Properties of PMMA end cap holders affect FE stiffness predictions of vertebral specimens

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Abstract
Bone cement is often used, in experimental biomechanics, as a potting agent for vertebral bodies (VB). As a consequence, it is usually included in finite element (FE) models to improve accuracy in boundary condition settings. However, bone cement material properties are typically assigned to these models based on literature data obtained from specimens created under conditions which often differ from those employed for cement end caps. These discrepancies can result in solids with different material properties from those reported. Therefore, this study aimed to analyse the effect of assigning different mechanical properties to bone cement in FE vertebral models. A porcine C2 vertebral body was potted in bone cement end caps, µCT scanned, and tested in compression. DIC was performed on the anterior surface of the specimen to monitor the displacement. Specimen stiffness was calculated from the load-displacement output of the materials testing machine and from the machine load output and average displacement measured by DIC. Fifteen bone cement cylinders with dimensions similar to the cement end caps were produced and subjected to the same compression protocol as the vertebral specimen and average stiffness and Young moduli were estimated. Two geometrically identical vertebral body FE models were created from the µCT images, the only difference residing in the values assigned to bone cement material properties: in one model these were obtained from the literature and in the other from the cylindrical cement samples previously tested. The average Youngs modulus of the bone cement cylindrical specimens was 1177 ± 3 MPa, considerably lower than the values reported in the literature. With this value, the FE model predicted a vertebral specimen stiffness 3% lower than that measured experimentally, while when using the value most commonly reported in similar studies, specimen stiffness was overestimated by 150%.

Keywords
PMMA bone cement, finite element model, vertebral bodies

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Introduction
Polymethyl methacrylate (PMMA) bone cement is extensively used in orthopaedic surgery for fixation of prostheses and to enhance screw stability. It is also widely used in experimental biomechanical tests as a potting agent, as it is readily available and is easily moulded into specimen specific fixtures. As a consequence, bone cement end caps are often included in specimen specific Finite Element (FE) models, particularly in spine studies, to increase geometrical and boundary condition accuracy.

The Youngs modulus of bone cement is reported to range from 2.1 to 3.1 MPa, depending on cement type, brand and on the procedure followed during mixing. The determination of bone cement compressive mechanical properties is usually made using short and thin cylindrical samples following ISO 5833:2002, therefore ensuring relatively uniform cooling as well as homogeneous and continuous properties.

Particularly for spine studies, while the majority of cement specimen holders prepared for experimental work are still cylindrical, they are considerably larger. Such change in dimensions could potentially generate differences in the final mechanical properties, such as material stiffness, as there would be a

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cooling gradient across the cement and air could be readily trapped inside the mould, giving rise to significant porosity and consequent depletion of mechanical properties.\textsuperscript{1,2,17,18}

A variation in the mechanical properties of the cement end caps could have a considerable effect on the numerical results of FE models, as the influence of load application and boundary conditions on FE vertebral body models has been found to be significant.\textsuperscript{3} In particular, the correct application of boundary conditions increases the accuracy of the FE models. Therefore, ensuring that the contact between specimen and fixtures is correctly represented and that the mechanical properties of the fixtures material are correctly defined would improve the accuracy of the numerical models, and would allow focus on more important experiment specific parameters, such as the accurate definition of bone material properties.

Recently, Digital Image Correlation (DIC) has seen increased levels of popularity in experimental biomechanics, mainly due to its non-invasive nature and its ability to output field measurement of both strain and displacement. These two characteristics afford DIC considerable advantages over more traditional techniques, and this is especially important when dealing with samples characterised by complex geometries such as vertebral bodies.\textsuperscript{19–22}

This study aimed to analyse the effect of the compressive mechanical properties of bone cement specimen holders on the stiffness prediction of finite element models of vertebral bodies.

Materials and methods

Experimental procedure

A C2 cervical vertebra was dissected from a juvenile porcine spine obtained from a local butcher and cleaned of all soft tissues. Transverse and posterior processes were removed so to isolate the vertebral body (VB). PMMA bone cement (Simplex SimplexP, Stryker Ltd, Newbury, United Kingdom) was mixed by hand at a room temperature of 15\textdegree C using a bowl and spatula mixing kit (HIGHVAc BOWL, Summit Medical, Bourton on the Water, UK). Care was taken to ensure the mixing frequency fell within 1 to 2 Hz to minimise air entrapment; mixing time varied between 45 to 120 s.\textsuperscript{2} The mixed cement was poured into a cylindrical PTFE mould of 50 mm diameter and 15 mm depth and the porcine VB was lowered onto it ensuring good coverage of the endplate had been achieved, while, at the same time, maintaining it parallel with the horizontal. The cement was left to cure for 30 min while the VB was held in position using a laboratory specimen stand. After curing, the sample was turned upside down and the second endplate was lowered onto another PTFE cement filled mould following the same procedure. Once both cement end caps had cured the PTFE moulds were removed and the sample was \textmu CT scanned, alongside two phantoms, at a voxel size of 0.1 mm using a Nikon XTH225ST Micro-CT Scanner Unit (Nikon Metrology Inc, Michigan, USA). The anterior aspect of the sample was covered with a layer of white paint and a black speckle pattern was applied to allow DIC measurements to be performed.

In addition to the VB sample, fifteen bone cement cylinders (\(n = 15\)) were produced using the same cement brand, procedure and equipment used to create the vertebral end caps; after mixing the cement was poured into the PTFE moulds and left to solidify. After 30 min, the now solid cement was removed from the moulds, machined to ensure that both top and bottom sides were flat and parallel, and sequentially numbered. The PMMA cylinders were \textmu CT scanned using the same parameters used for the vertebral sample while their characteristic dimensions, that is, length and diameter, were measured five times using a digital calliper having a resolution of 0.01 mm.

The vertebral sample and the fifteen cement cylinders were tested in axial compression using a 30 kN materials testing machine (Instron 5967, High Wycombe, United Kingdom). Each specimen was positioned in the centre of the machine baseplate and, in order to avoid any local deformations and to ensure that a uniform load would be applied, a steel plate was placed between the cement (this either being the top face of one of the cylinders or the flat face of the vertebral specimen cement end caps) and the crosshead of the materials testing machine (Figures 1 and 2(a)). A compressive ramp was applied at a rate of 1000 Nmm\textsuperscript{-1}, up to a maximum load of 10 kN, via a push rod. The push rod had a rounded end to reduce the contact area on the steel plate and to minimise the effect of possible misalignments. Load displacement curves were plotted for all samples. Stiffness was
evaluated between the loads of 3 to 5 kN, that is, the most linear part of the curves, using a custom algorithm developed within Matlab (v2016b, MathWorks Inc., Massachusetts, United States).

In the case of the cylindrical PMMA specimens, their known geometry allowed to plot stress-strain curves from which Young's modulus was calculated. Average values for cement stiffness and Young's modulus for the group were calculated, weighted by the reciprocal of the standard error of the slope of the line of best fit.23

The loading response of the vertebral sample was further analysed using DIC. Briefly, a single GigE DFK 23GP01 digital camera (The Imaging Source Europe GmbH, Germany) was positioned perpendicularly to the anterior surface of the VB. During compression one image was acquired every 5 s using a custom Matlab code. Ncorr V2.1,24 a Matlab based open source function, was used to calculate the displacement field on two regions of interest (RoIs) defined on the surface of the superior cement end-cap, close to the point of application of the load, and on the anterior part of the vertebral body, respectively (Figure 2(a)).

The average vertical displacement on each RoI was plotted alongside the testing machine load-cell data, thus allowing investigation of the loading response of different portions of the sample, namely displacement data obtained from the superior cement cap RoI allowed to infer the combined stiffness of the whole sample, that is, the combined stiffness arising from the superior cement cap, vertebral body and inferior cement cap (denoted K1, in Figure 2(a)); the vertebral body RoI allowed to estimate the combined stiffness arising from the vertebral body itself and the inferior cement cap (denoted K2 in Figure 2(a)).

**Numerical model**

The influence of the material properties of the cement end caps on predicted stiffness was studied by means of a specimen-specific FE model of the vertebral sample tested experimentally, Figure 2(b). The geometrical model was created from the previously acquired µCT image via ScanIP (v2017-18 Simpleware Synopsys, California, USA) and included the upper and lower bone cement holders, the C2 vertebral body, any cartilage remaining from dissection and the steel plate used to apply the load thus replicating the experimental set-up.

Model generation involved software tools such as flood filling, thresholding, painting, filtering and interpolation to create smooth geometries from the µCT image, while boolean operators were used to obtain a perfect contact interface between parts. Sections of the cartilage were only included in the model when tissue thickness exceeded three pixels, as recommended by software guidelines.25

The element types chosen for this study were a mixture of hexahedrons, to represent the internal trabecular structure orientation, and tetrahedrons, to represent and smoothen the external surface.9,12,26,27 The geometrical model was converted into FE numerical model and solved using ANSYS Mechanical ADPL (v18.2, ANSYS Inc, USA) installed on a Xeon 32 cores, 120GB RAM PC.

Bone cement, trabecular bone and steel were modelled as isotropic and linear materials while cartilage was assigned as a hyper-elastic material28 (Table 1). The properties for cartilage and steel were based on literature data; while cancellous bone properties were obtained from the grey-scale of the µCT image, adjusted with the phantoms grey-scale, using a standard relationship.29,30 Based on this VB model, two

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**Table 1.** Material properties used in the numerical model.

| Body       | Type                | Elastic component (MPa) | Poisson’s ratio | Reference          |
|------------|---------------------|-------------------------|-----------------|--------------------|
| Cartilage  | Hyperelastic        | $C_{10} = 0.3448$       | –               | Rohlmann et al. 28 |
|            | Neo-Hookean         | $D_1 = 0.3$             |                 |                    |
| Cement     | Isotropic           | 3000                    | 0.3             | Chevalier et al. 12|
| Steel plate| Isotropic           | 200,000                 | 0.3             | Lee 31             |
simulations were conducted: one using the Youngs modulus value for bone cement obtained from the experiments performed in the current study and another one using data from the literature.

The same load parameters as per the experiment were used in the FE study: a compressive load was applied at a rate of 1000 N/min on the plate up to a maximum of 10 kN. The point of application of the load corresponded to that used during the experiments and it was identified by measuring the distance of the point of contact of the push rod from the edge of the cranial specimen holder. For each VB FE model, three load-displacement curves were generated. The first two were obtained by plotting the reaction loads against the average vertical displacement of element nodes corresponding to the two ROIs used experimentally (Figure 2(b)). Stiffness values $K_1$ and $K_2$ were calculated from the linear portion of such load-displacement curves and compared to DIC experimental findings. The third set of curves were generated by plotting the average displacement of a volume of interest (VoI) having the same geometry and dimensions as the experimental cement cylinders, placed within the bottom cement end cap and loaded via the vertebral body. Stiffness calculated from this volume of interest (denoted $K_{cement}$) was compared to the average experimental stiffness value obtained from the 15 cement cylinders.

**Results**

**Experimental results**

The cement samples stiffness ranged from 112,690 to 176,270 Nmm$^{-1}$, with a weighted average for this group of 141,160 $\pm$ 33 Nmm$^{-1}$. The stress-strain curves for the 15 bone cement samples (Figure 3) were obtained from the load-displacement output of the material testing machine and each sample characteristic geometry. Youngs modulus was calculated in the range 3.5 to 5 MPa from the slope of line of best fit through the experimental data point and ranged from 778 to 1586 MPa. The weighted value of Youngs modulus for the whole dataset was 1177 $\pm$ 3 MPa.

Three load displacement curves were produced for the vertebral body specimen in the experiment. The first and second curve were obtained by plotting the machine load-cell output against the average displacement of interest (VoI) having the same geometry and dimensions as the experimental cement cylinders, placed within the bottom cement end cap and loaded via the vertebral body. Stiffness calculated from this volume of interest (denoted $K_{cement}$) was compared to the average experimental stiffness value obtained from the 15 cement cylinders.

**Numerical results**

A mesh sensitivity study was performed to check for convergence of the solution, resulting in a 1 mm element size. This resulted in two models comprising 486,081 elements each, one where cement properties were assigned based on the average value of Youngs modulus obtained experimentally in this study and one with the value obtained from the literature.

Stiffness values were calculated from both models using the reaction forces and the vertical movement of three regions of interest, and resulted in estimates for $K_1$, $K_2$ and $K_{cement}$ of 2844 Nmm$^{-1}$, 6415 Nmm$^{-1}$ and

| Table 2. Predicted and measured stiffness values. |
|-----------------------------------------------|
| | DIC | FEA (Ecement = 1177 MPa) | FEA (Ecement = 3000 MPa) | Instron |
|-----------------|-------|---------------------|----------------------|--------|
| $K_1$ (Nmm$^{-1}$) | 1949 | 2844 | 4448 | 2947 $\pm$ 6 |
| $K_2$ (Nmm$^{-1}$) | 6484 | 6415 | 8060 | – |
| $K_{cement}$ (Nmm$^{-1}$) | – | 105,110 | 269,310 | 141,160 $\pm$ 33$^*$ |

$^*$ Denotes experimentally measured stiffness of cement cylinder of dimensions equivalent to the bottom end cap in the FEA models.

Figure 3. Stress-Strain curves for all samples. The bold sections are the linear sections of the curves and the black line is the weighted averaged curve.
105,110 Nmm\(^{-1}\), respectively, when cement properties were assigned in the FE model based on our experimental value; and 4448 Nmm\(^{-1}\), 8060 Nmm\(^{-1}\) and 269,310 Nmm\(^{-1}\) when cement properties were assigned based on literature data, respectively (Figure 4 and Table 2).

**Discussion**

This study investigated the effect of the material properties assigned to cement end caps on FE models aimed at predicting the response of a vertebral body construct to quasi-static loading. FE is widely used in biomechanical investigations and recent studies have focused on the determination of the right approach to describe the material properties of the biological elements of said models, such as cancellous bone, cartilage, etc\(^{32–38}\); much less attention has been paid to other elements comprising the models, such as cement end caps.

Cement end caps are widely used in experimental spine biomechanics studies\(^{3–5}\); this practice arises from the desire of aligning the vertical axis of vertebral bodies, typically characterised by awkward geometries, to the line of action of the applied force and avoiding point loading. In order to correctly represent the boundary and contact conditions seen experimentally it is common practice to also include cement end caps within FE models\(^{3,4,6,9}\).

Compared to the approach adopted to model biological materials, much less importance has been given to correctly set the material properties of the bone cement, with properties typically being taken directly from the literature\(^{39–42}\). While adequate when applied to generic models, this approach fails to perform satisfactorily when good agreement with experimental data is sought in specimen-specific FE models. We hypothesised that the generic material properties assigned to bone cement in specimen specific models contribute to the discrepancies between numerical predictions and experimental data.

In this study fifteen bone cement samples, with dimensions comparable to cement end caps, were prepared in the open air and following a standardised mixing protocol\(^{2}\); the same procedure was used to create cement end caps onto which the porcine cervical VB was mounted. Each of the 15 cement samples was subject to a quasi-static loading ramp and the average Young's modulus for the group was calculated to be 1177 MPa, under half the value commonly reported in the literature and typically used in FEA investigations\(^{1,2,18,31,43}\).

An unusual level and distribution of porosity within the cement was evidenced in the present study (Figure 5). Here cement was mixed by hand, however this practice has been shown not to increase porosity in the solidified material when compared to vacuum-mixing\(^{44,45}\). We therefore attribute this unusual presentation to the physical size of the samples and the way in which they were produced.

Mechanical tests to determine the properties of bone cement are usually conducted on small cylinder of 5 mm diameter and 12 mm height (ISO 5833:2002)\(^{10}\), typically produced by pressing doughy cement into open ended cavities created within metal moulds. The metallic material, typically stainless steel, prescribed for mould construction and mould geometry (i.e. with two open ends) decrease the risk of air entrapment during specimen creation. Furthermore, the high thermal conductivity of the mould might contribute to a decrease of the temperature gradient within the sample, reducing the porosity gradient within the cement. On the other hand, bone cement end caps are usually large, with a diameter often in excess of 50 mm\(^{6,11–16}\) and are typically produced within polymer moulds, hence characterised by low thermal conductivity (at least compared to metals), which are sealed at one end to prevent

**Figure 4.** Load-Displacement curves for \(K_1\) from the FE model with Young's modulus for the bone cement end cap holders of 1177 MPa. Stiffness values were obtained in the most linear section, that is, between 3 and 5 kN.

**Figure 5.** Cross-sectional view of one of the cement samples (a) and cross sectional view of the caudal cement end cap (b).
cement leakage. The combination of mould size, its closed geometry and material all result in unfavourable conditions for the cement, with a high likelihood of a temperature gradient arising during polymerisation and air possibly being trapped within the polymer.

Having established an experimental value of Young’s modulus for cement specimens created following the same procedure as the specimen holder end-caps, the next step of the investigation focused on comparing the experimental and predicted response of the vertebral specimen to quasi-static loading. Two specimen specific models were created from the µCT image of the tested specimen. In the models material properties were assigned to cancellous bone based on image grey-scale values using a validated relationship, steel and cartilage material properties were obtained from the literature, while bone cement properties were assigned either based on the experimental results of the first part of this investigation or on literature data. Stiffness predictions obtained from the two models for the two RoIs outlined in Figure 2 (K1 and K2) for a volume of interest (Vol) contained within the bottom end cap and having dimensions comparable to the cement cylinders used in the first part of this study (Kcement).

DIC was used to isolate the experimentally measured stiffness response from different structures within the specimen to match the stiffness regions identified in Figure 2. Average DIC displacements defined on equivalent RoIs (Figure 2(a)) were used to estimate the equivalent stiffnesses to K1 and K2, and allow comparisons with predicted values obtained from the two FE models (Figure 2(b)). Numerical FE predictions for Kcement were compared to the experimental stiffness values obtained from the cement cylinders. When considering the full vertebral construct, that is, comprising the two cement end caps, the steel plate and VB, DIC led to an underestimate of the stiffness (denoted K1 in Figure 2 and Table 2) compared from the value obtained from the load-displacement out of the materials testing machine, 1949 to 2947 Nmm⁻¹, respectively (Table 2). This difference mainly arises from the slight anterior rotation of the top cement end cap upon application of the load noticeable in the DIC images. As a result of this rotation the displacement of the anterior part of the end cap is greater than the displacement at the point of application of the load; this has the effect of leading to DIC to underestimate sample stiffness by about 34% of the actual value. On the other hand, the FE model with cement properties derived from experimental data matched the experimental stiffness for K1 to within 3%, that is, 2844 Nmm⁻¹ compared to 2947 Nmm⁻¹; while the same FE model, but this time with cement properties obtained from the literature, led to an overestimate of the construct stiffness by around 151%, that is, 4448 Nmm⁻¹ compared to 2947 Nmm⁻¹.

The use of DIC in the experimental part of this study allowed us to infer the contribution of the cement end caps to the total stiffness of the vertebral sample while affording additional validation steps to the FE models. DIC allowed an experimental estimate of the stiffness of the VB and bottom cement end cap (denoted K2 in Figure 2 and Table 2). The FE model with cement properties derived from experimental data matched this to within 1%, that is, 6415 Nmm⁻¹ compared to 6484 Nmm⁻¹; cement properties obtained from the literature were assigned in the FE model this led to a stiffness overestimate of around 124%, that is, 8060 Nmm⁻¹ compared to 6484 Nmm⁻¹.

The average stiffness of the 15 cement samples was found to be in the order of 141,160 ± 33 Nmm⁻¹; this value is approximately 26% higher than the predicted stiffness of the equivalent geometry volume of interest defined in the bottom cement end cap, denoted Kcement in Table 2, in the case of the model with cement properties obtained experimentally, while the model with cement properties inferred from the literature led to an overestimate of 190%, 105,110 Nmm⁻¹ and 269,310 Nmm⁻¹, respectively. It is important to notice that Kcement in our models was calculated from the vertical displacement of a volume of interest defined within the cement end cap and loaded via the VB. As the cross-sectional geometry of the VB is not perfectly round it is inevitable that the volume of interest will contain elements which are not loaded, some of which are characterised by nodes exhibiting zero displacement, ultimately leading to an underestimate of the stiffness of the cement part. This is true independently of the properties assigned to this material in the model. This method of estimating cement stiffness is not expected to output results in good agreement with experimental data, however it gives an indication of whether the model behaviour is correct as it is expected to always lead to an underestimate of the stiffness value; the magnitude of this discrepancy being dependent on the level of cement coverage achieved while embedding the VB.

DIC allowed to isolate the contribution to overall specimen stiffness arising from different structures within the specimen and, by comparing experimental values to numerical predictions obtained from both models, it was found that the cement end caps accounted for most. However, when cement properties were assigned based on experimental data obtained from samples of equivalent geometry as the end caps and produced with a similar protocol, excellent agreement was obtained between experimental and numerical results.

Conclusion

In this study we have shown that precise setting of the material properties of bone cement will improve the accuracy of the FE stiffness predictions of vertebral samples. Therefore, it is recommended that an in-house characterisation of samples equivalent to the bone cement end cap fixtures is conducted to inform the correct properties to be assigned to this material in the model. Furthermore, we have outlined a technique
which allows for robust model validation by exploiting the versatility of DIC measurements.

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References
1. Chandler M, Kowalski RSZ, Watkins ND, et al. Cementing techniques in hip resurfacing. Proc IMechE, Part H: J Engineering Medicine 2006; 220(2): 321–331.
2. Lewis G. Properties of acrylic bone cement: state of the art review. J Biomed Mater Res 1997; 38: 155–182.
3. Jones AC and Wilcox RK. Assessment of factors influencing finite element vertebral model predictions. Convergence 2007; 129: 2–7.
4. Mengoni M, Vasiljeva K, Jones AC, et al. Subject-specific multi-validation of a finite element model of ovine cervical functional spinal units. J Biomech 2016; 49(2): 259–266.
5. Newell N, Little JP, Christou A, et al. Biomechanics of the human intervertebral disc: a review of testing techniques and results. J Mech Behav Biomed Mater 2017; 69: 420–434.
6. Hosseini HS, Clouthier AL and Zyss PK. Experimental validation of finite element analysis of human vertebral collapse under large compressive strains. J Biomech Eng 2014; 136(4): 041006.
7. Jones AC and Wilcox RK. Finite element analysis of the spine: towards a framework of verification, validation and sensitivity analysis. Med Eng Phys 2008; 30(10): 1287–1304.
8. Kopperdahl DL, Aspelund T, Hoffmann PF, et al. Assessment of incident spine and hip fractures in women and men using finite element analysis of CT scans. J Bone Miner Res 2014; 29(3): 570–580.
9. Pahr DH, Schwiedrzik J, Dall’Ara E, et al. Clinical versus pre-clinical FE models for vertebral body strength predictions. J Mech Behav Biomed Mater 2014; 33(1): 76–83.
10. ISO. 5833 Implants for surgery. Acrylic resin cements. Geneva: International Organization for Standardization, 2002.
11. Buckley JM, Loo K and Motherway J. Comparison of quantitative computed tomography-based measures in predicting vertebral compressive strength. Bone 2007; 40(3): 767–774.
12. Chevalier Y, Charlebois M, Pahra D, et al. A patient-specific finite element methodology to predict damage accumulation in vertebral bodies under axial compression, sagittal flexion and combined loads. Comput Methods Biomech Biomed Engin 2008; 11(5): 477–487.
13. Gustafson H, Siegmund G and Crypton P. Comparison of strain rosettes and digital image correlation for measuring vertebral body strain. J Biomech Eng 2016; 138(5): 054501.
14. Gustafson HM, Crypton PA, Ferguson SJ, et al. Comparison of specimen-specific vertebral body finite element models with experimental digital image correlation measurements. J Mech Behav Biomed Mater 2017; 65: 801–807.
15. Tozzi G, Danesi V, Palanca M, et al. Elastic full-field strain analysis and microdamage progression in the vertebral body from digital volume correlation. Strain 2016; 52(5): 446–455.
16. Wijayathunga VN, Jones AC, Oakland RJ, et al. Development of specimen-specific finite element models of human vertebrae for the analysis of vertebralplasty. Proc IMechE, Part H: J Engineering Medicine 2008; 222(2): 221–228.
17. Eyerer P and Jin R. Influence of mixing technique on some properties of PMMA bone cement. J Biomed Mater Res 1986; 20(8): 1057–1094.
18. Saha S and Pal S. Mechanical properties of bone cement: a review. J Biomed Mater Res 1984; 18(4): 435–462.
19. Gustafson HM and Crypton PA. Use of digital image correlation for validation of surface strain in specimen-specific vertebral finite element models. In: Proceedings of the 9th Ohio State University Injury Biomechanics Symposium, Omaha, NE, September 2013, pp.1–11. Ohio State University.
20. Palanca M, Brugo TM and Cristofolini L. Use of digital image correlation to investigate the biomechanics of the vertebra. J Mech Med Biol 2015; 15(2): 1–10.
21. Palanca M, Tozzi G and Cristofolini L. The use of digital image correlation in the biomechanical area: a review. Int Biomech 2016; 3(1): 1–21.
22. Ruspi ML, Palanca M, Faldini C, et al. Full-field in vitro investigation of hard and soft tissue strain in the spine by means of Digital Image Correlation. Muscles, Ligaments Tendons J 2017; 7(4): 538–545.
23. Taylor J. Introduction to error analysis, the study of uncertainties in physical measurements. 2nd ed. New York, NY: University Science Books, 1997.
24. Blaber J, Adair B and Antoniou A. Ncorr: open-source 2D digital image correlation matlab software. Exp Mech 2015; 55(6): 1105–1122.
25. Synopsys. Variability and accuracy of spine segmentation, 2016, https://www.synopsys.com/simpleware/resources/case-studies/lumbar-spine-segmentation.html (accessed 3 November 2020).

26. Hernandez BA, Gill HS and Gheduzzi S. Taguchi analysis of factors affecting finite element modelling of vertebral bodies. In: 8th World Congress of Biomechanics, 2018. Dublin: World Council for Biomechanics.

27. Robson Brown K, Tarsuslugil S, Wijayathunga VN, et al. Comparative finite-element analysis: a single computational modelling method can estimate the mechanical properties of porcine and human vertebrae. *J R Soc Interface* 2014; 11(95): 20140186.

28. Rohlmann A, Burra NK, Zander T, et al. Comparison of the effects of bilateral posterior dynamic and rigid fixation devices on the loads in the lumbar spine: a finite element analysis. *Eur Spine J* 2007; 16(8): 1223–1231.

29. Hernandez BA. *A study of impact loading of the spine*. PhD Thesis, University of Bath, UK, 2019.

30. Kopperdahl D, Morgan E and Keaveny T. Quantitative computed tomography estimates of the mechanical properties of human vertebral trabecular bone. *J Orthop Res* 2002; 20: 801–805.

31. Lee C. Properties of bone cement: the mechanical properties of PMMA bone cement. In: Breusch SJ and Malchau H (eds) *The well-cemented total hip arthroplasty Theory and Practice*, 2005, pp.60–66. Berlin, Heidelberg: Springer.

32. Chen Y, Dall’Ara E, Sales E, et al. Micro-CT based finite element models of cancellous bone predict accurately displacement once the boundary condition is well relicated: a validation study. *J Mech Behav Biomed Mater* 2017; 65: 644–651.

33. Costa MC, Tozzi G, Cristofolini L, et al. Micro finite element models of the vertebral body: validation of local displacement predictions. *PLoS One* 2017; 12(7): 1–18.

34. Dall’Ara E, Varga P, Pahr D, et al. A calibration methodology of QCT BMD for human vertebral body with registered micro-CT images. *Med Phys* 2011; 38(5): 2602–2608.

35. Mullins LP, Bruzzi MS and McHugh PE. Calibration of a constitutive model for the post-yield behaviour of cortical bone. *J Mech Behav Biomed Mater* 2009; 2(5): 460–470.

36. Reutlinger C, Bürki A, Brandejsky V, et al. Specimen specific parameter identification of ovine lumbar intervertebral discs: on the influence of fibre-matrix and fibre-fibre shear interactions. *J Mech Behav Biomed Mater* 2014; 30: 279–289.

37. Sahli F, Cuellar J, Pérez A, et al. Structural parameters determining the strength of the porcine vertebral body affected by tumours. *Computer Methods Biomech Biomed Engin* 2015; 18(8): 890–899.

38. Teo EC and Ng HW. Evaluation of the role of ligaments, facets and disc nucleus in lower cervical spine under compression and sagittal moments using finite element method. *Med Eng Phys* 2001; 23(3): 155–164.

39. Crawford RP, Rosenberg WS and Keaveny TM. Quantitative computed tomography-based finite element models of the human lumbar vertebral body: effect of element size on stiffness, damage, and fracture strength predictions. *J Biomech Eng* 2003; 125(4): 434.

40. Eswaran SK, Gupta A and Keaveny TM. Locations of bone tissue at high risk of initial failure during compressive loading of the human vertebral body. *Bone* 2007; 41(4): 733–739.

41. Maquer G, Dall’Ara E and Zysset PK. Removal of the cortical endplates has little effect on ultimate load and damage distribution in QCT-based voxel models of human lumbar vertebrae under axial compression. *J Biomech* 2012; 45(9): 1733–1738.

42. Maquer G, Laurent M, Brandejsky V, et al. Finite element based nonlinear normalization of human lumbar intervertebral disc stiffness to account for its morphology. *J Biomech Eng* 2014; 136(6): 061003.

43. Race A, Mann KA and Edidin AA. Mechanics of bone/PMMA composite structures: an in vitro study of human vertebrae. *J Biomech* 2007; 40(5): 1002–1010.

44. Macaulay W, DiGiovanni CW, Restrepo A, et al. Differences in bone-cement porosity by vacuum mixing, centrifugation, and hand mixing. *J Arthroplasty* 2002; 17(5): 569–575.

45. Messick KJ, Miller MA, Damron LA, et al. Vacuum-mixing cement does not decrease overall porosity in cemented femoral stems: an in vitro laboratory investigation. *J Bone Joint Surg Br* 2007; 89(8): 1115–1121.