# Strain uncertainties in digital volume correlation of bone via clinical PedCAT CT: a feasibility study

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## Abstract

Digital volume correlation (DVC) allowed measurements of the internal strain distribution in bone at both tissue and organ level. However, as this technique relies on the quality of the 3D images, it has been mainly used in conjunction with high-resolution microCT or SR-microCT imaging. An evaluation of how the technique could be potentially established as a diagnostic tool in combination with clinical CT is entirely missing to date. In this study a PedCAT clinical CT was used to establish the strain uncertainties produced on bone structure targets that may be relevant for a reliable use of DVC in the clinical practice. In addition FE modeling was used to predict possible force uncertainties to be associated to displacement errors from DVC.

Keywords: Digital volume correlation, Bone, PedCAT CT, Strain error, Finite element modelling.

# Introduction

Unlike standard radiographic imaging, computed tomography (CT) allows for a detailed 3D analysis of hard tissues, but imaging in a weight-bearing condition is still limited. Recently, PedCAT CT (Curvebeam, USA) emerged as a novel technology allowing, for the first time, 3D imaging under full-weight bearing [1]. This dual scanning modality could be potentially exploited to measure strains in combination with digital volume correlation (DVC). In fact, DVC typically requires two (or more) images acquired at selected loading steps (i.e. at rest and under weight bearing) to compute 3D full-field displacements and strains fields *in vivo* (i.e. calcaneus). However, before attempting any further clinical studies, the uncertainties of DVC-computed strains based on PedCAT CT images of general bone structures must be fully assessed. Moreover, finite element (FE) models can be exploited to predict the force uncertainties associated to the DVC measurement for subject specific clinical evaluations.

# Methods

Thoracic porcine vertebrae (n=3) were used as bone structure target for the DVC. The choice of using vertebrae (in a CT designed for foot/ankle) was driven by tissue availability and, as this is a feasibility study on DVC performance on clinical CT (not clinical images), this can be fully justifiable at this stage. Each unloaded specimen was immersed in saline solution and CT imaged (PedCAT CT, Curvebeam, USA) twice without repositioning, in order to reproduce a zero-strain condition. The CT was set to a voltage of 120 kVp and a current of 5  $\mu$ A. With an isotropic voxel size of 370  $\mu$ m and exposure of 12 ms, 361 projections were acquired for a total scanning time of approximately 2 min. A cubic volume of interest (VOI) of 35 voxels was cropped in the center of each vertebra. DVC computation was carried out with DaVis (DaVis-DC) software (v3.0, LaVision, Germany). Three sub-volume sizes were investigated (12, 10, 8 voxels), as well as a multipass scheme (12-10-8 voxels). Systematic/random errors [2, 3] and overall accuracy/precision [4] were calculated. Full-field strain maps (exx, eyy, ezz) were visualized onto the corresponding CT volume in order to identify possible preferential error locations in the bone using Avizo software (v9.0, FEI, US). FE modelling was carried out to predict the force uncertainties associated with the DVC computed displacements fields. Voxel-based FE models (ParOSol solver) were directly obtained from each VOI. The binarization was performed using a fixed global threshold (Ostu's method) and the boundary conditions (DVC displacements) were imposed to both upper and lower surfaces of

VOI. Each element was assigned a linear elastic isotropic constitutive law (Young modulus: 8 GPa, Poisson's ratio: 0.3, as in [5]).

### Results

Precision errors were smaller than 1000  $\mu\epsilon$  in all cases, with the lowest range from of 83  $\mu\epsilon$  to 204  $\mu\epsilon$  for the 12 voxels sub-volume. Average random errors reached ~3000  $\mu\epsilon$  in the worst case (strain in transverse plane, multipass) and were ranging from 149  $\mu\epsilon$  to 621  $\mu\epsilon$  for the 12 voxels sub-volume. Full-field strain on the bone tissue did not seem to highlight a clear distribution of error in the volume (Fig. 1a, b, c). The force uncertainties obtained with the FE analysis produced magnitudes ranging from 231 N to 2376 N (average: 1058 N, SD: 638 N). No clear trend on the produced force was observed in relation to the different computation sub-volume sizes from DVC.



Figure 1: exx (a), eyy (b) and ezz (c) strain error fields (S3, 12 voxels sub-volume) overlapped onto the correspondent CT image used for DVC computation.

#### Discussion

The results indicate levels of error that may be sufficient to investigate the strain distribution for physiological loads such as single leg stance (1000-1500  $\mu\epsilon$ ), and definitely tissue failure (7000-10000  $\mu\epsilon$ ) [6]. In fact, the highest precision error was constantly below 1000  $\mu\epsilon$  in all samples. No preferential distribution of the strain error was observed in the six components, as well as no preferential location of the strain in the bone volume. FE analysis produced important force uncertainties up to 2376 N. However, this is a preliminary investigation that uses arbitrary material properties from literature, instead of specific densitometry calibration. Moreover, the global thresholding strategy (Otsu) may have also influenced the final result. Further investigation will give a clearer indication on DVC performance in PedCAT CT, as well as force uncertainties predicted through FE modelling.

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#### References

- Richter, M., Seidl, B., Zech, S. and Hahn, S. (2014) PedCAT for 3D-imaging in standing position allows for more accurate bone position (angle) measurement than radiographs or CT *Foot and Ankle Surgery* 20, 201–207.
- [2] Palanca, M., Tozzi, G., Dall'Ara, E., Curto, M., Innocente, F., Danesi, V. and Cristofolini, L. (2016) Strain uncertainties from two digital volume correlation approaches in natural and augmented vertebrae: an organ-level analysis *J Mech Behav Biomed Mater* Submitted.
- [3] Tozzi, G., Dall'Ara, E., Palanca, M., Curto, M., Innocente, F. and Cristofolini, L. (2016) Strain uncertainties from two DVC approaches in prophylactically augmented vertebrae: local analysis on bone and bone-cement microstructures *J Mech Behav Biomed Mater* Submitted.
- [4] Liu, L. and Morgan, E.F. (2007) Accuracy and precision of digital volume correlation in quantifying displacements and strains in trabecular bone, *Journal of biomechanics* **40**, 3516-3520.
- [5] Follet, H., Peyrin, F., Vidal-Salle, E., Bonnassie, A., Rumelhart, C. and Meunier, P.J. (2007) Intrinsic mechanical properties of trabecular calcaneus determined by finite-element models using 3D synchrotron microtomography, *Journal of biomechanics* **40**, 2174-83.
- [6] Cristofolini, L. (2015) In vitro evidence of the structural optimization of the human skeletal bones, *Journal of biomechanics* 48, 787-796.