3D Full-Field Mechanical Measurement of a Shoulder Bone Under Implant Loading

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Abstract The mechanics of shoulder bones under implant loading is important to the success of shoulder replacement surgery. This work presents the results of a noninvasive three-dimensional (3D) full-field mechanical measurement of implanted shoulder bones under various physiologically realistic loading conditions. A glenoid implant was cemented in a human cadaveric specimen by a shoulder surgeon and loaded in a mechanical tester coupled with micro X-ray computed tomography (micro-CT). The micro-CT images of the specimen was taken under no-load, eccentric loading, and concentric loading conditions, respectively. Using image processing technique and digital volume correlation, the 3D displacement field inside the shoulder bone were calculated. The results were displayed using 3D visualization tools. The clinical implications of the results are discussed for the improvement of total shoulder replacement.

Keywords Implant · Shoulder bone · Micro-CT · Digital volume correlation

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Introduction

Glenoid implant loosening is the most common complication in the total shoulder replacement surgery. After 5 years, radiographic loosening rates have been observed to be 15–44% [1–4]. Glenoid implant loosening is related to the mechanics in the implant-bone structure. There is a need to study the biomechanics of the shoulder bone when glenoid implants are under loading conditions.

Micro X-ray computed tomography (micro-CT) techniques were used in our prior study to explore the damage of bone and loosening of the implant [5]. Digital volume correlation (DVC) of micro-CT images can provide three-dimensional (3D) displacement and strain distribution. It was recently applied on the study of implant-bone biomechanics [6–8]. In this study, we used mechanical testing coupled with micro-CT scans and the DVC method to study the deformation of shoulder bone under various physiologically realistic loading conditions.

Materials and Method

Sample Preparation

A fresh-frozen shoulder bone specimen (glenoid) was obtained. The soft tissues were stripped off. A commercial shoulder implant (glenoid component) (Bigliani/Flatow, Zimmer Inc., Warsaw, IN) was placed into the shoulder bone, with bone cement (Surgical Simplex P, Stryker, Kalamazoo, MI) filling up the bone-implant interface. The surgical operation was performed by a senior shoulder surgeon. The implant is three-pegged. It is made of polyethylene, and has a dimeter of 46 mm. The metal pin in the central peg of glenoid implant was removed to reduce image artifact under micro-CT.

The shoulder bone was then embedded in polymethyl methacrylate (PMMA, Ortho-Jet BCA, Lang Dental, Wheeling, IL), and sectioned to approximately $40 \times 40 \times 60$ mm in size to fit into the mechanical tester. The specimen was kept frozen until 12 h prior to the test, when it was thawed in a refrigerator.

In Situ Mechanical Testing

In situ mechanical testing of the implant in shoulder bone was performed using a mechanical tester (CT5000, Deben UK Limited, Suffolk, United Kingdom) coupled with micro-CT (Phoenix v|tome|x L300 multi-scale nano/microCT system, GE, Boston, MA) (Fig. 1). A compressive load was applied on the implant through a hemispherical polyoxymethylene indenter in order to mimic the contact loading from the humeral head.

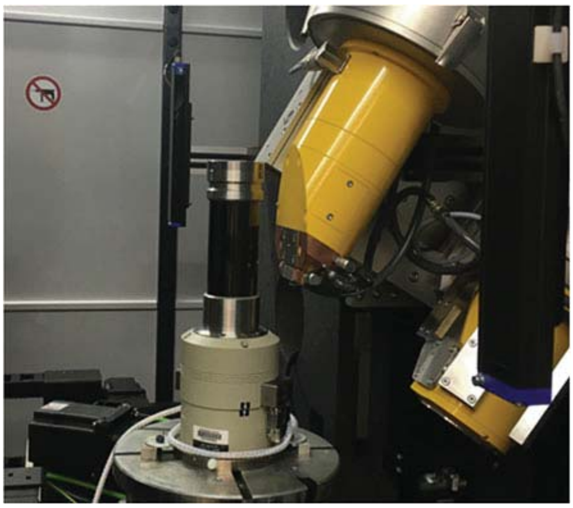

Fig. 1 The experimental setup for the mechanical testing coupled with micro-CT

The specimen was loaded at a displacement rate of 1 mm/min until the load reached 750 N. Then the load was maintained at this level for ~1 h for the specimen to almost fully relax. The compressive load was applied under three different conditions, where the glenoid component was aligned (1) 4 mm to the anterior side of the shoulder bone; (2) concentric to the shoulder bone and (3) 4 mm to the posterior side of the shoulder bone.

Micro-CT scans of the specimen were performed before the specimen was loaded and after the specimen was relaxed at the above-mentioned 3 loading conditions. A voltage of 150 kV and a current of 160 μA was used in the scans. Image sequences with sizes of ~2014 × 2014 × 2024 were obtained. The resolution of the images is 24 μm.

Image Segmentation and Registration

The micro-CT images were cropped in Avizo 3D analysis software (FEI Visualization Sciences Group, Burlington, MA) to obtain the images for the region of interest. They were then segmented using water-shed techniques in Avizo to several regions, including bone, implant and potting materials (Fig. 2). The images of bone were extracted for the following analysis. The images of bone were registered in Avizo to make the bottom 1/10 of the images aligned with each other.

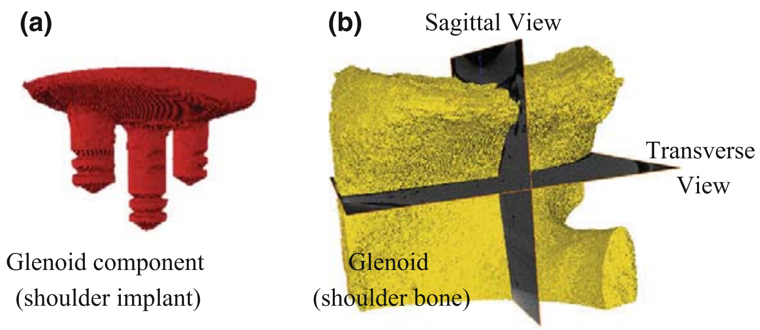

Fig. 2 Rendered 3D images of **a** implant and **b** bone obtained from segmentation of micro-CT images

Digital Volume Correlation (DVC)

Digital volume correlation (DVC) was performed in DaVis software (LaVision, Goettingen, Germany) on the extracted images of shoulder bone. The movements of each block of pixels were tracked by comparing the images at no-load and loaded states. A sequential correlation method was used. A coarser block size of 128 × 128 × 128 was used in the first trial to predict the movements. A block size of 64 × 64 × 64 was used in the second and also final step. The overlap ratio between adjacent blocks was chosen to be 50%. The deformation of shoulder bone was calculated for the above-mentioned 3 loading conditions.

Results and Discussion

Deformation Obtained from Image Registration

The registered images are displayed in Fig. 3, with the bottom 1/10 of the images at no-load and loaded conditions aligned together. It is consistent with the experimental setup, when the bottom of the specimens were fixed to the tester. The images at loaded conditions (yellow) was overlaid on the images at no-load condition (grey scale).

Deformation Obtained from DVC

The deformation of the shoulder bone along the loading direction was obtained from DVC. They are displayed in Fig. 4 on transverse cross-sections at ~2/3 of the specimen height. Negative sign is towards the loading direction.

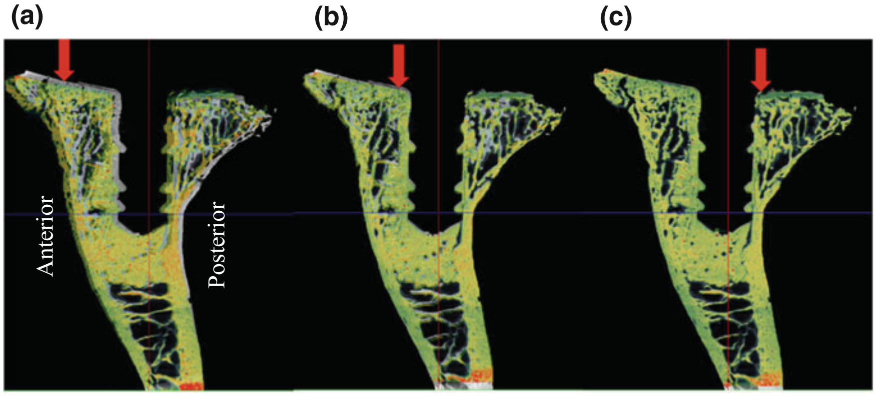

Fig. 3 Registered sagittal-views of shoulder bone with the bottoms aligned, for **a** eccentric loading to the anterior side, **b** concentric loading and **c** eccentric loading to the posterior side

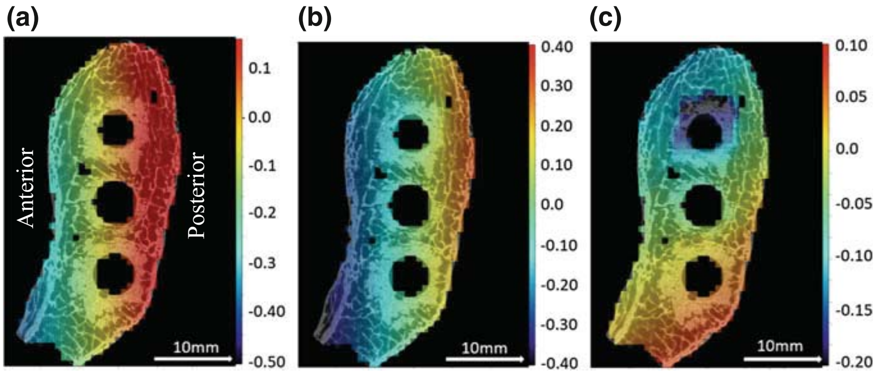

Fig. 4 Deformation of shoulder bone obtained from DVC for **a** eccentric loading to the anterior side, **b** concentric loading and **c** eccentric loading to the posterior side, displayed on a transverse cross-section. (unit: mm)

Discussion

The deformation fields obtained from image registration and DVC have good agreement with each other. The anterior side was pressed down in anteriorly eccentric loading and concentric loading conditions, while the posterior side rose up. In posteriorly eccentric loading conditions, the deformation was much smaller than that for the other two loading conditions. It can be attributed to the asymmetric geometry of shoulder bone.

Implications

The results show that the deformations of shoulder bone under various physiologically realistic loading conditions are different. They are different in the direction and in scale. In this particular specimen, it was more resistant to the posteriorly eccentric loading. Due to the limited sample size, it is just a proof-of-concept study. The results provide insights for the future improvement for the total shoulder replacement procedures.

It is needed to note that the DVC results in the cementing materials are not accurate. Future work are needed to improve the accuracy of the DVC in cement or to segment the images of cement from bone.

Conclusions

This paper presents the results of a study on the loading of shoulder glenoid implant. The deformation of a shoulder bone under various physiologically realistic loading conditions was measured in the in situ mechanical testing coupled with micro-CT. Image registration and digital volume correlation of the micro-CT images at no-load and loaded conditions provide the deformation of shoulder bone. The results obtained from the two methods have good agreement with each other. This particular shoulder bone specimen was more resistant to the posterior loading. Future directions include systematic studies of implant loading for more specimens under cyclic loading conditions.

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