ACTA ORTHOPAEDICA et TRAUMATOLOGICA TURCICA
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Research Paper

The effects of different cortical impingement scenarios on the biomechanical features of retrograde femoral nails in the management of distal femoral fractures: A finite element analysis

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ARTICLE INFO

Article history:
Submitted May 27, 2021
Received in revised form
April 4, 2022
Accepted May 4, 2022

Keywords:
Intramedullary nailing
Finite element analysis
Impingement
Malposition

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ABSTRACT

Objective: This study aimed to assess the effects of different cortical impingement scenarios on the biomechanical features of retrograde femoral nails in managing distal femoral fractures.

Methods: A mesh femur model was constructed using computed tomography (CT) images. Five different cortical impingement (CI) scenarios were designed: central model (CM), lateral CI (LCI), medial CI (MCI), anterior CI (ACI), and posterior CI (PCI). The fixation stability was evaluated by femoral head movement, stress, and elastic strain at the fracture site. The maximum stress on the femoral cortex and the implants were also measured.

Results: The maximal femoral head movements were 3.11 mm in ACI and 2.91 mm in MCI. Among all CI models, the highest stress value at the fracture site was recorded in ACI (18.9 MPa), and the maximum stress on the femoral cortex was determined in ACI (114.3 MPa). The highest microstrain value at the fracture site was measured in MCI (599.1 μstrain). In all scenarios, maximum stress was located around the proximal hole of the nail.

Conclusion: This study revealed that cortical impingement results in excessive loading on the retrograde femoral nail in managing distal femur fractures. MCI and ACI mainly cause this pathological loading. Problems related to supraphysiological loadings, such as implant failure and periprosthetic fracture, can be reduced by applying the nail in the central position.

Introduction

Distal femoral fractures constitute 3% of all femoral fractures.[1,2] Various surgical options such as antegrade and retrograde nailing, plate and screw fixation, and external fixation can be applied in the treatment of distal femur fractures.[2,3] Retrograde femoral nailing is a suitable treatment option in patients with distal and diaphyseal femoral fractures.[4] This technique has gained popularity due to advantages such as its applicability with minimal soft tissue dissection, a high union rate, and enabling mobilization in the early postoperative period.[5,6]

Cortical impingement is one of the important factors leading to mechanical problems after intramedullary nailing.[7-10] This condition can be defined as the contact of the nail with the cortex. After antegrade nailing, cortical impingement has been reported at a rate of 16%-34%.[9,11] Cortical impingement can also be seen in retrograde femoral nailing.[12-14] However, the incidence of cortical impingement in patients undergoing retrograde nailing is unknown. Cortical impingement can be associated with factors such as false entry point selection, over-reaming, and selection of improper length nails during retrograde nailing. As a result, cortical impingement may lead to several potential complications, such as cortical penetration of the nail, disability, and thigh pain.[9,11] Evaluation of the biomechanical aspects of cortical impingement may enlighten these potential complications in retrograde nailing.

Biomechanically, it is critical to place the intramedullary nail in the correct position on the bone for optimal distribution of the loadings. Malpositioning of the nails in the femoral canal has been associated with abnormal stress distribution in the bone and overloads on the implant.[15,16] However, to the best of our knowledge, there has been no study in the literature evaluating the biomechanical effects of cortical impingement on retrograde femoral nailing.

The aim of this study was to evaluate the effects of cortical impingement on retrograde nailing in femoral distal fractures using finite element analysis. Our hypothesis is that cortical impingement can cause increased loading on the cortical bone and intramedullary nail.

Materials and Methods

This study was performed using 3-dimensional static linear finite element analysis. The bone model was created by computed tomography (CT) images of a 38-year-old man who was evaluated for a suspected

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Cite this article as: *Taşatan E, Kocadal O. The effects of different cortical impingement scenarios on the biomechanical features of retrograde femoral nails in the management of distal femoral fractures: A finite element analysis. Acta Orthop Traumatol Turc. 2022;56(3):173-177.*

DOI: 10.5152/j.aott.2022.21212

fracture. Axial CT sections were transferred to open-source 3D Slicer software (version 4.11.0-2020-04-04), and cortical and cancellous bone mesh models were created.[17] The bone models were optimized using the Meshmixer (Autodesk Inc, San Rafael, Calif, USA) software. Then, mesh models were imported into Fusion 360 software (Autodesk®, Inc). A transverse fracture model was created 10 cm proximally from the knee joint surface. The retrograde nail modeled in the study was Expert R/AFN (DePuy-Synthes, Johnson & Johnson, Warsaw, Ind, USA). Considering the dimensions of the bone model, a nail of 10 mm thickness and 240 mm length was modeled.[18] The implant model was developed using templates in Sectra IDS7 (Sectra Imtec AB, Linköping, Sweden) software.

Creating scenarios

In the current study, 5 scenarios were created to evaluate cortical impingement. These scenarios were defined as the central model (CM), lateral cortical impingement (LCI), medial cortical impingement (MCI), anterior cortical impingement (ACI), and posterior cortical impingement (PCI) according to the direction of the impingement. In all scenarios, the nail entry point was determined as 1 cm anterior to the posterior cruciate ligament femoral insertion site and the center of the intercondylar sulcus.[19,20] Central model was created by positioning the proximal end of the nail at the midpoint in the anteroposterior and lateral planes in the medullary canal. While the distal tip of the nail was fixed, other models were created by positioning the proximal end in contact with the anterior, posterior, medial, and lateral cortices (Figure 1). Material properties are shown in Table 1.[21]

Finite element analysis

The finite element analysis was performed using Fusion 360 software (Autodesk®, Inc). The models were constrained at the lower ends of the medial and lateral femoral condyles. Hip reaction (735.4 N) and abductor muscle (564.6 N) forces were applied to simulate the early postoperative period,[22] and due to this, full weight bearing is not allowed immediately after surgery, 25% of the hip reaction force was applied.[23] The applied vectors and boundary conditions are shown in Figure 2. In all models, the amount of movement of the femoral head, maximum stress, and elastic strain values at the fracture, as well as the maximum von Mises stress in the femoral cortex and implants, were measured.

Results

Femoral loadings

The femoral head movement for CM was measured as 2.59 mm. Maximum femoral head motion was observed in ACI (3.11 mm) and MCI (2.91). The highest value of stress (18.2 MPa) at the fracture site was observed in ACI. On the other hand, the highest microstrain value was recorded in MCI (599.1). The highest and lowest von Mises stress values at the femoral cortex were measured as 114.3 MPa and 62.8 MPa in ACI and CM, respectively. The amount of femoral head movement and the loading values of the bone are shown in Table 2.

Loadings on the implants

In all of the models, the maximum von Mises stress was observed around the proximal hole of the retrograde nail (Figure 3). The highest and lowest maximum von Mises stress values on the nail were recorded in PCI (315.9 MPa) and LCI (275.1 MPa), respectively. The highest maximum von Mises stress values were recorded in the proximal upper screw. The highest von Mises stress value at the proximal upper screw was measured in the LCI model (730.7 MPa). Table 3 shows the maximum von Mises stress values at the implant.

HIGHLIGHTS

- Malpositioning of the nail in the femoral canal has been associated with abnormal stress distribution in the bone and overload on the implant.
- This study aimed to evaluate the effects of cortical impingement on retrograde nailing in femoral distal fractures using finite element analysis.
- The maximal femoral head movements were 3.11 mm in anterior cortex impingement and 2.91 mm in medial corticaI impingement. The highest stress value at the fracture site and the maximum stress on the femoral cortex was recorded in anterior cortex impingement scenario.
- The results indicate that central application of the nail is as important as the reduction in retrograde femoral nailing andpathological loading patterns are more pronounced, especially in medial and anterior cortical impingement scenarios.

Discussion

The main finding of this study was that cortical impingement causes increased loading on the bone and implants in retrograde femoral nail applications. To the best of our knowledge, this study was the first in the literature to evaluate the biomechanical effects of cortical impingement in retrograde femoral nailing. In this study, we observed that increased loading is related to MCI and ACI. Positioning the nail in the center of the canal may be important to avoid increased loading.

Intramedullary nailing is the gold standard surgical treatment of femoral shaft fractures.[24] Malpositioning is not rare in intramedullary nailing. Cortical impingement is one of the important causes of malpositioning. The cortical impingement may occur after antegrade[7,9-11] and retrograde femoral nailing.[12,14] Femoral deformities, excessively curved femoral morphology,[25] selection of a non-optimal entry point,[12] incompatibility between the nail and the femoral canal[11,13,14,26] and over-reaming[8,11] have been considered as the etiological factors for cortical impingement. Moreover, it has been reported that cortical impingement may be associated with problems such as cortex perforation, chronic pain, fixation failure, and malunion.[7,8,13]

One of the most important parameters determining the success of the treatment in intramedullary nailing is the stability of the fixation. In this study, femoral head movement with tensile loading and strain at the fracture line was considered for stability parameters. The fixation points were on the lower surface of the femoral condyles in the loading model used in the current study. Therefore, the amount of movement in the femoral head directly reflected the fixation stability.[23,27,28] In this context, it can be postulated that the centrally located retrograde nail is more stable than other models. It can be stated that the fixation stability is poor in anterior and medial cortical impingement scenarios.

Tensile loading in the fracture line is directly related to fixation stability. Increased tensile loads in this region is one of the major causes of fixation failure.[29] In this study, the maximum tensile loadings were at the lateral side of the fracture line. Higher tensile loading values were recorded in the fracture line in MCI and ACI compared to the other models. In addition, the highest elastic strain value was also measured in MCI. Strain, another important parameter, is inversely proportional to fixation stability. Therefore, it can be said that low elastic strain values reflect good fixation stability.[25] The recorded stress and strain values in the fracture line also suggest that medial and anterior cortical impingement should be avoided in retrograde nailing.

Increased stress in the femoral cortex can lead to secondary fractures.[23,25] In a biomechanical study comparing antegrade and

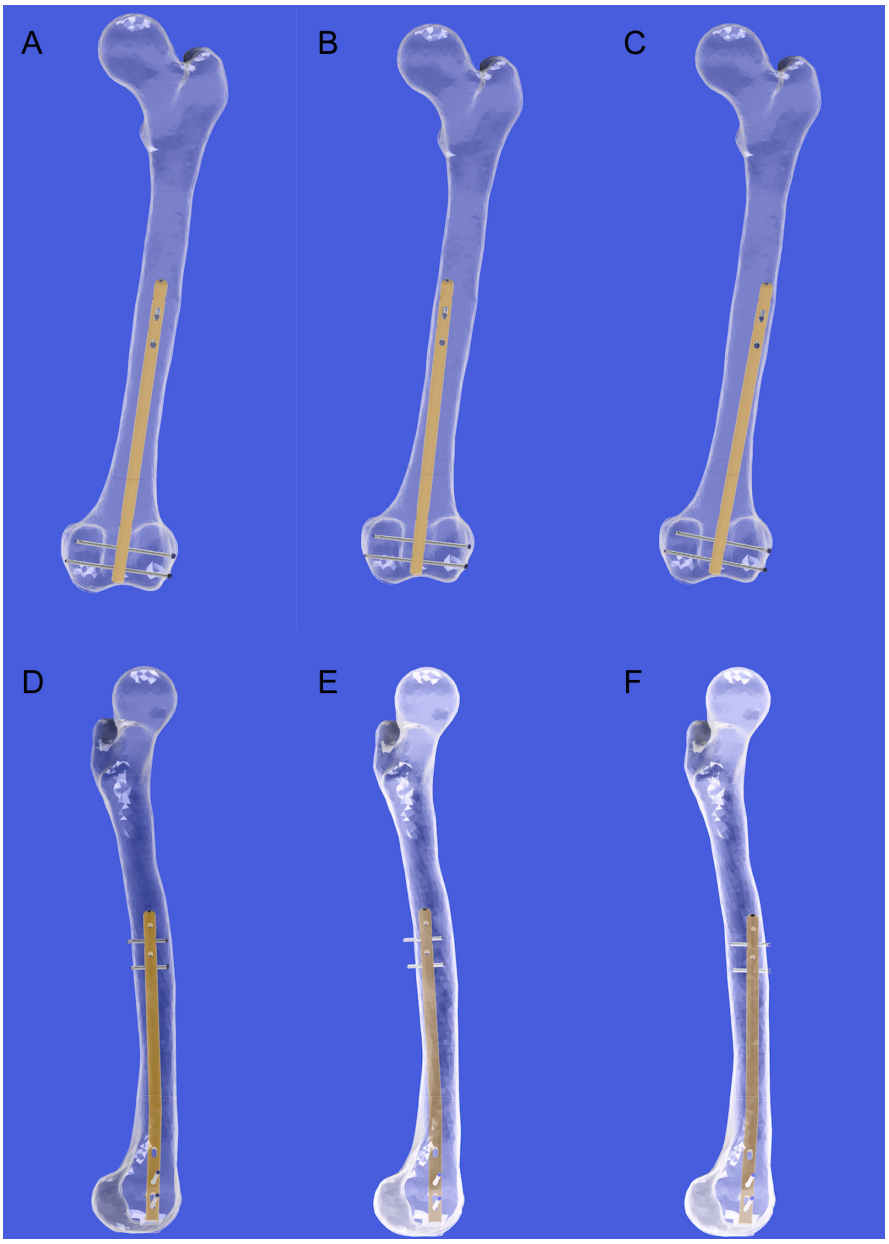

Figure 1. A-F. Five different scenarios were created for simulation. (A) central model (CM) from coronal view, (B) medial cortical impingement (MCI), (C) lateral cortical impingement (LCI), (D) central model (CM) from sagittal view, (E) posterior cortical impingement (PCI), and (F) anterior cortical impingement (ACI).

retrograde nailing techniques in the treatment of femoral shaft fractures, it was reported that the increased amount of stress on the cortical bone due to impingement was higher in retrograde nailing than in antegrade nailing.[23] In the current study, the highest femoral cortical stress value was measured in ACI and the lowest cortical loading value was measured in CM. In this context, it can be said that the increased loading due to medial impingement may be higher in ACI compared to the other scenarios. However, in this study, the early postoperative period after fixation was simulated. Since the bone geometry may change with callus formation after the union, no inference has been made about the loading regarding the late postoperative period.

Finite element analysis studies allow the evaluation of the loadings on the implant as well as on the bone.[15,28] In this context, the loading on the implant was tested in all scenarios. Increased loading on the implants may cause breakage of the fixation materials. The yield strength of Ti-6Al-4V, from which the retrograde nail and screws are manufactured, is 880MPa.[30] In all the models of this study, the maximum stress value on the retrograde nail was measured below this value. For this reason, it can be said that there will be no breakage in the implants due to insufficiency. In finite element studies, it has been reported that the highest stress value in the retrograde nail is at the interface of the nail and the proximal locking screws.[15,16,27,28] This condition may be related to increased stress around the proximal

Table 1. Material properties of the cortical bone, cancellous bone, and Ti-6Al-4V

Material properties	Cortical bone	Cancellous bone	Ti-6Al-4V
Young's modulus(GPa)	16	1	113
Poisson's ratio	0.36	0.3	0.35
Shear modulus (MPa)	3360	400	42 134
Yield strength (MPa)	108	7.5	882
Tensile strength (MPa)	133	9	1034

Figure 2. Boundary conditions and loads.

Table 2. Recorded loading parameters on the cortical bone

	MODEL				
Measurement	**CM**	**MCI**	**LCI**	**ACI**	**PCI**
Femoral head movement (mm)	2.59	2.91	2.68	3.11	2.82
Maximum stress at the fracture site (MPa)	11.5	16.3	12.95	18.2	12.5
Strain (µstrain)	368.8	599.1	503.7	508.2	434.2
Maximum stress at the femoral shaft (MPa)	62.8	89.7	69.7	114.3	70.1

CM, cenrtral model; MCI, medial cortical impingement; LCI, lateral cortical impingement; ACI, anterior cortical impingement; PCI, posterior cortical impingement.

Figure 3. Upper proximal screw hole was the typical maximum stress location of retrograde nail for all scenarios.

Table 3. Recorded maximum stress values on the implants

	MODEL				
Measurement	**CM**	**MCI**	**LCI**	**ACI**	**PCI**
Maximum stress on the nail (MPa)	321.8	312.5	275.1	314.6	315.9
Maximum stress on the proximal upper screw (MPa)	482.2	582.4	730.7	330.2	495.3
Maximum stress on the proximal lower screw (MPa)	154.4	230.1	301.1	220	160.9
Maximum stress on the distal upper screw (MPa)	29.1	48.1	33.2	38.3	31.2
Maximum stress on the distal lower screw (MPa)	57.6	107.7	54.1	152.7	104.4

CM, cenrtral model; MCI, medial cortical impingement; LCI, lateral cortical impingement; ACI, anterior cortical impingement; PCI, posterior cortical impingement.

holes, the first potential weak spot, as the load is transferred from proximal to distal on the nail.

This study has some limitations. Finite element analysis may not fully reflect in vitro scenarios. However, finite element analysis reveals difficult-to-measure loading patterns in an easy and detailed way. Another limitation of the study was that only the early postoperative period was simulated. The late postoperative period could not be simulated due to such difficulties as the standardization of the bone geometry with callus formation.

In conclusion, a cortical impingement in retrograde femoral nailing can cause excessive load on the bone and implants. Pathological loading patterns are more pronounced, especially in medial and anterior cortical impingement scenarios. The central application of the nail was noted to be as important as the success of the reduction in retrograde femoral nailing.

Ethics Committee Approval: This manuscript does not contain any studies with animals or human participants performed by any of the authors.

Informed Consent: Informed consent was obtained from the patient for the radiological image used in this study.

Author Contributions: Concept - E.T.; Design - E.T.; Materials - O.K.; Data Collection and/or Processing - O.K.; Analysis and/or Interpretation - O.K.; Literature Review - E.T.; Writing - E.T.; Critical Review - E.T., O.K.

Acknowledgments: The authors thank Dr. Anita L. Akkas (PhD in English Literature) for contributing to the English editing.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study has received no financial support.

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