Finite element based surgical optimization

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1. Finite Element Modelling in Biomechanics

The medical sector has always been a technology driven field, dominating the interest of engineers, biologist and chemists in a complimentary symbiosis with clinicians. Joining these translational disciplines, in the socio-economic quest towards effectively treating a continuously aging population, has led to the sophistication of both medical devices and implants. As surgical practice continues to evolve, patient specific implementation is gaining notable importance, transforming Computer Assisted Surgery (CAS) into one of the highest paced segments of the international healthcare system. CAS facilitates the conversion of preoperative images and other information into 3D models of individual patients, providing clinicians with haptic support during preparation of complex and/or delicate surgical procedures.

Over the past decade FE based medical modelling has risen from its period of infancy to become ubiquitous in biomechanics, from implant development (figure 1) and CFD analysis (figure 2) to clinical optimization. Even though simulation experts have developed sufficient predictive techniques, they are still struggling to reach a degree of clinical applicability and modelling is hitherto used predominantly for demonstration purposes. Extrapolating however conclusions from small collectives to the general population would yield erroneous statements, since the influence of inter-patient variability (gender, age, genetic predisposition, disease etc.) could considerably impair the prognostic capacity of the calculated results. The main obstacle however to the wide integration of customized FE modelling into preoperative planning lies in the multi-scientific expertise and the extensive effort required to develop patient specific models.

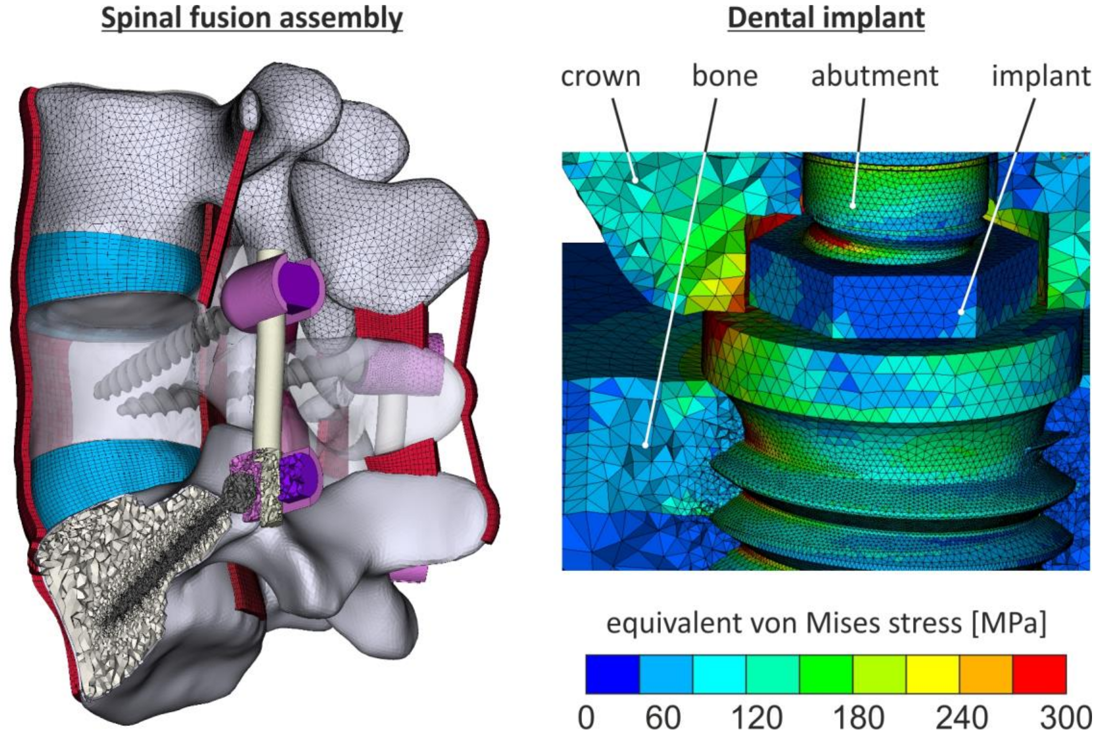

Figure 1: **FE based implant development and optimization**

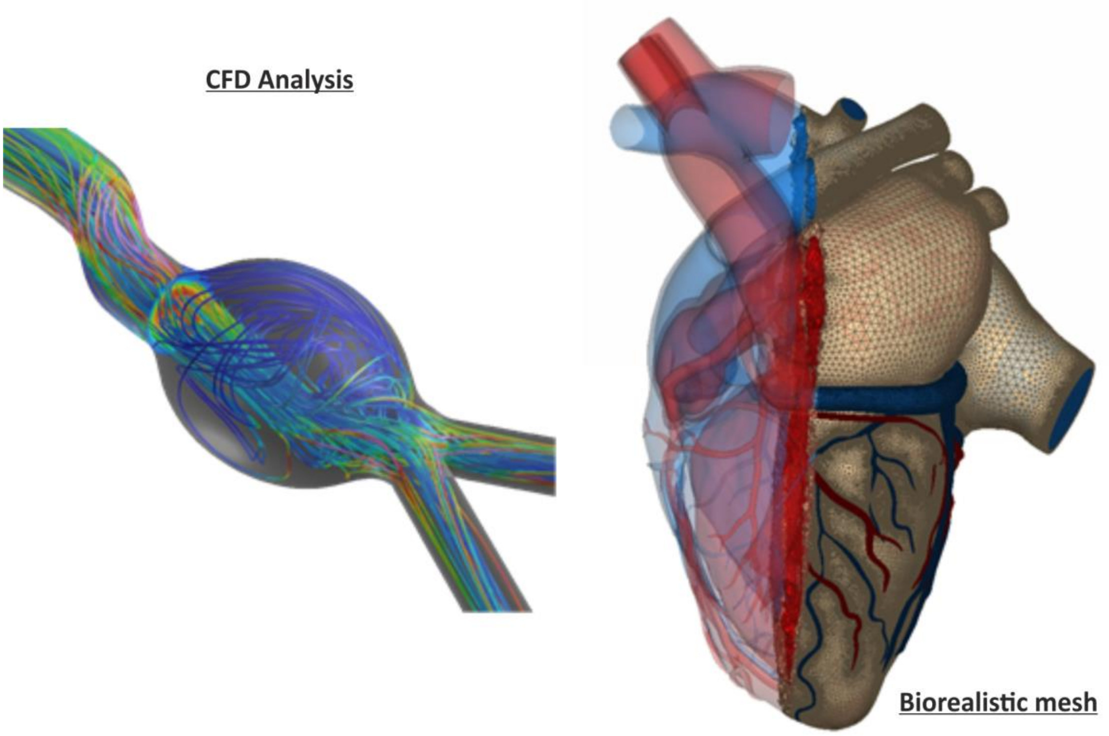

Figure 2: **CFD Analysis of an aneurism and a CAD/meshed heart model**

Recent literature suggests the use of application-specific software packages to overcome limitations arising predominantly in the preprocessing of such models, as current leaps in computational efficiency provide ostensibly higher performance, thus facilitating the simulation of exceedingly complex models.

This article provides insight to the clinical optimization of kyphoplasty based on the exploitation of a series of advantages provided by the mesh oriented pre-processor

ANSA and post-processor μETA (BEAT CAE Systems S.A.) and is intended as a proof of concept for related procedures.

2. FE based Surgical optimization of Kyphoplasty

FE anatomy models are hereditarily complex systems, as the co-existence of hyper-elastic materials (e.g. ligaments) with uncompressible ones (e.g. intervertebral discs) and entities of high structural integrity (e.g. bone and implants) complicates the integration of an explicit mesh approach. A recent example of a lumbar spine model, nominated amongst the finalists for the ISB Clinical Biomechanics award [2], was employed towards the optimization of kyphoplasty, a minimally invasive treatment for Vertebral Compression Fractures (VCFs). The present article highlights some results of this study with future procedure related aspects modelled thereinafter.

Kyphoplasty is based on the percutaneous injection of a filler material into a cavity of a collapsed vertebral body, created by an inflatable tamp. Next to reversing kyphosis, cemented augmentation increases the local rigidity of the treated vertebra and retrospective clinical studies have indicated this as potential etiology for follow-up fractures in adjacent spine levels. The pathogenesis however of secondary trauma remains subject to controversy within medical circles, as they could well be a symptomatic condition of evolving osteoporosis [3].

Surgical scenarios

A bio-realistic lumbar (L1-L5) spine was used to compare the biomechanical response of its preoperative state to the postsurgical cemented augmentation. The aim was to determine the degree to which kyphoplasty exaggerates force transmission to the adjacent vertebral bodies, thereby rendering those levels susceptible to future VCFs.

A variety of surgical scenarios was evaluated against a reference (healthy model). Bi-pedicular filling with Polymethyl-methacrylate (PMMA) was examined for sequential high restorations (-15^{o} to $+5^{o}$ to the anatomical correct curvature of the spine) as illustrated in figure 3. Recent literature [1] suggests that the effect of the remainder post-surgical kyphosis may considerably increase the load transfer to spine levels adjacent to the augmented body, thus predisposing them to echo fractures. This is based on the initial hypothesis that the VCF, imposes a progressive sagittal deformity onto the spinal column, thus shifting the upper body's centre of gravity anteriorly and altering the patient's gait.

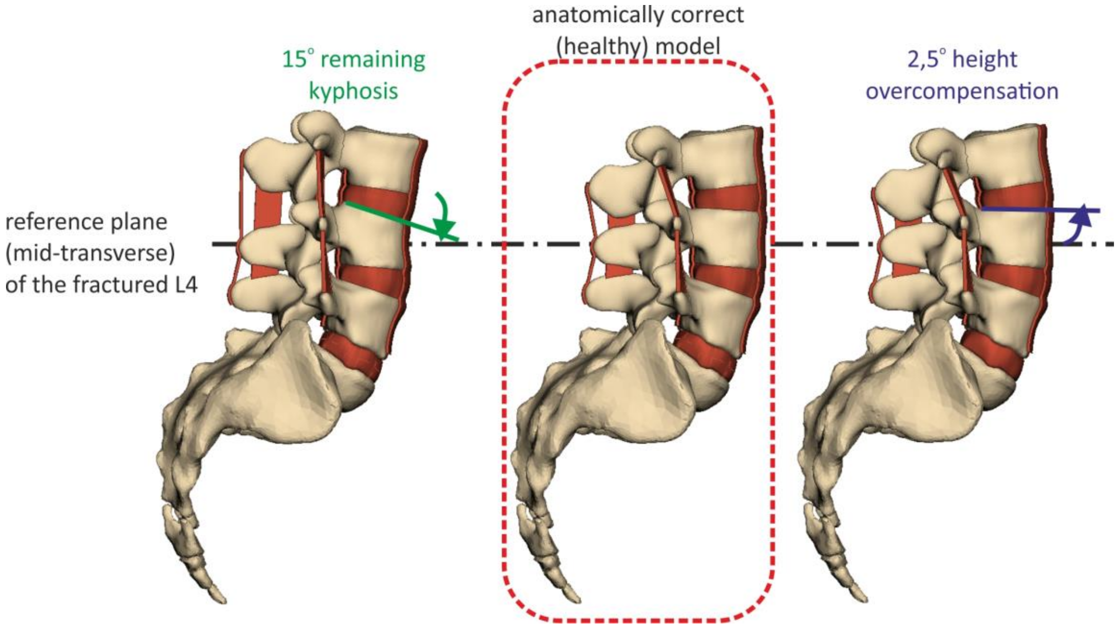

Figure 3: Range of height restoration considered in the post-operative models.

The wedge shaped VCF was induced through morphing and re-meshing the L4 and balloon kyphoplasty was modelled through two 3ml ellipsoid cavities symmetric to the sagittal plane of the traumatic vertebra. The L4 was selected based on epidemiologic studies [5] indicating a higher fracture prevalence in the L4-5, with the L4 facilitating insight to load transfer to either one of the adjacent levels (L3 and L5).

The relevant angulation of these reinforcements was the final parameter of the investigation, based on the assumption that the reinforcement-nucleous pulpous superimposition (as demonstrated in figure 4) would alter the force transfer to adjacent vertebral levels due to the nucleous pulpous load absorbing capacity.

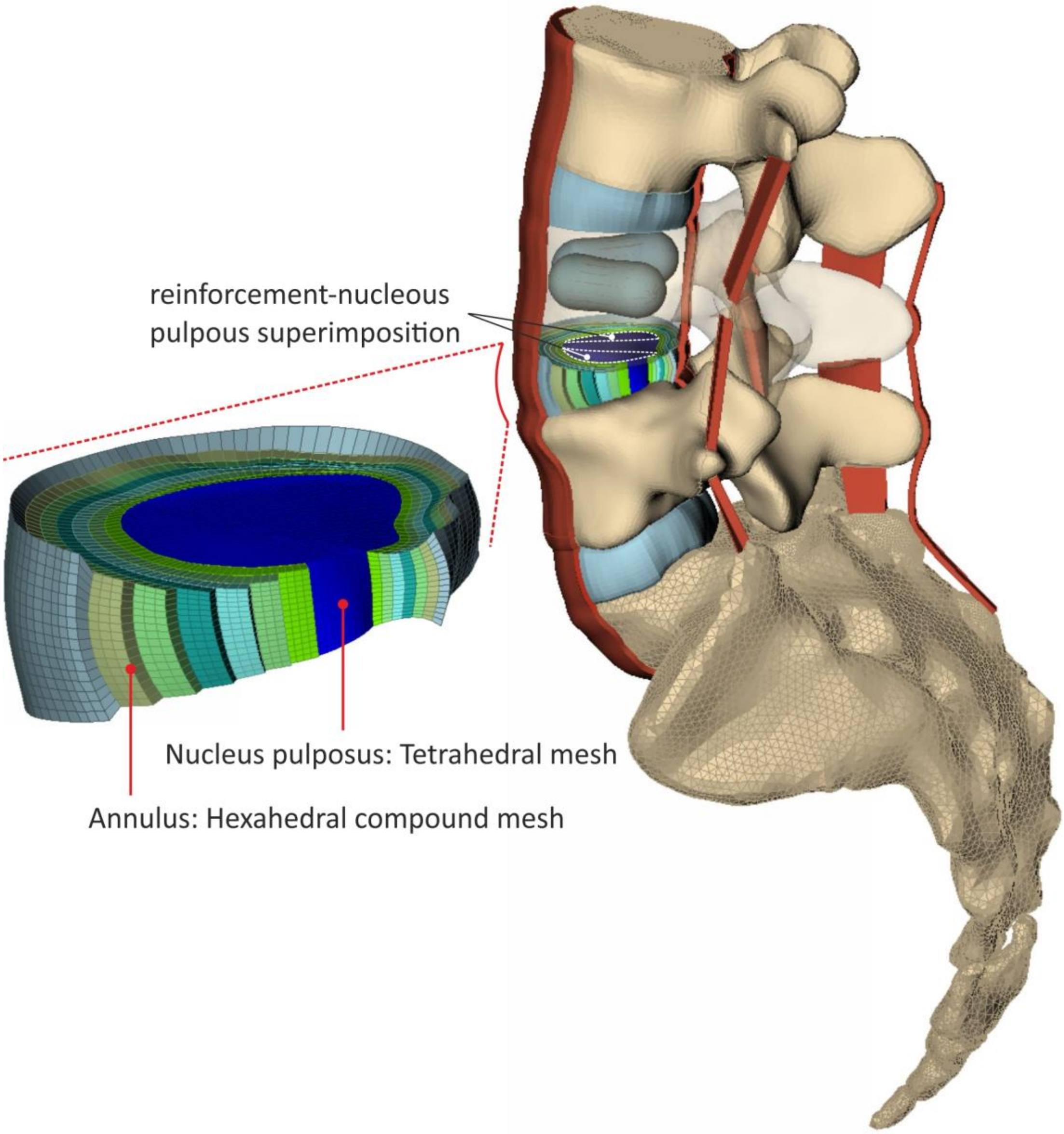

Figure 4: Details of the mesh grid and considered reinforcement-nucleous pulpous superimposition.

The model considered the Bone Mineral Density (BMD) of a progressive osteoporotic male since VCFs are classified predominantly as osteoporotic fragility fractures [4]. The load considered during the analysis corresponded to the stance phase of a mild running scenario, while further details (material properties, boundary conditions etc.) relating to the model can be quoted from [2].

Development of a mesh independent spine model

Achieving a degree of sufficient bio-realisticity is of fundamental importance when targeting a clinical audience, since an inherent difficulty of computational biomechanics is associated to the soundness of the model itself. In this sense, the verification of the theoretical model becomes an intrinsic aspect of an investigation [6], where erroneous predictions may yield catastrophic complications.

The development of an optimized mesh grid, is therefore a key feature of any numerical analysis involving the human anatomy. Uncompressible materials, for instance, require reduced integration elements to avoid element shear locking, which may in return provoke hourglassing. To suppress these phenomena, higher order elements and multiple material layers are used, an approach which is however complicated when meshing small fractions of a larger model. The nucleus pulposus of intervertebral discs (IVDs) within the human spine, is a material conventionally modelled as uncompressible and surrounded by elements of anatomic specific characteristics (e.g. element ration and orientation). The annulus fibrosus, structured peripheral to the nucleus, is accurately modelled by compound elements consisting of several layers proportional to the disc's endplates. These hexahedral elements foster crosswise positioned cable elements integrated at predefined angles within the element. Introducing mixed grid generation usually results in non-conforming interfaces which decrease computational efficiency. Combining mixed element technique with node sharing interfaces was another significant advantage of employing a mesh oriented pre-processor, which also eased the integration of entity based convergence studies. This ensured the use of optimum mesh density in terms of processing time vs. results accuracy, while maintaining vital geometric characteristics (e.g. feature lines) throughout the model.

3. Results-conclusions

The results presented refined clinical insight into the biomechanics of a reinforced spine segment. The most critical spine was consistently the one inferior to the treated vertebra (as shown in figure 5), emphasizing the relevance of its state to preoperative planning.

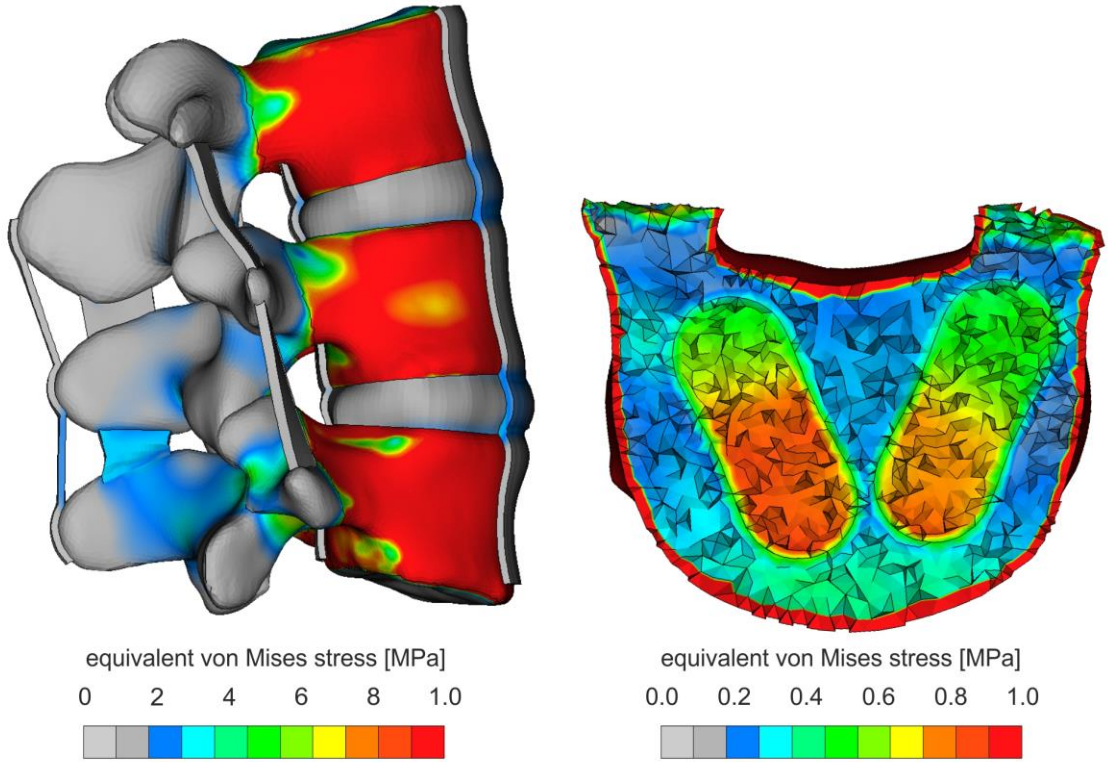

Figure 5: Characteristic Stress distribution of a realigned spine segment [2].

The simulation indicated the importance of procedure related parameters e.g. nucleus pulposus – implant superimposition, which couldn't have been identified neither in vitro nor in vivo. The results call for a center ward injection of the reinforcement material. This should act protectively towards the integrity of the IVDs, even in elderly, where the effect of this superimposition on the load transfer will be less pronounced due to disc degeneration.

The initial hypothesis of the dominating effect of remainder (post-surgical) kyphosis on fracture risk was validated, indicating a strong enslavement of height restoration to critical stress concentration in vertebral endplates adjacent to the augmented body. This can be attributed to alterations in the sagittal balance of the spine. A similar behavior was observed when overcompensating the wedge shape of the fracture, stressing the significance of realigning the spine to an anatomically healthy posture.

In retrospect kyphoplasty is likely to predispose adjacent spine level to secondary VCFs, which is however strongly associated to the surgeon's ability to reverse the kyphotic deformity.

4. *References*

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