In Silico Evaluation of Treatment of Periprosthetic Fractures in Elderly Patients After Hip Arthroplasty

Jacek Lorkowski, Renata Wilk, and Mieczyslaw Pokorski

Abstract

The aim of this study was to investigate the soundness of in silico finite element model (FEM) in the assessment of strain in the femur and in the components fixing the periprosthetic fracture in elderly patients after hip arthroplasty. From a group of 55 patients, aged 27–95, treated due to fractures after hip replacement in 2012–2018, 18 patients were separated out, aged over 85, out of whom 7 had type C fractures, according to the Vancouver classification. These seven patients formed the study group. The fractures were stabilized with a locking compression plate system and wire loops or by replacement of the endoprosthesis stem. The FEM was performed by processing radiological images of the femur, considering the stabilization type and osteoporotic bone characteristics. Each patient's FEM was counter compared to virtual in silico control showing a non-osteoporotic

bone structure. We found that the strain was distinctly greater at the bone-implant interface after surgical stabilization with a multi-hole plate and cerclage wire loops in osteoporotic periprosthetic fractures when compared to the virtual non-osteoporotic bone. We conclude that the in silico model enables the assessment of strain distribution at the bone-implant interface, which helps identify the biomechanical incongruity of traditional bone stabilization methods in patients with osteoporotic bones.

Keywords

Elderly patients · Endoprosthesis · Finite element model · Hip arthroplasty · In silico · Periprosthetic fracture

J. Lorkowski (✉)

Department of Orthopedics and Traumatology, Central Clinical Hospital of Ministry of Interior, Warsaw, Poland
e-mail: jacek.lorkowski@gmail.com

R. Wilk

Department of Anatomy, Health Science Department, Medical University of Silesia, Katowice, Poland

Hope Medical Institute, Newport News, VA, USA

M. Pokorski

Institute of Health Sciences, Opole Medical School, Opole, Poland

1 Introduction

Hip arthroplasty is a frequent procedure to improve quality of life, extend lifespan, and maintain mobility in osteoarthritis (Marshall et al. 2017). In the USA, more than 300,000 such procedures are performed annually, mostly in the elderly people. Technological improvements in implant production and advances in endoprosthesis implantation cause that treatments are carried out in increasingly elderly patients with weak bone structure (Caruso et al. 2018). While the procedure of implant placement usually ends successfully, complications such as

periprosthetic fractures are on the rise, reaching 1.7–4.1% of all arthroplasty procedures (Lee et al. 2018; Marshall et al. 2017). The fractures appear more often after revision arthroplasty than after primary endoprosthesis placement, 6% vs. 1%, respectively. The most frequent cause of periprosthetic fracture is a fall on the flat surface caused by slipping or tripping. However, there also are fractures without previous injury, which points to bone weakness that raises concern in the elderly over 85 years of age who, additionally, may have various comorbidities (Chou and Davis 2017; Marsland and Mears 2012). Female gender, osteoporosis with bone mass loss, rheumatoid arthritis, and osteolytic lesions, particularly in bone areas exposed to load, predispose to fractures (Caruso et al. 2018). According to the Swedish National Hip Arthroplasty Registry, the incidence of periprosthetic fractures is second only to bone infections as complications after arthroplasty, raising socioeconomic issues due to morbidity and mortality (Karrholm et al. 2016). Several classification systems have been developed to assess periprosthetic fractures, which have a varying ability to characterize the fracture in radiographs, the condition of the tissue surrounding bone implant, and the implant fixation (Tower and Beals 1999; Cooke and Newman 1988; Johansson et al. 1981). Currently, Vancouver classification is commonly used. It enables the assessment of fracture size, prosthesis required, and the selection of the best treatment method (Duncan and Haddad 2014).

The Vancouver classification consists of the following fracture types:

- Type A, fracture passing through the greater and lesser trochanters;
- Type B, fracture along the length of endoprosthesis, passing through the medial margin of the femur, which is further subdivided into:
 - Type B1, with preserved implant stability and good quality of bone matrix around the implant;
 - B2, with loose endoprosthesis but good quality of bone structure;
 - B3, with loss of stability of endoprosthesis and bone of deficient structure;
- Type C, fracture extending below the endoprosthesis (Marshall et al. 2017).

The assessment of implant fixation in type B and C fractures is often subjectively made by a surgeon who performs anastomosis (Huang et al. 2018), which may have a bearing on a greater number of reoperations in these categories. Type C fractures create the largest clinical difficulty since they hamper balance and locomotor stability, often resulting in repeat fractures (Pavone et al. 2019; Randelli et al. 2018). The current standard is to schedule surgery, based on the evaluation of the patient's condition supported by radiographs. In advanced age, extensive procedures take toll on the patient, so that surgical decisions should be weighed with caution. In such situations, the finite element method (FEM), based on a rapid 2D modeling, seems of potential applicability, to assess the distribution of strain occurring in the implanted bone. Therefore, the main purpose of this study was to investigate the soundness of an *in silico* FEM model for the assessment of strain in the femur and in the components fixing the periprosthetic type C fractures in elderly patients after hip arthroplasty.

2 Methods

In this retrospective study, 18 elderly patients, aged over 85, were separated out of a group of 55 patients, aged 27–95, treated due to femur fractures after hip replacement surgery performed between 2012 and 2018. Seven out of the 18 patients had type C fractures, according to the Vancouver classification. These seven patients formed the study group. The fractures were stabilized with a locking compression plate system and wire loops or by replacement of the endoprosthesis stem. Out of the remaining 18 patients, 5 had type B1, 3 had type B2, and another 3 had type B3 fractures. Type B fractures, usually occurring in bones having better structural quality, were not considered in this study.

Treatment outcome in type C fractures was evaluated 1 year after surgery using the Harris Hip Score (HHS) for the assessment of pain and joint mobility. The mean HHS score for this group was 71 ± 4.4 (SD) out of 100 points possible to achieve, which is considered a fair result (Harris 1969). In silico rapid modeling of fracture stabilization was based on patients' X-ray images of the femur obtained in the process of diagnosis and treatment. The method evaluates the strain arising in solid-state elements, which the bone belongs to, in the area initially divided into a specific number of simple finite elements that connect to each other at certain points in the periphery, called nodes (Lorkowski et al. 2018). After determining the distribution of the physical quantity inside finite elements, i.e., shape functions of nodes, calculations of differential equations for nodes are performed, while in the remaining parts of finite elements, the equation solutions are approximated. Then, boundary conditions are introduced into the system of equations, and the values of the physical quantities of interest in the nodes of interest are obtained. In this study, the degree and type of displacement in the nodes were determined, which allowed for the calculation of bone strain values.

Patients' X-ray images were used to make a geometric model of the femur with the implant and anastomosis used to stabilize the periprosthetic fracture. The model simulated fixation used for a fracture and stabilization depending on the bone parameters in elderly patients. Each osteoporotic patient's FEM was counter compared to virtual in silico control, containing the assumed healthy-like bone structure of a young adult with the corresponding distribution of elemental strains. The images were subjected to in silico modeling combining bone dynamics and FEM simulation, which allowed to visualize specific changes occurring in bones with different than normal characteristics, e.g., due to osteoporosis but also caused by the type fixation and by the endoprosthesis itself. The FEM model was created by automatically converting X-ray images

considered as a bitmap composed of 256 grayscale elements in the computer program CT2FEM 1.0. The program assigns the appropriate FEM value to each modulus of the grayscale element. Next, the created model was loaded into Ansys Discovery Design software (Canonsburg, PA) to divide the finite elements into groups representing different tissues, such as compact or spongy bone, and the materials the endoprosthesis and fracture fixation components were made of.

Bone strain can be described by Young's coefficient and Poisson's coefficient for elasticity of solids. Young's modulus is the ratio of tension arising in the material to the elastic deformation caused under the influence of acting force. It varies depending on the tissue being analyzed. In our case, 4 values were important, representing the examined tissues and the metal used for fixation: 5 GPa for compact bone, 3 GPa for spongy bone, 300 MPa for connective tissue and marrow cavity, and 210 GPa for fixation metal. In case of advanced osteoporosis in the elderly, the above standard values representing Young's modulus of bone elements were halved. Poisson's coefficient, on the other side, is the ratio between transverse strain to the corresponding axial strain. It was determined as 0.32 for all the tissues. Fragments of the FEM model representing different regions could be turned off or on as separate subgroups for the analysis. All fragments of a given type of tissue were treated in the same way (Wirtz et al. 2000).

3 Results

Final analysis of in silico modeling included the following types of stabilization of type C fractures on osteoporotic patients:

1. Multi-hole plate, three cerclage wire loops, and four screws in the distal segment.
2. Multi-hole plate, three cerclage wire loops, and five screws in the distal segment.

The screws in the distal segment were passing through the whole bone, i.e., across the opposite layers of cortical bone. Additionally, at the level

of endoprosthesis in the proximal segment, there were three screws, passing through only one cortical bone layer, and cerclage wire loops in both types of multi-hole plate stabilization above outlined. The results of FEM analysis obtained for either type of stabilization is exemplified below.

Re 1 Peri-implant strain in an elderly patient with advanced osteoporosis and a femur fracture stabilized using a four-screw multi-hole plate and three cerclage wire loops was 792.215 MPa at the fracture level (Fig. 1a). For comparison, the strain was reduced to 738.189 MPa, i.e., by 6.8% in the corresponding virtual model of a non-osteoporotic bone (Fig. 1b). Likewise, there were reductions in strain at the levels of the remaining three screws in the hypothetical young bone. Reductions in strain

were also noticed both above and below the anastomosis. The largest strain in the patient's in silico model, double that present at the fracture site, appeared below the downmost screw, where there also was the largest strain reduction in the virtual model of young bone, exceeding 100 MPa.

Re 2 Peri-implant strain in an elderly patient with advanced osteoporosis and a periprosthetic femur fracture stabilized with a five-screw multi-hole plate and three cerclage wire loops was 789.956 MPa at the fracture level (Fig. 2a). The strain was reduced to 737.180 MPa, i.e., by about 7%, in the corresponding virtual model of a control non-osteoporotic bone (Fig. 2b). Akin to the four-screw stabilization model, the strain was increasing toward the distal bone segments in both true osteoporotic and virtual non-osteoporotic bone

Fig. 1 Frontal plane image. In silico finite element method (FEM) analysis of distribution of biomechanical strain in periprosthetic type C femur fracture stabilized with a multi-hole plate and four screws distally. Additional three shorter screws, passing through only one cortical bone layer, and three-wire couplings are visible in the proximal section: (a) real image of osteoporotic bone in an elderly patient, (b) virtual model corresponding to the same but non-osteoporotic, hypothetically healthy-like bone; red mark in "a" marks the fracture gap

Fig. 2 Frontal plane image. In silico finite element method (FEM) analysis of distribution of biomechanical strain in periprosthetic type C femur fracture stabilized with a multi-hole plate and five screws distally. Additional three screws, passing through only one cortical bone layer, and three-wire couplings are visible in the proximal section: (a) real image of osteoporotic bone in an elderly patient, (b) virtual model corresponding to the same but non-osteoporotic, hypothetically healthy-like bone; red mark in “a” marks the fracture gap

models, being correspondingly lower by about 10% in the latter bone model. The strain amounted to 1580.000 and 1474.000 MPa, i.e., by 6.7% in the downmost bone segment, respectively (Fig. 2b).

Strain evaluation was also made after stabilization of a prosthetic femur fracture using a multi-plate four screws passing only through one cortical bone layer below endoprosthesis as seen in the proximal sections of the presented images. Differences between the true osteoporotic fractures and their corresponding virtual vis-a-vis were here less expressive. The bone strain was comparable in both osteoporotic and non-osteoporotic models above the fracture, in a range of 592 MPa and 599 MPa. The maximum strain was noticed at the fracture level, amounting to 2,309 MPa in osteoporotic and 2,397 MPa in

non-osteoporotic segments, an increase by about 4%. Stabilization of a femur fracture using a multi-hole plate and five screws passing through one cortical layer provided comparable strain values (data not shown). Thus, mounting the plate only to the underlying cortical bone layer blurs the difference in strain between the osteoporotic and non-osteoporotic conditions and shows a fourfold increase in strain at the fracture level.

4 Discussion

Periprosthetic fractures are a serious complication in patients after hip arthroplasty. Especially, type C fractures that appear below the prosthesis shaft are challenging to treat. Typically, treatment includes dynamic compression plates, plates and

cerclage wires, and non-locking plates. It is essential to choose the right length of a stabilizing plate. A shorter plate allows for a shorter surgical incision, reduces trauma to soft tissues, and shortens the surgery time. However, bone strain between the end of a prosthesis shaft and the proximal edge of a plate is high, risking a secondary fracture.

Another issue is the number of screws and wire loops used for the plate mount. Increasing their number and extent may cause unpredictable shifts in bone strain or raise substitute strains in other bone parts, leading to dysfunctional bone elasticity and eventually to prosthesis destabilization or repeat fractures (Lorkowski et al. 2014). Based on the present findings, we submit that mounting a metal plate using four screws, passing across the bone, with three cerclage wire loops suffices to achieve the optimum outcome. This conclusion stems from the results of *in silico* FEM modeling which showed that an increase in the number of screws to five caused a rather superfluous drop of about 4–5% in the strain along the femur bone, including the level of a multi-hole plate when compared to four screws. The assessment we made mostly concerned bone biomechanics. It did not include a biological context, for instance, peri-screw or bone itself infections or other bone pathologic conditions. It did include however osteoporosis, all too often occurring in elderly patients. Further, rapid comparing of the true patient's osteoporotic bone with its virtual non-osteoporotic, healthy-like counterpart enabled the assessment of changes in the strain distribution pattern caused by osteoporosis. We noticed that osteoporosis enhanced the bone strain around the multi-plate stabilizer of a femur fracture by about 7%, irrespective of the use of four or five screws. Nonetheless, the enhanced strain in periprosthetic fracture due to osteoporosis may be viewed as another argument to use fewer rather than more screws to maintain adequate osteoporotic bone elasticity.

When stabilizing a fracture, it is necessary to use cerclage wire loops above the prosthesis. Some surgeons also use additional shorter screws that pass through one cortical layer, reaching

down to the level of an endoprosthesis (O'Toole et al. 2006). The *in silico* model of this study failed to confirm that the use of cerclage wire loops prevents the occurrence of a relatively high bone strain at the level of a multi-hole plate. Moreover, the use of plate screws passing through only one cortical layer at the level of endoprosthesis did not lead to a significant strain reduction along the entire length of bone subjected to anastomosis.

Choosing a correct method of stabilizing type C fractures is a matter of uncertainty in therapeutic decision-making. The questions arise to what extent plate osteosynthesis should be used and whether plate stabilization of a fracture should be combined with the revision prosthesis. An obvious disadvantage of stabilization with a plate, particularly in the elderly, is a longer time required for mobilization of a limb operated on. In case of revision arthroplasty, physical mobilization is possible much earlier. However, arthroplasty, particularly with additional plate stabilization, is a much more extensive and thus aggravating procedure. In principle, all types of anastomosis share similar doubts. In patients with periprosthetic fractures, treated in a classic manner with open reduction of bone displacement and internal fixation (ORIF), the percentage of failures reaches 33% in all fracture types (Pavone et al. 2019). Zuurmond et al. (2010) have shown that 12 (55%) of 21 patients with type C fractures, who had a standard anastomosis with a non-locking plate or plates with cerclage wire loops, required reoperation. Better results have been noticed using locking plates in the less invasive stabilization system (LISS) for fracture fixation in another study, in which 11 of 12 patients have a post-surgery course free of complications (O'Toole et al. 2006). In the remaining patient, the plate broke down and required a replacement into a longer one. In another study, open reduction of bone displacement and double-plate fixation resulted in good outcome, with anastomosis union, in six of nine patients with type C periprosthetic femoral fractures (Lee et al. 2018). The three remaining patients had poor outcomes with nonunion, due mainly to

osteoporosis. In two of those three patients (80 and 82 years of age), a secondary femur fracture took place below the anastomosis 2 and 4 weeks after fixation with double plates and wires. The two patients underwent revision surgery, using a double-plate anastomosis covering a longer length of a femur, with good long-term outcomes. In the third patient, in whom the plate failed to anastomose resulting in a new fracture, good outcome also was present 24 months after replacement for a double-plate anastomosis.

Patients with type C fractures supplied with classic ORIF stabilization have often recurrent fractures that are far more difficult to treat (Randelli et al. 2018). Another issue is revision prosthesis replacement, if required, using a compression plate to stabilize the periprosthetic fracture. We have previously described an elderly patient with perioperative fracture in whom the distribution of strain occurring during fracture stabilization was at the bone-anastomosis boundary greater compared to the average control. A high level of strain appeared linked to the excessive number of cerclage wire loops used (Lorkowski et al. 2014). These results give a consistent impression that in elderly patients with osteoporosis, treated with classic anastomosis, a check on the strain distribution over the bone should be an indispensable clinical intervention to achieve the best post-surgery outcome and to minimize a risk of secondary fractures and reoperations. To this end, FEM modeling enables the selection of the most appropriate method of anastomosis while scheduling surgery. A 2D version of FEM provides prompt results, approximately in 1–2 h, which seems the optimum time to fix a fracture from the biomechanical standpoint, as opposed to 3D modeling that due to structural complexity requires 20- to 30-fold longer timeframe.

In patients with periprosthetic fractures, X-rays are part of routine examination, as opposed to less used computed tomography. At present, X-rays are the best source for in silico FEM modeling. The method contains several software-driven simplifications that tend to unify various tissues examined. Therefore, a model

contains approximations and rounding of details of bony structure, but the evaluation appears sufficient to illustrate changes taking place in the bone strain after application of different types of anastomosis. Further, the method appears well-suited to appraise the level of osteoporosis, particularly in the elderly patient and spare additional complications and suffering related to surgical revisions, prosthesis exchanges, or repeat fractures.

FEM modeling, based on the solid-state biomechanics, was originally created to aid arthroplasty and orthopedic implants. Recently, the method has become of increasing interest due to potential diagnostic and therapeutic utility also in other medical fields, with some adaptations to fluid mechanics. The method has been studied, *inter alia*, for the prediction of an extent of post-traumatic lung injuries, which includes the evaluation of the accompanying lung inflammatory components (Danelson and Stitzel 2015; Lorkowski et al. 2015). Other novel applications of FEM extend to the evaluation of the biomechanical properties of the eustachian tube that connects the middle ear to the nasopharynx, which has to do with cartilage stiffness and mucosal adhesion in otitis media (Malik et al. 2016). Modeling of coiling deployment during endovascular interventions for intracranial aneurysms (Damiano et al. 2019) or the evaluation of a rupture risk of abdominal aortic aneurism (Siika et al. 2019; Soto et al. 2018) are other examples of this apparently burgeoning field of medicine. Biomechanical fingerprinting of lung tissue perfusion changes underlying inflammatory disorders seems an intriguing possibility to enhance the diagnostics of SARS-CoV-2 pneumonitis and the like.

In conclusion, using the finite element modeling, we found that stabilization of type C periprosthetic fractures in the elderly patients is bound to enhance femoral strain at the bone-implant interface, due likely to osteoporotic bone changes. The strain is distinctly greater compared to that present in the young bone counterpart. In silico modeling enables the assessment of bone strain arising in periprosthetic fractures

after hip arthroplasty, which helps identify the biomechanical incongruity of traditional bone stabilization methods.

Conflicts of Interest The authors declare that they have no conflicts of interest in relation to this article.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Due to a retrospective nature of the material used in this study, a requirement to obtain approval from a local ethics committee as well as informed consent from individual participants were waived.

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