Reece Huff, Boston University College of Engineering

Optimizing Digital Volume Correlation to Study Vertebral Fractures

I. Introduction

The goal of my project was to improve the performance of an image-processing method used to study the mechanisms of bone failure in the spine. Failure of this bone, the vertebra, is known clinically as a “vertebral fracture”. Vertebral fractures comprise approximately 700,000 out of a total 1.5 million osteoporotic fractures annually [1]. Total costs due to vertebral fractures are estimated to be as high as one billion dollars per year in the U.S. [2].

A fundamental barrier to reducing the frequency of vertebral fractures is the lack of understanding of the properties of the vertebra that control when and how it fails. To address this problem, researchers have begun to use high-resolution, 3-D x-ray imaging to study the failure process in great detail [3]. My laboratory [4] and others [5] have developed image-processing methods that, when applied to a sequence of 3-D x-ray images obtained during mechanical testing, quantify the deformations that occur at the microscale throughout the vertebra at each stage of the failure process. These methods are based on a process known as digital volume correlation (DVC). Although powerful, these DVC methods are computationally time-consuming and in need of tools that facilitate robust assessments of accuracy.

Therefore, the specific objectives of my project were: (1) to evaluate a multiresolution DVC approach for increases in speed; and (2) to create an independent verification program to evaluate the accuracy of the DVC results.

II. Methods

Overview of Approach. DVC works by comparing two images of an object, one taken before the object is deformed and one after, and determining the deformation field that produces the best match between the images. The comparison is performed in individual sub-regions, or elements, that collectively discretize the object into a mesh (Figure 1); the outputs of DVC are the displacements of the corner points, or nodes, of each element. In my project, the images of the object (the vertebra) are obtained using micro-

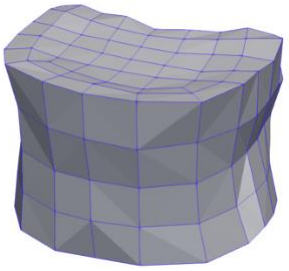

Figure 1. *Example of a DVC mesh of a vertebra.*

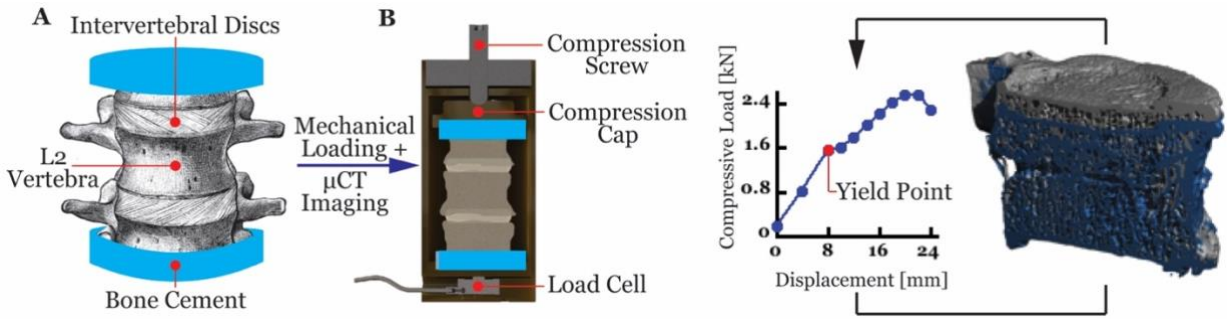

Figure 2. *Experimental procedure:* ***A.*** *Isolated L2 vertebra with adjacent vertebrae potted in bone cement to ensure uniform loading.* ***B.*** *Cyclic process of μCT imaging* and *compression of the vertebra incrementally by 2 mm until failure. In the rightmost panel, the deformed vertebra is in blue and the undeformed vertebra is in grey. Both are shown in cross-section to facilitate visualization.*

computed tomography (μCT), a high-resolution, 3-D x-ray imaging method. I perform a sequence of μCT scans of a vertebra as it is compressed to failure and then apply DVC to the resulting time-lapse sequence of images (Figure 2). In the remainder of this section, I describe the methods I used to speed the DVC computation time and to evaluate the accuracy.

Modifications to DVC Method. The multiresolution procedure I created (Figure 3) works as follows. I first downsample, or coarsen, the pair of μCT images. Next, I use rigid registration to register the pair of downsampled images to each other. I use the resulting rigid transformation matrix as the initial guess in a DVC run on the downsampled image pair. I then use the output of this run as the initial guess for the DVC run on the full-size image pair.

Verification of DVC Accuracy. I created an image transformation code that uses isoparametric interpolation to obtain a voxel-by-voxel assessment of DVC accuracy. Given the set of nodal displacements $\vec{u}_i$ produced by the DVC algorithm for nodes $n = 1 \ldots n$ in the element, I calculated the interpolated displacement $\vec{u}^P$ for every voxel P in the element as

$$\vec{u}^P = \sum_{i=1}^{n} \vec{u}_i \, f_i(\vec{x}^P) \qquad (1)$$

where $f_i(\vec{x}^P)$ represents the shape function [6] for node i evaluated at $\vec{x}^P$. These interpolated displacements were used to morph the μCT image of the deformed vertebra into the μCT image of the undeformed vertebra that would be predicted from the calculated $\vec{u}_i$. I then defined the accuracy of the DVC result as

$$Mismatch\,Value = \frac{\sum (I_1 - I_2^M)^2}{\sqrt{\sum (I_1)^2} \times \sqrt{\sum (I_2^M)^2}} \qquad (2)$$

where I_1 is the undeformed image and I_2^M is the morphed version of I_2, the deformed image. A lower Mismatch Value indicates higher accuracy. For validation purposes, I tested my program on an image pair where one image was artificially rotated by 16°. I then applied my program to a pair of images from an actual mechanical test (Figure 1).

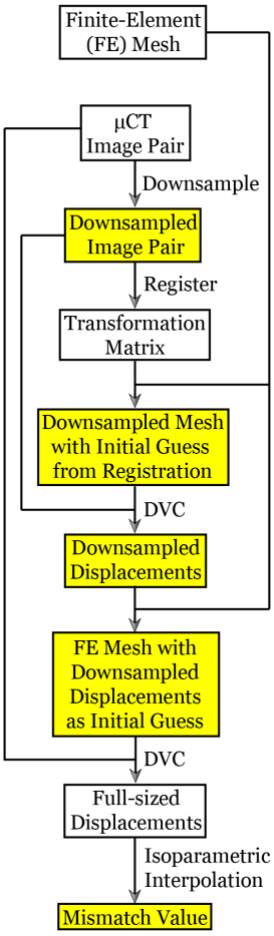

Figure 3. *The DVC algorithm: the modifications made are in yellow*

III. Results

My modifications to the DVC algorithm decreased run-time by 82.1% and decreased mismatch value by 0.0251% on average (Table 1). Additionally, the modified algorithm converged in fewer iterations.

Down Sample Factor	Mismatch Value	Number of Iterations	Total Run-Time
1	0.011947	31	3hr 18m
2	0.011944	9	1hr 55m
3	0.011944	10	1hr 45m
4	0.011944	10	1hr 55m
5	0.011944	11	1hr 40m

Table 1. Mismatch value and run-time with different amounts of downsampling

My isoparametric interpolation program produced qualitative and quantitative descriptions of the accuracy of the DVC algorithm. Results from the validation test (artificial 16° rotation) showed mismatch values ranged from 0.0033 to 0.051 among three vertebrae examined (Figure 4A,B). Results from the application to an actual mechanical

test showed that regions in and near the top end (“endplate”) of the vertebra had higher mismatch values than those near the bottom (Figure 4C,D).

IV. Discussion

Modifications to DVC produced dramatic improvements in speed. This achievement enables us to process increasingly larger data sets.

The independent verification program provides voxel-by-voxel qualitative visualization of the image matching quality. This allows me to easily identify mismatch errors, and thus guides selection of input parameters and further algorithm modifications to improve DVC performance. The areas of high error in and near the top endplate revealed by my program suggest that deformations in the top layer of the mesh are distributed non-linearly. This indicates deformations in the endplate are larger than those in the interior bone and thus that the properties of the endplate may be a key factor in vertebral fracture.

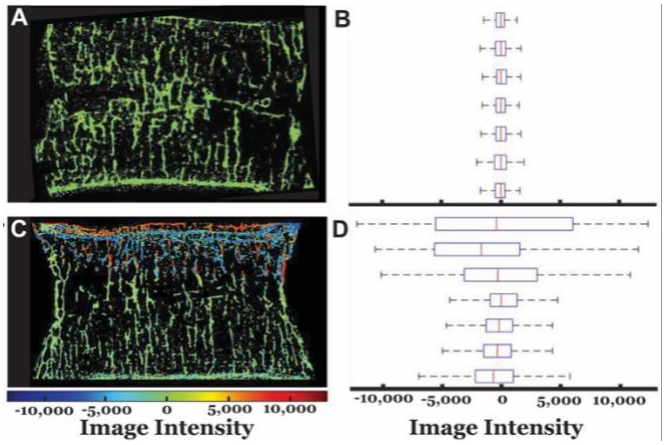

Figure 4: Validation of Program: A. *Cross-sectional view of the match between the pair of images of a vertebra where one image was artificially rotated by 16° and then morphed to the undeformed shape using the DVC result. Image intensity values of 0 indicate a perfect match.* ***B.*** *Distribution of intensity values in each of seven horizontal layers of A.* ***Application of Program: C,D.*** *Same as A,B but for vertebra that was deformed by compressive force.*

Future work includes using the downsampling approach recursively, *i.e.*, I could initialize the run for the 2x2x2 downsampled images with the output of registering 4x4x4 voxel downsampled images. In addition, my verification program could be used as an internal check of DVC accuracy whenever new DVC algorithms are tested. My work will continue to provide our lab with faster results and robust indications of accuracy as we investigate the properties of the vertebra that control when and how it fails.

V. References

[1] Riggs BL, Melton LJ III. The worldwide problem of osteoporosis: insights afforded by epidemiology. Bone 1995;17: Suppl:505S-511S

[2] R. Burge, B. Dawson-Hughes, D. H. Solomon, J. B. Wong, A. King, and A. Tosteson, “Incidence and Economic Burden of Osteoporosis-Related Fractures in the United States, 2005-2025,” J. Bone Miner. Res., vol. 22, no. 3, pp. 465–475, Mar. 2007.

[3] F. Gillard, R. Boardman, M. Mavrogordato, D. Hollis, I. Sinclair, F. Pierron, M. Browne, “The application of digital volume correlation (DVC) to study the microstructural behaviour of trabecular bone during compression,” Journal of the Mechanical Behavior of Biomedical Materials, vol. 29, pp. 480-499, Jan 2014.

[4] Hussein, A. I., Louzeiro, D. T., Unnikrishnan, G. U., and Morgan, E. F. (January 12, 2018). "Differences in Trabecular Microarchitecture and Simplified Boundary Conditions Limit the Accuracy of Quantitative Computed Tomography-Based Finite Element Models of Vertebral Failure." ASME. J Biomech Eng. 140(2): 021004.

[5] Zauel, R., Yeni, Y. N., Bay, B. K., Dong, X. N., and Fyhrie, D. P. (July 21, 2005). "Comparison of the Linear Finite Element Prediction of Deformation and Strain of Human Cancellous Bone to 3D Digital Volume Correlation Measurements." ASME. *J Biomech Eng*. February 2006; 128(1): 1–6.

[6] Zienkiewicz, O. C., and Robert L. Taylor. *The Finite Element Method for Solid and Structural Mechanics*, Elsevier Science & Technology, 2005.