Digital Volume Correlation analysis of 3D porous biomedical structures using GPU-assisted approach for FEM validation

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Summary: Digital Volume Correlation (DVC) GPU-assisted implementation was developed for the purposes of analysis of 3D porous biomedical structures. Cancellous bone cubic specimens from bovine femur loaded in-situ during micro-CT measurement and artificially generated highly porous bone-like scaffolds were used for preliminary tests together with Finite Element Method (FEM).

1. INTRODUCTION

Digital Volume Correlation (DVC) is a technique used for 3D deformations measurements. The technique makes use of volume images in undeformed state as reference, as well as in deformed state, allowing for calculation of the full 3D displacements and strains maps. Input volumes may be acquired from X-ray Micro-Computed Tomography (micro-CT) [1], Fluorescence Confocal Microscopy [2], Magnetic Resonance Imaging (MRI) systems for biological subjects, or via optical tomography for transparent media [3]. DVC is a powerful non-intrusive technique for the identification of sub-surface material deformation and is capable of identifying defects, discontinuities or cracks before they are even visible in the raw image. It is also capable of quantifying the full volume strain distribution and actual magnitudes of the material displacements around discontinuities. The level of information provided by this technique is extremely useful in validating Finite Element Method (FEM) [4].

2. EXPERIMENTAL METHOD

In presented DVC approach, algorithm measures internal 3D material displacement fields by correlating intensity patterns within interrogation windows. In first step 3D images of unloaded and loaded state are scaled down and registered using affine transform, being a starting point for minimization methods used in next step. In next step both original volumes are divided into small sub-regions (50×50×50 voxels or smaller). Each sub-region can then be transformed from unloaded state image using affine transform and can be compared to loaded state sub-region using simple sum of squares approach. Main task is to find proper affine transform coefficients, which can be considered as a minimization problem with 12 degrees of freedom. Unfortunately finding a global minimum requires many sub-region affine transforms, which becomes time consuming task, mostly due to heavy use of interpolation operations needed in transformation process. Hopefully every modern GPU processor is capable of making millions of such interpolations per second. Despite the fact that describied method can use full affine transform, it can also be used to find only translations components, which speeds up the process.

Main goal of presented implementation of Digital Volume Correlation technique was to create effective software dedicated to study strains inside 3D porous biomedical structures, including cancellous bone and tissue scaffolds. That requires access to many of DVC technique parameters such as: density of the grid points for which the elongations or displacements are calculated, or even the choice of a particular point in space in which deformation is calculated. Informations collected this way are crucial for robust validation of compression tests simulations performed using FEM.

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3. RESULTS

Cubic specimens of cancellous bone taken from bovine femurs from 6 slaughter animals in various ages (1-9 years old) and artificially generated bone-like porous scaffolds were used for preliminary tests. The specimens had various porosity depending on the age. All specimens were measured using X-ray micro-CT device (Nanotom S, GE Sensing & Inspection Technologies, Phoenix X-ray GmbH) equipped with a nanofocus X-ray tube with a maximum 180 kV voltage and in-situ loaded using compression machine (CT500, Deben). The tomograms were registered using a Hamamatsu 2300 $\times$ 2300 pixel 2D detector. The reconstruction of measured structures was performed using datosX software (ver. 2.1) with the use of a Feldkamp algorithm for Cone Beam X-ray CT. Reconstruction of the data was performed using VGStudio Max (ver. 2.1). All examined specimens were scanned at 100 kV of source voltage and 0.1 mA, with a 360-degree rotation of the specimen in 1800 steps. The exposure time was 500 ms, with a frame averaging of 3 and image skip of 1 applied, resulting in a scanning time of 60 minutes for each loading step. The reconstructed images with a voxel size of 6.5 um^3 were binarized using automatic global tresholding (Otsu method) and 3$\times$ resampled. Highly porous 3D bone-like tissue scaffolds models were artificially generated [5] and together with micro-CT measured cancellous bone specimens were used in voxel-based FEM compression simulations (ParOSol). Displacements maps from FEM compression test and corresponding DVC analysis for tissue scaffolds was illustrated in Fig. 1 to demonstrate general compliance of presented approach.

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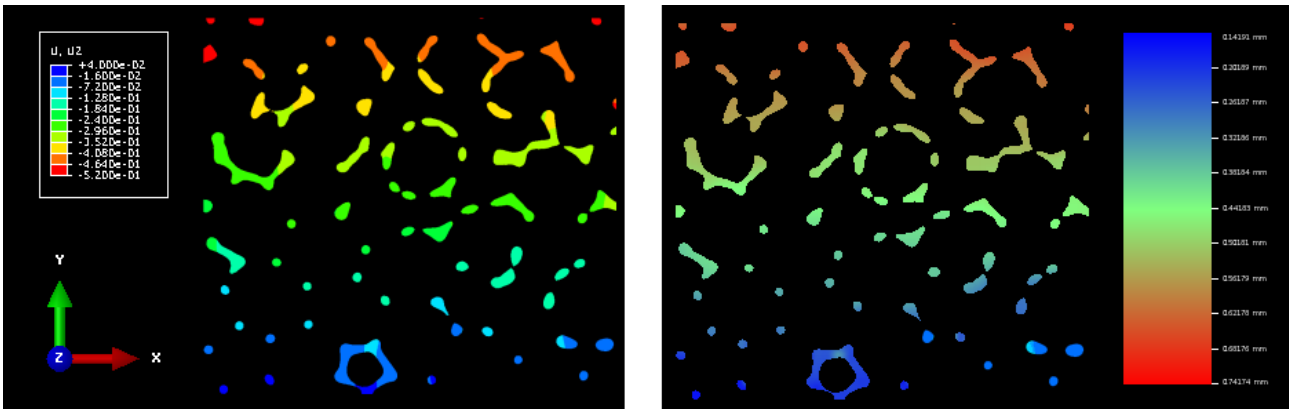

Figure 1: Displacements maps of tissue scaffold FEM compression (a) and corresponding DVC analysis (b).