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# *In Silico* Analysis of Bone Tension During Fixation of the Medial Malleolus Fracture After Ankle Joint Endoprosthesis

Jacek Lorkowski, Renata Wilk, and Mieczysław Pokorski

**Abstract**

Total ankle arthroplasty (TAR) is a procedure alternative to arthrodesis which enables the biomechanical stabilization of the ankle joint. The procedure is associated with a high risk of complications, including fractures of the medial malleolus. In this study, the finite element method (FEM), based on CT examinations, was used to model the ankle fracture fixation after TAR. Three types of fracture stabilization were considered: screw, Blount staple, and both screw and Blount staple. In the *in silico* model, the maximum stress tension was found at prosthetic junctions with the base, cone, and talar components of the tibial prosthesis. When the fracture was stabilized with the Blount staple, tension along the cone of the tibial component was about 12% of the maximum tension. Stabilizations with the screw alone or Blount staple combined with a screw on the medial side of the cone induced tension in the immediate vicinity twice as high. In the area of the medial malleolus, the tension was alike for both types of stabilization. The tension was lowest when using the Blount staple alone. We conclude that, contrary to the hitherto clinical routine of using screws, fracture fixation using the Blount staple leads to the lowest bone tension around the fixation of the medial malleolus fracture after ankle joint endoprosthesis.

**Keywords**

Ankle arthroplasty · Ankle joint · *In silico* · Finite elements · Periprosthetic fracture · Talocrural joint

J. Lorkowski (✉)
Department of Orthopedics and Traumatology, Central Clinical Hospital of Ministry of Interior, Warsaw, Poland

Faculty of Health Sciences, Medical University of Mazovia, Warsaw, Poland
e-mail: jacek.lorkowski@gmail.com

R. Wilk
Department of Anatomy, Faculty of Health Science in Katowice, Medical University of Silesia, Katowice, Katowice, Poland
e-mail: renatawilk@poczta.onet.pl

M. Pokorski
Institute of Health Sciences, Opole University, Opole, Poland

Faculty of Health Sciences, The Jan Długosz University in Częstochowa, Częstochowa, Poland
e-mail: m_pokorski@hotmail.com

## 1 Introduction

Total ankle arthroplasty (TAR) is a procedure more and more frequently performed. Contrary to the hip and knee joints arthroplasty, the reason for its implementation is usually not primary, but secondary to post-traumatic degenerative changes. The TAR is an alternative to arthrodesis that disrupts the proper functioning of the articular chain in the lower limb and impairs the entire biomechanics of the locomotor system (Morash et al. 2017; Basques et al. 2016). The currently used third-generation ankle prostheses provide better biomechanical fit and survival of endoprostheses than the previous generations, although it is not the only factor determining survival (Zafar et al. 2020). Among many factors qualifying and disqualifying to the TAR, particular attention is paid to the lack of vascular impairments in the operated limb. From the biomechanical standpoint and to avoid perioperative complications, good bone stock is a key factor (Van der Plaat and Haverkamp 2017).

Ankle arthroplasty procedures, although provide better biomechanical results when compared to arthrodesis, show a significantly higher percentage of complications that mostly depend on the learning curve that describes the progress in the surgeon's experience in performing the procedure (Morash et al. 2017; Basques et al. 2016). One of the complications often arising during the implantation of an ankle joint endoprosthesis is a periprosthetic fracture. At present, the number of intraoperative fractures is decreasing but postoperative fractures are on the rise (Haendlmayer et al. 2009). The most common fractures occurring during endoprosthesis implantation concern the medial or lateral malleolus. They usually result from the use of oscillating saws and accidental cuts of the ankle or from oversizing the endoprosthesis. The reported incidence of periprosthetic fractures varies among studies. Manegold et al. (2013) have reported the incidence of 2.2%, whereas Lee et al. (2013) put the incidence of medial malleolus fractures at 10% and lateral malleolus fractures at 0.6%. In a study by Clough et al. (2018), intraoperative medial fractures accounted for 9.7% of all ankle arthroplasty procedures performed. Zaidi et al. (2013) have also reported that medial malleolus fractures as the commonest complication of arthroplasty, with an incidence of 6% compared to 1% for the lateral malleolus. It appears that as the number of procedures increases, the incidence of intraoperative fractures declines (Basques et al. 2016). Nevertheless, the issue of periprosthetic fractures in the case of TAR remains clinically significant as it affects up to 10% of patients, which makes it essential to search for the optimal method of fracture stabilization.

The finite element method (FEM) is increasingly used to define the biomechanics of fracture stabilization (Jiang et al. 2019; Anwar et al. 2017). The method enables prompt computer-based modeling and visualization of biomechanical tensions at the ankle periprosthetic fracture (Lorkowski et al. 2015, 2020). The present study aimed to create an *in silico* model of tensions arising in the medial malleolus and endoprosthesis itself using different types of fracture stabilization. Such modeling could help clarify the unresolved issue of which type of stabilization in use carries the lowest risk of implant destabilization and failure of the entire ankle arthroplasty.

## 2 Methods

We developed an *in silico* model of the ankle joint after arthroplasty, specifically targeted at a fracture of the medial ankle. The model was based on three clinical cases. The modeled prosthesis was of the third generation, consisting of a tibial component with a cone, a talar component made of metal alloys, and a polyethylene insert. The evaluation of bone tension arising at the bone-endoprosthesis interface transversely passing through the medial malleolus was compared between the following methods of periprosthetic fracture stabilization:

- Cortical screw passing through the medial malleolus from its apex to the shaft of the tibia, transversely through the fracture gap
- Blount staple inserted with its tines above and below the fracture gap in the medial malleolus, stabilizing the fracture externally on the medial surface of the malleolus
- Combination of these two types of stabilization, i.e., a cortical screw and Blount staple.

The bone tension, arising after fracture stabilization, was compared to that generated at the bone-endoprosthesis interface without fracture. For modeling, we used computer tomography

(CT) images of the ankle joint of an exemplary patient with an implanted joint endoprosthesis. The images, presented as a bitmap in 256 shades of gray, were processed using the software-based image registration technique to quantify tension-induced metabolic bone changes on CT images, which enables the assigning of material features to each shade of gray in the image. The resultant tension displacements at the bone-implant interface were then elaborated using the FEM 2D modeling in the ANSYS software (Ansys Inc. 2010), which enables the evaluation of tension appearing in the mechanics of solids under the influence of various factors. The area FEM-tested is divided into simple finite elements with specific geometric shapes (triangles) connected by several points at the edges, forming "knots". After selecting the nodal functions that determine the distribution of the tested physical quantity within the finite elements, calculations in the differential equations enable the determination of knots' behavior while for other points they remain approximate. After introducing the boundary conditions for the system of equations used, it is possible to determine the type and degree of displacement in nodes, which reflects tension changes present in individual parts of the bone-implant system and fracture stabilization elements (Lorkowski et al. 2020).

Based on the X-ray images, a 2D model of the ankle joint tissues and the implanted prosthesis was prepared. Overall, 16 components were obtained visible on the contour map. The images show the components representing a particular type of tissue-like bones, articular cartilage, soft elements, parts of the endoprosthesis, and elements used to fracture stabilization (Fig. 1). Young's modulus, equal to the longitudinal stress divided by the strain, and Poisson's ratio, described as a ratio of the transverse strain in the direction perpendicular to the applied force and axial strain in the direction of the applied force, were calculated for individual tissues and stabilization elements (Table 1). The former is a measure of elasticity or the ability of a bone to resist changes in length when under longitudinal tension and the latter is the ability of a bone to expand in the direction perpendicular to the direction of compression. The transverse fracture gap in the medial malleolus was modeled and then, computer models of various types of fracture stabilization were made. The models included the fracture stabilization with a screw passing through the fracture gap along the long axis of

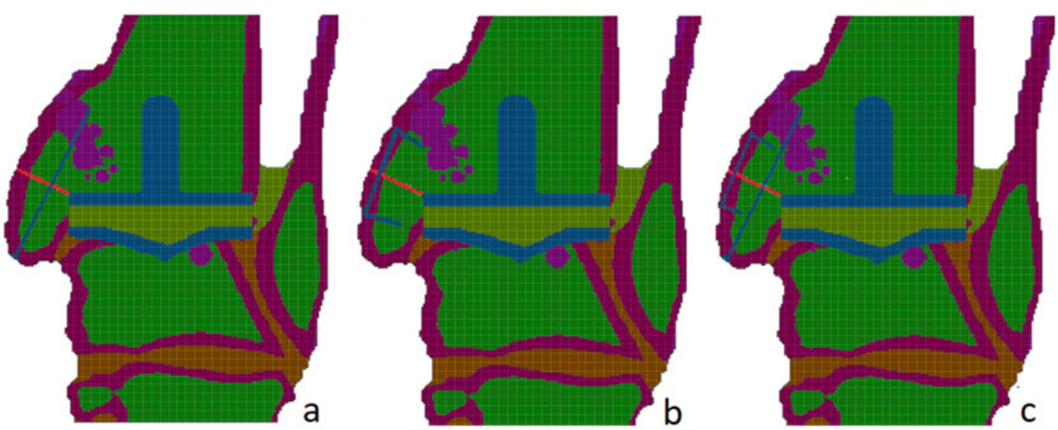


**Fig. 1** A 2D ankle tissue model with implanted endoprosthesis and the stabilization elements of the medial malleolus fracture. Fracture gap marked by a red stroke on the left-hand side: (**a**) cortical screw passing through the malleolus from its apex to the shaft of the tibia, transversely through the fracture gap; (**b**) Blount staple inserted with its tines above and below the fracture gap in the medial malleolus, stabilizing the fracture externally on the medial surface of the malleolus; (**c**) combination of the cortical screw and Blount staple

**Table 1** Young's modulus and Poisson's coefficient of individual tissues and elements of endoprostheses used for ankle fracture stabilization

| Material | Young's modulus | Poisson's coefficient |
|---|---|---|
| Bone | 5000 MPa | 0.32 |
| Cartilage | 150 MPa | 0.42 |
| Soft tissues | 800 MPa | 0.42 |
| Implant | 210 GPa | 0.32 |
| Stabilization components | 210 GPa | 0.32 |

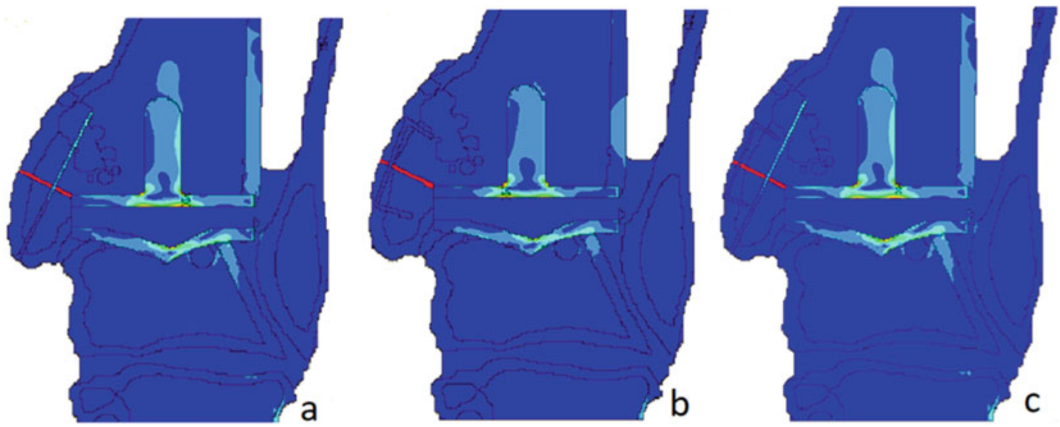


**Fig. 2** Bone tension evaluation (stress distribution) arising at the bone-endoprosthesis area after total ankle arthroplasty and stabilization of the medial malleolus fracture. Fracture gap marked by a red stroke on the left-hand side: (**a**) cortical screw passing through the medial malleolus from its apex to the shaft of the tibia, transversely through the fracture gap; (**b**) Blount staple inserted with its tines above and below the fracture gap in the medial malleolus, stabilizing the fracture externally on the medial surface of the malleolus; (**c**) combination of the cortical screw and Blount staple

the medial malleolus, which is most frequently used in the clinic, a Blount staple, sometimes used in this type of fracture, and a combination of the two. The FEM model was based on the force load of $F_\lambda = 7.28$ N, determined from an average load of 1 N/1 $mm^3$.

## 3 Results

Maximum tensions locally found at the bone-implant interface in the *in silico* model was 8.4 MPa. This magnitude of tension was found without a fracture or healed fracture at the base of the medial malleolus. Similar tensions were noted in the malleolus fracture fixed with a screw alone, Blount staple, and a Blount staple and screw together. Tensions arose in the central parts of the tibial and talar components of the implant and the bone-implant interface. However, the area of maximum tension in the tibial component covered the entire cone base and was about three times larger than that in the talar component (Fig. 2). The greatest tension occurred along the central axis of the limb, and not in the fracture fissure or the material stabilizing the fracture. In each evaluated case, greater overloads were found in the cortical than medial layers of lateral tibia and talus walls.

When the fracture gap was stabilized with the Blount staple alone (Fig. 2b), tension along the cone of the tibial component was about 12% of the maximum tension. The use of a screw alone or together with the Blount staple (Fig. 2a, c) doubled up the tension on the medial side of the cone of the tibial component and about the immediate vicinity. Additionally, stabilizing elements exert tension forces of similar magnitude in the extension of the tibia cone, targeting the posterior tibia wall. In the area of the medial malleolus, tensions were alike when stabilizing the fracture with a screw or together with the Blount staple. Tensions arising in the joining materials reached one-third of the maximum tension occurring in the entire biomechanical system in the case of screw alone or together with the Blount staple and one-fourth of the maximum tension in the case of Blount staple alone.

## 4 Discussion

In this study, we used a rapid FEM computer-driven modeling to evaluate tensions arising at the bone, endoprosthesis, and bone-endoprosthesis interface after total ankle arthroplasty. The modeling seems particularly useful in the assessment and prevention of the potential propensity for a fracture of the medial malleolus, an adverse event stemming from arthroplasty. The method is based on CT scans of the leg bones with an implanted ankle joint endoprosthesis, transformed into 2D images, aimed at providing the prompt evaluation results intraoperatively. The distribution of tensions arising after the endoprosthetic-related medial malleolus fracture was evaluated with the content of a stabilizing central cone in the tibial component. Noteworthy, we found differences in the magnitude and localization of tension depending on the way of fracture gap stabilization. In detail, the tension along the prosthetic cone of the tibial component approximated 12% of the maximum stress using the Blount staple. Stabilization with the Blount staple and screw together or a screw alone induced tensions on the medial side of the tibial cone component and its immediate vicinity twice as much.

According to the classification of Manegold et al. (2013), malleolus fractures are stratified into Type 1 – intraoperative fractures, type 2 – postoperative fractures resulting from a fall, and type 3 – fractures resulting from both bones overload and physiological stress on deficient elastic resistance. Concerning the exact location of a fracture site, the classification distinguishes type A – medial malleolus, type B – lateral malleolus, C – tibia, and D – talus. Fractures have the essential bearing on the implant stability, so an additional stratification distinguishes stable from unstable implants, anonymized as S and U, respectively, based on the X-ray or CT examination. Our present finite element model fits well into type 1AU intraoperative fractures. However, the model would also be adequate for those type 2 fractures in which there are no significant changes in bone anatomy apart from the fracture gap. Type 3 fractures are usually linked to altered bone structure. Therefore, the model would barely reflect clinical reality.

The prevalence of periprosthetic fractures arising during surgery can be as high as 20% (Brock et al. 2017; Manegold et al. 2013). In periprosthetic ankle fractures, it is recommended to use surgical stabilization to prevent displacement in the case of both intra- and postoperative fractures (Cody et al. 2018). The conservative treatment is recommended only for non-displaced fractures of the medial malleolus. Nonetheless, even in such fractures, the non-union occurs in 12–13% (Tsitsilonis et al. 2015). Intraoperative periprosthetic fractures are most often stabilized using Kirschner wires (K-wires), screws (Barnes et al. 2014), or locking plates (LCP) (Jiang et al. 2019). In some cases, Blount staples are used with satisfactory results (Schiedts et al. 1997). These methods have been studied in many aspects, but no consensus has been reached as to which one is the most effective. The prevalence of non-union in medial malleolus fractures ranges from 3% to 20% (Corey et al. 2019), which may result in implant destabilization. Jiang et al. (2019) have used the FEM for the evaluation of different types of stabilization in medial malleolus fractures and found that a screw inserted along the long axis of the medial malleolus from its apex, when the fracture gap runs horizontally, did not provide good results. Mounting a screw was not sufficient to prevent displacement. Further, tensions arising below the screw could chip the bone away and, as a result, the screw may go loose or fall out, causing severe pain as the screw head is close under the skin. The use of headless compression screws mitigates this problem in the stabilization of medial malleolus fractures and reduces the percentage of non-unions. The perception of pain after endoprosthesis stabilization exceeds *in silico* analysis. The suboptimal nature of prosthetic stabilization using screws alone is consistent with our present results.

The locking plates are another way to stabilize malleolar fractures, which was subject to finite element analysis (Anwar et al. 2017). The plates prevent bone damage and the fallout of a screw by transferring a portion of the tension from the screw placed along with the locking plate to the shaft of the tibia. Unfortunately, there is a danger of breaking a locking plate. Besides, mounting the plates using screws is technically difficult and not always feasible due to a restricted intraoperative area. The current stabilization systems of prosthetic fractures of the medial malleolus still fall short of the requirements of effectiveness. The search continues for new methods that would provide better effectiveness and safety of the obtained fracture unions.

Blount staples have been used for years in epiphysiodesis, i.e., correcting discrepancies in limb length in children or for correcting valgus knees (genu valgum) or claw knees (genu varum), showing as good results as other corrective modalities, e.g., the eight-plate method (Rodrigues et al. 2020). In the treatment of medial malleolus fractures, the use of Blount staples is not common, but a study by Schiedts et al. (1997) has shown promising results. A new technique of Blount staples placement developed by Burghardt et al. (2012) requires a smaller skin incision and provides easier access to the bone and a stable union of the fracture, which raises interest in using it in a greater number of orthopedic procedures in both children and adults. Patients whose fractures are a consequence of the implantation of an ankle joint endoprosthesis may benefit from this method as well. Therefore, in the present study, we used the finite element method to model the stabilization of the medial malleolus fracture after ankle arthroplasty using Blount staples. We demonstrate a lower level of tensions developing in the endoprosthesis area, which carries a lower risk of endoprosthesis destabilization and procedure failure, and therefore a lower risk of reoperation and arthrodesis. This study has limitations inherent for the theoretical analysis that requires assumptions about the patient's condition, bone quality, and the type of fracture we are dealing with. Nonetheless, we believe we have shown that, contrary to the hitherto clinical routine of using screws, fracture fixation using the Blount staple leads to a lower bone tension about the stabilization of the medial malleolus fracture after ankle joint endoprosthesis. The assessment of a potential practical reference of the proposed fixation method as well as perioperative finite element modeling requires alternative clinically oriented study designs.

**Conflicts of Interest** The authors declare no competing interests in relation to this article.

**Ethical Approval** All procedures performed in this study involving human medical data complied 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. This article concerned computer modeling based on anonymous clinical data. As it contains no identifiable personal data, no patient consent was required.

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