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Finite element method to study cervical postoperative stability

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ABSTRACT

A cervical spine model built by means of the finite element method was used to determine the risk of postoperative cervical instability in relation to the type of discectomy, in cervical disc herniation. Furthermore, this model was employed to check whether, at the adjacent levels of the fusion discectomy, the intervertebral translation during cervical movements will maintain the normal amplitude [normal ROM] or its amplitude will decrease.

The intervertebral displacement and the tension arising from motion and weight in the cervical vertebral structure were thus determined through computer modelling using the above-mentioned method and the software Abaqus. It resulted in a cervical spine model consisting of 739666 finite elements interacting through 210530 nodes, with biomechanical properties following the vertebral anatomical structures modelled.

Two movement situations were studied to determine the behaviour of this model. Firstly, the moment of force for flexion and extension of 1 Nm. Secondly, we aimed to establish the maximum flexion and extension for a normal cervical spine model in order to determine the momentum value of moving forces for each of them.

It was showed that both anterior cervical microdiscectomy without fusion and cervical discectomy with cage fusion (used for the surgical treatment of cervical disc herniation at one level), ensure postoperative vertebral stability when performed properly. Both types of surgery reduce the mobility of the cervical spine, although more in the case of fusion discectomy. The intradiscal tension increases in movement in both models, with a higher intensification in the fusion discectomy model.

The practical conclusion is that microdiscectomy without fusion is preferable in the case of a single-level cervical disc herniation occurred to a cervical spine without instability.

Keywords
cervical discectomy,
cervical postoperative stability,
finite element method,
microdiscectomy without fusion

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INTRODUCTION

Cervical spine stability after discectomy is evaluated biomechanically by determining the intervertebral displacement, tensions and stresses in the cervical spine. The finite element method is based on dividing complex structures into smaller ones, called finite elements, with simple geometric forms and easily to be included within the simulation of the process to be studied while tracking their parameters in situations close to real conditions. These finite elements are interconnected with each other at points called nodes, which define the requests as unknown parameters, respectively the movement or displacement and the load or stresses. We used a cervical spine model built through this method to determine the risk of postoperative cervical instability in relation to the type of discectomy.

Materials and methods

We worked with computer programs for image processing, for modelling finite elements of the cervical spine and simulating cervical motion and load. More precisely, we used the MIMICS software, which creates 3D models from 2D DICOM images. Thus, the images in DICOM format obtained from the CT scan of a normal cervical spine were introduced in MIMICS, transformed into points with 3D spatial coordinates, then exported to a special format (.stl). MIMICS software transposes images scanned by CT into a point cloud with spatial coordinates, creating a 3D model. Moreover, it can recreate the model of bone structures. The vertebrae model was obtained this way, whilst the other tissues, the intervertebral disc and ligaments were added manually.

The cervical vertebral model made in MIMICS in the form of coarse discretization was further processed to be used through the finite element analysis model. The vertebrae were imported into Abaqus CAE and the cervical spine model was recreated.

To build a model of the cervical spine with finite elements as closest to the real one, we assigned to each modelled structure the specific biomechanical properties of the column (elasticity, rigidity /deformability, resistance to deformation represented by Young's module, and Poisson's coefficient) for each finite element corresponding to the modelled anatomical structures (Table 1).

Table 1. Characteristics in terms of elasticity and strength attributed to the corresponding finite element of the modelled anatomical structures.

Anatomical structure	Finite element type	Modulus of elasticity (MPa)	Coefficient of Poisson
Vertebra - the bony cortex	First-order tetrahedral element:4 nodes	10.000	0.29
Vertebra - cancellous bone	First-order tetrahedral element:4 nodes	100	0.29
Anterior longitudinal ligament	Bar with 2 nodes	30	0.3
Posterior longitudinal ligament	Bar with 2 nodes	20	0.3
C1-C2 joint capsule	2nd order tetrahedral element:10 nodes	7.7	0.39
C1-C2 supraspinous ligament	Bar with 2 nodes	10	0.3
Yellow ligament C1-C2	Bar with 2 nodes	10	0.3
C2-C3 joint capsule	2nd order tetrahedral element, hybrid:10 nodes	10	0.3
C3-C7 levels joint capsule	2nd order tetrahedral element, hybrid:10 nodes	20	0.3
Yellow ligament levels C2-C7	Bar with 2 nodes	1.5	0.3
Interspinous, supraspinous ligament, levels C2-C7	Bar with 2 nodes	1.5	0.3

Thus, a cervical spine model consisting of 739666 finite elements that interact through 210,530 nodes resulted, with biomechanical properties according to the modelled vertebral anatomical structures (Figure 1).

Once this model with finite elements was settled, we were able to determine its behaviour at load and movement. In this purpose, we appreciated that the head weighs approximately 4.5 - 5.5 Kg and exerts an average force of 50 N applied to the vertebra C1, in the vertical direction lower oriented. Movements in the cervical spine are complex, but instability is evident especially in those of flexion and extension.

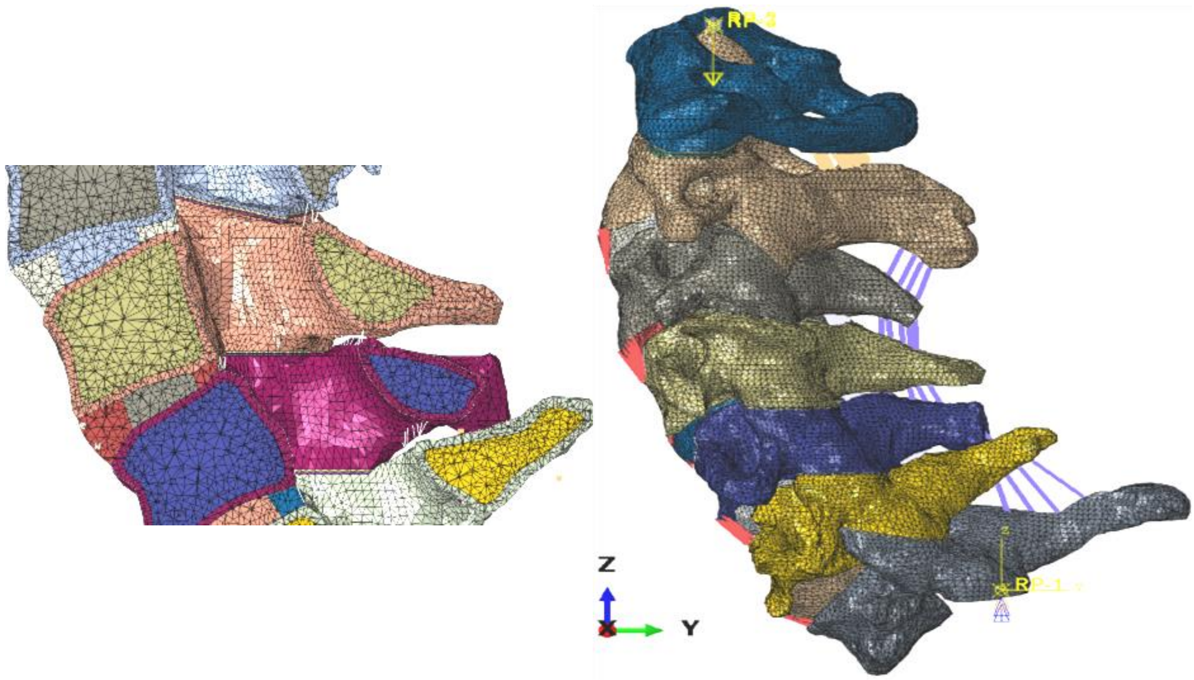


FIGURE 1. Cervical spine model obtained using the finite element method.

To study cervical instability during the flexion-extension movement, we considered the C7 vertebra as a fixed point. Then, we applied a force of displacement to the upper extremity of the cervical spine, respectively at the level of the C1 vertebra.

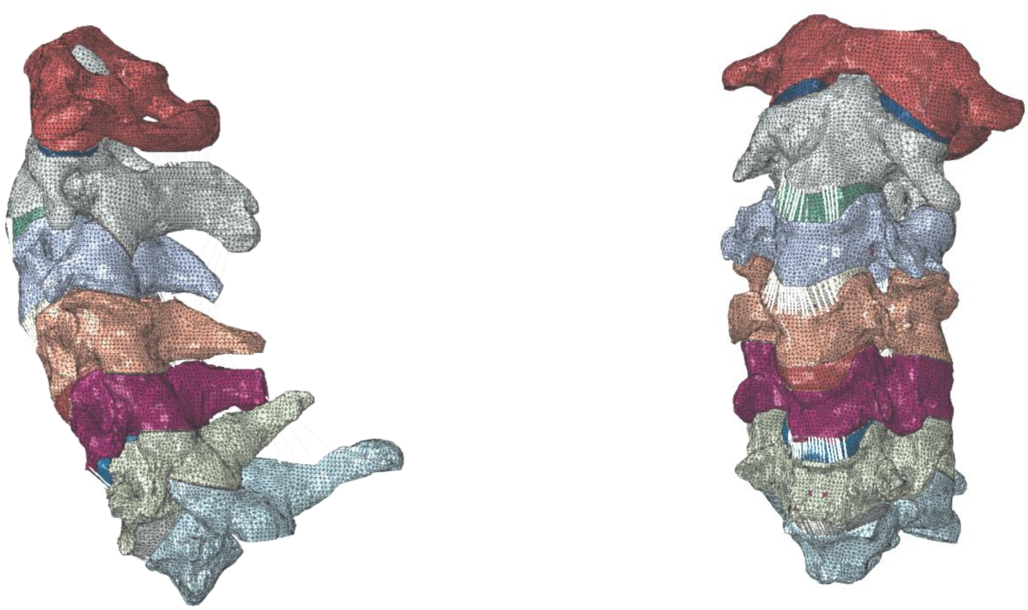
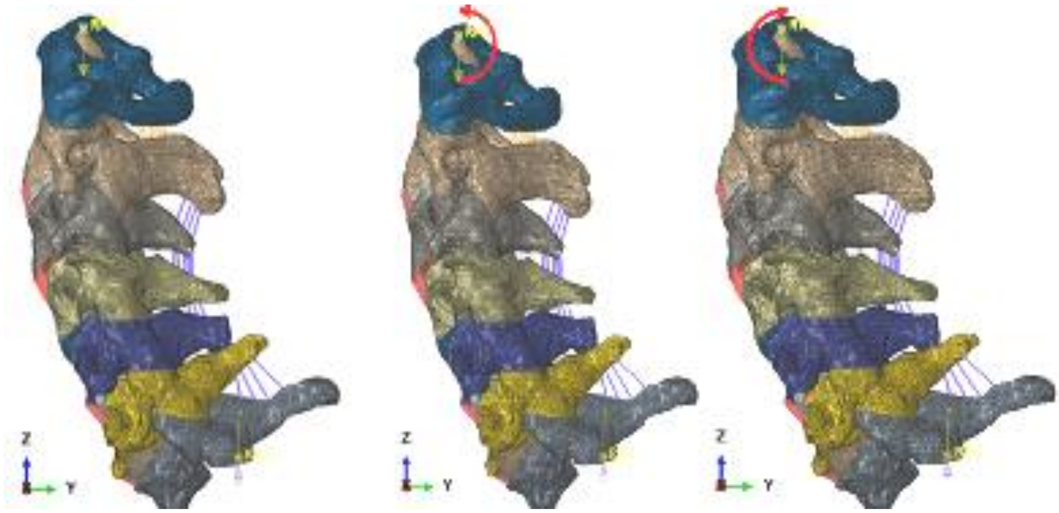


FIGURE 2. Cervical spine model obtained using the finite element method

Three models of the cervical spine were studied using this method:

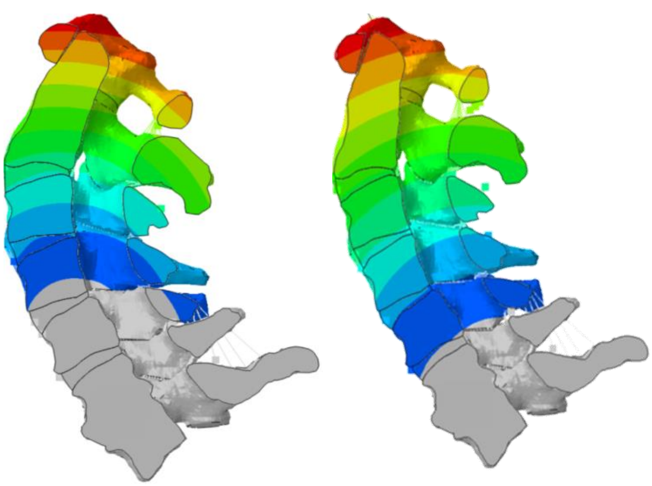
- a normal cervical spine,
- a cervical spine with microdiscectomy without fusionat the level C6-C7
- a cervical spine with discectomy and cage stabilization at the level C6-C7



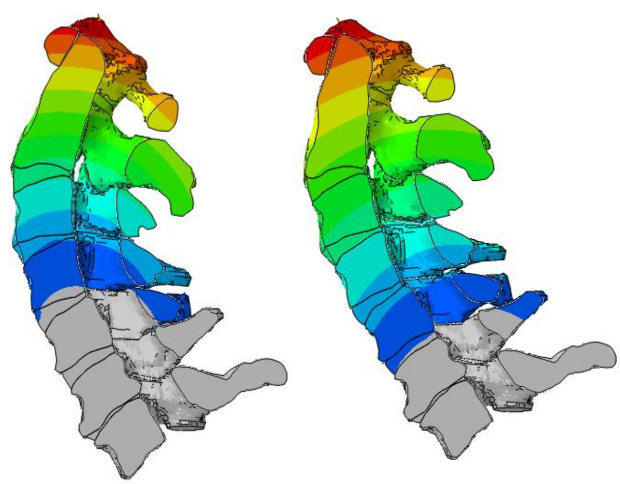
A. B. C.

FIGURE 3. Cervical spine model built by using the finite elements method (a), with the moment of the displacement force for the flexion (b) and extension movements (c).

For each model, movements of flexion and extension were simulated starting from the cervical intermediate position by applying a displacement force for flexion and extension, respectively by considering a moment of force applied to the movement.



A. B.



A. B.

FIGURE 4. Flexion movement by applying the force of 1 Nm
a. the model with microdiscectomy C6-C7
b. the model with discectomy and cage C6-C7

FIGURE 5. Extension movement by applying the force of 1 Nm
a. the model with C6-C7 microdiscectomy
b. the model with discectomy and C6-C7 cage

Two movement situations were studied to determine the behaviour of these three models, as follows:
- the moment of force for flexion and extension of 1 Nm,
- establishing the maximum flexion and extension for the normal cervical spine model and determining the

value of the momentum of the movement force for these movements.

These values are: the moment of force for maximum flexion is 7.3 Nm and the moment of force for the maximum extension is 2 Nm.

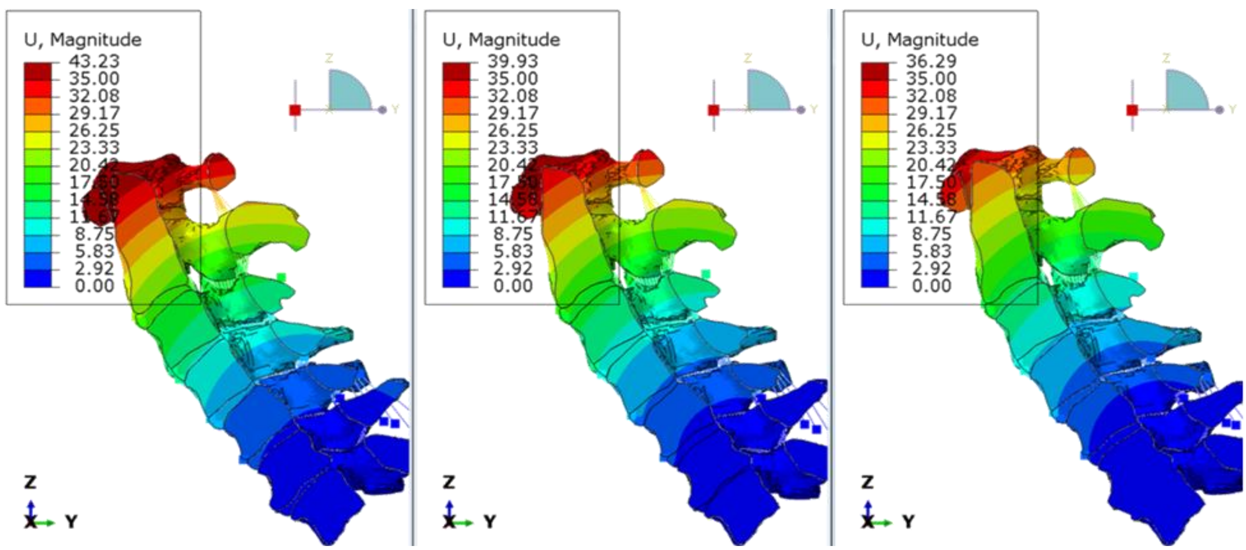


FIGURE 6. Flexion movement for the moment of force of 7.3 Nm, with cervical displacement at a. normal column, b. C6-C7 microdiscectomy and c. C6-C7 discectomy and cage model.

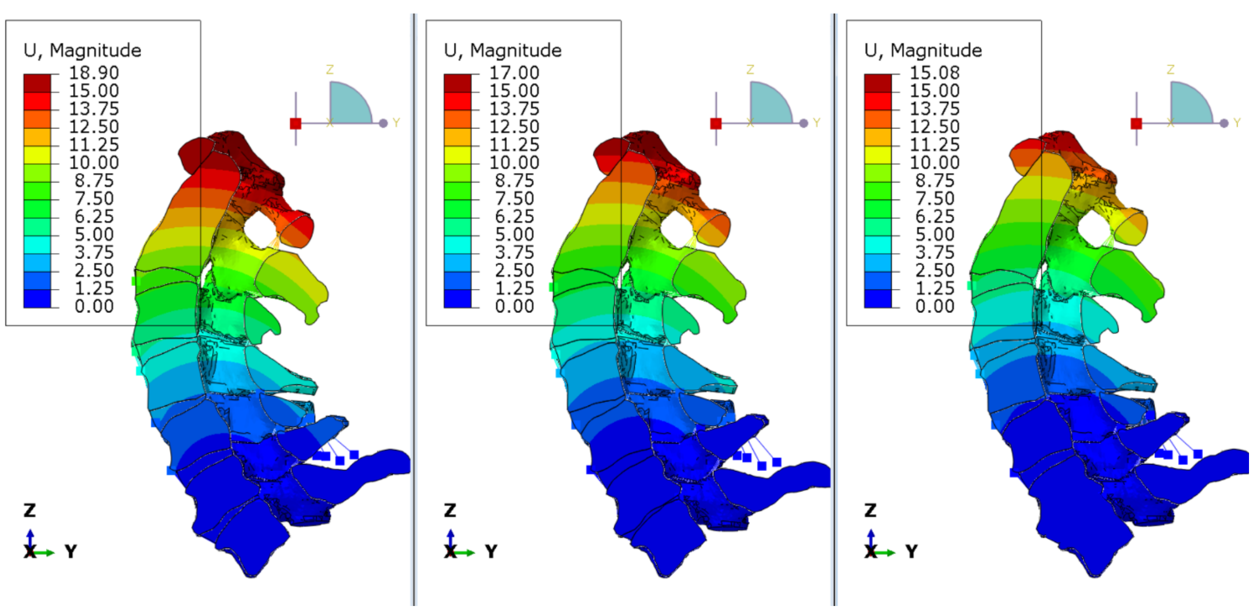
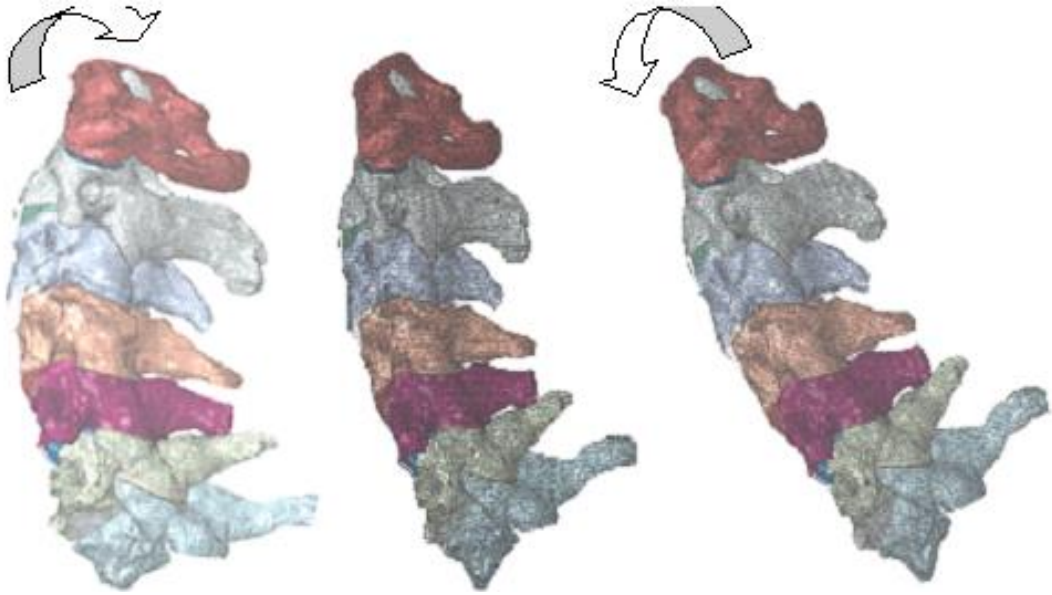


FIGURE 7. Extension movement by applying the force of 2 Nm, in the three models:
a- normal column, b- model with microdiscectomy C6-C7 and c- model with discectomy and cage C6-C7.



A. B. C.

FIGURE 8. Cervical models with discectomy and cage fixation at the C6-C7 level, at which mobility is studied: a. extension, compared with b. intermediate position and c. flexion

Movement	Model 1	Model 2		Model 3	
	mm	mm	% of Model 1	mm	% of Model 1
Extension	12.37	11.91	3.72%	11.12	10.11%
Flexion	11.65	10.63	8.76%	8.57	26.44%

TABLE 2. Cervical mobility in the sagittal plane when applying a moment of force of 1 Nm

RESULTS

We obtained the following results based on the finite element model with movement in flexion and extension by applying a moment of force of 1 Nm (Table 2).

In the cervical spine model operated for C6-C7 disc herniation by microdiscectomy without fusion, it was found that the height of the C6-C7 disc space decreased to 50% off the initial disc height although it still allows a degree of intervertebral mobility without the occurrence of vertebral instability.

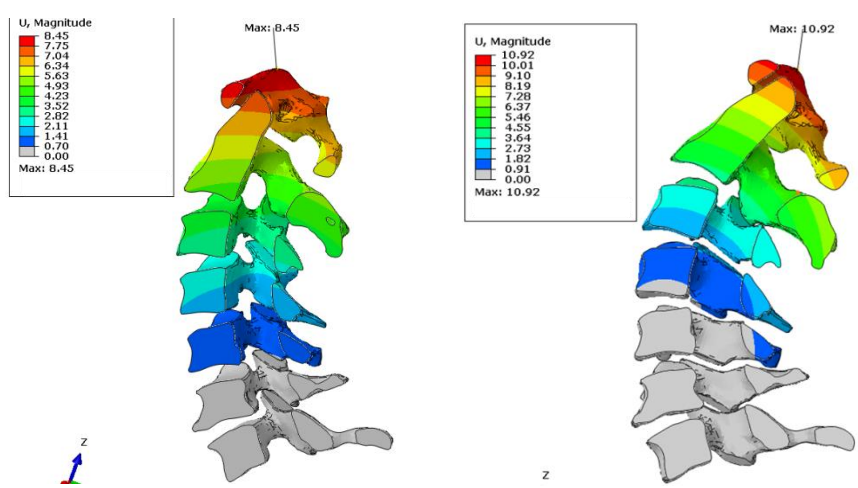


FIGURE 9. Cervical spine model with the extension of vertebrae

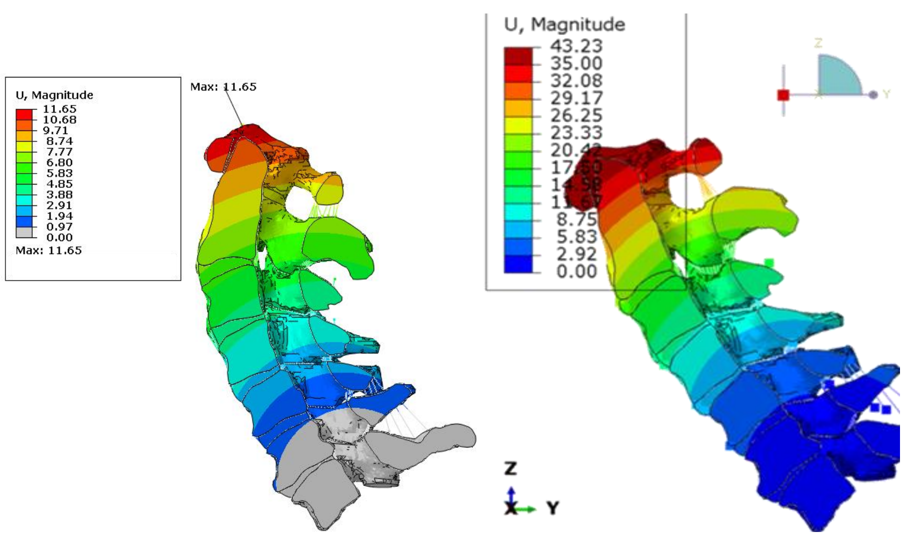
In the cervical spine model operated by discectomy and fusion using C6-C7 intervertebral cage, the operated disc space is blocked, there is no instability and the cervical movements of flexion and extension are performed by moving the upper vertebrae of the C6 vertebra. The C6 and C7 vertebrae form a fixed block and vertebral mobility is missing. It was found that surgery reduces the mobility of the flexion movement and blocks the C6-C7 disc space with a cage that reduces mobility with 26% in flexion. In the case of microdiscectomy without fusion, the overall cervical mobility decreases by 8.76% compared to the unoperated model.

When applying the moment of force corresponding to the maximum movement to the model of not operated cervical spine, respectively the moment of the force for flexion of 7.3 Nm and the moment of the force for extension of 2 Nm on the other two models, we obtained the results presented in Table 3.

The flexion and extension movement for all three models is much wider and the differences of mobility per the ensemble movement are 7.63% for microdiscectomy without fusion and 16.05% for discectomy with fusion.

TABLE 3. Cervical mobility at the moment of application of 7.3 Nm in flexion and 2 Nm in extension

Movement	Model 1	Model 2		Model 3		
	mm	mm	% of Model 1	mm	% of Model 1	% of Model 2
Extension	18.9	17	10.05%	15.08	20.21%	11.29%
Flexion	43.23	39.93	7.63%	36.29	16.05%	9.12%



A B

FIGURE 10. Flexion movement for the same model of the cervical spine with finite elements under the action of different moments of force: a. moderate flexion at the moment of force of 1 Nm and b. maximum flexion at the moment of force of 7.3 Nm.

DISCUSSIONS

Cervical disc herniation is a common degenerative pathology of the cervical spine and surgical treatment is the optimal solution in cases with surgery indication. A cervical discectomy removes from the anterior column an important component for resistance and the axial transmission of movement and weight and, consequently, may affect the stability of the cervical spine. The prospect of postoperative cervical instability has led us to this study, aiming to bring improvements to the operative techniques used so far or replace some of them in order to prevent or correct it.

We intended to determine the conditions in which post cervical discectomy instability may occur in relation to the surgical procedure used and to show which technique is appropriate to prevent it.

After microdiscectomy without fusion, postoperative healing is based on the formation of an intradiscal fibrous scar to ensures the stability of the cervical spine at the level operated. The postoperative intradiscal scar allows a minimum degree of mobility without overloading the adjacent levels.

In the case of discectomy with fusion, a block is formed between the vertebrae adjacent to the operated disc, with the advantage of keeping the normal foramina, but with the loss of the intervertebral mobility at the level operated.

We used the normal cervical spine model, not operate, to apply a moment of force of 1 Nm in flexion, respectively extension, from the middle position. It determined a small amplitude displacement, namely of 11.65 mm in flexion and 12.37 mm in extension compared to the initial position. The simulation of maximum flexion and extension on this model allowed us to determine the maximum value of the moment of force of displacement for the maximum amplitude of these movements, respectively for 7.3 Nm - maximum flexion and 2 Nm - maximum extension. The maximum values of displacement in flexion and extension for the normal model were 43.23 mm - flexion, and 18.9 mm - extension, starting from the initial intermediate position.

The cervical model of microdiscectomy without fusion at the level C6 - C7 had the following values of amplitude for the moment of force of 1 Nm applied on flexion and extension in movement: 10.63 mm in flexion and 11.91 mm in extension. This means a decrease in the amplitude of the cervical movement of 8.76% in flexion and 3.72% in extension. These values are not significantly lower compared to the amplitude of the normal movement in ordinary situations.

A moment of force of maximum amplitude resulted in 39.93 mm in flexion and 17 mm in extension. In this case, the decrease with respect to the amplitude of the normal maximum movement was of 7.63% in flexion and 10.05% in extension. It was found that the decrease in flexion in the patient operated for disc herniation at the C6 - C7 level by fusion without microdiscectomy is between 7.63% and 8.76% for maximum flexion, respectively for current flexion. In contrast to flexion, the extension movement decreased slightly, only with 3.72% for the current extension, but the amplitude of the extension decreases by 10%, determined by the moment of maximum force compared to these movements in the case of the cervical_spine.

In the third model, discectomy with fusion performed at the level C6 - C7, 1 Nm force produced a stronger decrease in the amplitude of movement: 8.57 mm in flexion, which means a decrease of 26.44% off the value of normal flexion, and 11.12 mm in extension, so with 10.11% less than the normal value. This decrease in amplitude of both movements of flexion and extension is significant and it is explained by the obstruction of the C6 - C7 disc space due to the fusion. Practically, the movement is produced by having as a fixed point the C6 vertebra. When a moment of force of maximum amplitude is applied on this model, it produces a flexion movement with the amplitude of 36.29 mm (meaning a decrease of 16.05% off the normal movement) and an extension of 15.08 mm, *i.e.* a decrease of 20.21% off the normal extension.

The simulation of flexion-extension movements on this third model established the marked decrease in cervical mobility as a whole, both for the current movement performed at a moderate request (moment of force = 1 Nm) and for the maximum movement, namely for a moment of force of 7.3 Nm in flexion and 2 Nm in extension. This decrease in amplitude in both flexion and extension is explained by the diminished length of the vertebral segment that executes the movement.

The study thus showed that limiting the moderate amplitude of the cervical movements is more important in the case of cage fusion discectomy compared to non-fusion microdiscectomy. The ration of amplitude decrease in movement between these two models is 3:1.

For a maximum movement, respectively for applying a moment of force of 7.3 Nm in flexion and 2 Nm in extension, the comparison between the biomechanical behaviour of the two cervical models showed that the decrease in the amplitude of movement is double in the case of discectomy with fusion than in the non-fusion model, both related to the normal, unoperated, cervical model.

Conclusions

The cervical spine model obtained through the finite element method (739666 finite elements and 210530 nodes), in which the vertebral mobility was simulated for usual and maximum movements, showed that both models of cervical spine operated ensure postoperative stability at the level of the operated intervertebral disc. Both types of surgery reduce the mobility of the cervical spine, most notably the model with fusion discectomy.

The practical conclusion is that microdiscectomy without fusion is preferable in the case of a single-level cervical disc herniation in a cervical spine without instability because, by comparing the two operative models, it appeared that microdiscectomy without fusion at one level does not significantly decrease the mobility of the cervical spine, nor does it tensile the overload intervertebral discs adjacent to the operated disc level.

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