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Short communication

Repeatability of digital image correlation for measurement of surface strains in composite long bones

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ABSTRACT

Digital image correlation (DIC) can measure full-field surface strains during mechanical testing of hard and soft tissues. When compared to traditional methods, such as strain gauges, DIC offers larger validation data (~50,000 points) for, e.g., finite element models. Our main aim was to evaluate the repeatability of surface strain measurements with DIC during compressive testing of composite femurs mimicking human bones. We also studied the similarity of the composite femur samples using CT. Composite femurs were chosen as test material to minimize the uncertainties associated with the use of cadaveric tissues and to understand the variability of the DIC measurement itself. Six medium-sized fourth generation composite human proximal femora (Sawbones) were CT imaged and mechanically tested in stance configuration. The force–displacement curves were recorded and the 3D surface strains were measured with DIC on the anterior surface of the femurs. Five femurs fractured at the neck–trochanter junction and one at the site below the minor trochanter. CT image of this bone showed an air cavity at the initial fracture site. All femurs fractured through a sudden brittle crack. The fracture force for the composite bones was 5751 ± 650 N (mean ± SD). The maximum von Mises strain during the fractures was 2.4 ± 0.8%. Noise in one experiment was 5–30 $\mu\varepsilon$. When applied loads were equalized the variation in strains between the bones was 20–25%, and when the maximum strains were equalized, variation in the other regions was 5–10%. DIC showed that the ability of nominally identical composite bones to bear high strains and loads before fracturing may vary between the samples.

1. Introduction

Reliable experimental data regarding the mechanical behavior of the femur is needed to validate methods that are used to evaluate femoral strength and bone quality (Pulkkinen et al., 2011; Seeman and Delmas, 2006; Väänänen et al., 2012). The agreement between the force–displacement curves from mechanical testing of cadaver femurs and from computational models (Cody et al., 1999; Keyak, 2001) is only one part of the validation, since it only compares the global behavior of the bone under loading. Use of strain gauges can strengthen the validation, but can only measure strains on the surface of the bone locally (Bessho et al., 2007; Oh and Harris, 1978; Trabelsi et al., 2011). In addition, they are not able to track the displacements of the bone during loading. High-speed cameras can identify where and how the fracture occurs during loading of the femur (Juszczyk et al., 2011; Dragomir-Daescu et al., 2011; de Bakker et al., 2009), but do not provide quantitative information about the displacements and strains during loading. The challenges when strains are calculated from the texture patterns of the radiographic images obtained from CT (Hardisty and Whyne, 2009; Smith et al., 2002) or X-ray (Bay, 1995; Toh et al., 2005) during loading are that imaging is usually limited by low temporal resolution and the cortical bone is often too uniform for correlation analysis (Norrdin et al., 2001).

Digital image correlation (DIC) is an optical technique that can measure surface strains of an object under load using one or several cameras (Vic-3D-2010). It tracks the displacements and strains on a surface painted with random black-and-white speckle pattern by dividing the surface to small areas and correlating them to an initial image. With two cameras, the 3D strains and

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displacements can be calculated using photogrammetry techniques (Vic-3D-2010 (Correlated Solutions, 2011)). Despite its strong potential, DIC has only been used in one study where a high-speed camera captured plane (2D) strains on the surface of the femur (Op Den Buijs and Dragomir-Daescu, 2010). However, strains measured in 2D are not directly comparable with the 3D strains from finite element (FE) models. In one recent study, 3D strains have been measured with DIC for one composite human proximal femur during mechanical loading in the linear region of the bone (Dickinson et al., 2011). However, the inter-sample repeatability of the mechanical testing and the DIC measurements using human femora, and behavior of the surfaces strains near fracture are still unknown.

The aim of the current study was to evaluate the repeatability of the DIC measurements, by conducting compressive axial mechanical testing of femora until fracture and simultaneously record surface strains with DIC. To minimize the variability which is observed between cadaver specimens, we used six nominally identical composite human proximal femurs, which has been shown to be representative of human femurs (Gardner et al., 2010; Heiner, 2008). Moreover, we aimed to characterize if the CT images of the bones revealed any inter-sample variations between the composite femora.

2. Material and methods

Six fourth generation medium-sized composite bones (model number: 3403) from Sawbones (Pacific Research Laboratories, Inc., Vashon Island, WA, USA) were examined. The shafts were cut 150 mm below the minor trochanter. The proximal parts were vertically aligned in the middle of a 50 mm high aluminum cylinder with an inner diameter of 50 mm and a wall thickness of 3 mm. The cylinders were filled with epoxy (Technovit 4071, Heraeus Kulzer, Germany) to fix the shafts. Shaft angles were measured from CT images (Supplementary data Table 1). Then, the anterior surfaces of the composite bones were painted with spray-paint for DIC with white background color and a black random speckle pattern. Finally, the bones and three mineral density phantoms (QRM, Germany) were imaged using a clinical CT scanner (SOMATOM Definition Flash, Siemens Healthcare AG, Erlangen, Germany) with isotropic resolutions of 0.24–0.29 mm.

The CT images of all composite bones were registered to the orientation of bone number 1 and interpolated to a cubic voxel size of 0.24 mm using the Analyze software (Analyze 10.0, Analyze direct, Inc., KS, USA). The differences in the thickness, shape and density between the cortices were quantified and have been reported in more detail in Supplementary data.

The bones were mechanically tested under axial compression (Fig. 1). The aluminum cylinders around the distal shafts were fixed with a clamp to a large cylindrical holder that kept the bones aligned during the test. The load was measured at the femoral head with a demobilized load cell (20 kN Zwick, accuracy $\pm 0.27\%$) while the bottom part moved upward with a constant displacement rate of 1.0 mm/min ($\pm 0.15\%$) until fracture (Fig. 1). From the load–displacement data, the maximum load and the slope of the linear region were calculated.

During mechanical testing, the anterior surfaces of the composite bones were recorded with two cameras (4 MPixels, Limess, Krefeld, Germany) with a frame rate of 4 Hz and pan angle of $22.0^\circ \pm 2.2^\circ$ to medial from anterior view (Fig. 1). The two cameras created a stereo view of the surface from which the 3D surface, displacements, and surface strains were calculated using the DIC program Vic-3D 2007 (Correlated Solutions, Inc., USA). Disturbance in DIC data was quantified (Supplementary data). The surfaces from the DIC data were registered to the CT images with MATLAB (R2011a, Mathworks, USA) using the iterative closest point algorithm to assess the accuracy of DIC to reconstruct the geometry.

The surface distributions of the Lagrangian first and second principal strains (ε_1 and ε_2) were analyzed. To compare the inter-bone variation of strains in all bones, the distributions of the von Mises strains were investigated at equal load of 4.9 kN and at equal maximum von Mises strain of 1.7%. In addition, the von Mises strain was evaluated against the load in a specific ROI, which was chosen at the head–neck junction where the strains were the highest.

3. Results

In all bones, the fracture was a sudden brittle crack. The fracture occurred in the neck–trochanter junction in all bones except in one bone where the fracture line went from the lateral trochanter to the site below the minor trochanter (Fig. 1). CT images showed that in this bone an air cavity was located at the initial fracture location at the lateral side of the major trochanter next to the neck axis (Supplementary data). The load–displacement curves showed similar behavior in the linear region for most bones, except for the bone in test 4 which had higher stiffness and ultimate strength than the other bones (Fig. 2). The ultimate load at fracture varied between 4954 and 6747 N (Supplementary data Table 1).

The RMS value of the temporal disturbance in the von Mises strains measured with DIC varied from 5 to 30 $\mu\varepsilon$ (Fig. 3). The amount of temporal disturbance was not related to the signal level. The disturbances in the data points next to each other were

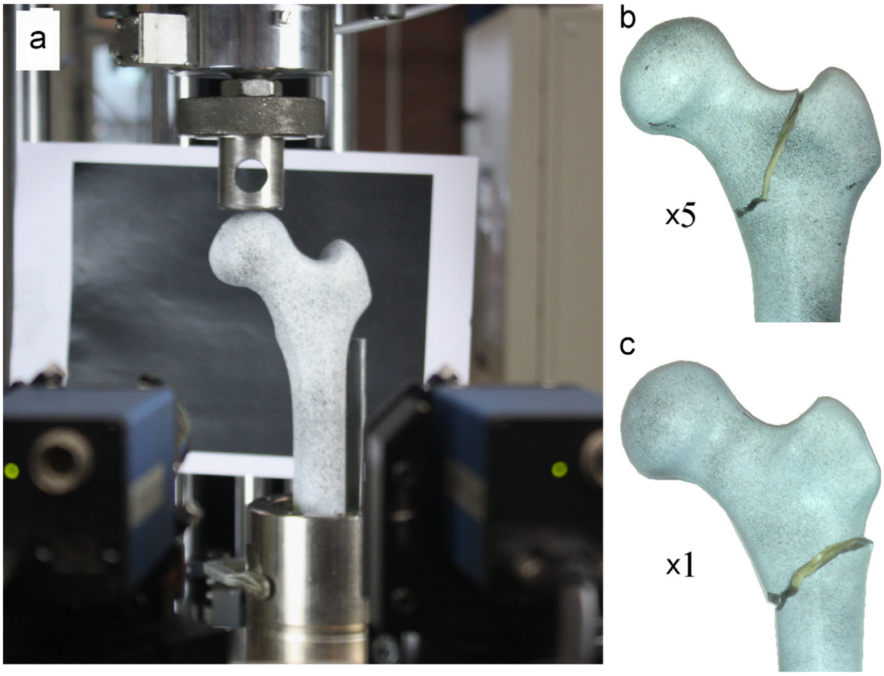

Fig. 1. (a) The axial loading setup with digital image correlation cameras for the composite proximal femurs. Fracture locations of bones 2–6 (b) and bone 1 (c).