European Spine Journal (2020) 29:977–985
https://doi.org/10.1007/s00586-019-06286-6

ORIGINAL ARTICLE

Cement augmentation of odontoid peg fractures: the effect of cement volume and distribution on construct stiffness

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Received: 16 August 2019 / Revised: 13 December 2019 / Accepted: 31 December 2019 / Published online: 4 January 2020

Abstract

Purpose The cement augmentation of a conventional anterior screw fixation in type II odontoid process fractures for elderly patients significantly increased stiffness and load to failure under anterior–posterior load in comparison with non-augmented fixation. The amount and quality of bone cement are usually taken ad hoc in clinical practise. In this study, we wanted to clarify the role of bone cement amount and its quality to the stiffness of odontoid and vertebrae body junction.

Methods Finite-element method was used to achieve different scenarios of cement augmentation. For all models, an initial stiffness was calculated. Model (1) the intact vertebrae were virtually potted into a polymethylmethacrylate base via the posterior vertebral arches. A V-shaped punch was used for loading the odontoid in an anterior–posterior direction. (2) The odontoid fracture type IIa (Anderson–D'Alonzo classification) was achieved by virtual transverse osteotomy. Anterior screw fixation was virtually performed by putting self-drilling titanium alloy 3.5 mm diameter anterior cannulated lag screw with a 12 mm thread into the inspected vertebrae. A V-shaped punch was used for loading the odontoid in an anterior–posterior direction. The vertebrae body was assumed to be non-cemented and cemented with different volume.

Results The mean cement volume was lowest for body base filling with 0.47 ± 0.03 ml. The standard body filling corresponds to 0.95 ± 0.15 ml. The largest volume corresponds to 1.62 ± 0.12 ml in the presence of cement leakage. The initial stiffness of the intact C2 vertebrae was taken as the reference value. The mean initial stiffness for non-porous cement ($E = 3000$ MPa) increased linearly ($R2 = 0.98$). The lowest stiffness (123.3 ± 5.8 N/mm) was measured in the intact C2 vertebrae. However, the highest stiffness (165.2 ± 5.2 N/mm) was measured when cement leakage out of the odontoid peg occurred. The mean initial stiffness of the base-only cemented group was 147.2 ± 8.4 N/mm compared with 157.9 ± 6.6 N/mm for the base and body cemented group. This difference was statistically significant ($p < 0.0061$). The mean initial stiffness for porous cement ($E = 500$ MPa) remains constant. Therefore, there is no difference between cemented and non-cemented junction. This difference was not statistically significant ($p < 0.18$).

Conclusion The present study showed that the low porous cement was able to significantly influence the stiffness of the augmented odontoid screw fixation in vitro, although further in vivo clinical studies should be undertaken. Our results suggest that only a small amount of non-porous cement is needed to restore stiffness at least to its pre-fracture level and this can be achieved with the injection of 0.7–1.2 ml of cement.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-019-06286-6) contains supplementary material, which is available to authorized users.

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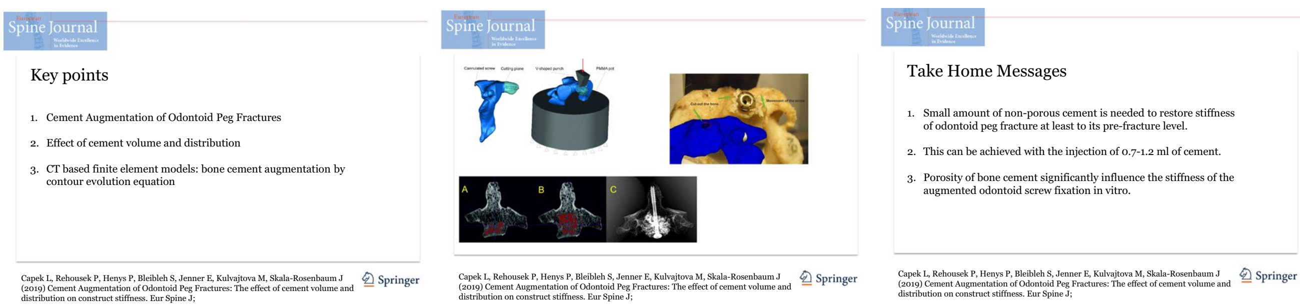
Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.



Keywords Fracture · Spine · Finite element · Bone cement · Odontoid

Introduction

Percutaneous vertebroplasty (PVP) is a low-cost, minimally invasive technique where bone cement is injected into the vertebral body. The principal goal of this technique is to relieve pain and strengthen the vertebrae against compressive loading. PVP was originally used to treat painful vertebral lesions caused by metastatic disease and osteoporotic fracture but now has a range of applications including augmentation of screw fixation [1]. Liebschner et al. [2] have shown in his study that inadequate filling of vertebral body during PVP can lead to a successful result in pain control, stiffening and stabilizing the fractured vertebrae.

PVP is commonly used for lumbar vertebrae where the overall strength of the spine segments to compressive load is most important. Recently, the PVP technique was proved to be applicable to the restoration of stability of cervical spine segments. The cement augmentation of screw fixation in low-density bone has been proposed as an effective method of providing stable fixation in type 2 odontoid peg fractures [3, 4].

Despite PVP being a relatively simple technique to perform, a number of complications have been reported. The majority of these are related to cement extrusion. The rate of cement extrusion is often obtained by X ray and leads to number of cement leaks per vertebra being underestimated [5].

The amount of cement extrusion reported varies across the literature from 41% to 90% of the injected volume [6–8]. Studies investigating PVP cement extrusion can be divided into two groups. First group showed that the volume of cement and the bone density of the vertebra are the key factor related to cement extrusion [7–10]. The second group tried to show the volume of cement and its distribution within the vertebra as the key factor for restoration of vertebral stiffness [11, 12]. Neither group has arrived at a clear conclusion explaining cement extrusion in PVP.

In this study, we compare the biomechanical properties of a widely available, unmodified cannulated screw with and without cement augmentation in the fixation of Anderson and D´Alonzo type II odontoid peg fractures by the finite-element method. We have shown in a previous study that cement augmentation of a conventional anterior screw fixation in type II odontoid process fractures for elderly patients significantly increased stiffness and load to failure under anterior–posterior load in comparison with non-augmented fixation [13]. The amount and quality of bone cement was taken ad hoc from clinical practise.

In this study, we wanted to clarify the role of bone cement amount and its quality to the stiffness of odontoid and vertebrae body junction. We investigated the relationship between the distribution and volume of cement inserted into the C2 vertebra and the stiffness of the fixation construct. We propose two specific hypotheses. The first hypothesis is that cementing only the base of the odontoid peg gives the same stiffness when compared to cementing the whole body. The second hypothesis investigates whether decreasing porosity of PMMA cement increases the stiffness of the fixation construct.

Materials and methods

The finite-element (FE) method is a standardised tool in biomechanics used for solving different tasks. It has been successfully used in the field of orthopaedic surgery for many years [2, 14, 15].

A general overview of the workflow for the experiments and evaluation of this study is given in Fig. 1. In this study, computer tomography (CT) data of ten fresh humans cadaveric C2 specimens from previous study were used [13].

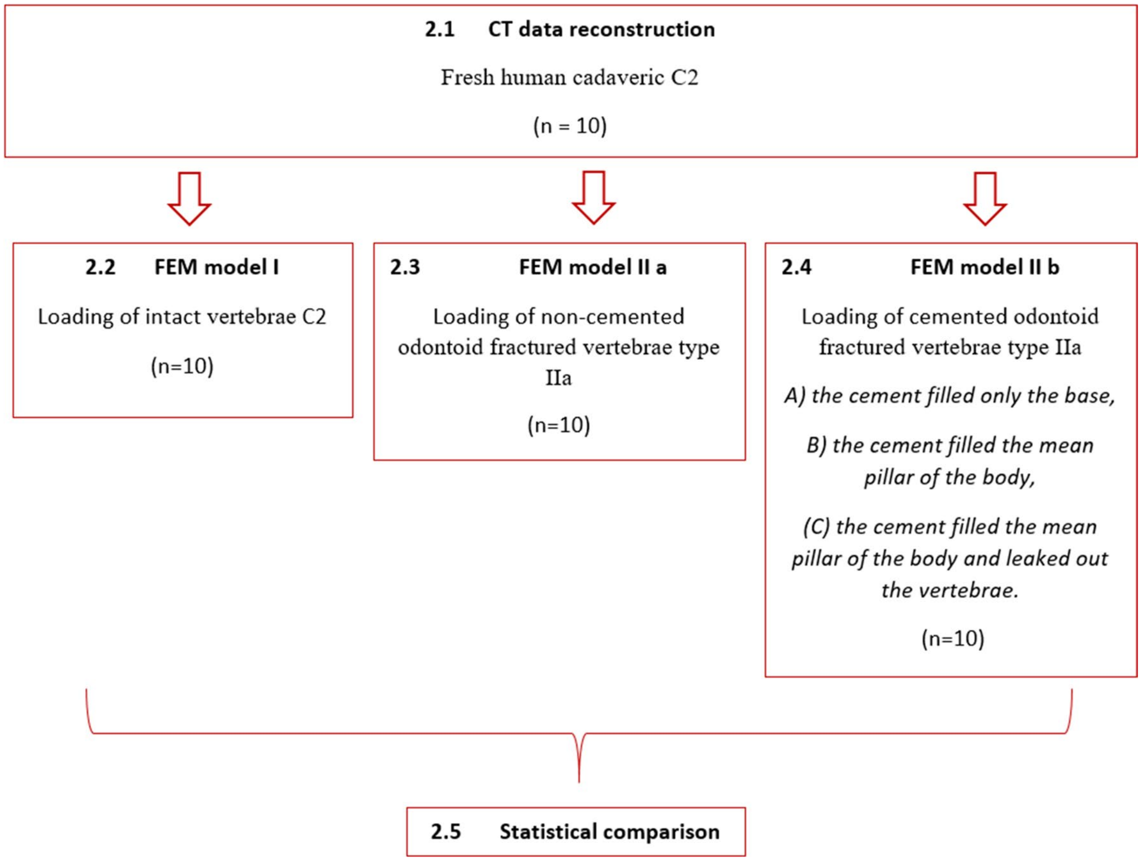


Fig. 1 A general overview of the workflow for the experiments and evaluation of this study

Fresh human cadaveric C2 specimens were obtained from deceased donors with a mean age of 83 years (range 72–93). Ethical approval was successfully obtained from the Ethics Committee at Third Faculty of Medicine Charles University of Prague, and the study was performed in accordance with the Human Tissue Act 2004. Patients were selected from predefined criteria with all patients being over the age of 70 years with osteoporotic changes. A computer tomography data set of the cleaned vertebrae acquired in vitro on an Somatom Definition AS (Siemens, Germany) was selected. The CT data set was acquired with the following technical parameters: 120 kV, 267 mA, slice thickness 1 mm. Proposed computational model is based on CT of scanned C2 vertebrae.

For each individual vertebra, following computer models were proposed:

Model I

The intact vertebrae were virtually potted into a polymethylmethacrylate (PMMA) base via the posterior vertebral arches (Fig. 2). A V-shaped punch was used for loading the odontoid in an anterior–posterior direction. The material properties of bone were assigned according to CT data in the software MITK-GEM by using the power law proposed in [16, 17].

Model II

The odontoid fracture type IIa (Anderson–D'Alonzo classification) was achieved by virtual transverse osteotomy. Anterior screw fixation was virtually performed by putting self-drilling titanium alloy 3.5 mm diameter anterior cannulated lag screw with a 12 mm thread (DePuy Synthes, Leeds, UK) into the inspected vertebrae. Between screw, bone and V-shape punch a segment-to-segment contact constraint with Coulomb's bilinear friction model was defined. The friction coefficient was set to 0.3. The contact problem constraint in a variational form was solved via a penalty approach with control of the penetration. The material properties of bone and cement vary according to following sub-models:

(a) Non-cemented vertebrae. The material properties were assigned in the same way as in model I.
(b) Cemented vertebrae. The augmentation process using radiopaque high viscosity PMMA cement (Vertecem,

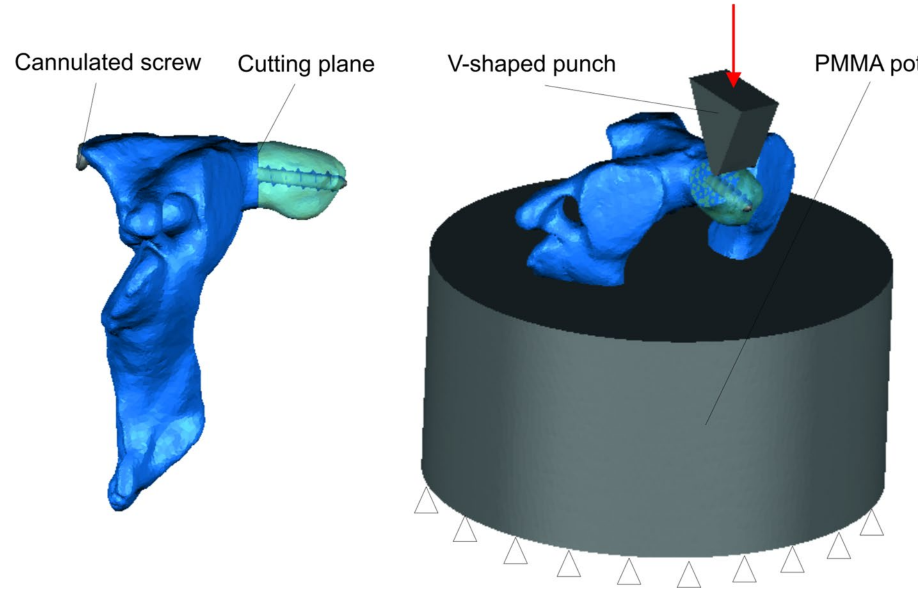


Fig. 2 Virtual experimental set-up

DePuy 26 Synthes, Leeds, UK) was simulated by contour evolution equation in the software ITK-SNAP described in [18]. The augmentation started at the base of odontoid peg, and three cases were observed: A) the cement filled only the base, B) the cement filled the mean pillar of the body, (C) the cement filled the mean pillar of the body and leaked out the vertebrae (Fig. 3). The material properties of bone were assigned in the same way as in model I (Fig. 4).

The finite-element model was created in the software MSC.Marc 2016.0 (MSC.Software, Czech Republic). The material properties of bone cement and titanium alloy were taken from the literature, Table 1. To show the influence of bone cement quality, the non-porous and porous material model was used in our simulations. The FE models were loaded, and initial stiffness was calculated according to [13]. Data were analysed using statistical software QC-Expert (Trilobit s.r.o., Czech Republic). The statistical significance of the mean difference of subgroups was tested with Welch's t test given that subgroups follow approximately normal distribution (skewness $\gamma < 0.15$). Significance level for these tests was set to $p < 0.05$.

Results

The cement volume changes according to desired area of bone void filling. The calculated volume of bone cement gained by contour evaluation process is summarised in Table 2. The mean PMMA cement volume was lowest for body base filling with 0.47 ± 0.03 ml and the mean height from the base 8.7 ± 0.8 mm. The standard body filling corresponds to 0.95 ± 0.15 ml and the mean height from the base 17.4 ± 1.2 mm. The largest volume corresponds to 1.62 ± 0.12 ml in the presence of cement leakage. (The height was not measured.)

The initial stiffness of the intact C2 vertebrae was taken as the reference value. The mean initial stiffness for non-porous cement ($E = 3000$ MPa) increased linearly ($R^2 = 0.98$) (Fig. 5). The lowest stiffness (123.3 ± 5.8 N/mm) was measured in the intact C2 vertebrae. However, the highest stiffness (165.2 ± 5.2 N/mm) was measured when cement leakage out of the odontoid peg occurred. The mean initial stiffness of the base-only cemented group was 147.2 ± 8.4 N/mm compared with 157.9 ± 6.6 N/mm for the base and body cemented group (Fig. 6). This

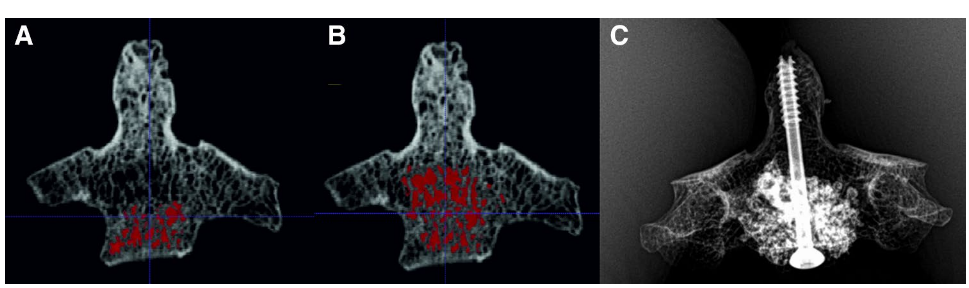


Fig. 3 Three stages of cement augmentation: **a** the cement filled only the base, **b** the cement filled the mean pillar of the body, **c** the cement filled the mean pillar of the body and leaked out the vertebrae

Fig. 4 Assigning the material properties to bone and bone cement in FEM model

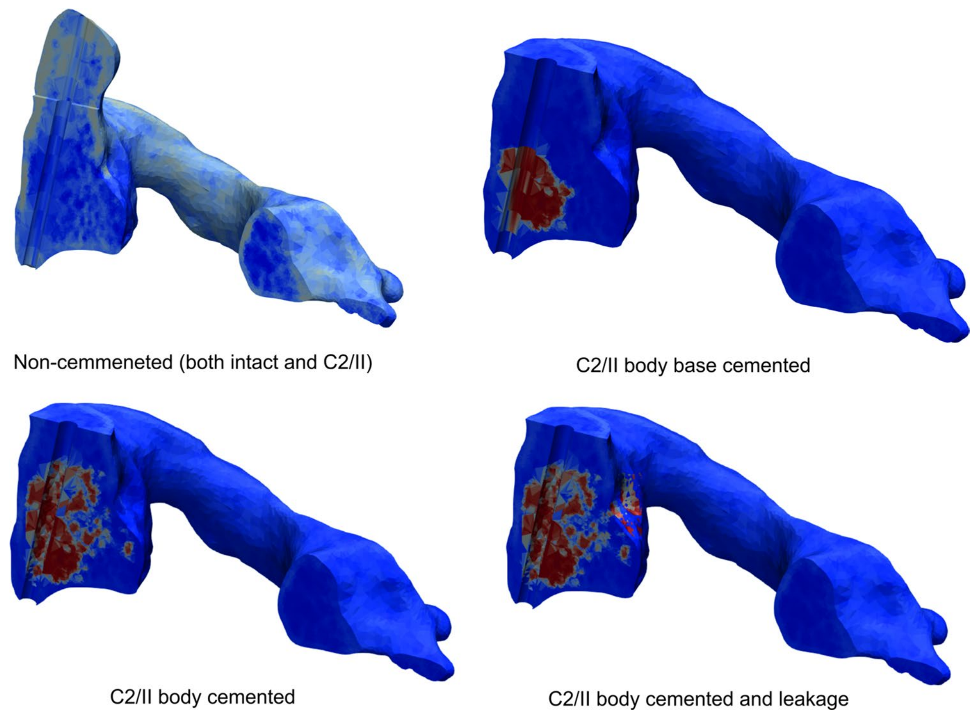


Table 1 Material constants used for linear elastic material

Material	Young´s modulus (MPa)	Poisson ratio (–)
Bone cement—non-porous	3000	0.3
Bone cement—porous	500	0.3
Ti6Al4V	117,000	0.38

difference was statistically significant ($p < 0.0061$). The mean initial stiffness for porous cement ($E = 500$ MPa) remains constant. Therefore, there is no difference between cemented and non-cemented junction. This difference was not statistically significant ($p < 0.18$).

The failure mode was also different. In case of non-cemented vertebrae, the screw cut out of the screw through the anterior aspect of the C2 vertebral body (Fig. 7). In the cemented vertebrae (no volume difference), the odontoid process and cemented screw bent together in the plane of applied force (Fig. 8). There was no cut-out of the screw trough the bone at the base and body of C2.

Table 2 Calculated volume of bone cement gained by contour evaluation process

Specimen	Age (years)	Gender	Volume of bone cement—body base (ml)	Volume of bone cement—body (ml)	Volume of bone cement—leakage (ml)
1	83	M	0.44	0.87	1.48
2	88	M	0.48	0.96	1.55
3	89	M	0.46	0.93	1.52
4	72	F	0.35	1.08	1.57
5	78	M	0.42	0.85	1.63
6	93	F	0.51	1.23	1.75
7	90	F	0.56	1.11	1.81
8	77	M	0.45	0.97	1.46
9	73	F	0.47	0.69	1.68
10	89	F	0.53	0.78	1.74
Mean	83.2 ± 7.26	–	0.47 ± 0.056	0.95 ± 0.15	1.62 ± 0.12

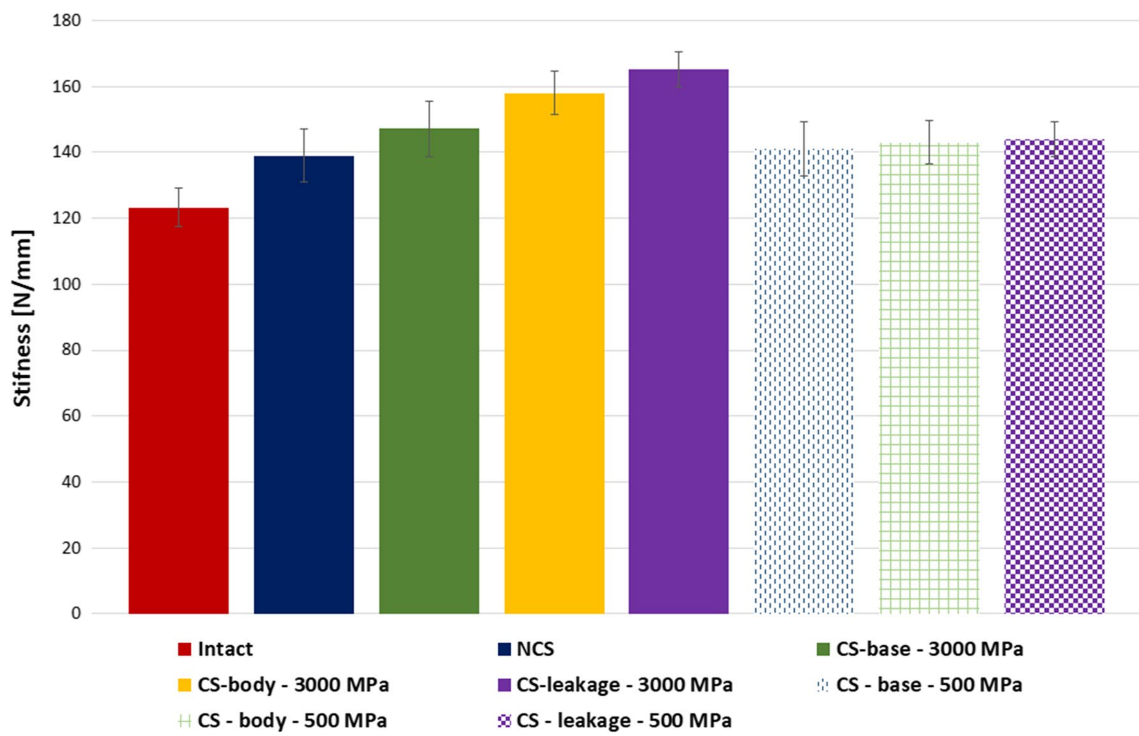


Fig. 5 The mean initial stiffness differences according to proposed virtual models

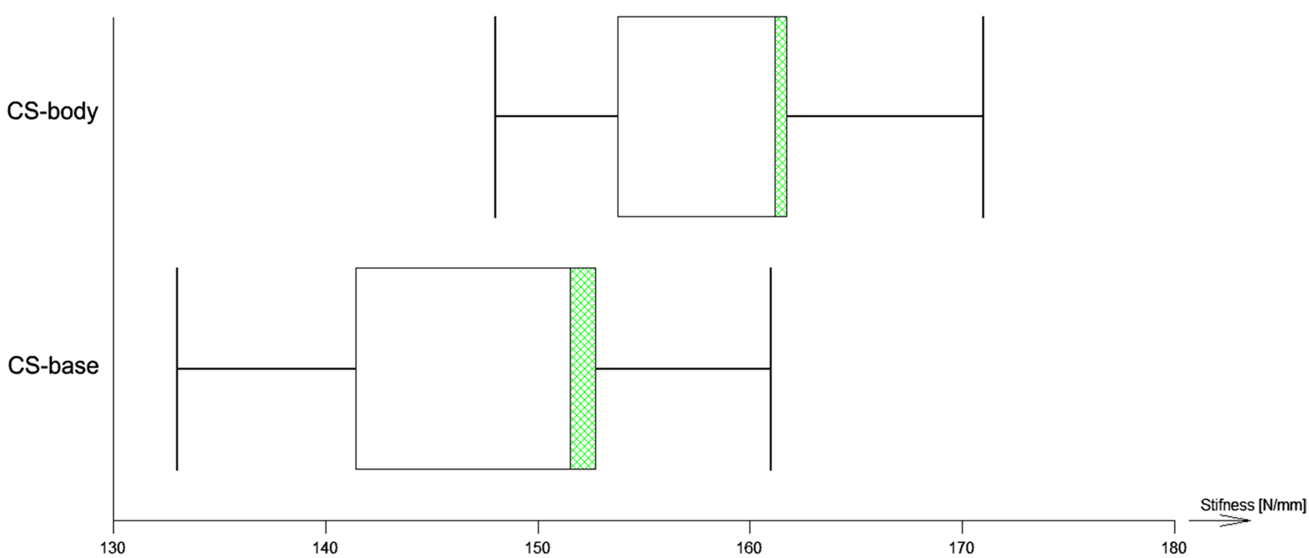


Fig. 6 The mean initial stiffness of the base-only cemented group compared to the body cemented group (upper hatched box = 75th percentile, lower hatched box = 25th percentile)

Discussion

Anterior screw fixation is recognised as the most widely accepted surgical procedure for the surgical treatment of unstable odontoid fractures [19, 20]. Cut-out through the anterior wall of C2 vertebrae has been reported to be the most common mode of failure [20, 21]. Therefore, modifying the procedure by augmenting of the screw with PMMA cement could function as a useful technique in the context of achieving a stable fixation at the odontoid and vertebral body junction. It subsequently decreases the

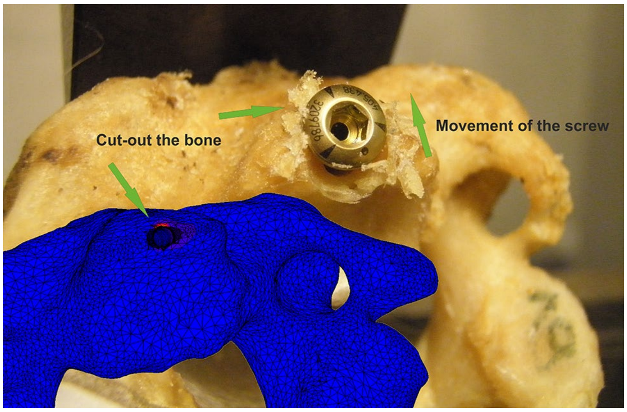


Fig. 7 The failure mode for non-cemented models

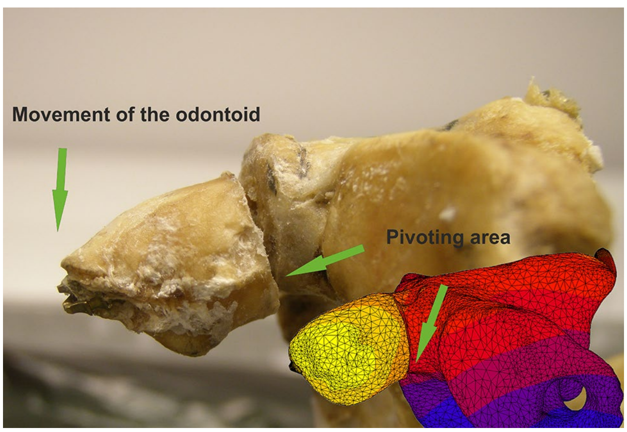


Fig. 8 The failure mode for cemented models

risk of anterior cut-out of the screw and should lead to a decreased failure of fixation in vivo [4]. To the knowledge of the authors, no biomechanical study exists, which studies the effect of bone cement volume and its quality on the stiffness of the cement-augmented odontoid screw fixation.

One important biomechanical concern for PVP is to minimise the amount of cement used and yet to improve stiffness and stabilization of cement-augmented screw fixation. We performed a comprehensive finite-element analysis to provide a practical theory for understanding and optimising the biomechanics of PVP of C2 odontoid peg fracture. We have shown that there is a linear increase in the stiffness of odontoid peg fracture lag screw fixation construct, according to the volume and distribution of the injected PMMA cement.

The evolution equation in ITK-SNAP software was able to show the variation of bone PMMA cement volume in the body of the C2 vertebrae. The mean bone PMMA cement volume was lowest for body base filling with 0.47 ± 0.03 ml; however, the standard body filling corresponds to 0.95 ± 0.15 ml and the largest volume corresponds to the case of the PMMA cement leakage to 1.62 ± 0.12 ml. These findings are consistent with our previous study findings, where the volume of 0.7–1.2 ml cement was used [13]. These results agree closely to those results from Liebschner et al. [2] study, where only a small amount of bone cement is required to restore stiffness and strength of the fractured lumbar vertebral body to its pre-fractured level. Our results suggest that only a small amount of bone cement is needed to restore stiffness to pre-fracture level and this can be achieved with the injection of 0.7–1.2 ml of PMMA cement. The use of a large volume of cement can result in substantial increases in stiffness which may compromise the overall kinematics of the adjacent motion segments and increases the risk of cement leakage. It is similar to long bone fracture healing process where the degree of stiffness can positively or negatively affect the healing process [22]. It should be noted that the differentiation in such a small amount of bone cement could be an issue in a clinical setting. In addition, cement leakage can occur quite early due to the different porosity of osteoporotic vertebrae.

Analysis of the construct stiffness showed that initial construct stiffness linearly increased by filling the vertebra body by PMMA cement. We found that the lowest stiffness was recorded for intact vertebrae, whereas it was recorded the highest in the presence of body cement leakage. Unfortunately, our first hypothesis was not proven as there is a significant difference between the mean initial stiffness of the only base cemented group when compared to body cemented group. The most significant finding was that cement porosity is reliable predictor of stiffness and may, therefore, be clinically useful metric to select appropriate augmentation agents. Augmentation with low volumes of a low porosity cement has significantly influenced the stiffness of the cement-augmented fixation and it may also produce higher pull-out force than larger volumes of high porosity cement. The strong correlation between cement porosity and stiffness indicate that minimising the porosity of cement is the best way to improve overall stiffness of fixation construct. Our study suggests that the technique of low porosity cement injection provides a safe and effective technique in treating these fractures. This conclusion is consistent with other biomechanical studies where only a small amount of cement is needed to restore stiffness [2, 23].

Clearly, interpreting the role of cement volume on pain relief, stabilization, and fracture healing is not in the scope of a cadaveric biomechanical study, but it is worth of considering a prospective clinical study. However, our results are consistent with previous clinical data suggesting that pain relief may be experienced with the injection of smaller volumes of cement than previously thought required [2, 22]. Several studies have shown that cement leakage is a frequent occurrence event in PVP, but it rarely resulted in clinical consequences if the extravasated volumes are small [22, 24]. There have been theoretical concerns about potential adverse effects with the use of PMMA. These concerns include the risk of thermal injury to regional soft tissue and toxicity from unreacted monomer [25]. In a biomechanical study using osteoporotic vertebral bodies, the risk of cement leakage was noted in 8 specimens. The extravasated volume was measured to be around 1 ml when the injected cement volume exceeded 6 ml [22]. In the present study, we have not investigated the extravasated volumes of cement.

We also showed, in this study, that technique of active contours image segmentation can be used for simulation of bone cement flow in the bone structure. Advantage of this approach lies in efficient simulation of cement flow in the bone structure comparing to computational flow dynamics [26, 27].

Remarkable information of this study can be also seen in explanation of failure mode of non-cemented and cemented C2 vertebrae. In case of non-cemented vertebrae, the screw cut-out through the anterior aspect of the C2 vertebral body. In case of augmented vertebrae, it was shown that only a small amount of bone cement (base only) can prevent the screw cut-out trough the bone at the base and body of C2.

A number of limitations are acknowledged in the present study. We addressed only the response to direct compressive loads. The technique did not involve assessing the mechanical consequences in terms of specimen stiffness in bending and load sharing between the augmented vertebrae and adjacent structures. In vivo loading of the spine, however, is complex, including a substantial bending component. Because confounding factors such as age, gender, body mass, bone mass index and disease can vary the geometric and mechanical properties of the tested vertebrae significantly, the issue arises as to the generalisation of loads reported in the study.

Conclusion

The present study showed that the low porous cement was able to significantly influence the stiffness of the augmented odontoid screw fixation in vitro, although further in vivo clinical studies should be undertaken. Our results suggest that only a small amount of non-porous cement is needed to restore stiffness at least to its pre-fracture level and this can be achieved with the injection of 0.7–1.2 ml of cement.

Acknowledgements This work was supported by the Charles University Grant Agency (GAUK) no. 816016.

Funding The manuscript has not previously been published in print or electronic form and is not under consideration by another publication.

Compliance with ethical standards

Conflict of interest Authors declare that there is no ethical problem or conflict of interest.

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