Journal of Biomechanics 43 (2010) 2374–2380

Contents lists available at ScienceDirect

Journal of Biomechanics

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

A nonlinear finite element model validation study based on a novel experimental technique for inducing anterior wedge-shape fractures in human vertebral bodies *in vitro*

E. Dall'Ara [a,*], R. Schmidt [b], D. Pahr [a], P. Varga [a], Y. Chevalier [a], J. Patsch [c], F. Kainberger [c], P. Zysset [a]

[a] Institute of Lightweight Design and Structural Biomechanics, Vienna University of Technology, Austria
[b] Department of Traumatology, Medical University of Vienna, Austria
[c] Department of Radiology, Medical University of Vienna, Austria

ARTICLE INFO

Article history:
Accepted 20 April 2010

Keywords:
Finite element modeling
Bone mineral density
Bone strength
Osteoporosis
Mechanical testing

ABSTRACT

Vertebral compression fracture is a common medical problem in osteoporotic individuals. The quantitative computed tomography (QCT)-based finite element (FE) method may be used to predict vertebral strength *in vivo*, but needs to be validated with experimental tests. The aim of this study was to validate a nonlinear anatomy specific QCT-based FE model by using a novel testing setup. Thirty-seven human thoracolumbar vertebral bone slices were prepared by removing cortical endplates and posterior elements. The slices were scanned with QCT and the volumetric bone mineral density (vBMD) was computed with the standard clinical approach. A novel experimental setup was designed to induce a realistic failure in the vertebral slices *in vitro*. Rotation of the loading plate was allowed by means of a ball joint. To minimize device compliance, the specimen deformation was measured directly on the loading plate with three sensors. A nonlinear FE model was generated from the calibrated QCT images and computed vertebral stiffness and strength were compared to those measured during the experiments. In agreement with clinical observations, most of the vertebrae underwent an anterior wedge-shape fracture. As expected, the FE method predicted both stiffness and strength better than vBMD (R^2 improved from 0.27 to 0.49 and from 0.34 to 0.79, respectively). Despite the lack of fitting parameters, the linear regression of the FE prediction for strength was close to the 1:1 relation (slope and intercept close to one (0.86 kN) and to zero (0.72 kN), respectively). In conclusion, a nonlinear FE model was successfully validated through a novel experimental technique for generating wedge-shape fractures in human thoracolumbar vertebrae.

1. Introduction

Osteoporosis is a common skeletal disease causing bone mass reduction and bone microstructural changes. In osteoporotic individuals, vertebral compression fracture is a major clinical problem with high morbidity and mortality (Jalava et al., 2003; Kanis et al., 2004). Accurate prediction of bone properties and the associated risk of fracture is necessary to identify whether an appropriate drug treatment is required to prevent a vertebral failure. Both dual energy X-ray absorptiometry (DXA) and quantitative computer tomography (QCT) are extensively used in clinics to non-invasively evaluate the vertebral fracture risk (Grampp et al., 1997) by computing the vertebral areal bone mineral density (aBMD) and vBMD, respectively. The correlation between vertebral strength and aBMD or vBMD measured *in vitro* shows a wide range of predictive capability: R^2=0.46–0.83 for DXA (Faulkner et al., 1991; Granhed et al., 1989) and R^2=0.16–0.67 for QCT (Buckley et al., 2007; Faulkner et al., 1991). The vertebral strength is better correlated if the minimum cross-sectional area (minCSA), measured from QCT images, is combined with vBMD (Buckley et al., 2007; Cheng et al., 1997; Crawford et al., 2003; Singer et al., 1995). Even though correlations may be strong, bone mineral density (BMD) alone or its product with minCSA can predict neither stiffness nor vertebral strength quantitatively.

FE models based on QCT images include information about the vertebral body geometry and bone density inhomogeneity. Therefore they may be used to predict vertebral stiffness and strength *in vivo*, but they need to be accurately validated with experimental tests *in vitro*. Recent studies showed good correlations between the predicted and the experimental vertebral strength (Buckley et al., 2007 N=77; Chevalier et al., 2009 N=12; Crawford et al., 2003 N=13; Imai et al., 2006 N=12; Liebschner

* Corresponding author. Tel.: +43 664 60 588 3172; fax: +43 1 58801 31799.
E-mail addresses: edallara@ilsb.tuwien.ac.at, enrico.dallara@libero.it (E. Dall'Ara).

0021-9290/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2010.04.023

et al., 2003 $N=13$; Mirzaei et al., 2009 $N=13$). However, the modest correlation between experimental and predicted vertebral stiffness ($R^2=0.54$ in Chevalier et al., 2009; $R^2=0.27$ in Buckley et al., 2007) supports that further refinements are needed both in the models and in the experimental setup.

Particular emphasis should be put on the definition of the boundary conditions during the experimental tests and consequently in their correct reproduction in the FE model. In most of the studies (Chevalier et al., 2009; Buckley et al., 2007; Crawford et al., 2003; Liebschner et al., 2003) the vertebral body cortical endplates were embedded in Poly-methyl-methacrylate during the compression test. In another case, rubber discs were positioned between the loading plate and the vertebra (Mirzaei et al., 2009) introducing an undetermined deformation component during the test. In the first case an unrealistic situation was modeled. These constraints introduce complications in modeling the behavior of the material inserted between the vertebra and the loading plate. Moreover, the embedding material constrains the vertebral body in a non-physiological way and may affect its failure mechanics. Furthermore, the anterior wedge-shape fracture of the vertebral body, that typically occurs *in vivo* (Jelsma et al., 1982), cannot be reproduced by loading the vertebra between two parallel planes. Therefore in some studies the rotation of the loading plate was allowed by means of a ball joint (Furtado et al., 2007; Imai et al., 2006; Liebschner et al., 2003). In all the mentioned cases, especially when a ball joint was used, the system machine-setup compliance analysis were not included into the calculation and may have affected the experimental vertebral stiffness measurement.

The aim of this study was to validate a nonlinear FE model for predicting vertebral stiffness and strength in a large number of human vertebral bodies *in vitro*, by means of a novel testing setup developed to induce anterior wedge-shape fractures.

2. Materials and methods

2.1. Sample selection

Ten human thoracolumbar spines (T12-L5) were received from the Clinical Department of Pathology, Medical University of Vienna, Austria. The donors (seven males, three females with age 44–82) did not suffer from any bone or cartilage disease. The Medical University of Vienna ethics commission approved the procedures applied during the present study. Three to five vertebrae were dissected from each spine (in total 43 specimens) and their soft tissues were removed. The bone tissue was kept frozen at $-20\ ^{\circ}C$ until the beginning of the sample preparation and in between the procedure steps.

2.2. Slice preparation

Two parallel cuts perpendicularly to the cranio-caudal axis were performed to remove both endplates (300 CP, Exakt Gmbh, Germany). The posterior elements were then separated from the vertebral body. To obtain plane and parallel surfaces, a 0.5 mm layer was removed from both sides of the vertebral body by polishing with a silicon carbide paper (P500, PM5, Logitech Ltd., Scotland). Cutting and polishing operations were performed under constant water irrigation. Twelve measurements of the slice thickness were performed along its perimeter with a digital caliper. The polishing procedure was repeated, removing 0.25 mm per iteration, until the difference between maximum and minimum became less than the 1% of the average thickness.

2.3. CT scanning and vBMD analysis

Each vertebra was submerged in 0.9% NaCl saline solution and exposed to vacuum for 10 min to remove air bubbles. A custom made Plexiglas chamber was used to position the immerged specimens and to align the cranio-caudal axis of the slice with the scanners. First, each slice was scanned together with a K_2HPO_4 calibration phantom (Model 3 CT Calibration Phantom, Mindways Software, U.S.A.) using a clinical QCT (Brilliance64, Philips, Germany) at two different resolutions. A lower resolution (LR-QCT, Fig. 1a–c) was used to evaluate the vBMD and a higher resolution (HR-QCT, Fig. 1d) was used to generate the FE models (Fig. 1e) and

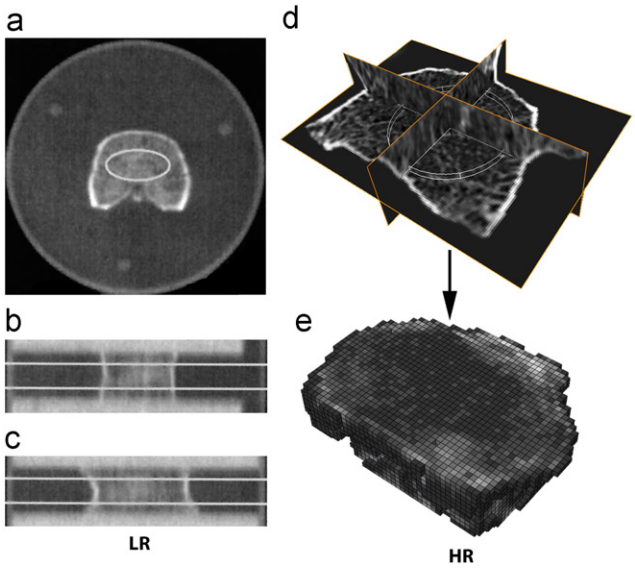

Fig. 1. Left: an example of a LR-QCT scan (a–c) used to compute the vBMD with the bright line representing the bounds of the ROI. Right: orthogonal sections from an example of HR-QCT image (d) and the corresponding FE model (e).

calculate the minCSA. Afterwards, each vertebra was scanned with a High Resolution peripheral-QCT (HR-pQCT: XtremeCT, Scanco Medical AG, Switzerland) to obtain a more accurate representation of the vertebral bone geometry, and therefore to better control the specimen positioning in the testing machine (described in the next section). An overview of the scanning procedures can be found in Table 1. The QCT and HR-pQCT images were then rotated and cropped to correct the small misalignments between the plane surfaces of the specimen and the scanning slices. Then, the images were registered, by using a rigid registration algorithm (ITK, Kitware, U.S.A.), to match the coordinate systems of the mechanical setup and of the FE models.

vBMD was computed from the LR-QCT images of each specimen with a commercial software (QCT PRO, Mindways Software, U.S.A.) using the standard clinical approach applied for lumbar spine analysis. An experienced QCT analyst defined a region of interest (ROI) in the trabecular bone of the vertebral body. The ROI was defined selecting manually the position of an elliptical area in the midvertebral transverse section (Fig. 1b), while maximizing its in-plane dimension by excluding the trabecular tissue close to the cortical shell and to the posterior wall. The area was then extended symmetrically into superior and inferior QCT slices to reach a nominal thickness of 9 mm (Fig. 1c, d). vBMD was calculated as the mineral content in the ROI divided by its volume. The calibration phantom was used to convert Hounsfield Units to equivalent vBMD in g/cm^3 (Kopperdahl et al., 2002; Crawford et al., 2003) for both QCT images.

2.4. Mechanical tests

Thirty-seven specimens were randomly selected for mechanical testing (Table 2). Samples with calcifications like osteophytes or with small lytic defects were intentionally not excluded. Each specimen was kept in 0.9% saline solution for at least 1 h before testing and then carefully positioned in the machine as follows. From the segmented HR-pQCT images, the center of mass (CoM) of each specimen was computed. The projections of the sagittal and the frontal planes containing the CoM were then plotted on a sheet of paper, together with the most caudal slice of the HR-pQCT image. To induce an anterior wedge-shape fracture, the CoM projection was translated in the anterior direction (Fig. 2a, b) of a fixed percentile of the width (W) of the most caudal slice of the vertebral body (0% in 2 cases, 5% in 21 cases and 10% in the left 14 cases). The loading axis was defined by the new reference point, and the projections of the reference planes were used for the correct alignment with the reference markers of the setup (Fig. 2c, d). The specimen was then positioned in the machine by using the contour of the image of the slice (Fig. 2d). A servohydraulic testing machine (Mini-Bionix, MTS system, U.S.A.) was used to compress the slices beyond 12% (Fig. 3a). Rotation of the loading plate was allowed by means of a ball joint (Fig. 3b). To avoid translations of the specimen the loading surfaces were sandblasted to increase friction (Fig. 2c). To circumvent testing device compliance, the axial displacement of three points of the loading plate were measured with three sensors (LVDTs: WA20, HBM, Germany) (Fig. 3c, d). The axial force was measured by means of a 100 kN load cell (U3 force transducer, HBM, Germany) (Fig. 3a). Ten preconditioning cycles were applied between 0 and 0.080 mm with a rate of 5 mm/min (Chevalier et al., 2008) and then a monotonic compression was applied with the same rate. Vertebral