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Digital volume correlation and micro-CT: An in-vitro technique for measuring full-field interface micromotion around polyethylene implants

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ABSTRACT

Micromotion around implants is commonly measured using displacement-sensor techniques. Due to the limitations of these techniques, an alternative approach (DVC-μCT) using digital volume correlation (DVC) and micro-CT (μCT) was developed in this study. The validation consisted of evaluating DVC-μCT based micromotion against known micromotions (40, 100 and 150 μm) in a simplified experiment. Subsequently, a more clinically realistic experiment in which a glenoid component was implanted into a porcine scapula was carried out and the DVC-μCT measurements during a single load cycle (duration 20 min due to scanning time) was correlated with the manual tracking of micromotion at 12 discrete points across the implant interface. In this same experiment the full-field DVC-μCT micromotion was compared to the full-field micromotion predicted by a parallel finite element analysis (FEA). It was found that DVC-μCT micromotion matched the known micromotion of the simplified experiment (average/peak error = 1.4/1.7 μm, regression line slope = 0.999) and correlated with the micromotion at the 12 points tracked manually during the realistic experiment (R^2 = 0.96). The DVC-μCT full-field micromotion matched the pattern of the full-field FEA predicted micromotion. This study showed that the DVC-μCT technique provides sensible estimates of micromotion. The main advantages of this technique are that it does not damage important parts of the specimen to gain access to the bone–implant interface, and it provides a full-field evaluation of micromotion as opposed to the micromotion at just a few discrete points. In conclusion the DVC-μCT technique provides a useful tool for investigations of micromotion around plastic implants.

1. Introduction

Cementless athroplasty aims to achieve biological fixation by bone ingrowth which in turn depends on micromotion, i.e. prosthesis translation relative to the interface of the host bone (Mavrogenis et al., 2009). Bone ingrowth occurs when micromotion is less than a threshold value reported to range between 40 and 150 μm (Bragdon et al., 1996; Duyck et al., 2006; Jasty et al., 1997; Leucht et al., 2007; Szmukler-Moncler et al., 1998; Vandamme et al., 2007).

Many investigations of micromotion around implants have used Linear Variable Differential Transformers (LVDTs) to measure micromotion in-vitro (Choi et al., 2010; Cristofolinia et al., 2003; Speirs et al., 2000; Suarez et al., 2012). These techniques are restricted to measurements at only a few points on the interface. Moreover, installing sensors damages the bone at the access points. Marker techniques were recently used to measure micromotion (Clarke et al., 2012; Gortchacow et al., 2012; Reiner et al., 2014). These techniques can assess micromotion at more points along the interface than the LVDT techniques but are still restricted to relatively few measuring points.

FE analyses provide full-field predictions of micromotion across the prosthesis interface and has advantages such as being non-invasive and providing direct access to the internal interface.

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However, FE is limited by the necessary input and assumptions. Many of the input parameters, such as interface properties or Young's moduli of the bone are not well characterised, which has a direct consequence on the accuracy of the resulting output of the models and experimental validation of FE models are therefore important.

The resolution of micro-CT images makes it conceptually feasible to measure the level of micromotion relevant to bone ingrowth (40–150 μm). However, it is impractical to track the relative movements of thousands of CT-voxels at the interface. In a different context Digital Volume Correlation (DVC) has been used to track the voxel patterns of cancellous structures from micro-CT images, resulting in full-field maps of bone deformation (Bay et al., 1999). The proposal of this study is that DVC and micro-CT in combination may be used to track the bone and prosthesis movement, producing micromotion maps over the entire bone–prosthesis interface. This technique will be referred to as the DVC-μCT technique.

The aim of this study was to develop the DVC-μCT technique to produce full-field maps of micromotion. There were three specific objectives: (1) to evaluate the accuracy of DVC-μCT micromotion in a simple experiment where the micromotion was known; (2) to determine the correlation between DVC-μCT micromotion and manually tracked micromotion in a more realistic experiment; and (3) to compare the full-field DVC-μCT micromotion against the full-field FE predicted micromotion in the realistic experiment. The purpose of these three objective was in each case to compare micromotion as assessed by the DVC-μCT method against the micromotion assessed by another method thereby establishing confidence in the DVC-μCT measurements.

2. Material and methods

2.1. DVC-μCT compared to known micromotion in simplified experimental set-up

One fresh porcine glenoid bone was cut to remove all cartilage and create a flat surface. The bone was fixed inside a customised device using bone cement, placing the flat bone surface against a polyethylene (PE) disc without compressing the two components. The disc, coated with a thin (150 μm) layer of porous titanium (Fig. 1a), was moved in a tangential (shearing) direction coinciding with the axial direction of the micro-CT scanner; the distance travelled was measured using a micrometre (Moore & Wright Ltd., Sheffield, England) which had an accuracy of 3 μm. This movement was a measure of the relative tangential movement between the bone and the PE disc, i.e. micromotion and the 'known' micromotion that the DVC-μCT measurements were compared to. Three 'known' micromotions of 40, 100 and 150 μm were evaluated, thus covering the range of interface micromotions reported as the threshold for bone fixation. The experimental set-up was suitable for testing within a micro-CT scanner causing only a small amount of image artefacts (Fig. 1b).

2.1.1. DVC and micro-CT scanning protocol

The DVC software package, Davis 8.1.6 (LaVision GmbH, Goettingen, Germany) was used in this study. The subvolume size, consistent with other works on trabecular bone (Gillard et al., 2014; Jandejsek et al., 2011; Madi et al., 2013), and values for other parameters used by the Davis software package are shown in Table 1.

Each micro-CT image was divided into two components; the coating of the implant and the bone (Fig. 1a). The DVC software tracked the coating and bone displacement separately, producing two displacement fields. From this data a customised script written in Matlab (The MathWorks Inc., Massachusetts, USA) identified pairs of coating and bone subvolumes at adjacent locations along the interface and extracted the relative displacements associated with these pairs, i.e. the interface micromotion. The magnitude of this micromotion vector was termed the absolute micromotion. The Matlab script further separated the micromotion vector into components tangential and normal to the prosthesis interface.

The micro-CT scans were performed first under unloaded and subsequently under loaded conditions using an X-Tek HMX ST225 scanner (Nikon Metrology X-Tek Systems Ltd., Tring, UK) and a transmission target with a 5 μm spot size. Voltage and current output were set at 175 kV and 160 μA, respectively. A copper filter with 0.25 mm thickness was used to reduce beam-hardening artefacts and 3148 projections were collected during the 20 min scan process. The projections were reconstructed using the Feldkamp back-projection algorithm within CT Pro XT 2.2 (Nikon Metrology X-Tek Systems Ltd., Tring, UK) to obtain a three-dimensional dataset (volume file format), with a 22 μm voxel size (reconstructed). A stack of rendered CT images was created using VGStudio Max 2.0 (Volume Graphics GmbH, Heidelberg, Germany).

2.2. DVC-μCT compared to manual tracking and FE micromotion in a clinically realistic set-up

In addition to the specimen used in Section 2.1, soft tissues were removed from seven fresh porcine glenoids before implanting a cementless glenoid prosthesis with a radial curvature of 28 mm (Affinis Vitamys, Mathys Ltd., Bettlach, Switzerland) using procedures specified by the manufacturer. This PE implant also had a thin coating of porous titanium. The bone was sectioned 40 mm below the glenoid surface and placed within a micro-CT compatible device (Fig. 2). A cobalt-chrome humeral component with a head radius of 24 mm was moved vertically and compressed into the glenoid. The articulating surface of the glenoid was aligned 12° from horizontal and this arrangement simulated the glenohumeal joint loading at 60° of humeral abduction. A screw was used to apply a compressive load of 575 N. These conditions simulate clinically relevant shoulder abduction and joint load (Terrier et al., 2007). The seven specimens were implanted into the bone simulating 7 positions of version: neutral, 5°, 10° and 15° of antervesion and retroversion, respectively. This version parameter was not of interest to this study but the specimens were included for the purposes of evaluating the DVC-μCT technique on a larger number of samples. Irrespective of the degree of version, the purpose was to evaluate if the micromotion assessed by DVC-μCT, manual tracking and FE was consistent.

Micromotion was measured at the peak load of a single load cycle. The test was displacement controlled and during the 20 min it took to scan the specimen the load relaxed by less than 3%. The specimen was preconditioned by applying three load–unload cycles to allow the prosthesis to settle into the bone bed prior to any measurements. The specimen was wrapped in wet saline tissue to keep it moist throughout the test.

The test was carried out within the micro-CT scanner and analysed using the DVC and Matlab software as described earlier to produce DVC-μCT micromotion across the interface of the glenoid implant.

2.2.1. Manual tracking of micromotion at discrete points from micro-CT scans

To evaluate the effect of using the DVC software to track micromotion the DVC-μCT micromotion was compared to manually tracked micromotion at 12 discrete points. The DVC-μCT micromotion and the manually tracked micromotion were based on the same micro-CT scans and therefore incorporated the same scanning and reconstruction errors. Therefore, any difference in results were due to the use of the DVC software. The profile of the implant is shown in Fig. 3 which also indicates the 12 discrete points where micromotion was manually tracked from the micro-CT images using ImageJ (National Institutes of Health, Maryland, USA). This process was labour intensive and only produced micromotions at a few points but was carried out for the purpose of evaluating the DVC methodology. The tracking involved manually inspecting the unloaded micro-CT images and identifying microscopic characteristic features in both the coating and the adjacent bone interface at the 12 discrete points. These features were then identified also in the loaded images and based on the changed position of the features between images the micromotion was assessed.

2.2.2. Comparison of DVC-μCT and finite element full-field interface micromotion

As a key reason for the interest in DVC-μCT is its ability to provide full-field micromotion maps across the implant–bone interface it was compared to the full-field predictions of the FE method. Conceptually, it is inappropriate to 'validate' real measurements by comparing them to theoretical FE predictions. This approach was used because the DVC-μCT method is new, while the FE method has a track record in this field.

An FE model simulating the experimental set-up and able to predict micromotion was constructed. The micro-CT scans of the bone–implant specimen were imported into imaging software Avizo 6.1 (Visualisation Sciences Group, USA). From the bone part of the micro-CT images a 3D model of the glenoid bone was built. The prosthesis manufacturer provided a CAD model of the implant, which was also imported into Avizo and a 3D model of the implant was built and positioned in the bone by superimposing the CAD based model over the implant part of the micro-CT image. These models were imported into FE software MARC/Mentat 2010 (MSC Software Corporation, USA) where FE analyses of mesh converged models consisting of 215,000 4-node tetrahedral elements were carried out. Mesh convergence was considered achieved when the micromotion from a mesh with roughly twice as many elements did not change the predicted osseointegrated area over the whole interface by more than 2% and the contour maps of micromotion (Fig. 7) appeared unchanged. The polyethylene of the glenoid was modelled as isotropic with Young's modulus 0.8 GPa (Pruitt, 2005) while a rigid sphere with a radius of 24 mm represented the humeral head (Fig. 4).