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REVIEW ARTICLE

Computational modelling of bone augmentation in the spine

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Summary Computational models are gaining importance not only for basic science, but also for the analysis of clinical interventions and to support clinicians prior to intervention. Vertebroplasty has been used to stabilise compression fractures in the spine for years, yet there are still diverging ideas on the ideal deposition location, volume, and augmentation material. In particular, little is known about the long-term effects of the intervention on the surrounding biological tissue. This review aims to investigate computational efforts made in the field of vertebroplasty, from the augmentation procedure to strength prediction and long-term *in silico* bone biology in augmented human vertebrae. While there is ample work on simulating the augmentation procedure and strength prediction, simulations predicting long-term effects are lacking. Recent developments in bone remodelling simulations have the potential to show adaptation to cement augmentation and, thus, close this gap.

Introduction

Demographic changes are among the most important challenges for our society in the 21st century. Advancements in modern medicine have reduced mortality rates and many members of our society are expected to reach old age. While there are about 810 million persons aged $\geq$ 60 years today, by 2050 this number is expected to surpass 2 billion [1]. As a consequence, the number of workers available to support one elderly person will decrease from eight to four in only 40 years [1]. If we want to ensure access to effective health care for the elderly population, we will be forced to control and reduce emerging costs. A key element will be the focus on the management of age-related diseases.

A particularly widespread disease among the elderly is osteoporosis—an illness that is characterised by a reduced bone mass and a concomitant increased fracture risk [2]. The morbidity of all osteoporotic bone fractures is

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substantial and severe cases in the spine and hip are also coupled with elevated mortality [3]. Osteoporosis is a major problem for health care systems because these fractures are frequent and often need extensive treatment. Recent estimates show that osteoporotic fractures cost the European Union €36 billion every year, and these costs are expected to more than double by 2050 [4].

A significant share of the financial burden is due to vertebral fractures. Estimates of clinically diagnosed vertebral fractures show that the lifetime risk of vertebral fractures at the age of 50 years can be $>$ 15% in women [5]. Worldwide, $>$ 1.4 million vertebral fractures are estimated to occur every year [6]—that is one fracture every 23 seconds. The yearly cost for osteoporotic fractures in the spine sum up to a total of €719 million in Europe alone [4]. Research in novel treatment options for spine fractures might therefore not only help reducing pain and impairments for patients, but also support controlling rising costs in general health care.

Vertebral compression fractures, mostly occurring in weak osteoporotic bone, are painful [7]. It is assumed that, in particular, the deterioration of the trabecular microstructure in the course of the disease leads to an increased fracture risk [8,9]. Patients typically need bed rest and are treated with medication [10]. However, advances in biomedical engineering give hope for a more widespread use of new intervention approaches that will help to reduce the period of bed rest, pain, and the need for pharmacologic treatment or even ideally prevent fractures. A particular potential lays in bone augmentation procedures such as vertebroplasty, because of the minimally invasive nature of these approaches. Vertebroplasty is an intervention where bone cement is injected percutaneously through a cannula into the fractured vertebral body to restore its mechanical stability [11]. With advancements in fracture risk assessment [12] potentially weak vertebrae can be detected and targeted prior to fracture. Thus, we hope in the future to use vertebroplasty to also prevent fractures by augmenting vertebral bodies that were previously defined as fragile.

Despite vertebroplasty being a straight-forward intervention, the close location of the vertebral bodies to vital organs and the spinal cord demands the reduction of side effects to an absolute minimum. Bone augmentation stabilises the spine and leads to functional improvements [13,14]. In addition, pain relief is reported in most cases [13—17], although some studies could not confirm greater pain relief compared with conservative treatments [18,19]. The immediate complications reported with vertebroplasty are mainly connected to cement leakage [14], but it remains unclear what the long-term impact of the intervention is. A strong but controversial concern with bone augmentation in the long-term is the occurrence of fractures in adjacent vertebrae due to the increased stiffness of the augmented vertebra [20,21].

Like in many other biomedical branches, the increased capability of computational tools opens new doors for the investigation of bone augmentation. Such tools allow not only studying the mechanisms of disorders, but also surgical treatments. Initially, computational models in musculoskeletal applications were based on idealised, simplified structures. Today, these models are typically based on image-derived geometries from computed tomography (CT) or magnetic resonance imaging and can thus be individualised to the specific patient [22]. In recent years, finite element (FE) analysis in particular has become a frequently used versatile, general purpose simulation tool. Not only does it allow a detailed description of the mechanical load transfer in the spine before and after vertebroplasty, but such simulations have the potential to predict optimal augmentation patterns and cement distribution for individual treatment planning. Advanced *in silico* experiments, modelling the biology of the bone, can help to better understand the long-term risks and outcomes of augmentation interventions. This review aims to describe the efforts made in computational modelling of bone augmentation in the spine, focusing on the clinical intervention itself, the biomechanical situation after the treatment, and predictions of the long-term outcome.

Computational modelling of the bone augmentation procedure

Vertebroplasty is a minimally invasive intervention to restore and stabilise fractured vertebrae by augmenting the bone with cement, typically polymethylmethacrylate. The bone cement is injected under local anaesthesia percutaneously through the back of the patient by means of a large-bore needle or cannula, directly into the vertebral body. The injection is monitored in real time with fluoroscopic guidance in order to assure deposition in the proper location, as well as to avoid cement leakage. It is important to keep the patient resting during the subsequent cement hardening period of about 1 hour [11,23].

More advanced imaging techniques could allow not only a more precise deposition of the cement, but combined with computational methods they have the potential to help the surgeon in the planning of the intervention for each patient by predicting the best position of the needle for the cement placement and by defining the optimal filling volume. Moreover, such simulations would also help to select or develop cements optimised for a specific intervention.

A simple approach on the organ scale to define the incision point and angle for the injection needle is described by Kobayashi et al [24]. Although it does not directly require computational tools, the method follows an algorithm and aims to target the middle of the cement deposition area and thus the needle position. On a horizontal CT scan at the level of the pedicles, the target is determined as the anterior one-third point along the median line. The incision point and angle are then derived by simulating the needle passing through the pedicle. The method assists treatment planning and allows a single incision for the bone augmentation.

A computational model of vertebroplasty including the needle incision and the cement injection is presented by Chui et al [25]. The model is designed for a virtual training setup and includes visual as well as haptic feedback. In order to be rendered in real-time, it is kept relatively simple, but still considers structures at tissue level. The resistance for the needle insertion is calculated in two phases; the cortical bone as a linear elastic material, the cancellous bone with the highly computationally efficient