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Biomechanical evaluation of anterior cervical spine stabilisation using the finite element approach

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This study develops a three-dimensional FE model of the C4-C6 unit of the cervical spine, with non-linear material properties of the joints and stabilised with an anterior fixation system, after a simulated injury. The model of the 3 vertebrae, the fixation plate and bone screws included non-linear definition of the ligaments and discs. Appropriate material properties from the literature were used. The motion characteristics of the spine segment, as well as the stiffness and strength of the stabilised unit, were compared with available experimental data. Clearly the fixation system replicates the intact spinal segment in static compression tests under a standard head's weight but improvements are necessary to design a more biomechanically relevant fixation system. The FE method proved to be essential for this kind of biomechanical analysis, and the model will be used in further investigations.

Keywords: biomechanics, cervical spine, finite element model, spinal instrumentation

1. Introduction

Although injury statistics generally attribute only 2% to 4% of serious trauma to the neck, any neck injury can have debilitating consequences such as permanent paralysis. The advent of land and air transportation has made us increasingly aware of the serious consequences that can result from a structural failure of the neck. As a result, a variety of devices have evolved that offer post-injury stabilisation of the damaged spine. The anterior approach and fusion of the lower cervical spine are well established in the treatment of nontraumatic disorders [1]. Plate fixation is usual when the vertebrae or the intervertebral discs are damaged. The main advantage here is immediate postoperative stability, but there are several disadvantages such as the risk of damage to mechanisms of speech and swallowing via direct or neural injury.

Only one attempt has been made to examine the biomechanical properties of a spine with an injury that has been stabilised by an anterior fixation plate, and to compare them with the properties of a non-fixed spine [3]. No FE models of this problem have been published although the use of computer models to simulate spinal mechanics is widely accepted. The finite element method (FEM) was introduced in

1956 but in biomechanics FE applications started with thorax modelling in 1970 and the vertebral column modelling in 1973 [8]. Most of the FE-Models concentrate on the mechanics of the lumbar spine with particular interest in the mechanics of the intervertebral disc but several models of the cervical spine were also published.

The aim of this study was to develop a FE-Model of anterior plating on a C5-C6 spinal unit which could be used initially to assess existing fixation plates, but ultimately could help design of a new fixation device. The model had to have a representative topology which included all those features of the cervical spine which are important for motion, as well as representative model stiffness incorporating the material non-linearities.

2. Methods

The presented three-dimensional model of the C4-C6 spinal unit was based on a FEM model by Heitplatz et al. [4], however the geometry of the vertebral bodies and the discs, as well as non-linear properties of the discs and the spinal ligaments, were totally revised. The geometry data were obtained from the full colour, male images of the Visible Human Project [5]. During digitisation, simplifications were made to the vertebral bodies and spinosus processes. The transverse processes are not connected to any spinal ligaments and therefore have no relevance for the model in its current state. The overall dimensions of the vertebrae were preserved and a special focus was given to the topology of the facet joints to allow realistic motion characteristics. The bony structure was seen as homogeneous and nearly rigid. It was decided to represent every ligament as a pair of 3-D tension-only spar elements, as they are able to simulate a non-linear characteristic of the load-deformation curve.

The intervertebral disc was modelled by a combination of a linear elastic base material with embedded sets of four non-linear 3-D spar elements. Two of them were tension-only and the other two were compression-only.

The geometry data for a model of the fixation system were measured from a Caspar Cervical Spine Plate L: 28 mm and Aesculap Bone Screw d: 3.5 mm, using standard measuring tools, with accuracy of 0.01mm.

The full model (Fig. 1) consisted of 4103 nodes and 9952 elements representing various spinal structures of the C5-C6 motion segment and the plate-and-screw fixation system.

The mechanical properties of spinal ligaments and intervertebral discs, used in this project, were examined by Myklebust [6] and Shea [7]. The Caspar Plate and Screws are made from titanium alloy, which properties are obtained by Black [2].

To fully examine the stiffness of the fixation system, two FE models were created. One of them simulated a spinal unit with the intervertebral disc damaged and removed, while the second one simulated more complex damage, with all the connecting structures removed.

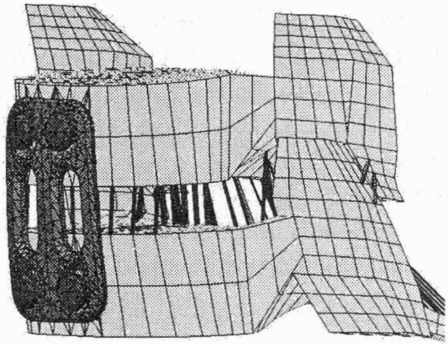


Fig. 1. FE model of the fixation system

The model responses were predicted for a compressive load of 500 N, a tension load of 300 N, a flexion moment of 3000 N×mm and extension moment of 5000 N×mm. Loading of the motion segment was accomplished by applying the forces and moments to the superior surface of C5, while the C6 vertebra was fully constrained at the inferior nodes of the vertebral body. An iterative solution was applied including the large deformation theory with a transformation matrix. The frontal solver of the ANSYS® ver.5.3 FE-package was used.

3. Results

The FE-model for the normal, healthy spinal unit was compared with data from Shea et al. [7]. The large deformation non-linear solution resulted in a strongly non-linear characteristic for the load–deformation curve (Fig. 2) which compares well with the independent experimental data. It is impossible to make an exact quantitative comparison due to the large standard deviation of ±26.7% found in Shea's experiment. Nevertheless incorporation of non-linear sets of spar elements into the system has clearly proven to be an effective measure to obtain realistic model stiffness for FE-Models of the cervical spine.

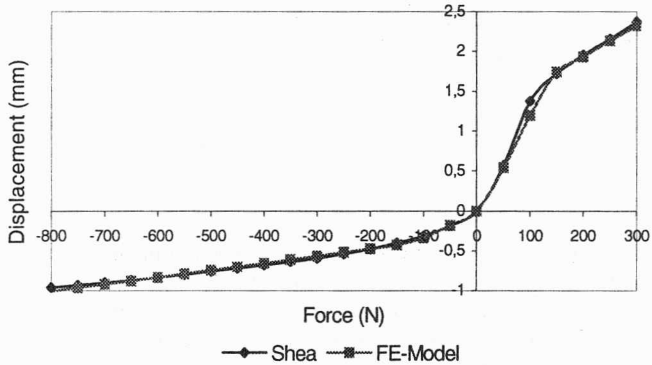
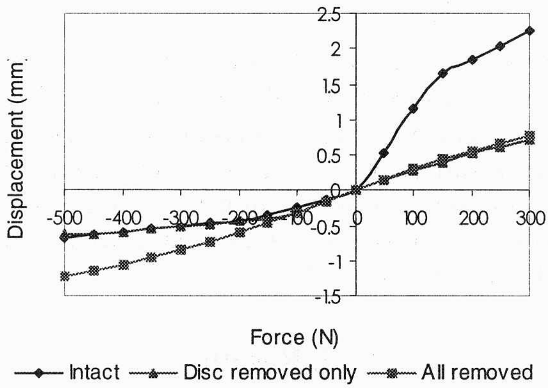


Fig. 2. Load–deformation curve of the C4-C6 spinal unit obtained from experimental studies (Shea) and FE-modelling (FE-Model)

Comparison of the stiffnesses of the FEM model of the C5-C6 spinal unit, with and without fixation system, in the compression test shows similar stiffness for the plated model with the facet joints, but much lower stiffness of the plated model without them (Fig. 3). The stiffness ratio (plated: intact) for the model with facet joints amounts to 95% (±10%), while for the model without them it amounts to 55%. In both cases the model of the stabilised spinal unit had similar stiffness values to the intact spine model only in the lower range of the compression test. The closest agreement was obtained under the standard head's weight.



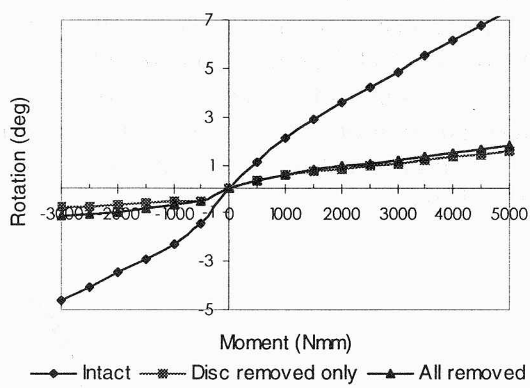


Fig. 3. Load–deformation curves obtained from the tests.
Intact – intact C5-C6 spinal unit; disc removed only – the same unit with fixation system and intervertebral disc removed; all removed – spinal unit with fixation system and disc, ligaments and facet joints removed

In the tension, flexion and extension tests, the fixation system appeared to be much stiffer in the whole range of loads. The stiffness ratio in the tension test reaches 400% for the model with the disc removed only and 360% for the model with all the connecting structures removed. In the flexion test it reaches 410% and 470%, while in the extension test it reaches 420% and 600%, respectively (Fig. 3). In all cases the influence of the connecting structures (spinal ligaments and facet articulations) can clearly be noticed and their importance in the biomechanics of spine's stability can be appreciated.

4. Conclusion

The cervical spine is a complex biomechanical system containing both passive structural and active neuromuscular components and is well suited for analytical study using engineering techniques. The FE method has an advantage in comparison with many other techniques in that it handles complex geometric configurations and material and geometric nonlinearities.

A non-linear, three-dimensional FE model of the cervical spine was developed. As far as was practical, it was validated by comparing the predicted data for a healthy spine against experimental values. The model performed very well; the difference between the model and the result achieved in experimental tests by Shea et al. [7] was less than 10%.

The introduction of cervical fixation systems to FEM modelling is novel. Only one attempt has been made to examine experimentally the biomechanical properties of a spine with an injury stabilised by an anterior fixation plate, and to compare them with the properties of a non-fixed spine. No FE-modelling attempts in this problem have been published. The results here show the importance of the facet joints and spinal ligaments in the biomechanics of the spinal motion segment. Unfortunately they are usually destroyed during the accident.

The Caspar fixation system is shown to behave like the intact spinal segment in static compression tests under a standard head's weight, but improvements are necessary; a fixation system which responds more like the intact spine under higher dynamic loads is needed. The model will be extended to consider other existing fixation systems and also novel solutions.

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