

In silico finite element modelling (FEM) in the realm of femur trauma

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Abstract

Introduction: Pertrochanteric femur fractures are bone traumas that are difficult to manage, with a substantial rate of union failure. Excessive stress exerted on the fragmented bones can cause nonunion, which requires salvage surgery. Bone stress as the underlying mechanism of nonunion is as yet unassessable, which makes it difficult to choose the method of restabilisation.

Aim of the research: We adopted an innovative method of *in silico* finite element modelling (FEM) to retrospectively simulate the pattern of stabiliser-bone stress distribution changes in proximal femur fractures, which may underlie the lack of osteosynthesis necessitating salvage surgery.

Material and methods: FEM concerned proximal femur A2 and A3 fractures in elderly patients who required restabilisation due to a failure to achieve union. The modelling was entirely virtual, with no patient involvement at any stage, and based on X-ray bone contour projections. We chose the non-standard ZESPOL method for restabilisation, in which the stabilising system is mounted about 10 mm apart from the bone surface.

Results: FEM showed the presence of substantial stabiliser-bone stress before achieving the union. ZESPOL stabilisation equalised and reduced stress, ending up in a full union.

Conclusions: An outstanding difference in stress distribution between the conditions of nonunion and union after salvage surgery reaffirms the conceptual basis for the stress-induced role in union failure. ZESPOL is viable stabilisation in difficult-to-treat conditions of pertrochanteric fracture nonunion. FEM can help in decision-making concerning the type of surgical repair needed for the optimal disburdening of compressive stress to accelerate osteosynthesis.

Introduction

Pertrochanteric fractures are common and sharply on the rise, accounting for nearly half of all hip fractures [1]. Primary pertrochanteric fractures are usually treated surgically with a lateral plate implant of a dynamic hip screw (DHS) or intramedullary gamma nails (GN) [2]. The success rate is variable, and nonunion occurs in about 2% of all fractures due to a variety of reasons [3, 4]. In the case of long bones, it may be as high as 20% [5]. The incidence of pertrochanteric fractures is increasing due to osteoporosis and falls occurring along the continuing extension of lifespan [6]. Destabilisation of fracture surgical fixation occurs mainly due to appreciable inner bone loss in the femur neck and head. Also, infections or allergic reactions to implant materials may occur [7, 8]. Pseudoarthrosis or nonunion is likely caused by an excessive stress load on the fragmented bones enhanced by patient non-compliance. Complications leading to

nonunion involve patient handicaps and pain and are clinically and socioeconomically costly. In such cases, salvage surgery is considered [9]. The decision about the kind of restabilisation is usually made on an individual basis, considering multiple factors, most notably the patient’s condition, fracture pattern, and bone and hip joint quality [10].

Among the various methods of restabilisation, one in which the plate stabiliser is mounted extra-osseously at a few millimetres from the bone surface raises particular interest. The method called “ZESPOL” was investigated in the 1980s–1990s [11, 12] and has been occasionally used since then, although it does not belong to the first-line armamentarium for pertrochanteric fracture fixation as currently recommended by the Association of Osteosynthesis (AO) [13]. In this method, the stabiliser plate is placed in a non-adhering way to the bone surface, which makes it better to take on torsional bone stress and accelerate fracture amal-

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gamation [14]. The inception of the ZESPOL approach likely reflected an intuitive effort to mitigate the structural stiffening of plate fixation that could jeopardise the amalgamation while using standard plate-nut-screw bone stabilisers [8, 10]. ZESPOL appears useful and even irreplaceable in difficult-to-manage operations due to fixation destabilisation conditions of spiral or oblique fractures, multi-fragmentary fractures generating internal bone stress, and bone bridging [15]. However, the skewed bone stress distribution as the underlying mechanism of nonunion has escaped the rigors of scientific verification.

Aim of the research

Here we used *in silico* finite element modelling (FEM) to investigate the pattern of stabiliser bone stress distribution changes in proximal femur fractures reoperated due to a failure of achieving union. FEM showed that the ZESPOL method consolidated the stress leading to its equalisation and reduction in the system, which reaffirms the conceptual basis for its clinical effectiveness.

Material and methods

The Ethics Committee of the Review Board for Research of Opole University in Poland waived the ethical and consent-seeking requirements for this work because it did not fulfil the criteria of a human medical experiment (decision no. 28/2024). This study was a retrospective virtual simulation of bone conditions based on fully anonymised X-rays, with no direct patient involvement in any form and at any stage of work. We reviewed the history files of 5 patients (F/M – 3/2; aged 55–89 years, BMI 30–40 kg/m²) who suffered from single-level fall-induced PT fractures. We created and evaluated *in silico* 2D FEM models based on anteroposterior X-ray bone contour projections of 3 patients randomly selected out of the 5, one with type A2 and 2 with type A3 fractures according to AO classification. The fractures were initially surgically stabilised with GN or DHS, respectively. Stabilisations failed without the union due to post-operative complications in 3–5 months. Restabilisation with GN was considered perilous in patients with degeneration of spongy content of the femur's neck in patients suffering from obesity and at risk of severe mobility handicap due to already obstructed hip joint adduction. Therefore, the ZESPOL method was chosen for surgical reconstruction with the application of axial pressure on bone fragments. In all patients, complete bone union was achieved in the following 4 months. After that time, patients began to fully bear weight on the operated limbs. The treatment results obtained after the reconstruction were fair/good (70–90-point range) according to the Harris Hip Score.

FEM is a computational assessment of stress appearing in solids under the influence of various external factors, using the algorithms of machine learning techniques. The modelling was performed using biomechanical and computational principles like those described previously in detail [16]. In the present work, FEM served to predict stress endpoints at the interfaces among the bone, anastomoses, and the stabilising system. Based on the anteroposterior X-ray of an AO-A3 femur fracture, a methodological vignette of the bone-stabilisation stress modelling is presented in Figure 1. Briefly, the image domain was divided into neighbouring areas interconnected with nodes composed of solid linear finite elements of 0.5 mm size, creating a mesh of individual material properties whose characteristics changed during simulation of external strain or load application. These characteristics were described by 2 indices: Young modulus (E) – indicating how much the material stretched and deformed under tensile stress, and the Poisson number (λ) – indicating the mean number of events occurring over a specific time.

The model's boundary conditions were restraints corresponding to the femur neck-head bone tissue according to the gravity force at the top and the densification layer at the bottom. The introduction of the boundary conditions system allowed the tracing of a degree of node displacements, which pertains to stress changes in parts of the image representing different bone tissues and fracture fixation elements. As a result, it was possible to quantify stress intensity. The image was then digitally processed into a bitmap in which a shade of grey, out of 256 conceivable shades, was allocated to material characteristics using CT2FEM 1.0 computer software (Mrzygłód, Cracow University of Technology, Cracow, Poland). *In silico* modelling was supported by Ansys computer software (Ansys Inc., Canonsburg, PA).

In silico FEM was performed after the reoperation to assess the stress distribution changes about the proximal femur, which could potentially underlie the repair failure. It was performed twice: a couple of months after the reconstruction but before achieving the union and about 4 months later after obtaining X-ray proof of union.

Results

Figure 2 A shows a representative example of AO type A3 pertrochanteric fracture. It was surgically treated using DHS, but the stabilisation failed after 4 months. The patient was then subjected to salvage surgery using the ZESPOL method, where the implant elements adjacent to the lateral surface of the proximal part of the femur shaft were mounted extra-osseous about 1 cm off the femur bone surface. The lasting full unions appeared 4 months afterward.

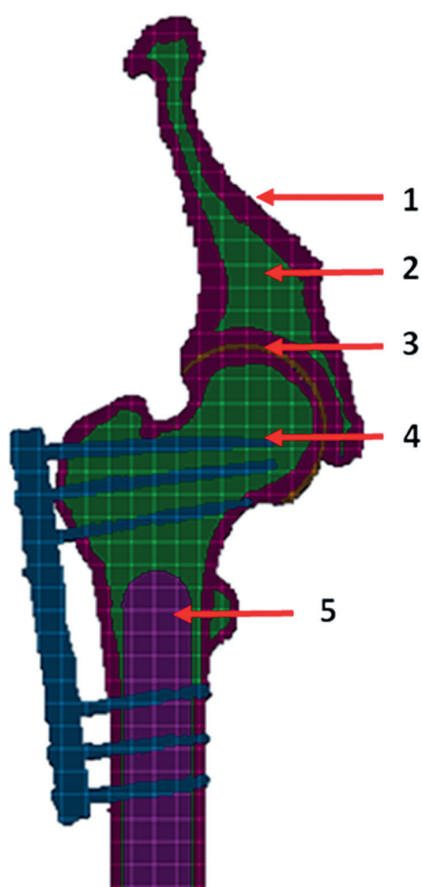


Figure 1. Schematic representation of finite elements modelling (FEM) of stress distribution in AO-A3 type of pertrochanteric femur fracture before union, based on an antero-posterior X-ray contour image. The scheme shows material properties assigned to individual areas depicted by colour: 1 – compact bone (Young modulus $E = 5 \text{ GPa}$, Poisson number $\lambda = 0.32$), 2 – spongy bone ($E = 3 \text{ GPa}$, $\lambda = 0.32$), 3 – articular cartilage ($E = 600 \text{ MPa}$, $\lambda = 0.42$), 4 – implant elements used for osteosynthesis ($E = 210 \text{ GPa}$, $\lambda = 0.30$), 5 – marrow cavity ($E = 0.6 \text{ MPa}$, $\lambda = 0.42$)

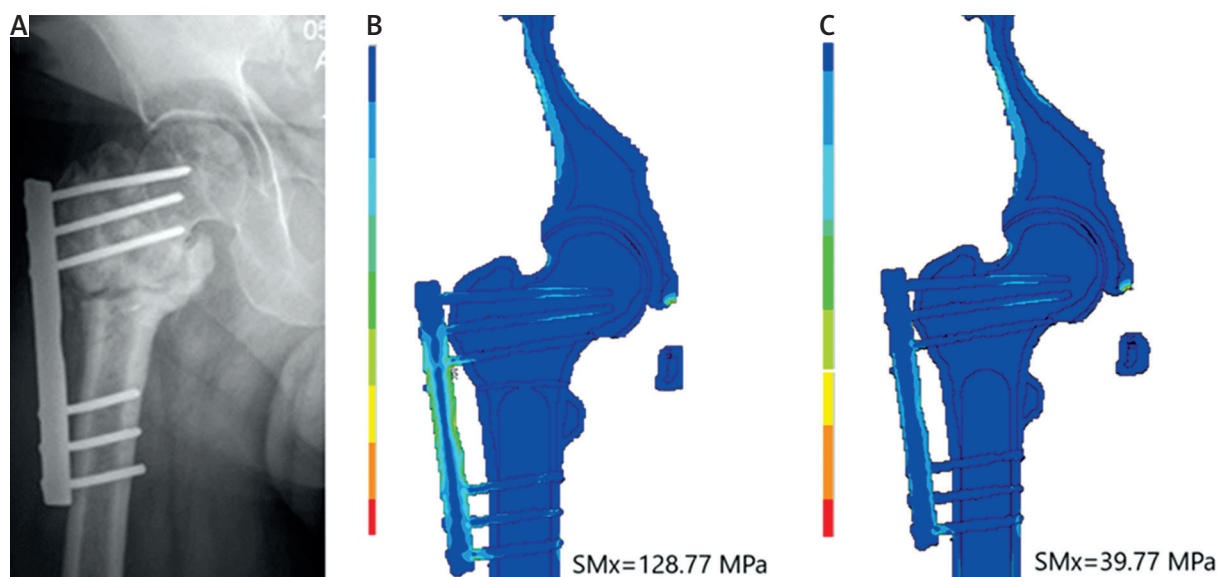


Figure 2. Pertrochanteric fracture type AO-A3 before union treated with ZESPOL stabilisation during salvage surgery. **A** – salvage surgery using ZESPOL fixation after the failure of dynamic hip screw system; **B** – Corresponding in silico finite element modelling (FEM) showing high stress taken on by the stabiliser; **C** – Full union with equalised and lower stress in the bone-stabiliser system. The implant's elements are adjacent to the lateral surface of the proximal part of the shaft of the femur
SMx – stress maximum in the stabiliser-bone system, *MPa* – megapascals.

In silico FEM was performed after the salvage surgery to assess the stress distribution about the proximal femur, which could potentially underlie the repair failure. Before achieving the union, the stabilising plate took on most tension acting on the bone, resulting in a large maximum stress level of 128.77 MPa (Figure 2 B). After achieving the union, the stress was distributed uniformly through the femur and the stabiliser system, with an overall more than 3-fold lower stress maximum of 39.77 MPa (Figure 2 C). The evenly distributed stress disburdens the bone system and is liable to help ensure the long-lasting viability of the union.

Discussion

The study aimed to assess the fixation-bone system stress occurring during the treatment of pertrochanteric fracture malunion after using standard supra-bone stabilisers of the kind GN or DHS for primary surgery. The current clinical routine has it that either fixation unused for primary surgery is used for salvage surgery. However, both apply a screw catching through the spongy bone layer of the femur neck. That is the layer often degenerated appreciably enough not to ensure that the screw is reinserted at a proper long bone-neck angle of about 125–145° for stable osteosynthesis. Here the advantage of the ZESPOL method becomes apparent. Mounting of the implant plate element about 1 cm away from the lateral surface of the proximal part of the femur shaft, reduces the screw insertion angle closer to the proper angle. Screws are then introduced partly through the firmer cortical bone layers, which minimises the loss of bone stock underlying fractures. A biomechanical advantage of ZESPOL could lie in the greater flexibility at the stabiliser-bone fragment junctions and a reduction of the plate-exerted tensile stress on the bone.

Here we acted on the premise that the stress at the stabiliser-bone interface, aside from patient non-compliance, could be a self-perpetuating detriment for proper bone amalgamation. The stress issue, albeit intuitively and empirically conjured, is a matter of guesswork rather than objective and quantitative observation. The issue can hardly be tackled in a controlled and replicable way in the harsh environment of an operating theatre, escaping the rigors of clinical verification. We availed ourselves of *in silico* FEM, attempting to better characterise and predict stabiliser-bone stress distribution in pertrochanteric fractures. FEM is an entirely virtual numerical-based method that allows simulating of the object's response to a given stimulus. In biomedicine, the method works best for the assessment of distribution and changes in structural loads [17]. It fits well into clinical orthopaedic research on traumatic structural stress displacement in bone pathologies, for which it is increasingly used [18, 19]. In the present study, FEM showed the outstanding

difference in stress distribution between the conditions of nonunion and union while using the ZESPOL method for effective pertrochanteric salvage surgery. In the union, stress was consolidated mostly at the stabiliser, taken off the bone, and overall reduced and equalised in the treatment system. FEM can help in decision-making concerning the type of surgical repair needed for the optimal disburdening of compressive stress to accelerate osteosynthesis.

This study has limitations. The number of patients and thus modelling sessions were small, the follow-up was not extended beyond 1 year from the injury time, and intra-method comparisons were unavailable as only one surgical approach could be chosen and performed in a patient. FEM is still in the experimental rather than practical use. The FEM method is not free of software subjective limitations and chosen virtual material and technical peculiarities and approximations. The FEM guidelines have not yet been worked out for use in orthopaedics.

Conclusions

We believe we have shown in this study that the ZESPOL method is a viable option for consideration in the context of difficult-to-treat conditions of salvage surgeries for nonunion of pertrochanteric traumatic fractures, and that the method's osteosynthesis advantage likely lies in bone stress disburdening. FEM appears to be a prompt and useful tool that broadens and refines knowledge on stress distribution changes factoring in osteosynthetic disruptions, which reaffirms the conceptual basis for its clinical effectiveness. The extrapolation of FEM results in clinical scenarios requires further proactive research.

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Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest.

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