

Validation of a process for developing finite element models to predict vertebral body stiffness:

What are the limits on valid inputs to this process?

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Introduction

As computational modeling methods in the field of orthopaedic biomechanics develop, there is a greater need for an agreed framework for the modeling process to demonstrate the robustness of the outcomes, particularly for clinical and industrial acceptance. In the spine, this has led to the development of specimen-specific models of the vertebrae which allow direct validation of the model outputs against corresponding experimental tests.

However, there is a danger that this move to specificity means that computational models lose some of their advantages over experimental testing and may limit their application to the simulation of particular specimen-specific samples rather than trends in a population. This paper examines the validation of a process used to produce specimen-specific models, rather than the validation of one unique model, and explores how much the nature of the inputs to that process affect confidence in the results. A series of studies are presented to illustrate the function and limitations of the process and the results are used to discuss how the validation process might be tackled in future spinal modeling.

Materials and Methods

The focus of this work was on the prediction of stiffness of the vertebral body. A process was developed in which finite element models were generated with the geometry and material properties specific to individual vertebrae [1]. The main steps are shown in Figure 1. Briefly, each vertebral specimen was imaged using micro-computed tomography (μ CT); the images were downsampled and segmented to extract the vertebral geometry on a mm scale; a finite element mesh was generated at a calibrated refinement level and inhomogeneous material properties were assigned based on the underlying image brightness levels. A laboratory procedure, where the stiffness of each vertebra was established by loading in a materials testing machine, was used as the gold standard with which to compare the computational model predictions. The boundary conditions and loading regime in the model were matched to the experimental testing setup.

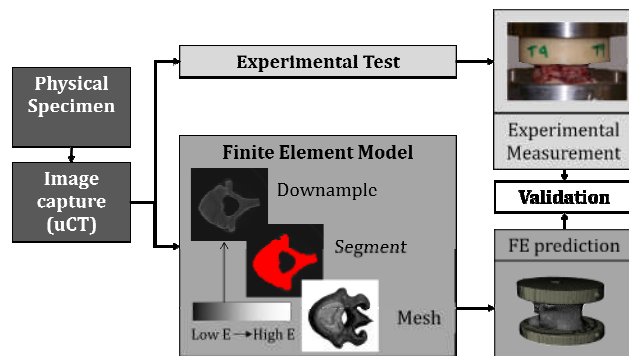


Figure 1: FE modeling and validation process

Each aspect of the modeling process, such as the relationship used to assign the elastic modulus from the grayscale image data and the mesh density, was initially calibrated against experimental stiffness results for a set of porcine vertebral specimens.

Study 1: Validation of the process Once the process was established, it was applied to an independent set of porcine vertebrae and the stiffness results compared with experimental tests on the same specimens.

In order to evaluate the extent to which this process could be applied and still generate valid results, two further studies were then undertaken.

Study 2: Application to different species The same process was applied to μ CT images of cadaveric vertebrae [2], imaged under the same conditions in the same device.

Study 3: Application to treated vertebrae A further study was undertaken on human specimens that had been augmented with cement as part of a study of vertebroplasty [2].

In both cases, following imaging, the specimens were tested in the laboratory to provide a means of direct validation.

Results

The results of all the studies are presented in Figure 2.

Study 1: The mean absolute error in the predicted stiffness across the models in the validation set was 5.2% (n = 6).

Study 2: When switching from porcine vertebral bodies to human ones, it was found that one aspect of the process had to be changed. Namely, the relationship between the image grayscale and the inhomogeneous material properties was different and had to be re-calibrated. This meant that the process had to be re-validated for this new application.

Following calibration, a further test on independent specimens again yielded good agreement (absolute error = 12%, n = 4).

Study 3: In the case of the cement augmented specimens, it was found a manipulation of the relationship between image brightness and material properties was not sufficient, and there was poor agreement between the FE predictions and corresponding experimental results (Figure 2). More significant additions to the model generation process were necessary, again meaning further validation.

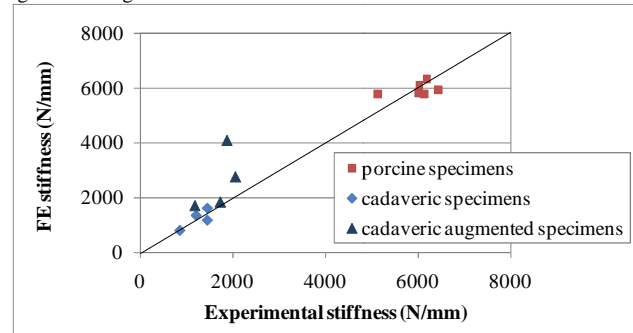


Figure 2: Comparison of experimentally-measured and FE stiffness values for each of the studies

Discussion and Conclusion

A specimen-specific finite element model development process was developed using one set of specimens and validated using an independent set. Having validated the process, rather than validating any single model, the process can then be used to generate many different models. This enables a larger population of models to be generated from image datasets without the time, expense and waste of experimental testing. However, it is challenging to clearly define which images constitute valid inputs to this process and which do not. From Studies 2 and 3, it is clear that the validation must encompass the range of models that will be generated using the process. Any deviation from this, may require an adjustment (in the case of Study 2) or a major modification (in the case of Study 3) to the process, which then necessitates further validation.

In conclusion, validation of a modeling process with multiple possible inputs will enable the development of a much larger population of patient-specific models. However, defining the set of inputs for which the process remains valid is not trivial. A combination of engineering judgment and adherence to the original specification for the development process, will help to identify when potential inputs may breach validity.

References

- [1] Jones and Wilcox, Journal of Biomechanical Engineering, 129, pp. 898-903, 2007;
- [2] Wijayathunga et al, Journal of Engineering in Medicine, 222, pp.221-228, 2008

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