Sensitivity analyses for subject-specific Finite Element models of spine fixation

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Keywords: spine, vertebral fractures, posterior fixation, finite element, sensitivity analysis

1. Introduction

Vertebral fractures represent a societal burden because of healthcare costs associated with a deteriorated quality of life. It has been estimated that the characteristics and shape of the fractured vertebra are associated with the age, the bone mineral density, and the type of forces generating the injury [1, 2]. Vertebral burst fractures are due to compressive forces, which generate centrifugally extruded fragments, and are treated with different techniques to stabilise the injured level. The posterior pedicle screw fixation, which creates a bridge that shifts part of the load on implants, is the most popular surgical treatment of vertebral burst fractures [3]. Pedicle screws are inserted bilaterally one or more levels above and below the fractured vertebra and tightened by two rods. Among the post-operative complications associated to this operation, loosening and failure of screws could result in loss of correction and kyphosis [4]. In these cases, a revision surgery may be necessary [5]. To prevent this risk, it is still not clear in the literature which are the optimal criteria to choose the surgery-related parameters controlled by the surgeon. Our hypothesis is that, *in silico* Finite Element (FE) models of pedicle screw fixation could be useful to predict the post-operative outcomes of spinal fixation and to provide quantitative information to help the decision process of surgeons. Therefore, the goal of this study was to generate, verify and test the sensitivity of a computed tomography (CT)-based subject specific FE model for the assessment of the stability of pedicle screws implanted in the vertebral body.

2. Methods

2.1 Generation and verification

The anonymized pre-operative scan (0.97x0.97x0.62 mm^3 voxel size) of the thoracolumbar spine of one male patient with a burst fracture in L1 was analysed. The L2 vertebra was segmented and modelled. A fixation with screws was simulated. In particular, two Aesculap® S4® Element MIS Monoaxial screws were virtually inserted by a Boolean subtraction by following a medical protocol [6]. Subject-specific, linear FE models simulated a quasi-static compressive load on the head of screws (100N vertical load on each screw). The screw was simulated as homogenous linear elastic material (E = 102GPa, v = 0.36) and the bone as heterogeneous linear elastic material (E as function of the bone mineral density, v = 0.3). 10-nodes tetrahedrons were used with an element size which was varied separately in the bone and in the simplified screws for verification purposes. Six different element sizes in screws (0.4 – 1.2 mm) were tested for two meshes of the bone (one coarse: 3 mm; one fine: 1 mm) to find the optimal element size with respect to variations of the Von Mises stress (σ_{VM}). Moreover, eight element sizes in the bone (0.9 – 3 mm) were tested. In this case, the metric was the Minimum Principal Strain (ε_{p3}) in the vertebra.

2.2 Sensitivity analysis

Once fixed an optimal element size, a sensitivity analysis on diameter and length of screws was performed for both the realistic (R, with thread) and simplified (S, without thread) pedicle screws. Three different diameters (7.5, 6.5, 5.5 mm) and three different lengths (50, 45, 40 mm) were tested. The σ_{VM} in the screws and the ε_{p3} in the bone were determined for each configuration.

3. Results and discussion

All tested element sizes for the simplified screws provided a relative difference in σ_{VM} lower than 10% with respect to the finest mesh. For the sensitivity analyses, the smallest element size for the screw (0.4 mm) was chosen because the computation time was not significantly affected. For the vertebral body a maximum element size of 1.0 mm, which showed a difference in ε_{p3} of about 8% with respect to the finest mesh (0.9 mm), was chosen.

The same maximum element size used for the S screws (0.4mm) and bone (1.0mm) was used also for the model with realistic screws (Figure 1). In fact, although an element size equal to 0.8 mm was sufficient to obtain a relative difference in σ_{VM}

(in R screws) lower than 10% with respect to the finest mesh, the smallest element size was chosen for further analyses as the simulation was almost equally fast. For the bone, a maximum element size of 1.0 mm, showed a difference in εp3 of about 1 % with respect to the finest mesh (0.9 mm), while the coarser mesh (1.3 mm) presented a relative difference of about 10 %.

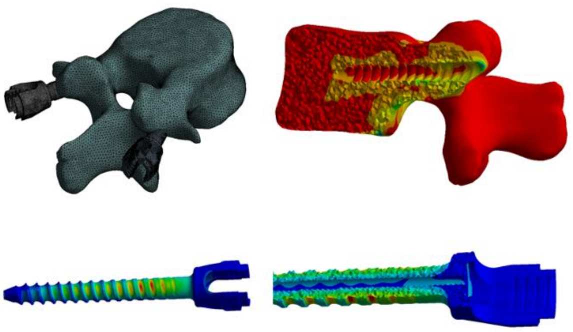

Figure 1: The mesh and results of the model with two screws (l = 45 mm, d = 5.5 mm) inserted at pedicles. On the top right, the ε_{p3} distribution in the bone in a cross-section along the longitudinal axis of the screw. Below, the σ_{VM} distribution in the right screw, from the bottom and in cross-section.

Diameter (mm)	**7.5**	**6.5**	**5.5**
Length (mm)	**40**		
S_Sc_σ_{VM} (MPa)	55	60	79
R_Sc_σ_{VM} (MPa)	86	90	97
S_Bone_ε_{p3} (%)	-0.47	-0.43	-0.51
R_Bone_ε_{p3} (%)	-0.50	-0.40	-0.51
Diameter (mm)	**7.5**	**6.5**	**5.5**
Length	**45**		
S_Sc_σ_{VM} (MPa)	52	59	79
R_Sc_σ_{VM} (MPa)	86	86	95
S_Bone_ε_{p3} (%)	-0.34	-0.30	-0.58
R_Bone_ε_{p3} (%)	-0.31	-0.35	-0.56
Diameter (mm)	**7.5**	**6.5**	**5.5**
Length (mm)	**50**		
S_Sc_σ_{VM} (MPa)	51	59	75
R_Sc_σ_{VM} (MPa)	81	82	92
S_Bone_ε_{p3} (%)	-0.27	-0.29	-0.51
R_Bone_ε_{p3} (%)	-0.31	-0.33	-0.50

Table 1: Peak σ_{VM} in screws and peak ε_{p3} in the vertebra, for both the simplified and realistic model, for each tested diameter and each tested length.

Both the simplified and realistic models presented a higher sensitivity to changes in the diameter (S: $\Delta\sigma_{VM}$ = 8-35%, $\Delta\varepsilon_{p3}$ = 9-49%; R: $\Delta\sigma_{VM}$ = 0.4-12%, $\Delta\varepsilon_{p3}$ = 6-44%) than in the length of screws (S: $\Delta\sigma_{VM}$ = 0.1-7%, $\Delta\varepsilon_{p3}$ = 1-43%; R: $\Delta\sigma_{VM}$ = 0.4-9%, $\Delta\varepsilon_{p3}$ = 3-39%). In most cases, higher absolute strains in the bone and stresses in the screws were observed for models with lower diameter. Differences in σ_{VM} (18-36 %,17-40%, 18-37 %) and in ε_{p3} (0-7 % ,3-15%, 2-13 %, Table 1) were found between the models with realistic or idealized screws (lengths equal to 40, 45 and 50 mm, respectively).

4. Conclusions

The results suggest that both diameter and length of pedicle screws are important parameters to consider for evaluating the risk of failure of the implant and of the bone with subject-specific FE models. Moreover, the geometry of the screw should be modelled realistically in order to obtain reliable results. This approach will be used in the future to evaluate the best fixation strategy for patients with burst fractures.

5. Acknowledgements

This project was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement Spinner No. 766012.

6. References

[1] J.T. Schousboe. Epidemiology of vertebral fractures. *J Clin Densitom*, 19(1):8-22. 2016
[2] F. Magerl, M. Aebi, S.D. Gertzbein, J. Harms, S.Nazarian. A comprehensive classification of thoracic and lumbar injuries. *Eur Spine J*, 3(4):184-201. 1994
[3] K. B. Wood, W. Li, D. R. Lebl, A. Ploumis. Management of thoracolumbar spine fractures. *Spine J*. 14(1):145-64. 2014
[4] M. F. Butt, M. Faroq, B. Mir, A. S. Dhar, A. Hussain, M. Mumtaz. Management of unstable thoracolumbar spinal injuries by posterior short segment spinal fixation. *Int Orthop*. 31(2):259-64. 2007
[5] A. L. Carl, S. G. Tromanhauser, D. J. Roger. Pedicle screw instrumentation for thoracolumbar burst fractures and fracture-dislocations. *Spine*. 17(8 Suppl):S317-24. 1976
[6] S.D. Gertzbein, S. E. Robbins. Accuracy of pedicular screw placement in vivo. *Spine*. 15(1):11-4. 1990