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Finite element analysis of the stability of retrograde intramedullary nail and plate-screw combinations for periprosthetic femoral fractures following total knee replacement

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Abstract. – OBJECTIVE: Periprosthetic fractures following total knee replacement are rare but challenging. The goal of the treatment is to achieve the most stable fixation that allows early mobilization. Therefore, the aim of this study was to evaluate the biomechanical results of the use of different fixation systems in the treatment of distal femur periprosthetic fractures with finite element analysis.

MATERIALS AND METHODS: A total knee prosthesis was implanted in Sawbone femur models. A transverse fracture line was created in the supracondylar region and was fixed in four different groups. In group 1, fracture line fixation was fixed using retrograde intramedullary nailing. In group 2, fixation was applied using a lateral anatomic distal femoral. In group 3, in addition to the fixation made in group 1, a lateral anatomic distal femoral plate was used. In group 4, in addition to the fixation made in group 2, a 3.5 mm limited contact dynamic compression plate (LC-DCP) was applied medially. Computed tomography (CT) scans were taken of the created models and were converted to three-dimensional models. Axial and rotational loading forces were applied to all the created models.

RESULTS: The least deformation with axial loading was observed in the double plate group. Group 3 was determined to be more advantageous against rotational forces. The greatest movement in the fracture line was found in group 2. The application of the medial plate was determined to reduce the tension on the lateral plate and increase stability in the fracture line.

CONCLUSIONS: Combining a lateral anatomic plate with intramedullary nailing or a medial plate was seen to be biomechanically more advantageous than using a lateral plate or intramedullary nailing alone in the treatment of distal femoral periprosthetic fractures.

Key Words:
Distal femur, Periprosthetic fracture, Retrograde intramedullary Nail, Finite element analysis.

Introduction

The incidence of periprosthetic fracture seen following total knee arthroplasty (TKA) varies between 0.3% and 2.5%, and this rate can increase in revision cases up to 38%[1-3]. Reduced bone stock, disrupted blood flow, and the fact that most TKA patients are osteopenic are factors that make the treatment process more difficult[4]. With the increase in the number of TKA operations performed each year, an increase in the incidence of periprosthetic fractures is expected. Generally, periprosthetic fractures are seen in the distal femur supracondylar region[5]. The aim of the treatment is to provide appropriate alignment while protecting bone stock and obtaining a stable joint that will allow early movement.

Although historically, conventional plates have been used in the internal fixation of these fractures, these have now been almost completely abandoned because of high complication rates. In fractures that extend distally, angled wedge plates and dynamic condylar plates can still be used[6]. Currently, with the minimally invasive application of the most frequently used locking compression plates, soft tissue damage can be reduced, and a biological environment can be preserved, which will provide bone union by protecting periosteal blood flow[6]. In newly developed implants, holes allowing locking at different angles is another advantage of the system[7].

Another implant, which has become widely used in the treatment of periprosthetic fractures, is intramedullary nailing. The most important advantages of this system are that reduction can be obtained without opening the fracture line and that both endosteal and periosteal blood flow are protected due to reamerisation[8].

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In addition, it has important advantages that affect the surgeon's choice, such as its minimally invasive application, not disrupting the biology at the fracture line, long implants providing more successful fixation in complex fractures, and allowing early weight bearing[9].

The flexible nails used in the past are no longer used as they are not resistant to rotational and compression forces. Rigid intramedullary nails, which are currently used, can be applied antegrade or retrograde, but retrograde nails are preferred in the treatment of periprosthetic fractures as they allow more locking from the distal side[8].

Retrograde nails are contraindicated in cases where an implant in the canal, such as patella baja, joint ankylosis, narrow femoral canal, existing hip arthroplasty, or the femoral component does not allow retrograde entry[10]. Such situations should be reviewed before surgery, and the surgeon should make good preoperative planning.

There are recent studies[11-13] that have stated that the combined use of implants in trauma surgery reduces the risk of implant-related complications. In a 2013 study, Chen et al[14] showed that supporting locking plates with a strut graft increased fixation strength in distal femur periprosthetic fractures. In a biomechanical study by Başcı et al[11] in 2015, the combination of intramedullary nailing and a lateral anatomic plate was shown to increase fixation strength in osteoporotic distal femur fractures.

The implant to choose for the patient should be planned according to the surgeon's experience, the morphology of the fracture, and the patient's expectations. Before the operation, the advantages and potential risks of the methods that can be chosen for fixation should be explained to the patient in detail and a detailed consent form should be signed[15,16].

No consensus has yet been reached in the literature regarding which method is more advantageous. This study aimed to use finite element analysis to examine the effects on fixation strength of combinations of intramedullary nailing and the plate screw system, the efficacy of which has been proven in the literature.

Materials and Methods

Bone Models

The study was conducted on 2 Sawbone (Pacific Research Laboratories, Vashon, WA, USA) femur bone models, 490 mm in length, with normal density cortex and soft spongeous bone. Appropriate cuts were made on the bone models and a Zimed® (Gaziantep, Turkey) TKA femoral component was implanted. The periprosthetic fracture model was formed by making a transverse osteotomy with a 2 mm osteotome at a distance of 85 mm from the distal end.

Study Groups

Four separate groups were formed for distal femur fracture fixation. In Group 1, fixation was applied with retrograde intramedullary canal nails (Zimed®, 10 x 300 mm) with 2 distal and 2 proximal locking nails. In Group 2, fixation was applied with a Zimed® 21-hole distal femur anatomic plate (DFAP) and 9 locking cortical screws (4 proximal, 5 distal). In Group 3, fixation was made as in Group 1 with the addition of a Zimed® 19-hole DFAP and 7 cortical screws (3 proximal, 4 distal). In Group 4, fixation was made as in Group 2 with the addition of a Zimed® 3.5 mm 7-hole limited contact dynamic compression plate (LC-DCP) and 6 locking cortical screws (3 proximal, 3 distal).

Formation of the 3-Dimensional Models

Computed tomography (CT) scans of 1 mm were taken of the 4 groups. The images obtained in DICOM format were segmented using ITK-Snap software (Cognitica, Philadelphia, PA, USA). Then, 3-dimensional models were formed using the Solidworks program (SolidWorks Corporation, MA, United States) (Figure 1A-C). The number of nodes of the finite element models created for the 4 internal fixation models are 159068, 159330, 161715, and 169572, respectively.

Finite Element Analysis

The 3-dimensional geometries created were transferred to the ANSYS Workbench program (Ansys, PA, USA) on which FEA was to be performed. The transverse fracture gap was standardized at 5 mm. The material characteristics for each model were defined (Table I).

Loading and Limit Conditions

Body weight was assumed to be 70 kg. The hip joint rotation point is determined as P0. The hip joint can only make translational movements along the mechanical axis, as determined by the red line in Figure 2. C1 was determined as the knee joint rotation point. C2 was determined as the lateral condyle point drawn perpendicular to the mechanical axis of the femur. The forces acting on bone tissue during normal walking were taken from the literature[17,18]. The forces acting on

Table I. Material properties.

Material	Young Modulus (GPa)	Shear Modulus [GPa]	Bulk Modulus [GPa]	Poisson Ratio
Cortical bone	12.6	4.85	10.5	0.3
Cancellous bone	0.104	0.04	0.087	0.3
CoCrMo	210	80.77	175	0.3
Ti-6A1-4V	114	43.84	95	0.3

GPa: gigapascal; CoCrMo: cobalt-chrome-molybdenum; Ti-6A1-4V: titanium-aluminium-vanadium alloy.

Table II. Effective forces during walking.

Forces [BM%]	X	Y	Z	Point
Hip Joint	54	32.8	229.2	P0
Abductor Muscles	8.1	12.8	78.8	P1
Tensor Faciae Latae	6.7	10.9	5.8	P1
Vastus Lateralis	0.9	18.5	92.9	P2

BM: Body Mass = 700 N.

the hip joint, abductor muscle force, tensor fascia latae and vastus lateralis forces are shown with their vectorial acting points (Figure 2). Effective forces during walking, the limits of movement and the loads formed were presented as numerical values (Table II). The contact characteristics between the implant and bone tissue were defined as shown in Table III.

Results

Axial Loading Findings

The strongest structure under axial loading was determined to be Group 4. The axial deformation results of Group 3 and Group 4 were seen to be significantly similar to each other. The strongest structures were seen to be Groups 3 and 4, according to the axial loading results. The group with the lowest strength was Group 2, in which fixation was made with a lateral plate alone (Figure 3).

Rotational Loading Findings

The worst results were seen in Group 1. The best results regarding rotational stability were determined to be those in Group 3 (Figure 4).

Findings of Separation Between the Fragments

Upon examining the separation values at the medial end, Group 2 showed the highest separation, while Group 4 had the least (Figure 5A-B).

Implant Stress Findigs (von-Mises Values)

Upon evaluating Groups 1 and 2, it was found that the stress created in the lateral plate was about two times more than the stress formed in the intramedullary nails. The regions where maximum stress was formed were the same region in Groups 1 and 2 and in the fracture line. In Group 3, the amounts of maximum stress in both the lateral plate and the intramedullary nails were seen to be lower compared to Group 1 and Group 2. In Group 4, the application of the medial plate was

Table III. Contact properties.

Plate - Cortical tissue	Frictional contact (μ = 0.3)
Plate - Locking screws - Bone tissue	Bonded contact
Intramedullary nail - Cortical tissue	Frictional contact (μ = 0.3)
Femoral component - Cortical tissue	Bonded contact

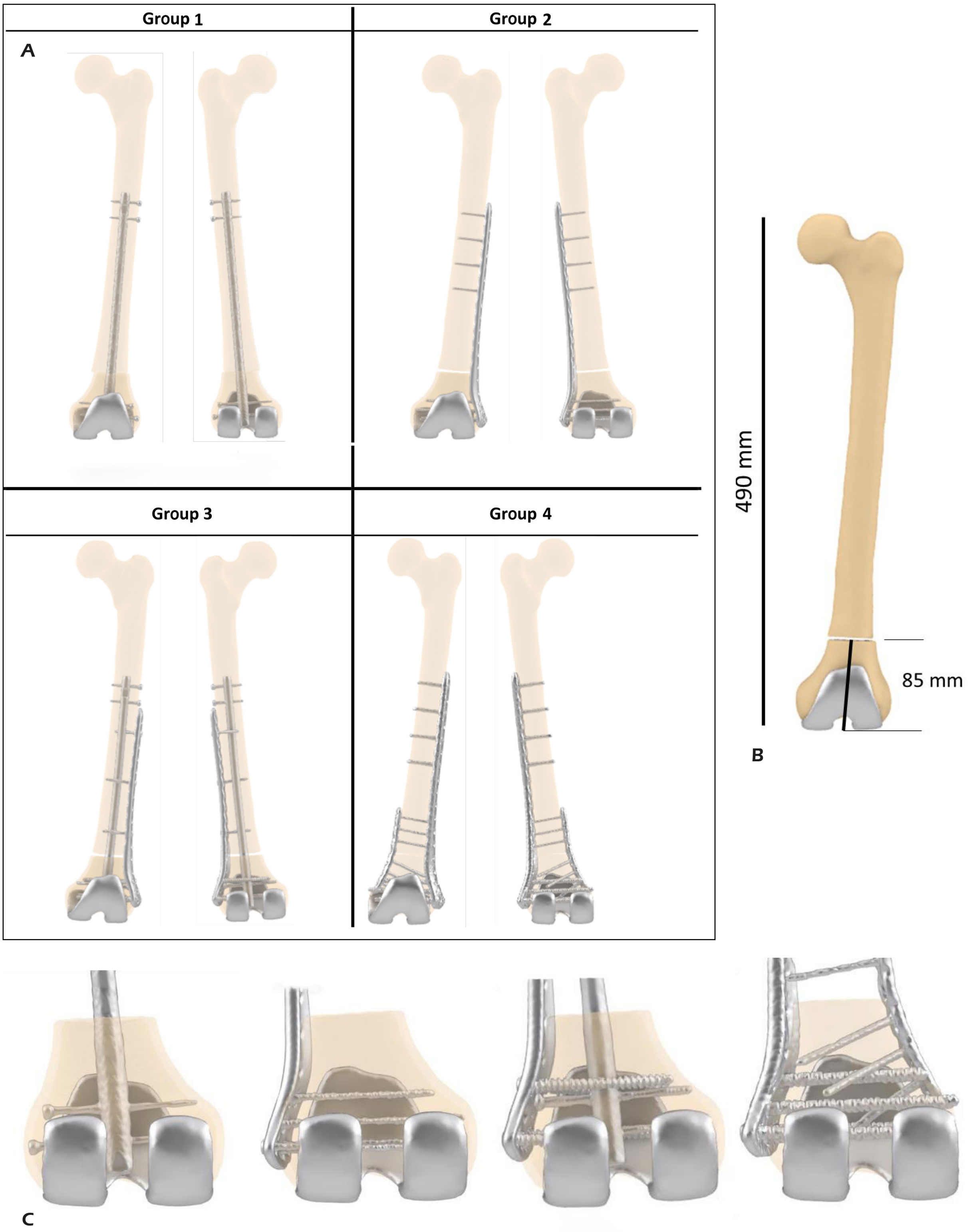

Figure 1. Fixation group models. **A**, General views of the four fixation groups. **B**, Periprosthetic fracture model and measurements. **C**, Detailed views of the distal fixations.

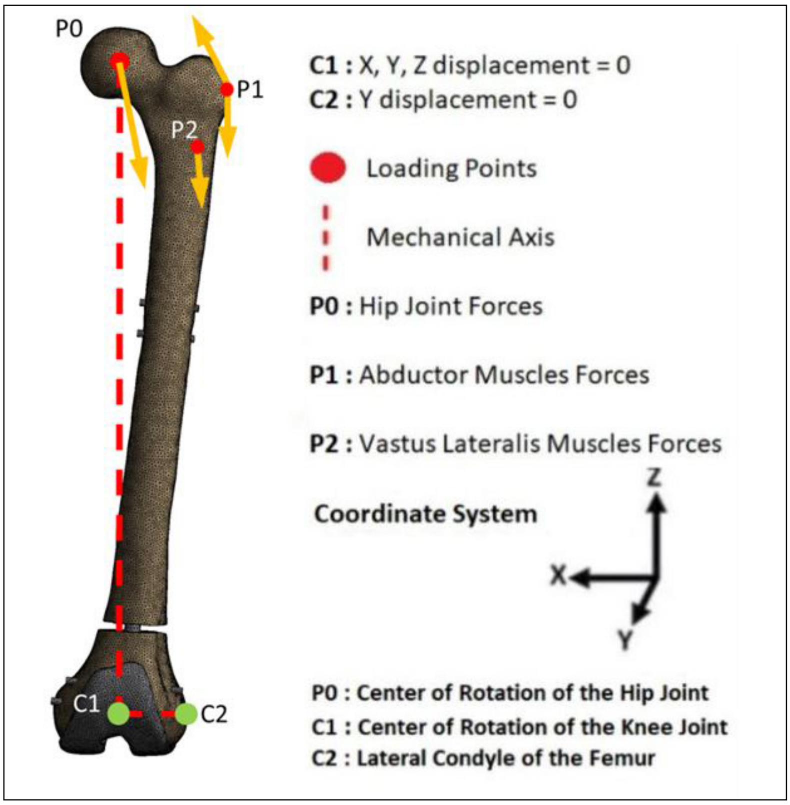

Figure 2. Effective forces and numerical values of the loads during walking.

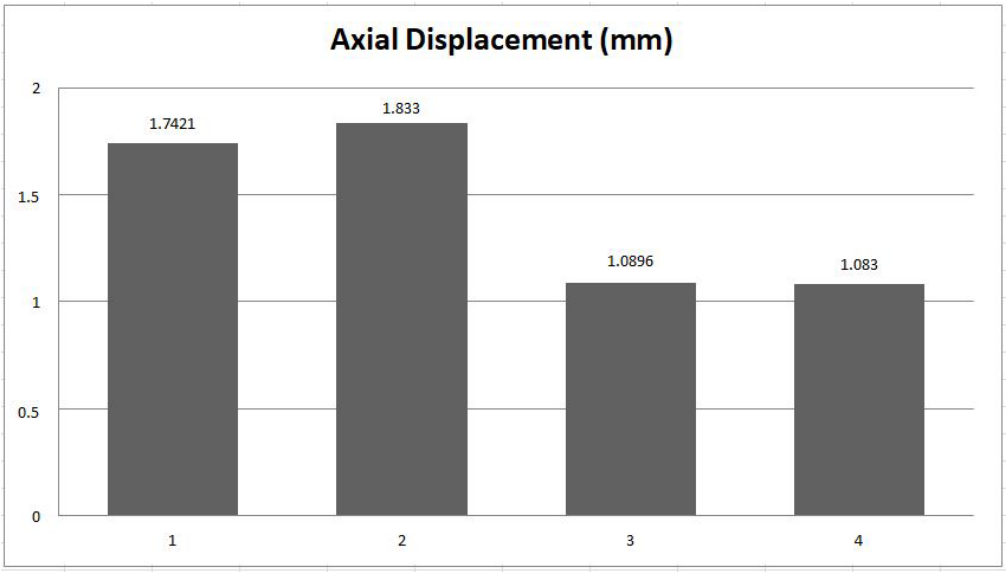

Figure 3. Axial displacements of the fixation groups.

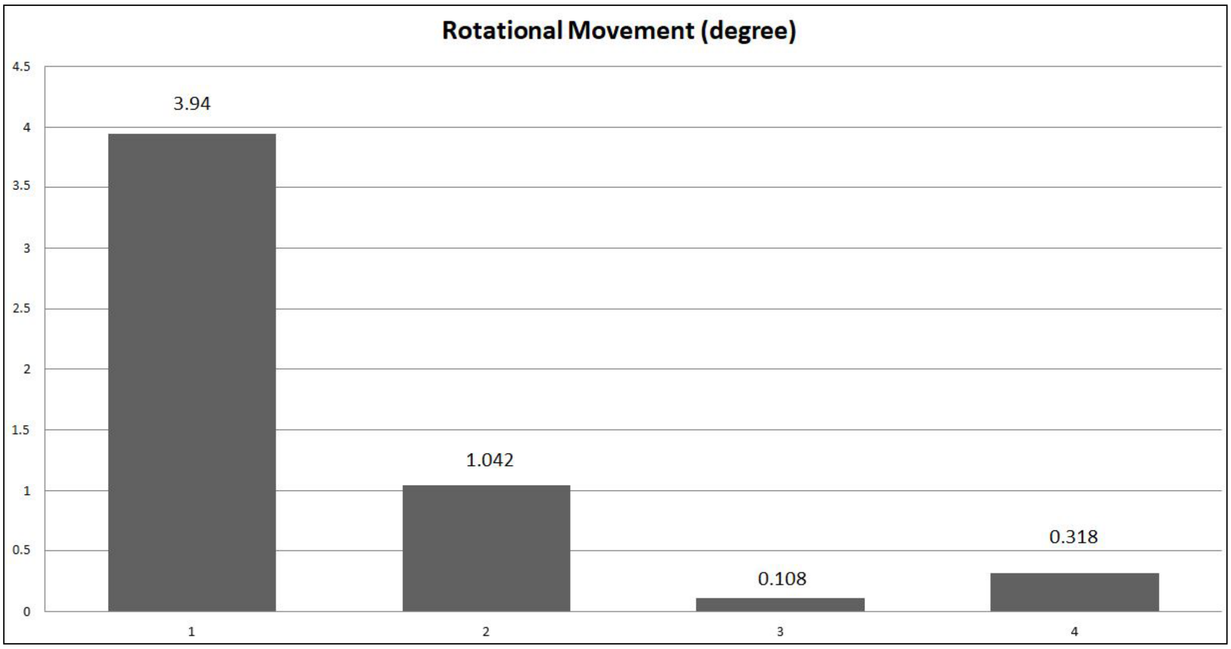

Figure 4. Rotational movement values.

seen to have reduced the stresses formed on the lateral plate and contributed to axial and rotational stability (Figures 6-9).

Discussion

The results of this study showed that the application of double plates and plates together with intramedullary nailing increased fixation strength compared to the use of these implants alone. When a lateral plate is combined with a medial plate or with intramedullary nailing, movement in the fracture line is reduced, and there is more resistance to axial loading. A 3.5 mm plate added from the medial was seen to reduce stress on the lateral plate. In a study by Bologna et al[19] 21 patients with distal femur fractures were retrospectively examined, and bone union was found to be significantly higher in the group where a medial plate was applied in addition to a lateral plate. In another study by Steinberg et al[20] 32 distal femur fractures, of which 8 had periprosthetic fractures, were examined, and successful results were obtained in all 30 patients treated with double plates.

In the current study, the use of a lateral plate together with intramedullary nailing was found to result in a structure more resistant to rotational forces. In a biomechanical study in 2015 by Başcı et al[11] it was concluded that the combination of lateral plate and intramedullary nailing in distal femur supracondylar fractures increased stability against axial and rotational forces. Although that study was not conducted on periprosthetic fractures, it was seen to be similar to the current study with respect to the study's principles and results.

Wright et al[21] conducted a biomechanical study in 2020 comparing the use of intramedullary nailing and double plates. Similarly, in the current study with bone models with distal femur fracture, 4 separate groups were compared, and as a result of the biomechanical tests, it was concluded that the group applied with double plates was more advantageous in all loading conditions compared to the group applied with intramedullary nailing and lateral plate. When intramedullary nailing was combined with a lateral plate in this study, the nail thickness was less, and the number of locking screws was reduced. Considering that this could have been the reason for the decrease in stability, identical nails and an equal number of distal locking screws were used. Consequently, no significant difference was seen between the application of double plates and the application of intramedullary nails together with a lateral plate.

In 2022, Lim et al[22] evaluated osteoporotic distal femur fractures and showed that min-

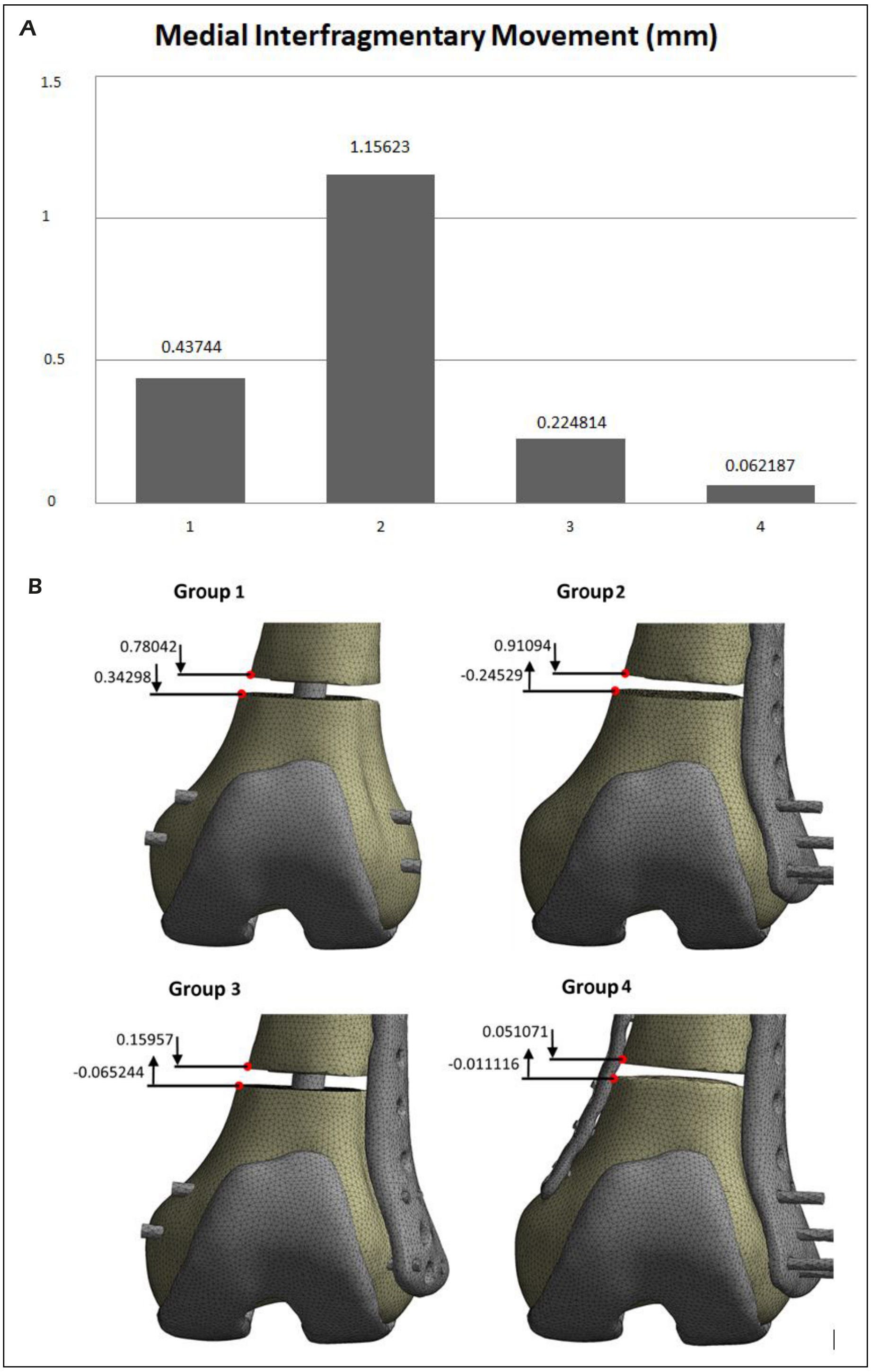

Figure 5. **A**, Interfragmental movement values. **B**, Medial displacement values of the proximal and distal fragments.

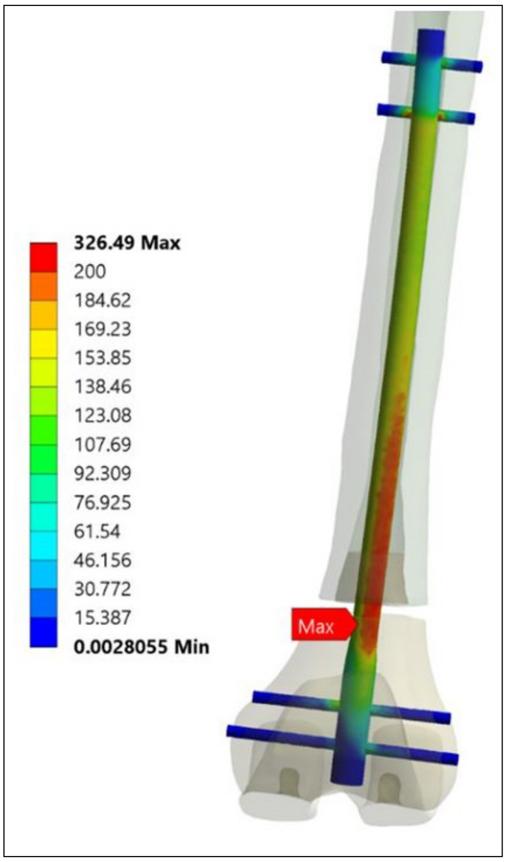

Figure 6. Implant stress values of the first group.

imally invasive application of medial and lateral plates increased stability in fixation and encouraged early weight-bearing of patients. It was stated that in patients with early mobilization, functionality increased, and complication rates decreased.

Using finite element analysis in a 2012 study, Chen et al[14] compared lateral plate, intramedullary nailing, and allograft combinations in periprosthetic distal femur fractures. In contrast to other studies in the literature, it was concluded that a strut graft applied intramedullary did not provide any additional stability to the locking plate.

In a biomechanical study by Todorov et al[23] in 2018, bone models with distal femur fractures were fixed with double plates, lateral plate, and lateral plate+intramedullar strut graft. It was concluded that the application of double plates was more successful than the intramedullary strut graft, but surgeons may still consider strut graft as an alternative.

This study evaluated changes in the fracture line against physiological loading using the finite element analysis method. The results need to be supported by further biomechanical studies on real bone models and randomized controlled clinical studies.

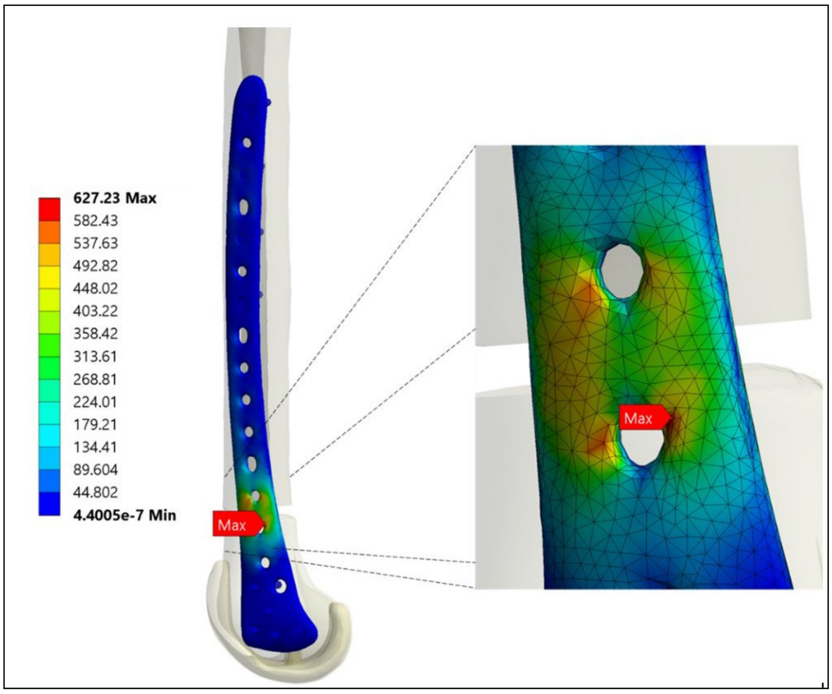

Figure 7. Implant stress values of the second group.

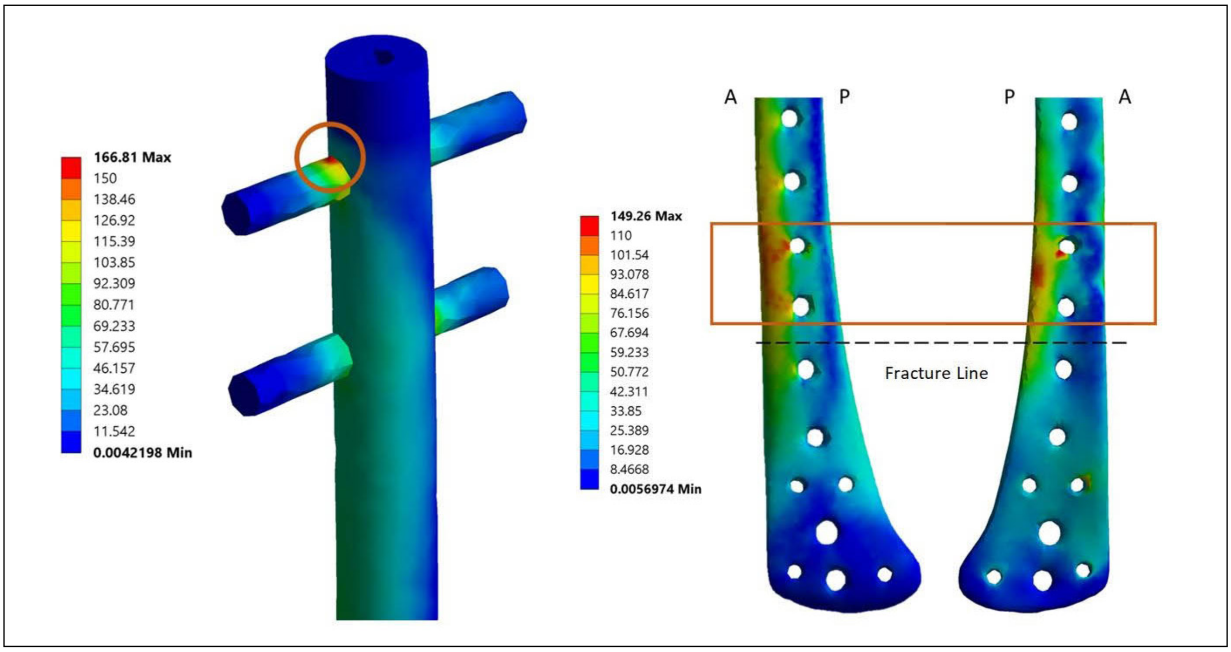

Figure 8. Implant stress values of the third group.

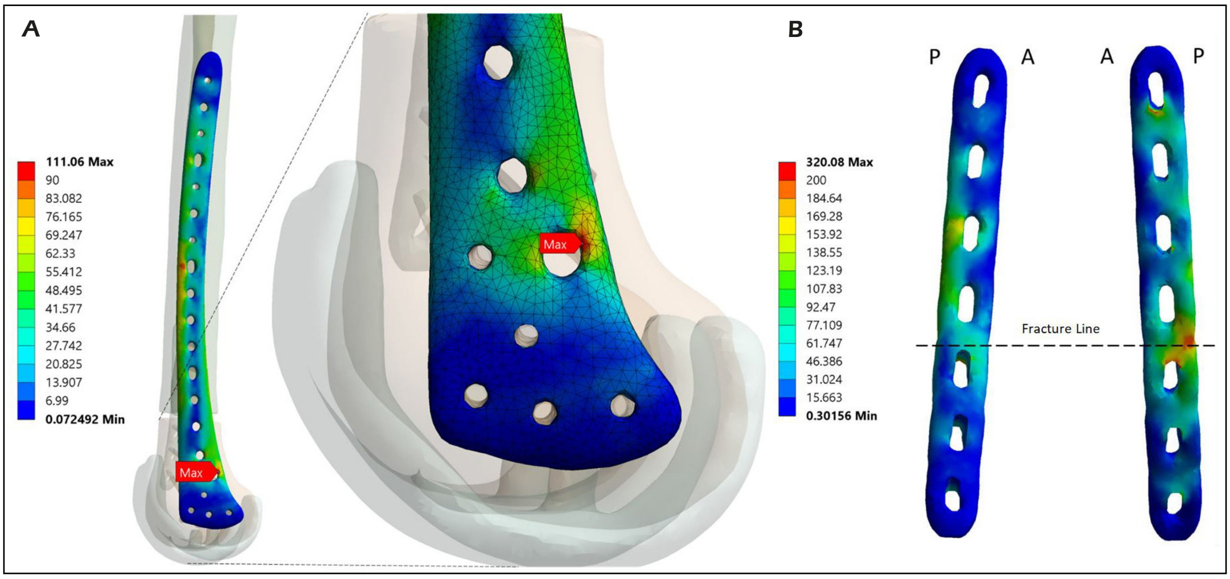

Figure 9. **A**, Stress values of the lateral plate. **B**, Stress values of the medial plate.

Limitations

The study has limitations, such as not having data obtained from human studies, being open to computer manipulation, and not being able to fully imitate soft tissue effects.

Conclusions

The finite element analysis in this study determined that support of a lateral anatomic plate with intramedullary nailing or a low-profile plate applied from the medial contributes to stability in the fracture line of distal femur periprosthetic fractures and will provide a more balanced load distribution. Nevertheless, further prospective clinical studies of larger samples are needed to support these results.

Conflict of Interest

The authors declare that they have no conflict of interest.

Funding

No funding was received.

Informed Consent

Not applicable.

Data Availability

All data generated or analyzed during this study are included in this published article.

Ethics Approval

Ethics Committee permission was obtained with decision No. 139/01 on 06.06.2022 from Dışkapı Yıldırım Beyazıt Training and Research Hospital.

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Authors' Contributions

Both authors contributed equally to the planning of the study, preparation of the study groups and comparison of the obtained data. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

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