Vertebral strength prediction under anterior compressive force using a finite element model for osteoporosis assessment

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1. Introduction

Vertebral fractures are one of the most common clinical manifestations with the major adverse consequences of osteoporosis as they usually occur under non-traumatic loading conditions. Height loss, back pain and functional disability are the most encountered consequences of vertebral fractures with repetitive fracture experience more likely occurring within a year after the first fracture. Early diagnosis of osteoporosis is therefore important for vertebral fracture prevention as drug treatments are more effective before perforation of the trabeculae (Mc Donnell et al. 2007). Bone mineral density (BMD) measured by dual energy X-ray absorptiometry (DXA) is the most clinically used method to diagnose osteoporosis. However this technique can only predict 40–70% of vertebral fractures as it only measures areal BMD which does not account for three dimensional (3D) geometry and BMD distribution (Sornay-Rendu et al. 2005). The combination of patient-specific 3D geometry and 3D BMD distribution is necessary to predict vertebral strength. Finite element models (FEM) derived from quantitative computed tomography (qCT) images are used to predict failure strength of vertebral bodies (Crawford et al. 2003; Imai et al. 2006; Buckley et al. 2007). Most of these models were validated under axial compressive forces to the vertebral body while vertebral fractures are more associated with eccentric compression (Lunt et al. 2003). The purpose of this study was to compare the performance of the aBMD from DXA and qCT-based FEM in predicting experimental vertebral strength. The experimental set up allowed for anterior compression testing on isolated vertebral bodies to ensure repeatable loading condition simulating an anterior wedge-shape fracture.

2. Methods

2.1. Subheading

Eleven lumbar spines (5 M and 6F aged: 82 years ± 7) were scanned on a qCT machine (Scanner ICT 256, Philips Healthcare, Cleveland, OH, 120 kV, 1489 mA/s and a voxel size: 0.39 mm × 0.39 mm × 0.33 mm) along with a calibration phantom (QRM-ESP, QRM GmbH, Germany) to map gray scale values to BMD. DXA measurements (Hologic Inc, Waltham, MA, USA) were performed with each spine positioned in a 15 cm water bath. BMD was calculated using the A-P scanning protocol. The 28 vertebrae (8 L1, 11 L2 and 9 L3) were then cleaned from all soft tissue and the posterior elements were transected. The vertebral bodies were potted in PMMA for parallelism before anterior compressive tests were conducted using a spherical seating loading platen (Instron Ltd., High Wycombe, UK) with the centre of rotation aligned with the anterior third of the vertebral body (Figure 1). Specimens were destructively tested in compression at 1 mm/min. Vertebral strength was defined as the ultimate load achieved and axial stiffness was calculated as the slope of the force–displacement curve.

A FEM was built based on the qCT images using a hexahedral mesh generated with a custom-built algorithm (8300 elements and 190,306 nodes).

Material properties for each element were assigned using density-modulus relationship (Kopperdahl et al. 2002). PMMA was modelled (E = 2.5 GPa, ν = 0.3) with the lower layer constrained and the upper layer joined by rigid elements to a node located at the anterior third of the vertebra to apply anterior compressive load. ™Simulations were run on ANSYS software (ANSYS Inc., Canonsburg, PA, USA). The vertebral failure load was

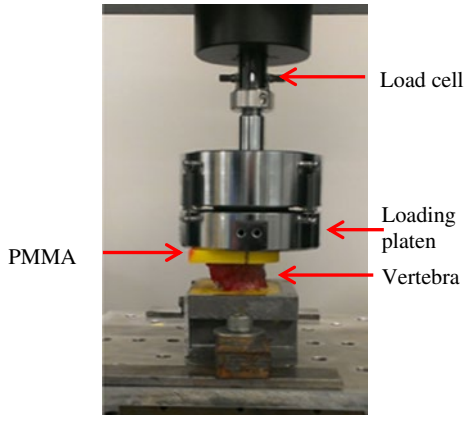

Figure 1. Experimental setup for anterior compressive test of an isolated vertebral body.

defined when a contiguous region of 1 mm³ of elements reached 1.5% deformation (Sapin-de Brosses et al. 2012). Vertebral strength and stiffness determined from qCT-based FEM were compared to the experimental output. Linear regression analysis was performed to find the best predictor for experimental vertebral strength estimation.

3. Results and discussion

Mean BMD determined from DXA was 724 mg/cm² ± 182 with a *t*-score ranging from −5.1 to 1. BMD was moderately correlated to experimental vertebral strength ($R^2 = 0.74$, $p < 0.0001$) (Table 1).

Average experimental and FEM vertebral strength were 3145 N ± 1573 and 3074 N ± 1423 respectively and were strongly correlated to the experimental vertebral strength ($R^2 = 0.95$, $p < 0.0001$) (Figure 2). Mean difference in vertebral strength was 78 N ± 381 [min = −659; max = 849] with a root mean square error of 12% (382 N) and a SEE of 11% (333 N).

Previous FEM derived from qCT images demonstrated squared correlation (R^2) coefficients ranging from 0.77 to 0.95 in the prediction of *in vitro* vertebral strength (Crawford 2003; Imai 2006; Buckley 2007). Imai et al. (2006) found a 0.95 R^2 coefficient with a nonlinear FE analysis to predict fracture site. However their model included an optimization algorithm that increases their computation time which is not appropriate for routine clinic. The present study proposed a model with a strong correlation ($R^2 = 0.95$) to predict experimental vertebral strength with an average computation time of 27 s, which is more appropriate for clinical application. The next step would be to validate this model *in vivo*.

Table 1. Linear regression analysis between the experimental vertebral strength and: areal BMD (aBMD) from DXA, FEM strength ($\boldsymbol{F}_{FE}$) and stiffness ($\boldsymbol{K}_{FE}$), and experimental stiffness ($\boldsymbol{K}_{expe}$).

	R^2	Slope	Intercept	SEE %
aBMD	0.74*	7.44	−2244	25
F_{FE}	0.95*	1.13	−313	11
K_{FE}	0.92*	0.35	−597	14
K_{expe}	0.85*	0.77	−1062	19

SEE indicates standard error of the estimate.
*$p < 0.0001$.

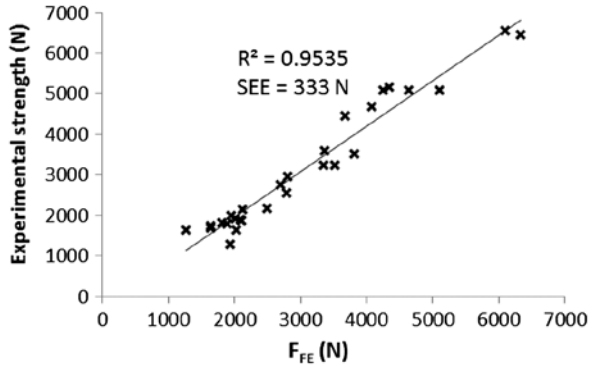

Figure 2. Linear regression of experimental vertebral strength as a function of FEM predicted strength (FFE).

4. Conclusions

With a strong correlation of 0.98 and a computation time of less than 30 s, the present FE model can predict vertebral strength in anterior compressive force.

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