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Research paper

Spatial resolution and measurement uncertainty of strains in bone and bone–cement interface using digital volume correlation

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ABSTRACT

The measurement uncertainty of strains has been assessed in a bone analogue (sawbone), bovine trabecular bone and bone–cement interface specimens under zero load using the Digital Volume Correlation (DVC) method. The effects of sub-volume size, sample constraint and preload on the measured strain uncertainty have been examined. There is generally a trade-off between the measurement uncertainty and the spatial resolution. Suitable sub-volume sizes have been be selected based on a compromise between the measurement uncertainty and the spatial resolution of the cases considered. A ratio of sub-volume size to a microstructure characteristic (Tb.Sp) was introduced to reflect a suitable spatial resolution, and the measurement uncertainty associated was assessed. Specifically, ratios between 1.6 and 4 appear to give rise to standard deviations in the measured strains between 166 and 620 με in all the cases considered, which would seem to suffice for strain analysis in pre as well as post yield loading regimes.

A microscale finite element (μFE) model was built from the CT images of the sawbone, and the results from the μFE model and a continuum FE model were compared with those from the DVC. The strain results were found to differ significantly between the two methods at tissue level, consistent in trend with the results found in human bones, indicating mainly a limitation of the current DVC method in mapping strains at this level.

1. Introduction

Digital Volume Correlation (DVC) has experienced rapid growth in recent years as a result of more accessible volumetric imaging methods such as high-resolution X-ray computed tomography (CT) and greatly increased computational power. DVC was first introduced as a method of mapping three dimensional through-volume strains in trabecular bone (Bay et al., 1999), as an extension from the 2D digital image correlation (DIC) (Sutton et al., 1983) for surface

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strain mapping. The essence of the approach is tracking the displacements of small regions of pixel subsets (DIC) or volume voxel subsets (DVC) in successive images taken in both unloaded and loaded states, and mapping the strains from the displacements using appropriate correlation algorithms. Unlike DIC, which relies on surface speckle patterns applied externally to track in-plane displacements, DVC utilises naturally occurring microstructure features for tracking 3D displacements from which strains are estimated. A spatial-domain DVC process (Bay, 2008) involves: i) The specification of a region of interest (ROI) populated by discrete points where displacement values are sought; ii) estimation of the displacement vector at each measurement point by correlation of a reference and a target image volume and iii) an objective function defined to quantify the degree of match between the original and trial subvolumes using algorithms such as the sum-of-squares coefficient (SSCC) or the normalised cross-correlation coefficient (NCCC). A global minimum within a ROI is found through searches and strain tensor estimated at each measurement point from a cloud of neighbouring points using a least squares fit to a series expansion of the displacement vector field.

One of the most common DVC procedures is based on 3D reconstructed images from X-ray micro-Computed Tomography (μCT) (Bay, 2008; Bay et al., 1999), where images with resolutions down to micrometre level can be obtained (Durand and Rüegsegger, 1992). The DVC technique has since been applied in a number of biomaterials for 3D measurement of displacements and strains, including trabecular bones (Liu and Morgan, 2007; Madi et al., 2013; Bay, 1995; Smith et al., 2002; Bay et al., 1999; Gillard et al., 2014), scaffolds (Madi et al., 2013), cortical bones (Almer and Stock, 2005; Hoc et al., 2006; Dall'Ara et al., 2014), whole bones (Hardisty and Whyne, 2009; Hussein et al., 2012), corneas (Fu et al., 2013) and a biomaterial composite (Tozzi et al., 2012, 2014).

The knowledge of measurement uncertainty using the DVC approach is of vital importance in the application of the DVC method to quantify strains in materials with rich microstructural details. The accuracy and precision of DVC measurement of displacements and strains are significantly influenced by the characteristics of the material texture under study. The influence of a number of parameters on the measurement uncertainty has been examined (Roberts et al., 2014), including objective function, shape function, image subset size and voxel size. The voxel-size of a volume is known to be strongly dependent on the scanning parameters of μCT and is considered an important indicator for image quality and noise level (Liu and Morgan, 2007). X-ray hardening and scattering in bones may lead to dimensional errors thus strain errors, an influence which may be reduced by filtration measures (Meganck et al., 2009). A pre-set of rigid body displacement was found to have a strong influence on the measured strain precision in trabecular bone samples (Gillard et al., 2014). As opposed to controlled application of speckles on surfaces in DIC (Lecompte et al., 2006), DVC predominantly relies on the naturally occurring microtexture to resolve full-field displacement and strain distributions (Bay, 2008), hence the measurement accuracy and precision are largely dictated by the micro-texture of the material.

Although a fine micro-texture is essential for a DVC analysis, microstructural features also give rise to noise during imaging and correlation processes; hence the choice of a suitable sub-volume size is important for the DVC analysis. There is generally a trade-off between the choice of sub-volume size and the spatial resolution. Too small a sub-volume size is more susceptible to noise; whilst an excessively large sub-volume is unable to capture the microstructural details leading to inadequate spatial resolution (Sun and Pang, 2007; Gillard et al., 2014). The chosen sub-volume size should therefore be a compromise between the measurement uncertainty and the spatial resolution, and it may be estimated based on the relationship between the standard deviation of the strain measured and the sub-volume size as well as the required spatial resolution. For biomaterial composites, such as a bone–cement interface (Tozzi et al., 2012, 2014), strains will need to be resolved in a microstructure with both constituents. This presents a challenge in choosing the appropriate micro-CT scanning parameters and a sub-volume size suitable for multiple constituents simultaneously. In this type of materials, the chosen sub-volume size should be able to capture the microstructure details whilst the strain uncertainty remains low or acceptable. The porous phase should be considered primarily but scanning parameters should also be suitable for both phases.

A balance between high spatial resolution and acceptable measurement uncertainty is particularly important when tissue level information is needed. Micro-finite element models built from μCT images have been used to simulate the mechanical behaviour of bones at tissue-level (Niebur et al., 2000; Eswaran et al., 2007) and continuum-level (van Rietbergen et al., 1995; Verhulp et al., 2006); whereas DVC has been used as a tool for validation purposes (Zauel et al., 2006). However, information obtained at tissue level from μFE models is highly sensitive to the input material parameters, constitutive laws and meshing methods; whilst results from DVC are volume averages and highly sensitive to processing parameters such as sub-volume size. Further work is required to improve the fidelity of tissue level analysis for a range of material systems so that quantitative analysis at this level could be carried out with confidence.

The main objectives of the present work are: i) To provide a detailed assessment of the measurement uncertainty in a bone analogue (Sawbone), bovine trabecular bone and bone–cement interface in relation to spatial resolution; ii) to evaluate the effects of selected operational parameters on the measurement uncertainty using DVC and iii) to compare the results from a μFE model and DVC in a model cellular material sawbone at both continuum and tissue levels. Suitable ratios of sub-volume size to a microstructure dimension (Tb.Sp) were chosen to be reflective of the spatial resolution for the three cases studied, as well as for the cases from Liu and Morgan (2007), and the measurement uncertainties were estimated. Additionally, it is the first time a biomaterial composite, in the form of bone–cement interface, a generic case of interest in implant fixation of many types,