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Assessing 3D mechanical changes in weight bearing CBCT using Digital Volume Correlation

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Introduction

In situ, real-time and high-resolution micro-computed tomography (microCT) imaging, combined with digital volume correlation (DVC), has emerged as a powerful technique for the 3D visualization of internal full-field displacements and strains at different stages of a loading experiment. Over the last two decades, this technique has been successfully used to investigate the deformation and failure mechanisms of several biomaterials and tissues, including trabecular bone.[1]

There are a number of critical parameters in the design of a DVC experiment, including spatial resolution, texture correlation, noise/CT artifacts, measurement uncertainties, and the loading mode/magnitude. Previous DVC trabecular bone studies were performed at a micrometer scale using industrial or synchrotron-source imaging.1 At this scale, the trabecular struts are well resolved (at the cost of higher dose) and can be used as tracking features for DVC.

Background

The Planmed Verity Extremity Scanner is a cone beam computed tomography (CBCT) scanner used at Saint Luke's Radiology (Oxford, UK). It is a low-dose, fast scanner that collects full scans at a 0.1–0.2 mm voxel size. Typically, two scans are collected: one in a supine position and one in an erect standing position. This dual scanning approach is useful for capturing the realignment of bones under full body weight, along with the position of tissues, joint spaces, and potential fractures.

Technical challenges and solutions

Recently, feasibility studies have emerged that combine DVC with PedCAT bone imaging in order to assess whether DVC can be used with weight-bearing CBCT to measure 3D internal tissue deformation.[2] At a voxel size between 100 and 200 µm, bone struts are less resolved with weight-bearing CBCT than high-resolution microCT (**Figure 1**). Weight-bearing CBCT's

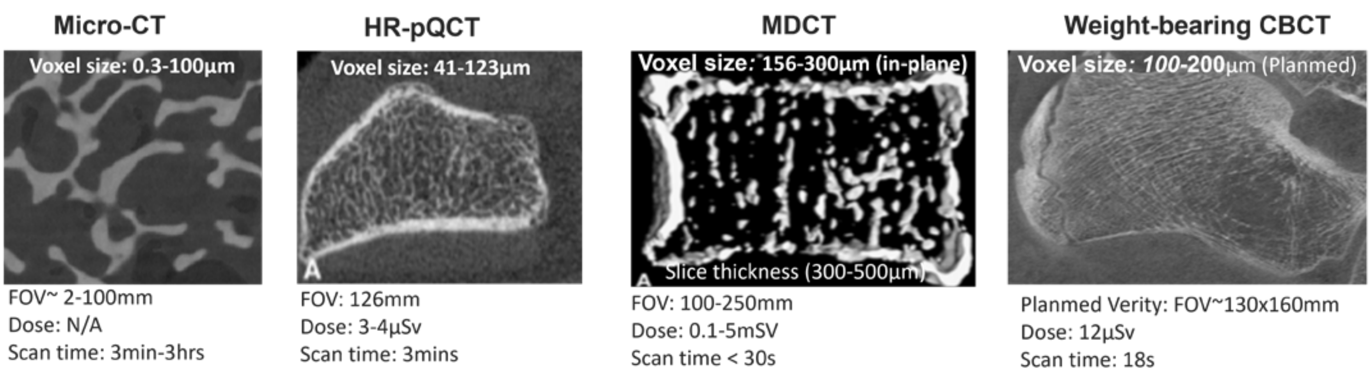

Figure 1. The spatial resolution of trabecular bone imaging with various CT methods.

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spatial resolution is somewhere between high-resolution peripheral quantitative CT (HR-pQCT) and multidetector CT (MDCT).[3] Although this scale of observation is not suitable for quantifying the morphology of bone struts, they are still visible, and the preserved texture between supine and standing measurements makes CBCT a potential candidate for DVC tracking.

Methods

CT images of an overstressed ankle and a subchondral insufficiency fracture in a knee were acquired in supine and standing positions using the Planmed Verity Extremity Scanner with a 200 µm pixel size. The CT data was imported into Thermo Scientific™ Amira™ Software for DVC, which offers both a local and a robust, global finite-element DVC (FE-DVC) approach. Prior to analysis, the data was pre-aligned using sophisticated registration algorithms to remove rigid body motion. Due to the complex anatomy of the tissues, the global FE-DVC approach was used to capture the exact shape of the tissues (calcaneus, tibial plateau, and femoral condyle); these were segmented using a marker-based watershed algorithm and converted into 3D tetrahedral grids. A mesh size of 32 voxels provided a reasonable balance between spatial resolution and measurement. This was established by performing a DVC uncertainty measurement analysis, where two consecutive scans in supine position were acquired using the same scanning settings. (For a mesh size of 32 voxels, the displacement and strain precision were found to be 0.1–0.2 voxels and 0.2% respectively.)

Digital Volume Correlation (DVC)

DVC works by correlating volumetric images of a structure before and after deformation. XDVC in Amira Software is designed to handle complex samples and difficult images, such as those obtained from CBCT. DVC is performed simultaneously across the whole specimen using a finite element method and the robust global approach.[4]

Workflow implementation

1. **Mesh generation:** The specimen is discretized using a finite element mesh made of tetrahedra, which is flexible enough to capture complex shapes like the calcaneus (Figure 2).

2. **DVC analysis:** The DVC workflow includes the measurement of precision and accuracy, automated DVC for time series under small or large deformations, DVC of large datasets, and the analysis of difficult materials with poor textures through mechanical regularization.

3. **Integration and automation:** Python integration in Amira Software is utilized to automate the workflow, from data registration to mesh generation, DVC analysis, and visualization. This automation is crucial for speeding up the entire workflow.

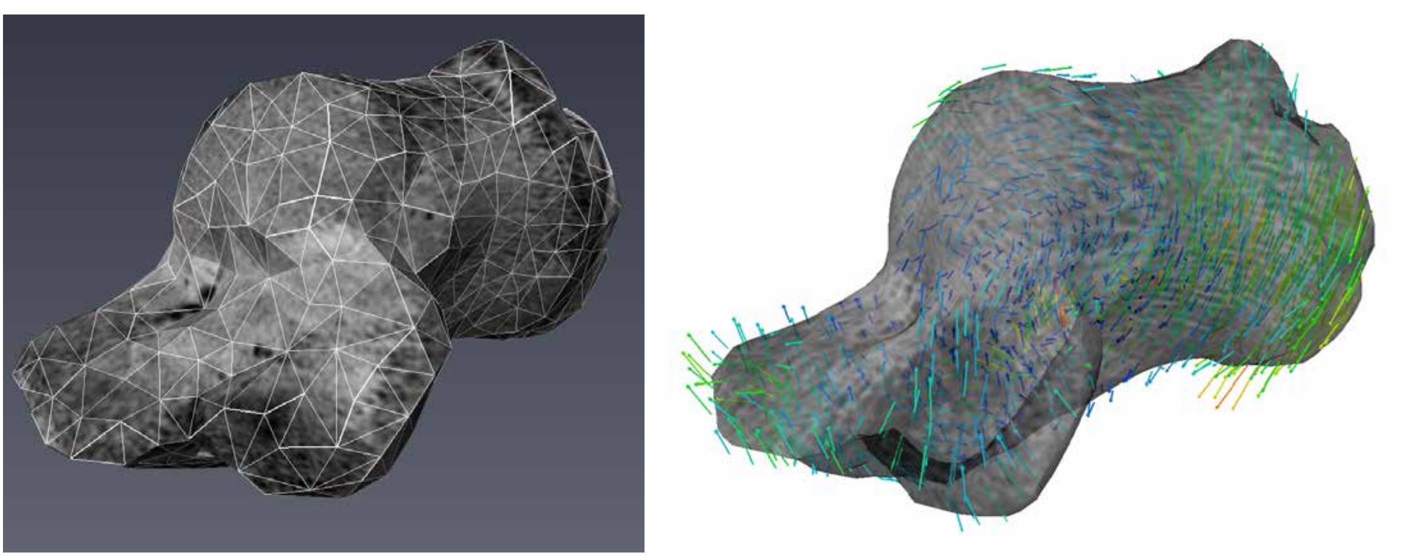

Figure 2. 3D tetrahedral grid of a patient's calcaneus and the corresponding 3D vectors computed between supine and standing positions.

Preliminary results

The displacement field was able to be tracked with the local bone texture, despite this approach having ~10x less spatial resolution compared to traditional microCT imaging (Figure 2). The displacement vectors were computed at each node of the mesh and the correlation quality was judged based on the map of the correlation residuals. (I.e., the difference between the reference image and the deformed image that was corrected by the measured displacement field). The standard deviation of the residuals was ~4% of the dynamic range, and was attributed to noise/artifacts.

Application example

An overweight patient's calcaneus was analyzed to map displacement in 3D and visualize displacement vectors. For clinicians, this information may be useful for measuring bone displacement and assessing joint instability under full body weight. From the displacement data, the components of the strain tensor were derived, focusing on the third principal strain, which indicates the most compressive strain. Regions of high compressive strain (~-4%) were localized at the bottom of the calcaneus and in the anterior process, suggesting a risk of fracture (Figure 3).

Discussion

DVC between supine and standing CBCT enabled the successful 3D mapping of displacements and strains inside a calcaneus bone structure, with a displacement precision of 0.1–0.2 voxel and a strain precision <0.2%. Additionally, comparison of loaded/unloaded strain maps for the affected ankle/knee can be compared with the corresponding (unaffected) control to determine if these maps can be linked to the diseases/deformities impacting patients

Conclusion

DVC was successfully used to quantify deformation-induced changes between CBCT imaging in supine and standing positions. This method is a promising complementary tool for the diagnostic process, potentially enhancing the comprehensive diagnosis of foot and ankle conditions when combined with ultrasounds and other patient information.

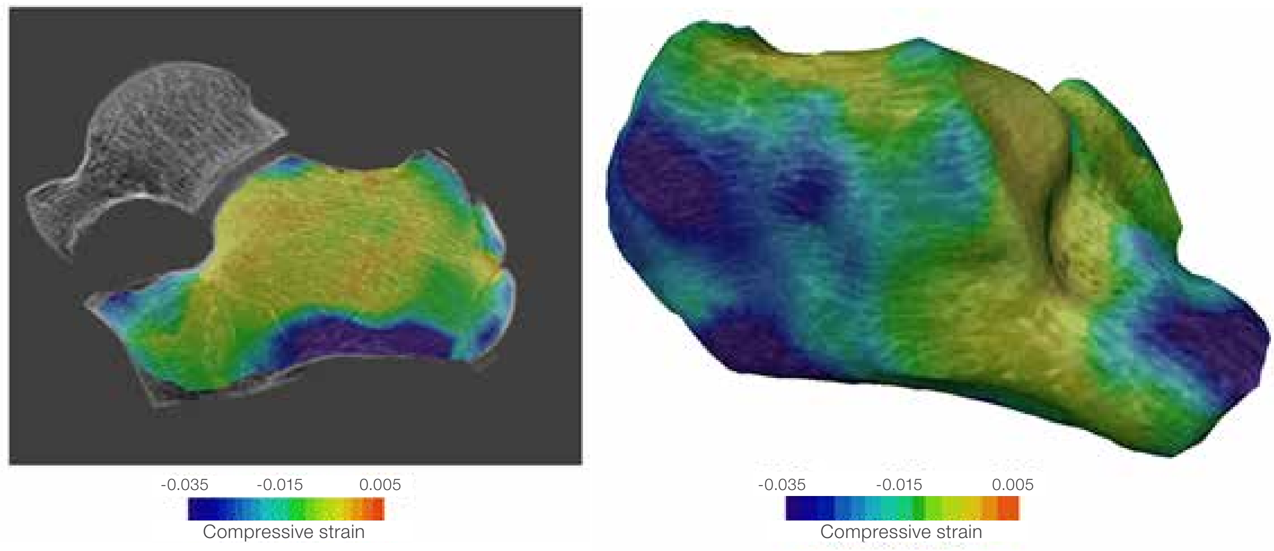

Figure 3. Third principal strain revealing high compression at the bottom of the calcaneus and in the anterior process.

References

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Notes

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