciarelli, M. J.; Kuhn, J. L.; Brown, M. B.; Feldkamp, L. A.: The relationship between the structural and orthogonal compressive properties of trabecular bone., Journal of Biomechanics 27(4), 1994, 375-389. https://doi.org/10.1016/0021-9290(94)90014-0
[6] Keller, T. S.: Predicting the compressive mechanical behavior of bone, Journal of Biomechanics, 27(9), 1994, 1159-1168. https://doi.org/10.1016/0021-9290(94)90056-6

[7] Keyak, J. H.: Improved prediction of proximal femoral fracture load using nonlinear finite element models, Medical Engineering Physics, 23(3), 2001, 165-173. https://doi.org/10.1016/S1350-4533(01)00045-5

[8] Keyak, J. H.; Lee, I. Y.; Skinner, H. B.: Correlations between orthogonal mechanical properties and density of trabecular bone: use of different densitometric measures, Journal of Biomedical Materials Research, 28(11), 1994, 1329-1336. https://doi.org/10.1002/jbm.820281111

[9] Keyak, J. H.; Falkinstein, Y.: Comparison of in situ and in vitro CT scan-based finite element model predictions of proximal femoral fracture load, Medical Engineering Physics, 25(9), 2003, 781-787. https://doi.org/10.1016/S1350-4533(03)00081-X

[10] Liebschner, M. A.; Kopperdahl, D. L.; Rosenberg, W. S.; Keaveny, T. M.: Finite element modeling of the human thoracolumbar spine, Spine (Phila Pa 1976), 28(6), 2003, 559-565. https://doi.org/10.1097/01.BRS.0000049923.27694.47

[11] O'Connell, G. D.; Vresilovic, E. J.; Elliott, D. M.: Comparison of animals used in disc research to human lumbar disc geometry, Spine, 32(3), 2007, 328-333. https://doi.org/10.1097/01.brs.0000253961.40910.c1

[12] Rho, J. Y.; Hobatho, M. C.; Ashman, R. B.: Relations of mechanical properties to density and CT numbers in human bone, Medical Engineering Physics, 17(5), 1995, 347-355. https://doi.org/10.1016/1350-4533(95)97314-F

[13] Shirazi-Adl, S. A.; Shrivastava, S. C.; Ahmed, A. M.: Stress analysis of the lumbar disc-body unit in compression. A three-dimensional nonlinear finite element study, Spine, 9(2), 1984, 120-134. https://doi.org/10.1097/00007632-198403000-00003

[14] Wijayathunga, V. N.; Jones, A. C.; Oakland, R. J.; Furtado, N. R.; Hall, R. M.; Wilcox, R. K.: Development of specimen-specific finite element models of human vertebrae for the analysis of vertebroplasty, Proceedings of the Institution of Mechanical Engineers, Part H, 222(2), 2008, 221-228. https://doi.org/10.1243/09544119JEIM285