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Strain uncertainties from two digital volume correlation approaches in prophylactically augmented vertebrae: Local analysis on bone and cement-bone microstructures

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ABSTRACT

Combination of micro-focus computed tomography (micro-CT) in conjunction with *in situ* mechanical testing and digital volume correlation (DVC) can be used to access the internal deformation of materials and structures. DVC has been exploited over the past decade to measure complex deformation fields within biological tissues and bone-biomaterial systems. However, before adopting it in a clinically-relevant context (i.e. bone augmentation in vertebroplasty), the research community should focus on understanding the reliability of such method in different orthopaedic applications involving the use of biomaterials. The aim of this study was to evaluate systematic and random errors affecting the strain computed with two different DVC approaches (a global one, "ShIRT-FE", and a local one, "DaVis-DC") in different microstructures within augmented vertebrae, such as trabecular bone, cortical bone and cement-bone interdigitation. The results showed that systematic error was insensitive to the size of the computation sub-volume used for the DVC correlation. Conversely, the random error (which was generally the largest component of error) was lower for a 48-voxel (1872 micrometer) sub-volume (64–221 microstrain for ShIRT-FE, 88–274 microstrain for DaVis-DC), than for a 16-voxel (624 micrometer) sub-volume (359–1203 microstrain for ShIRT-FE, 960–1771 microstrain for DaVis-DC) for the trabecular and cement regions. Overall, the local random error did not appear to be influenced by either bone microarchitecture or presence of biomaterial. For the 48-voxel sub-volume the global approach was less sensitive to the gradients in grey-values at the cortical surface (random error below 200 microstrain), while the local approach showed errors up to 770 microstrain. Mean absolute error (MAER) and standard deviation of error (SDER) were also calculated and substantially improved when compared to recent literature for the cement-bone interface. The multipass approach for DaVis-DC further reduced the random error for the largest volume of interest. The random error did not follow any recognizable pattern with the six strain components and only ShiRT-FE seemed to produce lower random errors in the normal strains. In conclusion this study has provided, for the first time, a preliminary indication of the reliability and limitations for the application of DVC in estimating the micromechanics of bone and cement-bone interface in augmented vertebrae.

1. Introduction

The efficacy of prophylactic augmentation with injectable biomaterials (i.e. poly-methyl-methacrylate (PMMA)-based cements) in improving the mechanical stability of vertebrae is still a matter of debate (Kamano et al., 2011; Cristofolini et al., 2016). In particular, a deep understanding of internal microdamage in the bone tissue and at the cement-bone interface, which could potentially promote further damage to treated vertebrae, is currently missing.

This is probably due to the intrinsic limitations in most experimental techniques like digital image correlation (DIC) (Palanca et al., 2015b) (Schreier and Sutton, 2002) in not being able to capture and quantify internal microdamage evolution under load. In this perspective, digital volume correlation (DVC) is ideal to investigate the local

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internal damage in treated vertebrae. In fact, with the rapid progress of micro-focus computed tomography (micro-CT) in conjunction with *in situ* mechanical testing (Nazarian and Muller, 2004; Tozzi et al., 2012, 2013), DVC has become a powerful tool to examine full-field internal deformations in trabecular bone (Liu and Morgan, 2007; Gillard et al., 2014; Dall'Ara et al., 2014, Roberts et al., 2014), cortical bone (Christen et al., 2012; Dall'Ara et al., 2014), whole bones (Hussein et al., 2012, 2013; Danesi et al., 2016; Tozzi et al., 2016), cellular scaffolds (Madi et al., 2013) and cement-bone interface (Tozzi et al., 2014).

In order to expand the applications of DVC to biological tissues, including investigation of clinically-relevant issues such as bone augmentation, it is important to understand what is the error associated to the DVC measurement for specific sets of images, scanning protocols and correlation strategies. To this extent, the uncertainties of DVC in calculating strain in bone tissue have been quantified (Roberts et al., 2014). Moreover, the strain uncertainties in relation to a virtual displacement applied to one single micro-CT image was also evaluated (Madi et al., 2013). However, it is recommended that strain uncertainties of any specific DVC approach are quantified on repeated scans (i.e. in a known deformation field such as zero-strain) to account for the intrinsic noise of the input images. This repeated scans methodology has been already adopted to quantify strain errors associated to trabecular bone (Liu and Morgan, 2007; Gillard et al., 2014; Dall'Ara et al., 2014), cortical bone (Dall'Ara et al., 2014), whole bones (Hussein et al., 2012) and cement-bone interface (Zhu et al., 2015). However, as DVC typically exploits different correlation and strain calculation strategies to compute strains (i.e. local vs global approaches, different registration metrics, etc.), it is important to quantify the level of uncertainty in the strain determination, by comparing two or more DVC methodologies using the same original image dataset. Palanca et al. (2015) compared the output of three different DVC approaches (a global and two local ones) applied on the same micro-CT biopsies of trabecular and cortical bone, where accuracy and precision in strain fields for both virtual displacements and repeated scans were investigated. Moreover, the presence of preferential components (normal or shear) for strain measurement in the different correlation approaches was also evaluated (Palanca et al., 2015).

Given a specific pattern/texture inside the bone specimen, DVC uncertainties are affected by the features that can be recognized in the sequence of images, which in turn depends on the spatial resolution of the image, and on the number of voxels included in the computation window (sub-volume) (Roberts et al., 2014). This pattern distribution can be related to the intrinsic natural features of the material (i.e. trabeculae in trabecular bone) or to radiopacifier particles usually incorporated in bone cements (i.e. ZrO_2 and $BaSO_4$) (Lewis, 1997). Thus, the DVC-computed strain errors can be affected by the presence of biomaterials within the bone. Zhu et al. (2015) proposed a first attempt to investigate the strain uncertainties in specimens including cement and bone. They focused on images with voxel size of 22 micrometer, with smallest computation sub-volume of 32 voxels. The noise affecting computed strains was lowest within the cement (~500 microstrain), slightly higher in the bone regions partially interdigitated with cement (~700 microstrain), and more than doubled in the trabecular bone (~1400 microstrain). Zhu et al. (2015) used a single local DVC approach based on Fast Fourier Transform (described as DaVis-FFT in Palanca et al., 2015) with multipass and overlaps up to 75%, on one single cement-bone specimen in dry conditions, focusing on a single component of strain (the axial one, e_{zz}). However, recent literature in the DVC computation of bone tissue (Palanca et al., 2015) clearly indicated how DVC strain uncertainties obtained for the same local approach (DaVis-FFT) used in Zhu et al. (2015) are very much reduced if a direct correlation (described as DaVis-DC) is used instead of a FFT-based one (DaVis-FFT), and no overlap is used in multipass strategy. Furthermore, it is known (Gillard et al., 2014; Palanca et al., 2015) that looking at one single strain component (i.e. e_{zz}) is not sufficient for a complete understanding of the error pattern, as variability of strain error among the six components could be quite large. Very recently, uncertainty analyses of local and global DVC approaches applied to the whole natural and augmented porcine vertebrae were performed (Palanca et al., 2016b). In that study it was found that, despite the strain error produced similar trends in function of the computation sub-volumes for both groups, in the augmented vertebrae the random error of the strain components computed with the two DVC methods were different, especially for higher spatial resolution. In particular, the augmentation increased the error for the global approach, while reducing it for the local. It is not clear yet how the DVC errors are influenced by the tissue microstructure and by the biomaterial distribution.

The main aim of this study was to evaluate and quantify strain measurement uncertainties at tissue level in five specific locations within different augmented vertebrae. This was done in order to better understand how the bone microstructure (trabecular and cortical), the presence of biomaterial and its integration with bone (cement-bone interface) could explain differences in performance of the two DVC approaches.

2. Methods

2.1. Specimens

Five thoracic vertebrae (T1-T3) were harvested from fresh porcine thoracic spines. All the surrounding soft tissues were removed, as well as the growth plates. The endplate areas of the vertebrae were potted in poly-methyl-methacrylate (PMMA) similar to Danesi et al. (2014). The spinous process was used to center the specimen in the transverse plane and align it about its vertical axis. The posterior arch was subsequently removed. Cement routinely used for vertebroplasty (Mendec Spine, Tecres, Italy) was then injected in the vertebral bodies by means of a proprietary device, following the instructions of the manufacturer. This is an acrylic-based cement, containing pellets of $BaSO_4$ (~300 micrometer) as a radiopacifier. The vertebrae were heated before and after augmentation in a circulating bath at 40 °C, to allow optimal flow and consolidation of the cement.

2.2. Experimental procedures and volumes of interest (VOIs)

All the specimens (n=5) were placed in a loading device (CT5000, Deben Ltd, UK) equipped with a custom-designed environmental chamber, in order to closely simulate *in situ* loading conditions that are typically being applied to such vertebral bodies (Danesi et al., 2016; Tozzi et al., 2016). The specimens were immersed in saline solution and constrained against rotation inside the loading device with sandpaper disks glued to the bottom compressive platen. Each unloaded specimen was micro-CT imaged (XTH225, Nikon Metrology, UK) twice without repositioning, in order to reproduce a zero-strain condition. Prior to each imaging session a full conditioning of the micro-CT (up to 225 kV) was performed to stabilize x-rays and reduce at minimum fluctuations in the selected settings (i.e. kV, microA), throughout the duration of test. The micro-CT scanner was set to a voltage of 88 kV and a current of 110–115 microA. With an isotropic voxel size of 39 micrometer and exposure of 2 s, the image acquisition was performed with a rotational step of 0.23°, over 360° for a total scanning time of approximately 90 min.

In order to investigate the performance of the DVC approaches for the different bone tissues (cortical and trabecular), for the cement, and for the interdigitated regions, five volumes of interest (VOIs) were identified within each vertebral body. The five VOIs were cropped using MeVisLab (MeVis Medical Solution AG, Germany) and consisted in parallelepipeds of 300*300*432 voxels for the largest possible area that could be inscribed in all vertebrae (VOI-1, data presented in Palanca et al. (2016b) and reported here for completeness and for comparison)