FINITE ELEMENT BASED IMPLANT OPTIMIZATION AND PREOPERATIVE PREPARATION

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KEYWORDS –
Lumbar Spine, Finite Element Analysis, Kyphoplasty, Spinal Fusion

ABSTRACT –
Over the past decade the medical sector has been revolutionized through its interaction with modern mechanics and engineering. Human modelling has become ubiquitous to this effort, facilitating bio-realistic preoperative preparation and simulation based optimization of aloplast implants. Lumbar spine pathologies are no exception to this. With a life-time prevalence of 70% they have grown to epidemiologic proportions raising the attention of physicians all over the world. Recent advances in spine modelling have established this methodology as an effective alternative to in vitro examination, as Finite Element simulations allow in situ evaluation of the highly interdisciplinary phenomena governing spine biomechanics.

A dynamic endo-anatomical model of a lumbar spine was developed considering anatomical based mesh generation, non-linear properties, muscle action and solid ligamentous tissue, thus accurately reflecting the constantly altering and highly complex response of the human spine dictated by both, external stimuli and gait.

Based on this model, patient specific surgical treatment for osteoporotic/osteolytic vertebral compression fractures can be preoperatively evaluated. The effect of uni- and bipedicular filling during balloon kyphoplasty was assessed in terms of the retrospective local rigidity and elevation of load transfer to adjacent vertebral levels. This allowed the prediction of post-surgical pathogenesis, as patients diagnosed with a prevalent vertebral fracture have been reported to be susceptible to further trauma by a fivefold increased risk.

The model was furthermore employed to optimize the integration spinal fixation implants, in treatment of deformities or immobilization of degenerative intervertebral discs, to determine the resulting stiffness and the loss of overall mobility.

1. INTRODUCTION

Lumbar spine pathologies are reported as one of the most prevalent trauma in industrialized environments and thus dominate the interest of orthopedic surgeons [Waters, 1993]. Spine biomechanics are however characterized by highly interdisciplinary phenomena entailing hundreds of muscle reactions activated during every day activities. Finite Element (FE) modelling has emerged as a valuable technique, elucidating in situ stress development within the spine and indicating regions susceptible to critical loading. The complexity of these models increases at an amazing pace as there consists a consensus throughout literature that patient specific models should consider non-linear properties and solid ligamentous tissue [El-Rich 2009], which are vital to determine etiology of spinal injury.

Vertebral compression fractures (VCFs) are an increasingly common occurrence among spine pathologies, primarily caused by osteoporosis or malignancies [Cooper 1992], while epidemiologic studies foresee an increase of related pathologies [EPOS 2002]. Patients diagnosed with a prevalent vertebral fracture are considered susceptible to further trauma in adjacent spine levels, a phenomenon that has been extensively addressed in literature [Heaney 1992, Lindsay 2001]. Balloon kyphoplasty is a minimally invasive surgical treatment for VCFs with promising clinical potential, during which a filler material is percutaneously injected into a cavity of a degenerated vertebral body, created by an inflatable tamp. Even though the pathogenesis of follow up fractures has been experimentally investigated both in vitro [Boger 2007, Berlemann 2002] and in vivo [Fournol 2007] it still remains widely inconclusive whether VCFs are a potential sequela of the reinforcement procedures, as indicated by retrospective clinical studies [Fribourg 2004], or a symptomatic condition of the gradual loss of bone mineral density due to evolving osteoporosis [Uppin 2003, Grados 2000]. The first part of this investigation aims at determining the effect of cemented augmentation on the load transfer to adjacent vertebral levels through advanced FE simulations of various surgical approaches.

Spinal fusion is the second topic in this paper. This procedure is primarily used to relieve pain due to abnormal vertebral motion caused by degenerative conditions. Spine fixation is also considered the preferred approach for the restoration of deformities, i.e. scoliosis and kyphosis [Rajae 2012]. Late techniques favour immobilization and are able to restore extensive congenital and degenerative deformities, are however susceptible to prolonged diurnal loading causing loosening and eventual failure [Cho 2010]. Even though some FE studies have been employed to study the occurring biomechanics of transpedicle screw fixation (Faizan 2012), the effect of several surgical related aspects on the load transfer and increase in stiffness of the treated spine segment still remains elusive. The developed model was employed to determine the effect of implantation angle and depth as well as that of the immobilization material on the resulting stiffness and load transfer within the fused spine segment.

2. METHODS

Model development

A FE model of a bio-realistic lumbar (L1-L5) spine is introduced to compare the biomechanical response of its healthy state to the postsurgical one for two types of invasive procedures. The bony model was reconstructed through medical imaging techniques (high resolution CT). The intervertebral discs (IVD) and connecting ligaments were reverse engineered based on the surface of the interposing vertebral bodies [Tsouknidas, 2012]. The final preoperative model is illustrated in the left part of figure 1.

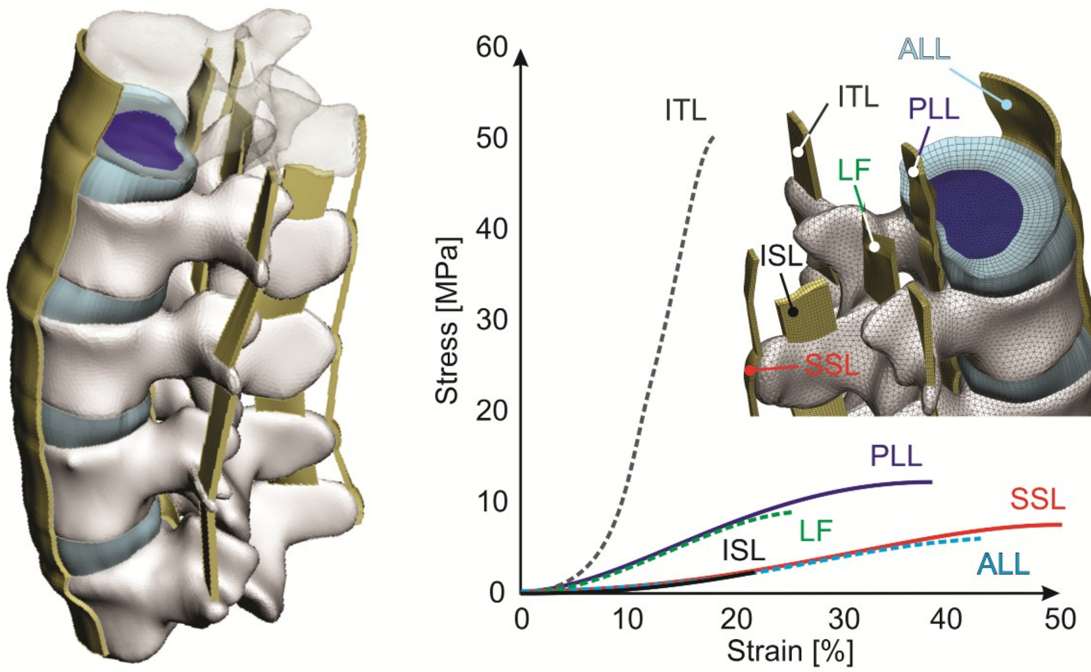

Figure 1 – Lumbar spine model and mechanical properties of ligamnets.

The mesh grid was generated in ANSA, in order to consider anatomic characteristics (i.e. integration of annulus collagen fibres). The Vertical Force Component (VFC) of the ground reaction force during a mild running scenario was considered as the applied load. The model was simulated in Abaqus with non-linear, stress strain dependent material properties (see figure 1), thus allowing insight to occurring dynamic response of the spine segment.

Model Verification

When targeting a clinical audience, the verification of the theoretical model becomes a fundamental aspect of the investigation (Viceconti 2005), as erroneous predictions may yield catastrophic complications.

In this context the development of a mesh independent grid was considered a key feature of the analysis. Convergence studies, conducted separately on every model entity, indicated the optimum mesh density in terms of processing time and results accuracy. To avoid element shear locking which may occur during the simulation of visco-elastic tissue, reduced integration elements were employed throughout the model. This approach however has been reported to lead to the appearance of hourglassing and was therefore combined with second order elements consisting of at least 4 element layers (for ligamentous tissue), to further supress these phenomena.

Model Validation

The introduced model was validated based on a trend analysis (Lund 2012), thus emphasizing on the soundness of the conceptual model. The model was divided into sub-entities i.e. IVD/vertebrae and their simulated biomechanical response compared to heuristically determined benchmarks values (compression, torsion, extension and flection) presented elsewhere (Tsouknidas 2012). The intact model behaviour was then evaluated against existing in vivo studies (Panjabi et al. 1994) for several loading scenarios. Based on the foregoing setup, the developed model is accepted to provide an adequate degree of confidence for a qualitative risk estimation of the procedure variables involved in kyphoplasty.

3. RESULTS

The effect of kyphoplasty on the load transfer to adjacent spine levels

Ellipsoid cavities, imitating 3ml PEEK reinforcement, were inducted into the L4 vertebrae (see figure 2) to examine load transition over the adjacent levels towards L3 and L5. A typical developing von Mises stress field for bi-pendicular filling (at mid stance) is demonstrated in right part of figure 2, corresponding to a cross-section in the transverse plane. Uni- and bi-pedicular filling were found to exhibit varying stress fields, suggesting that the biomechanical response of the FSU depends not only on filler material but also on the injected volume and distribution (Chevalier 2008).

As the simulation considers dynamic loading of the spine segment, it was expected that the highest stress would develop mid-stance, corresponding to the active peak of the vertical ground reaction force during propulsion. The dynamic evolution of the max von Mises stress in the adjacent endplates is demonstrated in figure 3. The plotted values correspond to the highest stress recorded in either one of these spine levels.

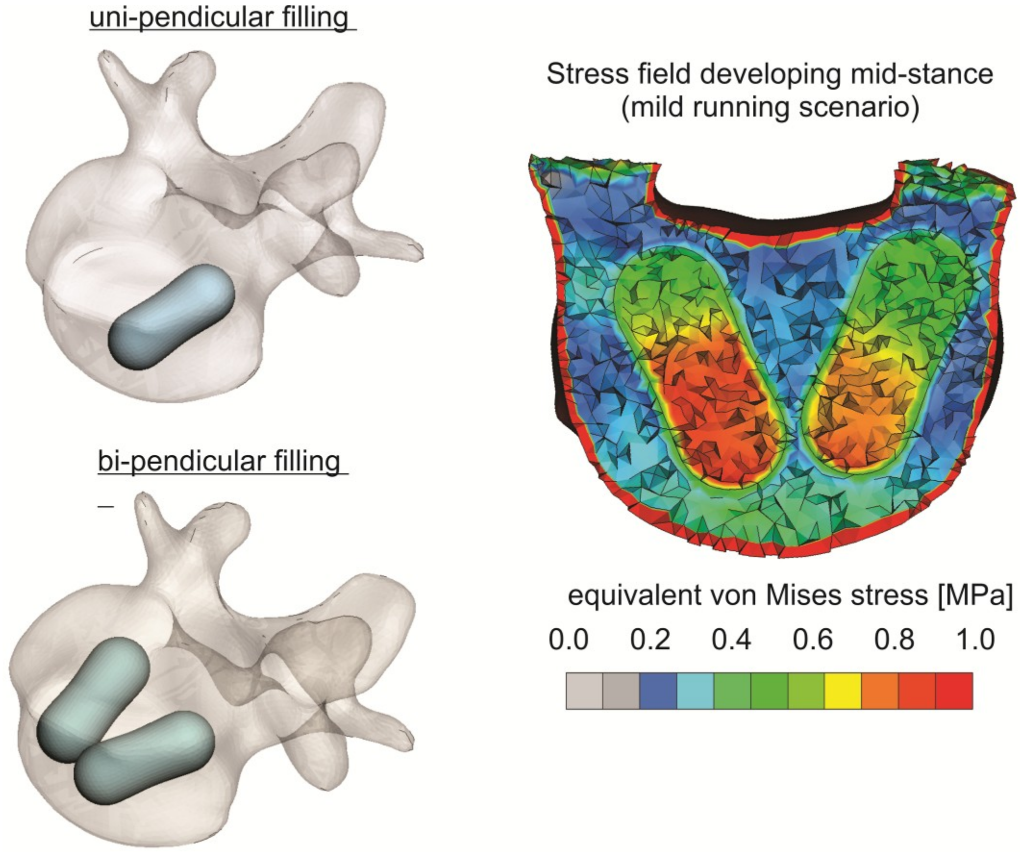

Figure 2 – Uni- and bi-pendicular kyphoplasty and typical stress field for the symmetrical implantation.

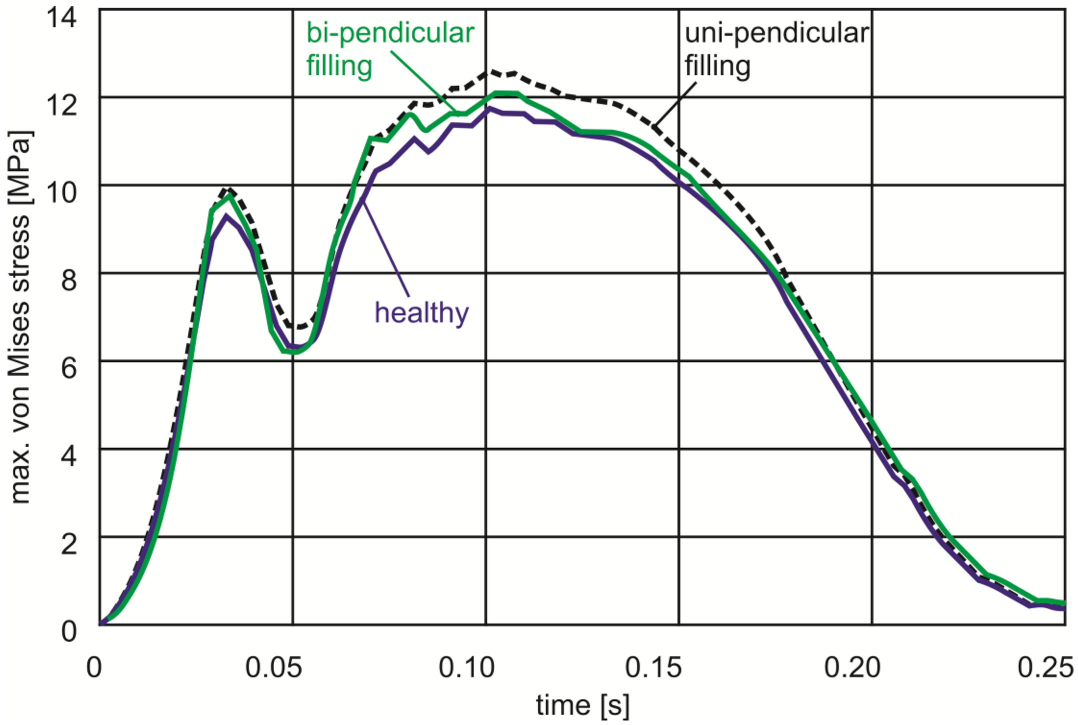

Figure 3 – Dynamic evolution of the calculated max stress in the adjacent vertebral endplates.

Patient specific optimization of spinal fusion

A polyaxial pedicle screw with a double lead thread and a provisional locking system was considered as the main component of the spinal fusion device. This implant type facilitates spanning of screws over adjacent vertebral levels, at a predefined relative angle within the

sagittal plane. The effect of the insertion angle was investigated on the preliminary hypothesis that altering the geometry of a pedicle based fixation will affect the load transfer within the system and thus result in different stiffness values. Two rod materials (Ti alloy and PEEK) were simulated during the analysis to quantify the effect of fixation stiffness and developing stress field. The implantation depth was considered as the final surgical parameter.
The pedicle screw was scanned with a μ-CT device (Werth TomoScope HV Compact) at a spatial resolution of 10μm, to reconstruct its 3D shape. Some features of the implant were considered as redundant for the analysis (i.e. the internal immobilization mechanism) as their consideration would increase the complexity and computational effort, without contributing to the bio-realisticity of the model.
A compressive load of 50 N was applied on the superior screw whereas the inferior one was restricted of any movement. A second loading scenario, corresponding to 10 Nm torsion of the vertebral column, was also adopted. The model was simulated in ANYS 14.0 considering linear elastic material properties [Gornet, 2011].
The implantation of the pedicle screws at a 10° relative angle, lead to a stress decrease of approximately 10% for the Ti and 15% for the PEEK rod scenarios when compared to parallel placemenrt, as illustrated in figure 4.

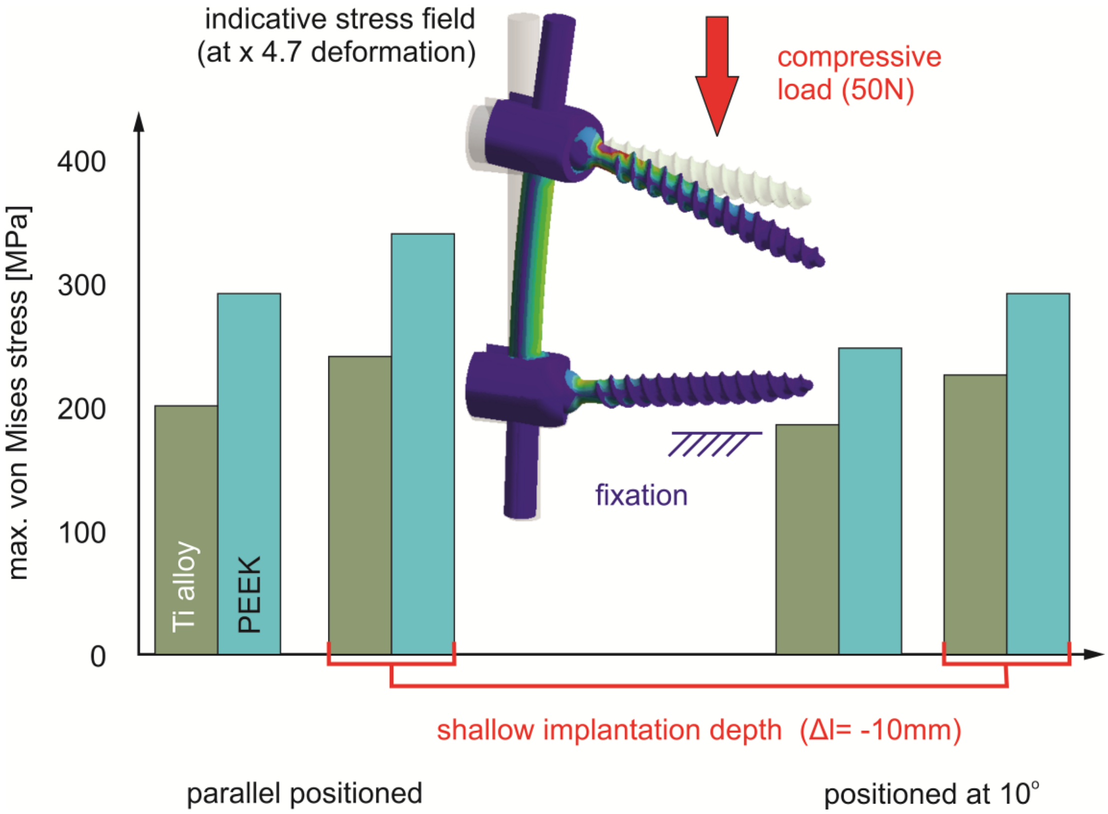

Figure 4 – Parameter dependent max. von Mises stress developing on a transpedicle screw.

Parallel positioning in return, resulted in higher stiffness of the fixation system. The range of motion increased significantly for PEEK based immobilization [Gornet, 2011] and shallow implantation. This was even more pronounced during the application of torsion. The simulated displacement values for the two rod materials as well as the implantation depth and relative angulation are demonstrated in figure 5.

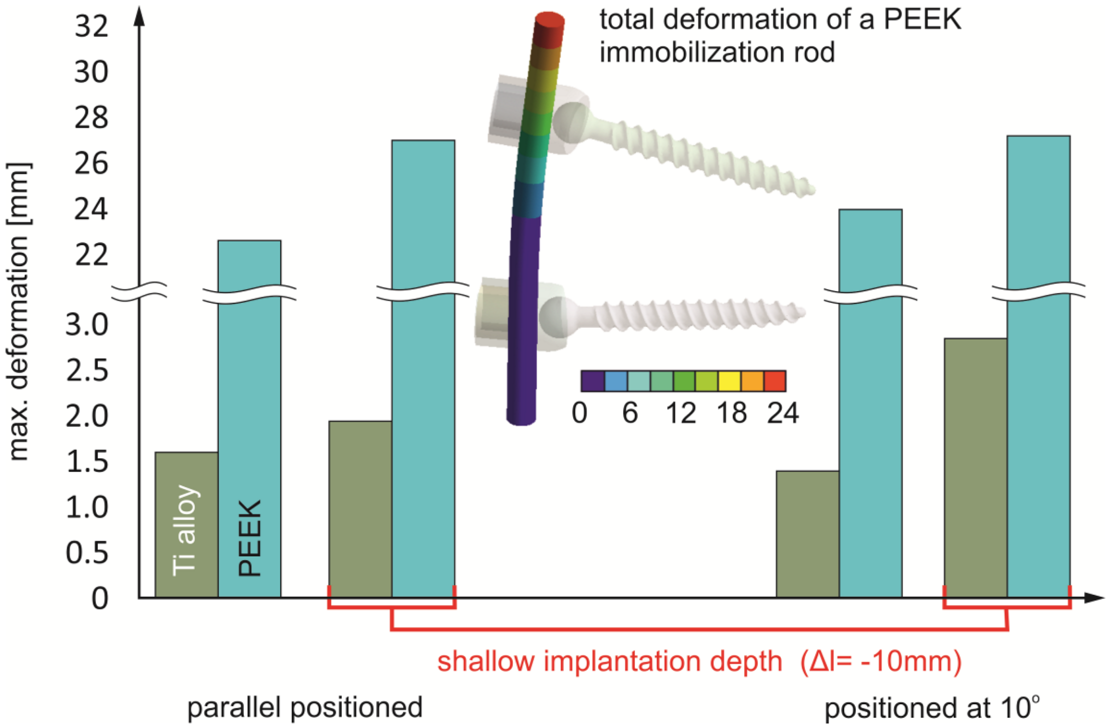

Figure 5 – Impact of surgical parameters on the stiffness of the fixation system.

4. CONCLUSIONS

Kyphoplasty

The results of our study contradict the statement that kyphoplasty predisposes adjacent spine level secondary fractures, as no significant biomechanical changes in the load transfer to the adjacent non treated spine levels were recorded. Is likely that follow-up fractures are related to the natural propagation of the initial pathology and the change in spine biomechanics due to the kyphotic dysplasia.
In all cases, the spine level inferior to the treated vertebral body, was registered with a higher fracture risk than other adjacent vertebrae and thus, its state should be considered during preoperative preparation.
Bi-pendicular filling exhibited a more uniform stress distribution within the treated vertebra, comparing favourably to uni-pendicular reinforcement in terms of endplate loading.
Kyphoplasty should be, in retrospect, considered as beneficiary to the load transfer within a traumatized spine segment as it reverses the initial deformity to an adequate degree.

Spinal Fusion

The simulated results indicate that implantation during spinal fusion should be always performed as deep as possible. Parallel screw positioning is preferable for non-osteoporotic patients and the choice of rod material depends on desired rigidity. Osteoporotic patients should be treated with Ti rods and inclined screws positioning, in order to avoid critical stress development within the vertebrae.

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