Finite element simulation for the prediction of mechanical failure in the lumbar spine surgery

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1. ABSTRACT

Finite Element spine modeling can be useful for computer assisted surgery planning providing help in assessing the risk of mechanical failure. The aim of this study is to provide a patient specific finite element model of the lumbar spine where surgical gesture was considered and to evaluate its relevance as a predictive tool for lumbar spine surgery.
A three-dimensional FEM of the L1-Sacrum lumbar spine with geometrical personalization was used. Mechanical properties were based on published data. Then, main characteristics of degenerative pathologies and surgical gestures were considered, and posterior implants were modeled. The sacrum was fixed and Flexion compression loads were applied on the L1 vertebra. Then, results of simulations were post-processed to obtain stresses in the discs and along implants.
Clinical cases were collected to evaluate the models relevance. 66 cases instrumented with rigid screw rod systems were considered. 13 of the collected cases were “failed cases” in which patients had screw breakage or screw loosening.
Blind simulations were performed for all these patients and the results were qualitatively compared with the clinical outcome.
Numerical results highlighted the specific behavior of 12 models for which loads on screws and rods were markedly higher than those of all others. The analysis of the clinical outcome emphasized that 9 of these 13 models corresponded to patients with a mechanical failure.
For the first time a patient specific model was proposed for lumbar spine surgery planning. By increasing the number of modeled clinical cases, it could be possible to improve this model and to provide an help for surgery planning.

2. INTRODUCTION

Finite Element Method (FEM) is useful to analyze mechanical behavior of human body structures. Several authors have investigated the mechanical behavior of intact, injured and instrumented vertebral segments using finite element models. Some of these studies proposed a combined approach using in vitro experiments and FEM, parameterization of the spine geometry allowed analyzing the effects of geometrical parameters on the

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mechanical behavior [1] however regarding spinal implants, evaluation only considered "standard spine" which is not accurate enough to develop a predictive tool based on FEM. The aim of this study is to provide a patient specific finite element model of the lumbar spine where surgical gesture was considered and to assess its relevance as a predictive tool for lumbar spine surgery

3. MATERIALS AND METHODS

3.1 Patient Specific Finite Element Model

A fully validated three-dimensional finite element model of the lumbar spine was used for this study [2]. For the geometrical personalization of the FEM, a specific algorithm based on a statistical vertebral model was adapted [3,4] to obtain the 3D shape and position of each vertebra using the identification of the four corners of vertebral bodies using sagittal X-ray of the patient.

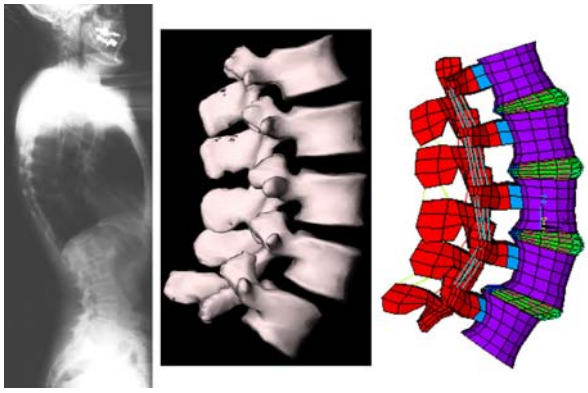

Figure 1: Example of the personalized FEM obtained from the identification of the 4 corner of each vertebral body.

This model takes into account the geometric and material non-linearity. Surface contact elements were considered for the articular facets, and material properties of soft tissues were defined according to published data [5], then refined in a parameter identification process so that the numerical results fit with those of the LBM database.
Posterior implants for osteosynthesis were modeled using beam elements and integrated in the spine FEM. This modeling was fully parameterized to take into account the surgical strategy (material, rod diameter, screws diameter and length…) and the surgical gesture (arthrectomy, discectomy…).
Main characteristics of degenerative pathologies were modeled through the geometrical personalization: disc height, sagittal listhesis…
Therefore; flexion-compression loads were applied on the L1 vertebra (value depending on patient weight and sagittal imbalance)
Finally, results were post-processed to assess: the maximal equivalent Von Mises stress in the disc matrix and the maximal force in the disc fiber for each functional unit. But also, the normal stresses, the equivalent bending moment and the equivalent shear stresses for screws and rods. The distribution of these parameters was expressed along the implant.

3.2 Finite element model evaluation

In vitro evaluation of instrumented spine FEM was performed using 24 L4-Sacrum fresh human cadaveric spines (male, age range 57-69 years, mean age 63 years) tested with the 2TM (2 Têtes Micrométriques) spine segment testing machine[4] according to the ENSAM-CNRS procedure [*6*].

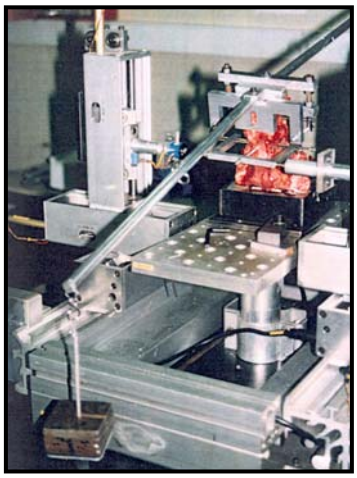

Figure 2: the 2TM (2 Têtes Micrométriques) spine segment testing machine

The sacrum was fixed and quasi-static moments of flexion-extension, lateral bending and torsion were applied on the L4 vertebra by 1 Nm step up to 10 Nm. The six 3D vertebral displacements (3 linear and 3 angular) of the L5 vertebra regarding the sacrum were measured. For each specimen, three configurations were tested: *intact*, *instrumented* with L4-S1 rigid screw-rod devices (3 different rigid instrumentations were considered, 6 specimens for each one) and *injured* by performing a L5-Sacrum discectomy.
Mean geometry FE model was used with the same boundary conditions as in vitro experiments and with the same configurations: intact, instrumented and after resection of disc elements. Experimental and numerical load/displacements curves and range of motion (ROM) were compared.

3.3 Retrospective evaluation of the model as a predictive tool

A clinical case collection was engaged to evaluate the tool accuracy/ability in modeling the spine of a given patient. Requirements for the clinical collection have consisted in general patient data (Height, weight…), Sagittal X-rays of the patient (for geometrical personalization), pathology and surgery descriptions and finally post-operative results. Two subsets of clinical data were created: “non complicated cases”, meaning no documented complication at the last follow-up and “failed cases” in which patients had an implant mechanical failure.
66 clinical cases instrumented with rigid screw-rod systems were collected and successfully simulated; they presented a mean follow up of about 2 years. As there was no X-Ray of the full spine, the spine geometry was described using sagittal X-Ray of the lumbar spine and the sagittal balance was estimated by the surgeon.
11 clinical cases presented a screw breakage after the surgery: 2 others presented clearly bone loosening around screws.

[4] The test device and protocol are labeled by a quality certification NF EN ISO/CEI 17025.

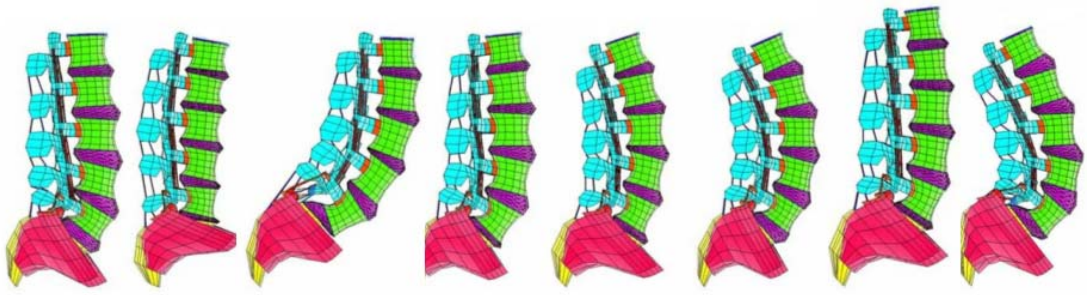

Figure 3: Example of personalized patient FEM obtained from sagittal X-rays

Blindfold numerical simulations were performed successively for these instrumented patients either at the L4-Sacrum or at L5-Sacrum levels (respectively 24 and 42 patients). Finally numerical results were qualitatively compared with the clinical outcome in order to estimate the FEM consistency.

4. RESULTS

Concerning in vitro evaluation of the instrumented model, numerical load displacement curves have been compared to experimental ones for all load cases and for all configurations (intact, instrumented, and injured). The numerical curves presented similar patterns as experimental ones. Numerical ranges of motion were within the experimental corridors and effect of instrumentation and injury were similar to those observed experimentally.

Regarding to retrospective evaluation; among the 66 patients, results highlighted the specific behaviors of 12 patients for which mechanical loads on screws and rods were markedly higher than for the others. The analysis of the clinical outcome indicated that 9 of them were “complicated case”.

Only 3 of the 53 “non complicated cases” demonstrated numerical results with particularly high stresses.

Finally, finite element simulations allowed to predict 9 (3 and 6 respectively at L4/S and L5-S levels) on 13 failure cases among a total of 66 patients.

5. DISCUSSION

The process presented in this study allowed to obtain a 3D reconstruction of the patient spine and then to personalize geometrically a detailed finite element model for a given.

The full simulation process is automatic for most of the patients. It only requires manual intervention in case of severe deformation of the spine: high grade of spondylolisthesis or high disc degeneration.

Regarding to the retrospective evaluation, even if the proportion of clinical cases is unbalanced between successes and failure cases, finite element simulations allowed to identify 9 of the 13 failure cases. Model results appear to be coherent with in vivo findings. Then, for most of successful surgery, simulations results were very similar each other, that means than in future, by increasing the number of modeled clinical cases and according to first observations, it will be possible to define a set of reference values for successful surgery

6. CONCLUSION

For the first time a patient specific model was proposed for lumbar spine surgery planning. Even if the proportion of clinical cases is unbalanced between successes and failure cases, first simulations were promising in the ability of the FE modelling to identify preoperatively the risk of mechanical implant failure for a given patient, with its own geometry, pathology, implant and surgery. Then, by increasing the number of modeled clinical cases, it could be possible to improve this model and to provide an help for surgery planning.

7. REFERENCES

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