

Mechanical behavior of a calcium phosphate ceramic bone graft used in the rehabilitation of a C4 human vertebra

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Abstract. The main results of a static analysis with a finite element model of the cervical section between C3 – C5 of a human spine are reported. In this case, it is assumed that the element C4 is completely damaged and has to be replaced. Therefore, a bone graft was installed between the anterior side of C3 and C5. Besides, a cervical plate of 55 mm. was fixed at the same side with 4 expansive screws. The resultant stresses caused by compression loads were analyzed and the displacements between the graft and adjacent vertebrae were calculated. Three loading conditions were applied: 80 N, 637.5 N and 6374.5 N. The first one corresponds to the head weight. In the second case, it is assumed that the average patient weight is supported by those vertebrae, while in the last one; the compression load failure is applied on the vertebrae.

Results show that displacements were lower than 3 mm between the graft and the adjacent vertebrae. In accordance with the concept of spine stability after Müller [1], the arrangement is a stable one. Another advantage is that no wires are used in this surgical technique. Two more issues should be noticed. There is no risk that the plate may be broken and the geometry of the bone graft allows bone regeneration. These results are on line with those observed in preliminary experimental tests with porcine vertebrae.

Introduction

Diverse studies on cervical section of human spine show that some fractures of the vertebral body [1, 2, 3, 4, 5, 6] or a vertebral disc [7] after an accident are critical. Consequently, patients are involved in a rehabilitation process, which will take between 3 to 6 months, in order to return to their normal life. Nevertheless, when the vertebral body fails completely, an immediate medical attention is needed. For this purpose, the damaged zone is isolated. The vertebral body is replaced with a bony graft, by means of a Corporectomy technique [8]. In order to ensure the stability of the graft and make it easy a rehabilitation process of the vertebrae, a complex surgical operation is required. Thus, the objective is to simplify the orthopaedic procedure.

Different studies have analysed the cervical region C3 - C7, an example is [9]. In all the cases, the structural behaviour under compression is considered. It is not used a cervical plate or a bone graft [10]. Qualitative conclusions may be obtained in order to explain the mechanical behaviour of the cervical region.

A different approach is required in order to analyze the influence of a cervical plate and a bony graft in the replacement of a damaged C4 vertebra. Under this work, the structural integrity of an arrangement with C3- C5 cervical section, in which C4 is replaced with a bony graft and cervical plate is studied.

1. Statement of the problem.

In modern surgical techniques, the damaged vertebral body is removed. Adjacent surfaces are prepared and a bone graft, previously conformed, is fixed. Following this process, it is necessary to include a cervical plate (Figure 1), and a wire is used on the posterior side of the spine (Figure 2).



Fig. 1 Cervical plate used for a Corpectomy using an anterior side.

As a consequence, the patient has to use a collar, which supports and prevents movements, which affect the damaged zone. During the therapy period, several X-Ray plates are taken in order to study the behaviour of the bone graft, wire or cervical plate used. If the surgical medic considers that an adjustment is required, other surgical operations will be carried out. Reports indicate that a patient with a Corpectomy needs around 4 - 6 operations during this therapy [5].

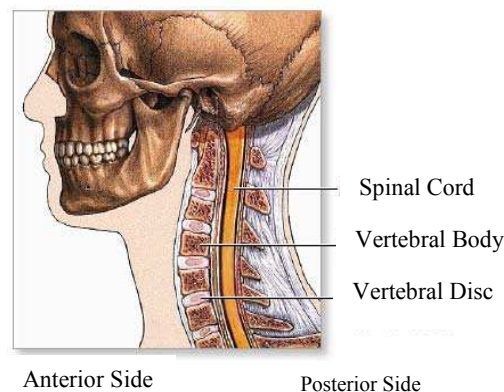


Fig. 2. Anterior and posterior spine sides of a human.

In this study, it is proposed to avoid the use of wires and include only a trapezoidal bone graft and cervical plate. In order to ensure structural integrity, the displacements among these elements should be lower than 3.5 mm.

2. Numerical Analysis

A Finite Element Model of C3, C4 and C5 cervical section has been developed, a bone graft replacement of C4 vertebra was introduced and a cervical plate manufactured by Ortosintese (model 3317/04), which increase stability, was also considered within the modelling. This model was created with Mechanical Desktop (figure 3) and ANSYS (figure 4). It has 95782 tetrahedral elements (SOLID 95) with 157633 nodes.

As mentioned above, three different compression loading conditions were considered, namely 80 N, 637.5 N and 6374.5 N. The first one corresponds to the head weight. The second case is when the average patient weight is applied on the arrangement. While in the last, it is the failure compression load applied to the vertebrae.

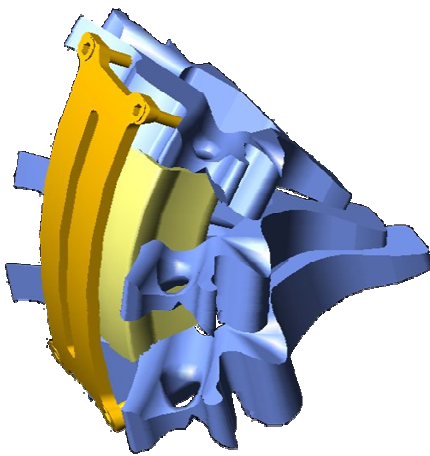


Fig. 3 3-D CAD Model of C3-C5 Cervical.

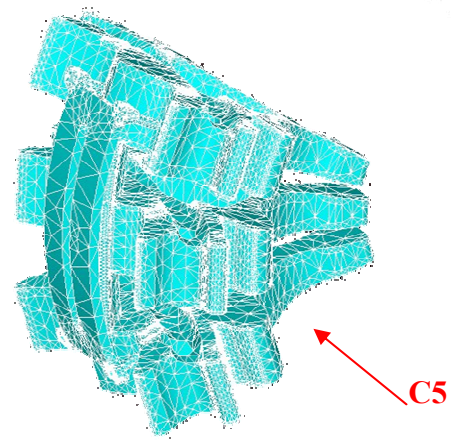


Fig. 4 FEM C3-C5 Cervical Model.

Figure 5 shows the compression load being applied on C3 vertebra while the nodes on the bottom surface of C5 are fixed.

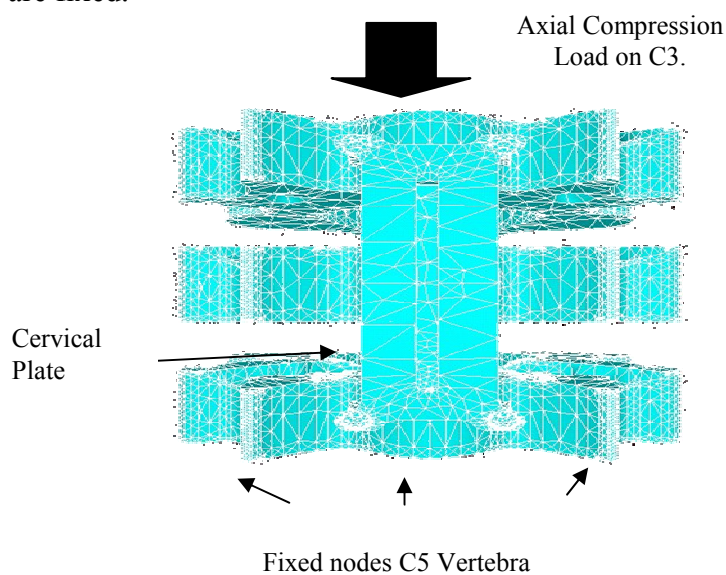


Fig. 5 Boundary Conditions for FEM Model

The Mechanical properties considered for the materials are shown in table 1.

	Property	Value	Units	Reference
CORTICAL BONE	Young Module	12	[GPa]	[7]
	Poisson's Ratio	0.2		
BONE GRAFT	Maximum Compression Stress Strength	5 -15	[MPa]	[12]
CERVICAL PLATE AND SCREWS 3317/04 OS (Ortosintese) (Ti6A14V)	Young Module	102	[GPa]	[11]
	Poisson's Ratio	0.3		
	Yielding Stress Strength	827	[MPa]	

Table 1. Mechanical Properties for the FEM Cervical Model.

3. Obtained results

Table 2 summarizes the obtained results. For the three cases, the stress level of the bone graft is low. For the most critical one, case 3 the resultant stress is below the top limit, so it is not expected the bone graft to be damaged. It should be mentioned as well that the resultant displacement among the surfaces of the vertebrae and the bone graft is lower than 3 mm. This is in accordance with the criteria of Müller [1] and, this guarantees stability of the Spine.

	Von Mises Stress on the Bone Graft [MPa]	Maximum Displacements [mm]
CASE 1 [80 N]	0.124	$6.857 e^{-4}$
CASE 2 [637.5 N]	0.986	0.0054
CASE 3 [6374.5 N]	9.867	0.0546

Table 2. Results for the 3 cases reported.

Because of the bone is graft is a synthetic material and its structure and composition is very similar to the bone tissue, a quick bone regeneration is warranted. The mechanical behavior of this material may be considered as orthotropic.

Regarding the Finite Element model, several materials are considered, namely bone, stainless steel, titanium alloy and bone graft. The applied loads generate stresses which are in the elastic range of all these materials. Besides, a common parameter is required to evaluate the severity of such stresses. Accordingly, the Von Mises criterion is used to evaluate the failure conditions of bone and metallic surgical materials. This makes easy the comparison of the results with those reported in the open literature. In the case of the bone graft used in this arrangement, the maximum principal stress is 9.867 MPa, which is lower than 15 MPa.

Figure 6 shows Von Mises stresses, when the 6374.5 N compression load is applied. The critical zones are those adjacent to the contact points. The resultant maximum stress in this case was 9.867 MPa, which is lower than compression stress failure of the cortical bone.

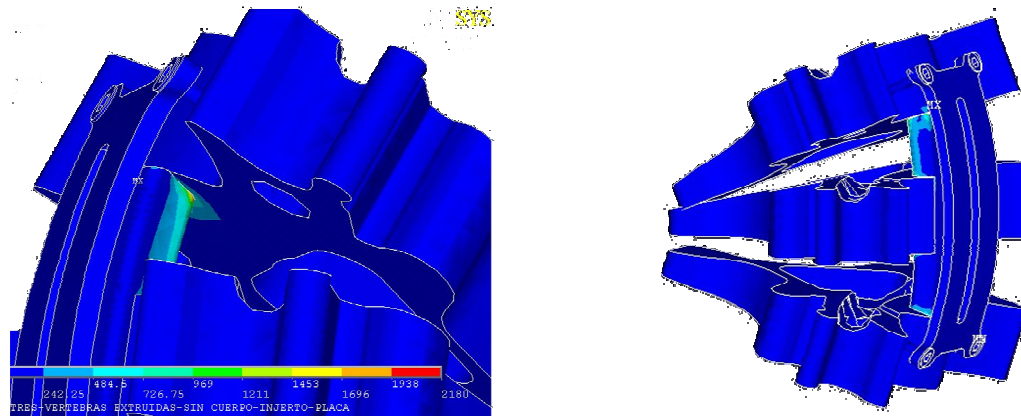


Fig. 6 Von Mises Stresses generated for the FEM Cervical Model.

The inclusion of a cervical plate is utmost importance. It was found that under the bone graft failure conditions, the compression stress obtained (9.867 MPa) is within the allowed limit of failure. As a result it may be considered that the maximum allowed load is around 6375 N. At the same time, the cervical plate is contributing in the structural stability of the arrangement. This is very important, because the bony manufacturers recommend that the compression load should be reduced as much as possible, because of the material fragility.

In accordance with the point of view of the orthopedist, the cervical fusion is benefited, based on the geometry of the bone graft, as it is a wedge that reduces the displacements among vertebral body surfaces of C3 and C5.

4. Conclusions

The displacements on the vertebrae surfaces are smaller than those suggested by Müller [1]. Besides, the resultant stresses show that this arrangement has a good structural integrity. For the bone graft, the stresses were lower than those reported in the open literature [12]. While for the cortical bone of the cervical vertebra it is not expected it to be damaged, because of the same criteria [10]. In accordance with the opinion of the orthopedist, this situation is desired, because the complexity of the surgical procedure is reduced, as no wires are introduced in the arrangement. Furthermore, the resultant stability allows bone regeneration.

In a second part of this work, to be published later, experimental analysis has been carried out with porcine cervical vertebrae. Preliminary results show that the numerical results are in accordance with those obtained experimentally.

5. Acknowledgements

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6. References

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