Journal of Biomechanics 45 (2012) 2035–2040

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

3D identification of trabecular bone fracture zone using an automatic image registration scheme: A validation study

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ARTICLE INFO

Article history:
Accepted 13 May 2012

Keywords:
Trabecular fracture zone
Image processing
Three-dimensional automatic registration
Fracture parameters
Trabecular bone

ABSTRACT

Accurate identification of the local fracture zone is an important step towards the failure assessment of trabecular bone. In previous *in-vitro* studies, local fracture zones were visually identified in micro-CT images by experienced observers. This is a time-consuming and observer-dependent approach and it prevents any large-scale analysis of local trabecular fracture regions. The scope of this study is the application and validation of a new registration scheme for the automatic identification of trabecular bone fracture zones.

Six human trabecular specimens were extracted from different anatomical sites. Five specimens were mechanically tested and scanned using micro-CT. For each specimen pre- and post-failure micro-CT datasets were obtained. The sixth specimen was scanned twice without any mechanical compression and was used to test the accuracy of the proposed scheme. The registration scheme was applied to the acquired datasets for the automatic identification of the fracture zone. The proposed scheme comprises of a three-dimensional (3D) automatic registration method to define the differences between the two datasets, and the application of a criterion for defining slices of the pre-failure dataset as "broken" or "unbroken". Identifications of the fracture zones were qualitatively validated against visual identification of observers. Furthermore, "full 3D" fracture zone identification, based on the presented scheme, was proposed.

The proposed scheme proved to be more accurate and significantly faster than the currently used visual process.

1. Introduction

Trabecular mechanical behaviour is an important issue for the assessment of bone fracture risk. Numerous studies analysing the mechanical behaviour of the trabecular bone structure have been reported in the literature (Goldstein et al., 1993; Goulet et al., 1994; Ciarelli et al., 2000; Matsuura et al., 2007; Perilli et al., 2008).

Several parameters related to the identification and prediction of a fracture zone, and of the fracture event in general have been used in both clinical studies (Marshall et al., 1996; McCreadie and Goldstein, 2000; Donaldson et al., 2009; Watts et al., 2009) and *in-vitro* studies (Nazarian et al., 2006, 2008; Perilli et al., 2008; Tassani et al., 2010). *In-vitro* studies considered the local analysis of the trabecular structure and compared it to the global one, in order to identify the weakest point of the structure and, therefore, the fracture zone.

In the reported studies, fracture zones are identified by visual inspection of each micro-CT acquired slice of the specimens, often requiring a blind comparison among operators (Nazarian et al., 2006; Perilli et al., 2008). Consequently, the whole procedure is time-consuming and operator-dependent, and therefore not applicable to large scale analysis. Automatic techniques should be applied to identify fracture zones in different specimens subjected to mechanical testing, providing accuracy and reproducibility of the results and reduction of the execution time required.

In the present study, a new methodological approach based on image processing is proposed and validated for the automatic identification of trabecular bone fracture zones in micro-CT datasets after mechanical testing.

2. Materials and methods

2.1. Data acquisition

Six human trabecular bone specimens, cylindrical in shape (10 mm diameter, 26 mm height), were extracted from the epiphyses of two femurs and two tibiae (Fig. 1) and embalmed, according to procedures reported in the literature (Van Sint Jan and Rooze, 1992; Ohman et al., 2008; Tassani et al., 2011).

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http://dx.doi.org/10.1016/j.jbiomech.2012.05.019

Fig. 1. Extraction sites of trabecular specimens for femur and tibia.

Five specimens underwent compressive testing (model Mini Bionix 858, MTS Systems Corp., Minneapolis, MN, USA) (Ohman et al., 2007; Perilli et al., 2008). All specimens were scanned using a micro-CT scanner (model SkyScan 1072, SkyScan, Kontich, Belgium) before and after (pre- and post-failure datasets) the mechanical test, using an isotropic voxel size of 19.5 μm (Perilli et al., 2007a, 2008; Tassani et al., 2011).

The sixth specimen was used to perform an accuracy test. Thus, the specimen was scanned twice without mechanical compression. The two resulting datasets are hereafter called TestSet-I and TestSet-II.

2.2. *The proposed registration scheme*

Automatic identification of the fracture zones was performed in a two-step approach:

(a) Application of a 3D automatic registration method.
(b) Identification of fracture zones.

2.2.1. *3D automatic registration method*

The proposed method is a surface-based registration technique (Matsopoulos et al., 2003; Matsopoulos, 2009). The method was applied on the pre- and post-failure datasets of every specimen in order to highlight the differences related to the compressive test. Analytically the registration method comprises the following steps:

Step 1: Application of a segmentation process by means of a global fixed threshold (Perilli et al., 2006, 2007b).
Step 2: Definition of a measure of match (MOM) that quantifies the spatial matching between the pre- and post-failure sets.
Step 3: Maximization of the MOM.

The geometrical transformation employed was the rigid transformation model (van den Elsen et al., 1993).

The 3D automatic registration method was applied as follows. Two subsets of the post-failure set were initially defined: the upper and the lower subset, relative to the fracture zone, consisting of a maximum of 50 contiguous slices. The upper subset consisted of slices between the first upper slice of the set, and a randomly selected slice located above the fracture zone. A similar procedure was performed for defining the lower subset. Thus, the two subsets correspond to an "unbroken region". These subsets are shown in Fig. 2a (yellow areas). The proposed registration method was applied twice, for aligning both the upper and the lower post-failure subsets to the pre-failure set (Fig. 2b and c).

2.2.2. *Criterion for the identification of the fracture zone*

The trabecular fracture zone was defined as the region presenting brittle fracture or plastic deformation of at least one trabecula. In order to automatically identify the fracture zone on the pre-failure set, each slice was classified as "broken" or "unbroken" according to the following methodology (Fig. 3). For each slice, ROIs of the pre-failure and registered post-failure dataset were obtained from the segmented images. Each ROI was selected by the identification of single disconnected objects. Therefore, every disconnected trabecula lying on the slice was identified as a ROI. If ROIs of the pre- and registered post-failure dataset had an overlap inferior of a threshold $x\%$, the ROI was classified as broken. The *Broken*

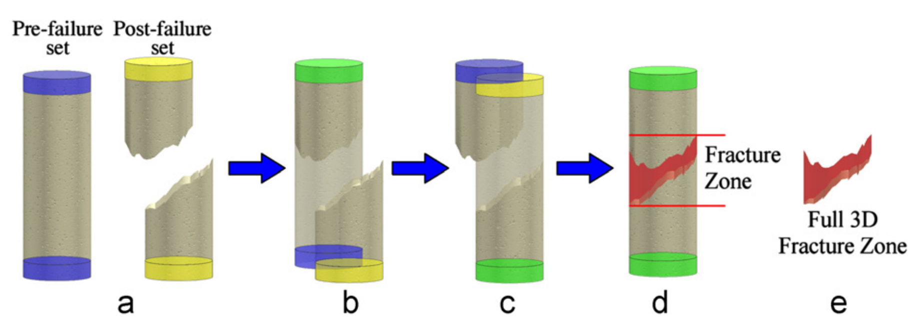

Fig. 2. Application of the proposed 3D registration scheme. (a) The pre- and post-failure sets. Upper and lower subsets are identified on the post-failure set (yellow areas) and are registered on the corresponding areas of the pre-failure set (blue areas). (b) Application of the registration method involving the upper post-failure subset and the pre-failure set. (c) Application of the registration method involving the lower post-failure subset and the pre-failure set. (d) All the slices including the misaligned zone are classified as broken using the identification criterion and identified as "fracture zone". (e) The Full 3D fracture zone is identified as the VOI including only the misaligned zone (red area).