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Comparative studies of cervical spine anterior stabilization systems - Finite element analysis

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ABSTRACT

Background: The object of the study was to assess the impact of one-level stabilization of the cervical spine for both anterior static and dynamic plates. Segments C2–C6 of the cervical spine, were investigated, from which was determined the stress and strain fields in the region of implantation and adjacent motion segments. The purpose was the comparison of changes that affect the individual stabilizers.
Methods: For testing we used finite element analysis. The cervical spine model takes into account local spondylodesis. The study includes both an intact anatomical model and a model with implant stabilization.
Findings: The analysis covered the model loaded with a moment of force for 1 Nm in the sagittal plane during movement. We compared both the modeled response of the whole fragment C2–C6 and the response of individual motion segments. The largest limitation of range of motion occurred after implantation with static plates. The study also showed that the introduction of the one-level stabilization resulted in an increase in stress in intervertebral disc endplates of adjacent segments.
Interpretation: The results indicate that the increase in stress caused by stiffening may result in disorders in remodeling of bone structures. The use of dynamic plates showed improved continuity strains in the tested spine, thereby causing remodeling most similar to the physiological state and reducing the stresses in adjacent segments

1. Introduction

A large percentage of back pain arises due to overload mechanisms. Dysfunctions of the spinal cord, nerve roots, blood vessels, bone and ligamentous elements of the spine are mostly caused by osteoarthritis, trauma or cancer. Regardless of the etiopathogenesis of a spinal injury, the effects are similar to instability of the spine, and the dislocation of intervertebral discs, as a result of pressure on the structure of the nerve and blood vessels (Czyz et al., 2012). Treatment of significant dysfunction of the cervical spine, resulting from long-term overload, requires the use of the surgical techniques of anterior resection of the intervertebral discs and rear access and the use of implants. This surgical approach with the use of stabilizers is based primarily on the decompression and restoration of spinal function and nerve roots, restoring stability in the damaged spinal motion segment and the reconstruction of the anatomical structure (Bedzinski, 2011). The large number of methods for the treatment of dysfunction of the spine, the plurality of solutions for the construction of implants and the variety of surgical techniques suggest that there is no one certain method. The "gold standard" for surgical treatment of disc herniation is to perform an anterior cervical discectomy and fusion (ACDF) with platelet stabilizers and disc implants (Stein et al., 2014). The incidence of postoperative complications in the case of joints inadequately matched by the structure may result in pseudoarthrosis (Bedzinski et al., 2010). The introduction of the implant causes most change in the stiffness of the spine at the implantation site and adjacent segments, which has a negative impact on the mobility and the distribution of the loads. Dysfunctions of adjacent segments are observed in 25% of patients in ten years after the operation and lead to accelerated degeneration of the spine and the secondary necessity of reoperation (Hilibrand et al., 1999). According to studies conducted by Hussain et al. (2013) this may be the result of hypermobility and unnatural strain values in adjacent levels of the fixation (Hussain et al., 2013). Therefore, the selection of method and the method of treatment require a careful analysis of the functional anatomy and the individual elements of the spine prior to implantation and the prediction of potential changes in their functioning after implantation. As already mentioned, one of the elements is local stiffness. A significant focus of research has been to optimize intervertebral stiffness, including the selection of bone grafts or implants. From observations and research in static systems to prevent implant-induced

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stiffness of the spine, there has been a move to use dynamic plates whose task should be to change the distribution of strains in the adjacent vertebrae (Hakalo et al., 2008). Dynamic plates create the possibility of some mobility, thereby kinematically they are closer to the action of the anatomy of the spine (Connor et al., 2012).

A comparative analysis has been undertaken of studies into the stress and strain caused by cervical spine anterior implantation. One element of this study was to develop a numerical model of the cervical spine (C2–C6) with the use of stabilization of the anterior and local spondylodesis. The aim of the study was to evaluate the effect on the stiffness of the cervical spine syndrome and the strain distribution of plate used to schedule the stabilization, strain, and displacement in the other mobility segments. These studies should provide some assistance in evaluating the selection of stabilization systems, depending on the existing cervical spine dysfunction.

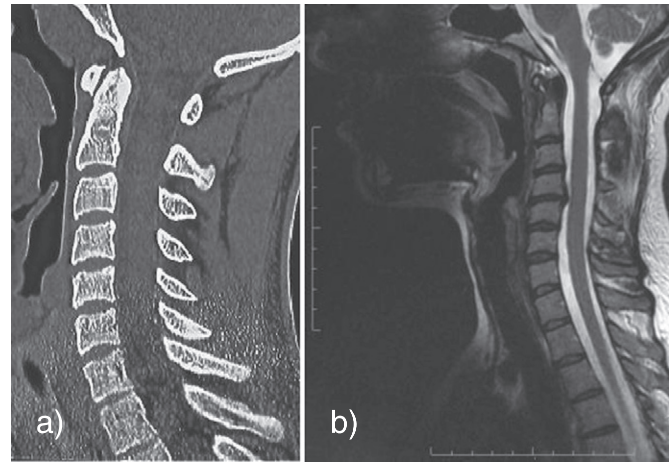

Fig. 1. Images: a) CT of intact cervical spine — base for geometrical model FE b) MRI cervical spine with C4C5 intervertebral herniation.

2. Methods

For the purposes of optimizing the choice of implant construction in addition to clinical and analytical methods numerical methods are also used, including the finite element method. The application of this method requires boundary conditions obtained from experimental biomechanical studies, both numerical and physiological (Bedzinski, 2011). Clinical studies and in vitro experiments, including animal models and numerical models, make it possible to reproduce the mechanisms of damage and dysfunction leading to improved prevention, diagnosis and treatment of the spine (Panjabi, 1998; Kumaresan et al., 1999a, 1999b; Kallemeyn et al., 2009). A key problem is the construction of a numerical model which reflects physiological conditions. Depending on anatomical–functional conditions, model elements are attributed to the characteristics of the non-linear interaction between the other discs, ligaments and soft tissues (Mazgajczyk et al., 2012). Obtaining the distribution of internal forces, which is connected with the strain and stress distribution, can be used to evaluate the biomechanical systems that always refer to the physiological spine. This makes it possible to determine future changes that may occur in the region of the fixation. Studies were performed on single-segment implants made of different biomaterials. Application of the finite element method (FEM) is currently the most commonly used method for simulating spinal stabilization systems, such studies have previously been carried out by Yoganandan et al. (1996) and Teo et al. (2007) (Yoganandan et al., 1996; Teo et al., 2007). A positive aspect of numerical methods is the possibility of non-invasive testing taking into account the differences in anatomical and degenerative conditions in each specific clinical case, which allows for the selection of individual treatment strategies and the design of implants (Kurtz and Edidin, 2006). This paper includes a model of the spine portion composed of five vertebrae (C2–C6), on the basis of a simulation which was verified by analysis of the range of motion and stresses in the segments adjacent to the stabilized region. The C2–C6 model consisted of vertebrae (cortical and cancellous bone), intervertebral discs (nucleus pulposus, annulus grounds and annulus fibers), ligaments and the articular surfaces. During the analysis of the impact of stabilization on the range of motion and the effect of changes in the stiffness of the adjacent segments, it was decided only to analyze the flexion and extension for the moment of force of 1 Nm (Panjabi et al., 2001a, 2001b; Wheeldon et al., 2006). This model was also used in these situations: a physiologically intact cervical spine and dysfunction of the single-segment of the implanted static and dynamic plates (Fig. 1).

We compared both the modeled response of the whole fragment C2–C6 and the response of individual motion segments. It is worth noting that the range of motion segments integrated in the level C2–C6 differed in relation to the individual segments that were analyzed. This observation demonstrates the validity of the segments of the spine model based on experimental studies conducted on the segments and full cervical models on the basis of relevant mechanical testing of the whole segment (Wheeldon et al., 2006; Palomar et al., 2008; Mackiewicz et al., 2014). During the surgical use of the cervical spine implants strain stabilizers were analyzed. There was also a test of the impact of these systems on the stabilization of the spinal motor segment C4–C5 and the segments adjacent to the site of the implant. Stabilizers have different mechanical properties from anatomical structures, which results in significant changes in the kinematics and has an impact on the continuity of the load distribution on the border of the implant-segment from the spine. The tested models reflect the level of spine, which consisted of five cervical vertebrae C2–C6, and they were developed on the basis of the results of computed tomography images (CT) of the spine of a 24-year-old man (Fig. 1a). Data in DICOM format obtained from the CT was imported directly into 10.01 Mimics Materialise 10.1, which enabled the restoration of 3D geometry. On the basis of three-dimensional models a spatial geometric configuration of the cervical spine was prepared. The next stages of the research enabled the establishment of the solid and finite elements shown in Fig. 2.

The study modeled stabilizing plates using 6.13-3 ABAQUS software. In order to copy the shape of the stabilizers, 3D design tiles were made using SOLIDWORKS software (Table 1).

Based on the analysis of the literature, cancellous bone of the vertebrae was modeled with nine-node solid elements, while the cortical bone, due to its small thickness, was modeled with six-node shell elements (Kumaresan et al., 1999a, 1999b; Hussain et al., 2011; Toosizadeh and Haghpanahi, 2011). Simplification assumed that the thickness of the cortical bone is identical over the entire surface of the vertebrae, i.e. 5 mm (Panjabi et al., 2001a, 2001b; Toosizadeh and Haghpanahi, 2011; Jacyna, 2014). On this basis, we received a number of elements respectively for vertebrae:

- C2 not applicable, it was only a geometrical model;
- C3: solid—3933, shell—1522;
- C4: solid—3653, shell—1544;
- C5: solid—3792, shell—1562;
- C6: solid—3218, shell—1558.

The next stage was the modeling of the geometry of the intervertebral disc. The shape was chosen on the basis of the CT image analysis and the literature. The model assumes that the volume of the nucleus pulposus occupies about 50% of the central area of the disc and is constructed of 20-node elements and the external annulus creates 10 layers of fibers arranged at an angle of 45° relative to each other modeled by tendon elements (Kumaresan et al., 1999a, 1999b; Panzer and Cronin, 2009; Kallemeyn et al., 2009; Faizan et al., 2012; Burkhart et al., 2013; Nerurkar et al., 2010). Due to the complexity of the modeling some