Medical Engineering and Physics 37 (2015) 599–604

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Finite element analysis predicts experimental failure patterns in vertebral bodies loaded via intervertebral discs up to large deformation

Allison L. Clouthier[1], Hadi S. Hosseini, Ghislain Maquer, Philippe K. Zysset*

Institute for Surgical Technology and Biomechanics, University of Bern, Stauffacherstrasse 78, 3014 Bern, Switzerland

ARTICLE INFO

Article history:
Received 4 July 2014
Revised 14 January 2015
Accepted 22 March 2015

Keywords:
Finite element analysis
Spine segment
Large deformations
Vertebral fracture
Boundary conditions
Disc degeneration

ABSTRACT

Vertebral compression fractures are becoming increasingly common. Patient-specific nonlinear finite element (FE) models have shown promise in predicting yield strength and damage pattern but have not been experimentally validated for clinically relevant vertebral fractures, which involve loading through intervertebral discs with varying degrees of degeneration up to large compressive strains. Therefore, stepwise axial compression was applied *in vitro* on segments and performed *in silico* on their FE equivalents using a nonlocal damage-plastic model including densification at large compression for bone and a time-independent hyperelastic model for the disc. The ability of the nonlinear FE models to predict the failure pattern in large compression was evaluated for three boundary conditions: healthy and degenerated intervertebral discs and embedded endplates. Bone compaction and fracture patterns were predicted using the local volume change as an indicator and the best correspondence was obtained for the healthy intervertebral discs. These preliminary results show that nonlinear finite element models enable prediction of bone localisation and compaction. To the best of our knowledge, this is the first study to predict the collapse of osteoporotic vertebral bodies up to large compression using realistic loading via the intervertebral discs.

1. Introduction

Vertebral compression fractures are associated with increased risk of subsequent fractures, pain, decreased quality of life, and mortality [1,2] and the risk of such fractures increases with age [3]. Dual energy X-ray absorptiometry (DXA) is currently used to estimate fracture risk clinically; however, it cannot accurately identify individuals who will suffer a fracture [4] and does not account for three-dimensional geometry or local changes in bone density and orientation. Patient-specific nonlinear finite element models based on quantitative computed tomography (QCT) are able to predict vertebral strength more accurately than DXA [5] and models based on micro-computed tomography are being increasingly used in studies of vertebral strength and failure [6–10].

Attempts have been made to predict failure locations resulting from axial compression through patterns of strain [11,12], damage [13,14], and failed tissue [15]. Most of these finite element models, however, have been validated against experiments where the vertebral endplates were either embedded in a stiff material [16], removed [17], or fixed to rubber discs [18]. These methods eliminate the need to model the complex material behaviour of the intervertebral disc as well as ambiguity in material properties due to unknown levels of disc degeneration. However, these boundary conditions have a significant effect on the prediction of vertebral strength and failure patterns [19–22]. Additionally, failure of vertebrae loaded via healthy intervertebral discs is often initiated in the endplates [23,24] and the constraint imposed by the unrealistically stiff experimental boundary conditions, such as polymethylmethacrylate (PMMA) embedding, prevents deformation of the endplates, and thus, simulation of this common type of vertebral failure. Moreover, models that have simulated loading via the intervertebral disc have used simple linear elastic material models for the disc without direct experimental validation [25–27].

The majority of finite element models used to study vertebral strength and failure have been implemented only for small strains [17,18,25]. However, *in vivo*, vertebral fractures often involve significant loss of height [28,29]. While simulation up to, or just beyond, initial yield provides valuable information about initial failure location, it offers little insight into subsequent areas of failure or the evolution of damage that results in bone compaction at higher compressive strains. Such information may be beneficial in understanding mechanisms of fracture and vertebral body collapse. In a recent study [30], a combined experimental and computational analysis of the collapse

* Corresponding author. Tel.: +41 31 631 59 25; fax: +41 31 631 59 60.
E-mail addresses: allison.clouthier@queensu.ca (A.L. Clouthier), hadi.seyed@istb.unibe.ch (H.S. Hosseini), ghislain.maquer@istb.unibe.ch (G. Maquer), philippe.zysset@istb.unibe.ch (P.K. Zysset).
[1] Present address: Department of Mechanical and Materials Engineering, Queen's University, 130 Stuart St., Kingston, ON, Canada.

http://dx.doi.org/10.1016/j.medengphy.2015.03.007
1350-4533/

of single vertebral bodies embedded in PMMA under large deformation was reported. Accordingly, the aim of this study is to extend the previous results to the collapse of vertebral bodies loaded via the intervertebral discs.

Specimen-specific nonlinear finite element models were developed for two spine segments tested experimentally in stepwise loading beyond 30% vertebral compression. The ability of the two models to predict the experimental failure pattern was evaluated using both healthy and degenerated disc conditions, as well as embedding of the vertebral endplates.

2. Material and methods

2.1. Experiment

2.1.1. Sample preparation

Two spine segments were obtained from a single human cadaver spine donated to the Centre of Anatomy and Cell Biology of the Medical University of Vienna with the signed informed consent requested by the local ethics commission. Each segment consisted of one full vertebral body between two intervertebral discs and two half-vertebral bodies (Specimen 1: T9-T11, Specimen 2: T11-L1). The cadaver spine was stored at −20 °C prior to sample dissection and hydration was maintained using 0.9% saline solution during preparation. Spine segments were obtained by cutting vertebral bodies transversely, cleaning surrounding soft tissue, and isolating from their posterior elements. For each segment, the inferior and superior half-vertebral bodies were embedded in PMMA such that approximately 5 mm of bone remained out of the PMMA block in the half-vertebrae.

2.1.2. Mechanical testing

The spine segments were loaded in a stepwise manner with a device used in a previous study [30] designed to apply a compressive load inside a high-resolution peripheral computed tomography (HR-pQCT) machine. The PMMA surfaces of the segment were glued to the loading platens of the device and the radiolucent chamber was filled with 0.9% saline solution. A fine-thread screw connected to a thrust bearing was used to manually control axial displacement without applying any torque. During the mechanical testing, radial pin holes allowed approximate tracking of applied displacement and a load cell contained in the device captured the resulting force. The registered HR-pQCT images enabled the exact measurement of the applied axial displacements corresponding to the varying number of voxels in the cranio-caudal direction at each loading step. Due to the stepwise nature of the experiments and the sharp drop of force after failure, it was not possible to accurately capture the force–displacement curves. Instead, the focus was prediction of failure zones as this is of greater importance in large strain analysis of bone compaction.

To image the initial configuration of the segments, a preload was applied to fix the specimen in place and minimise time spent in the toe region and the device was imaged using a HR-pQCT system (XtremeCT, Scanco Medical AG, Brüttisellen, Switzerland) at a resolution of 82 μm. For all subsequent steps, displacement was applied using the loading screw, the specimen was allowed to relax for 25 min, and then the device was imaged, resulting in a total relaxation time of 50 min. This process was repeated until approximately 30% deformation was achieved in the central vertebral body, with applied displacement being increased following loading step 3 and 6 while relaxation time was kept constant. The displacement applied to the spine segments at each loading step as measured on the HR-pQCT images is given in Table 1. The increasing rate of applied compression allowed completion of each stepwise loading experiment within 12 h.

Table 1.
Applied displacement: the total displacement applied by the loading screw to the spine segments, measured from the HR-pQCT images. The applied displacement was increased after load steps 3 and 6.

Load step	Applied displacement (mm)	
	Specimen 1	Specimen 2
1	0.16	0.33
2	0.49	0.66
3	0.90	1.07
4	1.80	1.97
5	2.79	2.87
6	3.85	3.94
7	6.15	6.07
8	8.36	8.20
9	10.66	10.91
10	13.20	13.45
11		15.99

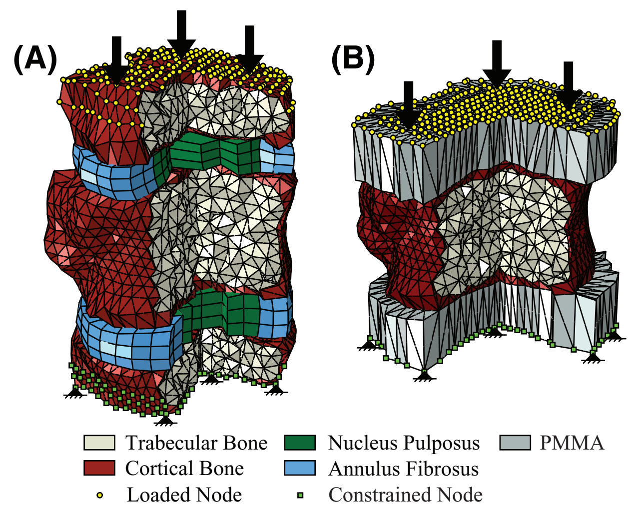

Fig. 1. Finite element meshes: finite element meshes used for Specimen 2. (A) Mesh for the whole spine segment, including intervertebral discs. (B) Mesh with PMMA embedding of centre vertebra endplates. Displacements and constraints were applied as shown.

2.2. Finite element model

2.2.1. Mesh generation

HR-pQCT images obtained of the initial configuration were used to create finite element meshes consisting of quadratic tetrahedral elements for the vertebral bodies of the spine segments following an automated meshing procedure [31,32] in Medtool (www.dr-pahr.at). An analysis of mesh sensitivity using this meshing procedure and material model was performed previously [14,33]. To create meshes for the intervertebral discs, the space between vertebral bodies was manually segmented from the HR-pQCT images in ITK-SNAP [34] and converted into an analytic surface in SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France). This surface was then meshed with linear hexahedral elements in CUBIT (Sandia National Laboratories, Albuquerque, New Mexico) and elements sets were created for the nucleus pulposus and annulus fibrosus such that the nucleus represented approximately 43% of the total intervertebral disc volume [19,35]. Finally, to establish an interface between the discs and the vertebral endplates, the corresponding surfaces were tied. The resulting meshes of the spine segments (Fig. 1A) comprised 29,630 and 44,808 elements for Specimens 1 and 2, respectively.

For the embedded boundary condition case, two PMMA blocks were extruded from the endplates of the centre vertebral body mesh using quadratic tetrahedral elements, as shown in Fig. 1B.