ELSEVIER

The Spine Journal 13 (2013) 1281–1292

THE SPINE JOURNAL

Basic Science

Strain distribution in the lumbar vertebrae under different loading configurations

Luca Cristofolini, PhD[a,b,*], Nicola Brandolini, MSc[a], Valentina Danesi, MEng[a,b], Mateusz M. Juszczyk, PhD[a,b], Paolo Erani, BEng[a], Marco Viceconti, PhD[c]

[a]*Laboratory for Medical Technology, Rizzoli Orthopaedic Institute, Via di Barbiano 1/10, 40136 Bologna, Italy*

[b]*Department of Industrial Engineering, School of Engineering and Architecture, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy*

[c]*Department of Mechanical Engineering, The University of Sheffield, Mappin St, Sheffield, S1 3JD, United Kingdom*

Received 18 May 2012; revised 1 March 2013; accepted 1 June 2013

Abstract

BACKGROUND CONTEXT: The stress/strain distribution in the human vertebrae has seldom been measured, and only for a limited number of loading scenarios, at few locations on the bone surface.

PURPOSE: This in vitro study aimed at measuring how strain varies on the surface of the lumbar vertebral body and how such strain pattern depends on the loading conditions.

METHODS: Eight cadaveric specimens were instrumented with eight triaxial strain gauges each to measure the magnitude and direction of principal strains in the vertebral body. Each vertebra was tested in a three adjacent vertebrae segment fashion. The loading configurations included a compressive force aligned with the vertebral body but also tilted (15°) in each direction in the frontal and sagittal planes, a traction force, and torsion (both directions). Each loading configuration was tested six times on each specimen.

RESULTS: The strain magnitude varied significantly between strain measurement locations. The strain distribution varied significantly when different loading conditions were applied (compression vs. torsion vs. traction). The strain distribution when the compressive force was tilted by 15° was also significantly different from the axial compression. Strains were minimal when the compressive force was applied coaxial with the vertebral body, compared with all other loading configurations. Also, strain was significantly more uniform for the axial compression, compared with all other loading configurations. Principal strains were aligned within 19° to the axis of the vertebral body for axial-compression and axial-traction. Conversely, when the applied force was tilted by 15°, the direction of principal strain varied by a much larger angle (15° to 28°).

CONCLUSIONS: This is the first time, to our knowledge, that the strain distribution in the vertebral body is measured for such a variety of loading configurations and a large number of strain sensors. The present findings suggest that the structure of the vertebral body is optimized to sustain compressive forces, whereas even a small tilt angle makes the vertebral structure work under suboptimal conditions.

Keywords: Lumbar spine; Strain distribution; Vertebral body; In vitro mechanical testing; Structural optimization

Introduction

Trauma, osteoporosis, and bone metastases are the most common causes of vertebral fractures, which can lead to severe consequences and mortality [1–3]. Success of treatments such as fixation or augmentation can be jeopardized by limited understanding of spine biomechanics [4–7].

FDA device/drug status: Not applicable.

Author disclosures: ***LC:*** Grant: European Commission (G, Paid directly to institution). ***NB:*** Grant: European Commission (G, Paid directly to institution). ***VD:*** Grant: European Commission (G, Paid directly to institution). ***MMJ:*** Grant: European Commission (G, Paid directly to institution). ***PE:*** Grant: European Commission (G, Paid directly to institution). ***MV:*** Grant: European Commission (G, Paid directly to institution).

The disclosure key can be found on the Table of Contents and at www.TheSpineJournalOnline.com.

* Corresponding author. Department of Industrial Engineering, University of Bologna, Viale Risorgimento, 2, 40136 Bologna, Italy. Tel.: +39 051 2093266.

E-mail address: luca.cristofolini@unibo.it (L. Cristofolini)

1529-9430/$ - see front matter
http://dx.doi.org/10.1016/j.spinee.2013.06.014

In-depth knowledge about the stress distribution in the vertebral body is fundamental to improve the understanding of spine biomechanics in health and disease, during aging [8], and improve surgical treatment [9]. Because of the difficulty of accessing in vivo the musculoskeletal loads in the spine, in vitro measurements of the load-strain relationship in the vertebral body can provide valuable indirect information about spine biomechanics.

In vitro biomechanical tests on the vertebral body often focus on fracture (eg, [10–12]). In most such studies, the strain distribution was not investigated. One of the first studies on the strain distribution in the vertebral body was carried out by means of brittle coating, photoelasticity [13], and 17 strain gauges [14], for different compressive loads. The effect of an inclined load (16°) has been investigated on functional spinal units using three to four strain gauges [15]. The contribution of the neural arch to load transfer was investigated by Hongo et al. [16] with 11 triaxial strain gauges (eight on the vertebral body), with a compressive load. Strains induced by compression and shear loads were quantified with three triaxial strain gauges on the vertebral rim, and one on the end plate surface [17]. Fracture risk was assessed by Kayanja et al. [18], but the most stressed region could not be identified as only one gauge was applied on each vertebral body. Later, three triaxial strain gauges were used to assess the changes due to cement augmentation [19]. When uniaxial gauges are used (eg, [20]) it is possible to determine neither the value of principal strains nor their direction.

Axial compressive loading is probably the most frequent in vitro loading condition (eg, [11,21–25]). In some cases, also eccentric compression [26–28] or anterior bending [10,29] were simulated.

Finite element (FE) models can provide valuable insight in the stress/strain distribution [30–32]. Validation of FE models is mandatory to prove their accuracy and closeness to reality [33–35]. A combined numerical-experimental study was presented by Imai et al. [36], in which four strain gauges were used to validate the FE predictions. A combination of experiments and FE modeling was used to estimate the elastic modulus of the cortical shell, based on the measured stiffness of the vertebral body [37].

The summary above highlights that the strain distribution in the vertebral body has been measured with a limited number of strain gauges; for a limited set of loading configurations.

The aim of the present study was to explore the effect of different types of loading on the strain distribution in the vertebral body of the lumbar vertebrae.

Materials and methods

Nondestructive tests were performed on vertebral bodies of L1, L3, and L5 vertebrae. The strain distribution on the bone surface was investigated by means of triaxial strain gauges. Different loading configurations were performed to obtain a comprehensive characterization of the strain distribution.

Bone specimens

Six thoracolumbar spines were obtained through an ethically approved donation program from donors who did not suffer from musculoskeletal pathologies. Specimens were computed tomography scanned (BrightSpeed, General Electric Medical Systems, Waukesha, WI, USA) to document bone quality and lack of abnormality or defects. Tests were performed on three adjacent vertebrae segments (eight specimens in total, Table 1), allowing physiological loading of the vertebral body through its adjacent intervertebral discs.

All the surrounding soft tissues were removed, including the ligaments. For each specimen, the adjacent vertebrae were potted in acrylic cement (Restray, Salmoiraghi, Mulazzano, Italy) (Fig. 1). A six-degrees-of-freedom clamp was used to hold the central vertebra to align its upper and lower vertebral rims parallel to the ground, fitting two parallel references. The spinous process was used to center the specimen in the right/left direction and align it about its vertical axis. To isolate the mechanical behavior of the vertebral body from the surrounding structures, after potting the posterior arch was resected through the pedicles and removed.

During the tests, the specimens were kept hydrated with physiological saline solution. Specimens were stored sealed in bags at −24°C when not in use.

Strain measurement

Eight triaxial-stacked strain gauges were equally spaced around each vertebral body, at mid-height (Fig. 2). Both 1-mm grid (FRA-1-11-3L, TML Tokyo Sokki Kenkyujo, Tokyo, Japan) and 3-mm grid strain gauges (UFRA-3-350-11-3L, TML) were used, depending on the space available. Strain gauges were bonded following an established procedure for wet cadaveric specimens [38], which included the following:

- Accurate removal of soft tissues with a scalp and sandpaper (grade 400);
- Degreasing first with ethanol, then with a cocktail of acetone and 2-propanol;
- Bonding the strain gauges with cyanoacrylate glue (CN-Adhesive, TML);
- Waterproofing the strain gauges with polyurethane protection (M-COAT A, Vishay-MicroMeasurements, Raleigh, NC, USA).

To avoid overheating, a grid excitation of 1 V was selected for the 1-mm gauges, whereas the 3-mm gauges were excited at 2 V. Strains were sampled at 5,000 Hz using a multi-channel data-logger (System 6000, Vishay-MicroMeasurements), together with the signals from the testing machine and all other transducers. The principal strains ε_1 and ε_2 and the angle θ_p of the principal planes