The effect of voxel size and signal-to-noise ratio on the measurement uncertainties of a global Digital Volume Correlation approach

M. Palanca[1], A.J. Bodey[2], M. Giorgi[3], M. Viceconti[4], D. Lacroix[4], L. Cristofolini[1], E. Dall'Ara[3]

[1] Department of Industrial Engineering, Alma Mater Studiorum – Università di Bologna, Bologna, Italy
[2]Diamond Light Source, Oxford, UK
[3]Department of Oncology and Metabolism and INSIGNEO Institute for in silico Medicine – University of Sheffield, Sheffield, UK
[4]Department of Mechanical Engineering and INSIGNEO Institute for in silico Medicine – University of Sheffield, Sheffield, UK

marco.palanca2@unibo.it

Introduction

The Digital Volume Correlation is a powerful measurement technique used to evaluate the displacement and strain full-field maps inside heterogeneous specimens, through the comparison of 3D images acquired before and after the loading [1].
Several studies measured the reliability of this approach applied to bone structures scanned with laboratory source micro computed tomography (LS-microCT), by quantifying the mean absolute error (MAER) and the standard deviation of the error (SDER) in a known zero-strain condition [2-5]. These results showed that there is an inverse relationship between the SDER of the DVC method and its measurement spatial resolution. For example, DVC applied to LS-microCT images of bone is suitable to identify regions where the tissue is strained beyond yield (>8000-10000 microstrain) but for exploring the physiological range (1000–2000 microstrain) only spatial resolution of approximately 0.5-1.5 mm provides SDER considered acceptable (<200 microstrain).
Synchrotron radiation microCT (SR-microCT) imaging can be used to acquire images with better signal-to-noise ratio and lower voxel size, which improve image resolution. Therefore, while DVC applied to SR-microCT images has the potential of providing more precise strain measurements, it is currently not known to what extent the precision would improve for applications on dense cortical and highly porous trabecular bone.
The aim of this work is to evaluate the measurement uncertainties of a global DVC approach based on LS-microCT and SR-microCT images acquired for two microstructures.

Material and Methods

Cylindrical specimens of cortical and trabecular bone were extracted from a fresh bovine femur and embedded in acrylic resin. Both samples (Fig. 1) were scanned twice without any repositioning ('repeated scan test').

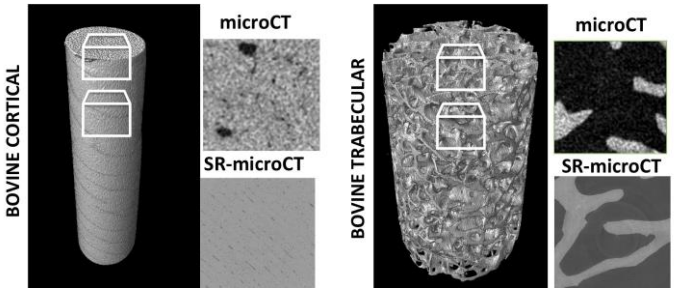

Fig. 1: Cortical Bone (left) and trabecular Bone (right) scanned with the LS-microCT and the SR-microCT

The imaging was performed using:
- LS-microCT (SkyScan 1172, Bruker, Belgium): 258 projections of 1180 ms exposure, 10 Megapixels 12-bit digital cooled ORCA-HR CCD; 1 mm Aluminum beam hardening filter; power: 10 W; voltage: 59 kV for the trabecular bone and 70 kV for the cortical bone; voxel size: 9.96 micrometer, previously used in [2]; one specimen per group was scanned;
- SR-microCT at beamline I13-2 of Diamond Light Source (Oxford, UK): 4000 projections of 53 ms exposure, fly-scanning with a $CdWO_4$ scintillator-coupled pco.edge 5.5 detector with 4x magnification, a filtered (950 micrometers C, 2mm Al, 20 micrometers Ni) polychromatic 'pink' beam (5 to 35 keV) of parallel geometry; voxel size of 1.6 micrometer; three specimens of trabecular bone and four specimens of cortical bone were scanned.
- SR-microCT images down-sampled to 8 micrometers isotropic voxel size in order to study the effect of voxel size.

The couples of repeated scans (LS-microCT, SR-microCT, SR-microCT down-sampled) were processed with a global DVC approach that combines a deformable registration algorithm (ShIRT) used to evaluate the displacement maps, with an FE solver to compute and visualize the strains. ShIRT computes the

displacements at the nodes of a grid overlapped to both images, with distance between the nodes equal to the nodal spacing, NS. The uncertainties of the DVC were evaluated in function of the chosen spatial resolution (NS) that ranged from 50 to 500 micrometers.
The measurement uncertainty was evaluated as the standard deviation of the error (SDER), computed as the standard deviation of the average of the six component of strain calculated for each node of the grid for each specimen [6]. Medians and standard deviations of SDER were computed for samples with more than one specimen.

Results
For both kinds of tissue, and all the types of images a larger measurement spatial resolution corresponded to lower SDER, (Fig. 2).

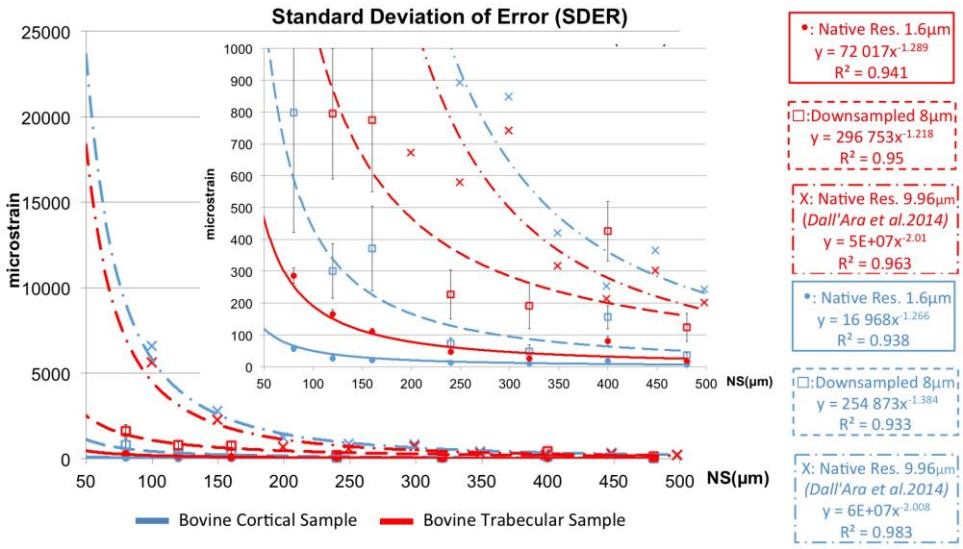

Fig. 2: SDER in function of the measurement spatial resolution (NS) for bovine cortical (blue) and trabecular (red) samples. Medians and standard deviations are reported for SR-microCT (dots) and SR-microCT down-sampled (squares). Crosses refer to results obtained with LS-microCT images. On the right fitting power law are reported.

Maximal spatial resolution in order to obtain SDER lower than 200 microstrains, considered acceptable for investigations of bone deformation, were:

- 480 (trabecular) and 550 (cortical) micrometers for the LS-microCT;
- 320 (trabecular) and 240 (cortical) micrometers for the SR-microCT down-sampled.
- 80 (trabecular) and 41 (cortical) micrometers for the SR-microCT;

Discussion
This study showed that using high-quality tomograms obtained by synchrotron radiation microCT decrease the measurement uncertainties of a global DVC approach with respect to those obtained with laboratory source microCT [2]. DVC could therefore be used with SR-microCT data to evaluate displacement and strain in the physiological range with remarkable spatial resolution. The improvement was shown to be a combination of better signal-to-noise ratio and the smaller voxel size.

References

1. Roberts B.C et al(2014) *JBiom***47**: 923-934.
2. Dall'Ara E.et al(2014) *JBiom* **47**: 2956-2963.
3. Palanca M et al(2015) *JBiomEng* **137**: 071001-14.
4. Palanca M et al(2016) *JBiom* **49**: 3882-3890.
5. Tozzi G. et al(2017) *JMBBM* **67**: 117-126.
6. Liu et al(2007) *JBiom* **40**: 3516-3520.

Acknowledgements

The authors would like to acknowledge Dr Yuan Chen, Dr Andre Castro, Dr Ana Campos Marin, Ms Claudia Wittkowske, Mr Luke Boldock and Dr Kazimir Wanelik for help during experiments at Diamond Light Source. We acknowledge Diamond Light Source for time at the Diamond-Manchester Imaging Beamline I13-2, under proposal MT10315. This study was partially funded by the FP7 European program MAMBO (PIEF-GA-2012-327357) and by the EPSRC Frontier Grant (MultiSim project code EP/K03877X/1). Marco Palanca acknowledges the 'Marco Polo' travel grant.