Joint Diseases and Related Surgery

Jt Dis Relat Surg
2025;36(3):683-695

ORIGINAL ARTICLE

Evaluation of the effectiveness of Kirschner wires in preventing lateral hinge fractures in high tibial osteotomy: A finite element analysis

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ABSTRACT

Objectives: This study aims to investigate the effect of Kirschner wires (K-wires) placed in the lateral hinge on lateral cortical fractures occurring during medial opening wedge high tibial osteotomy (MOWHTO) technique.

Patients and methods: The mechanics of different models were compared using the finite element analysis and mathematical simulations. The first model is without K-wire control model, the second and third models are with one and two K-wires, respectively. The gap displacement (mm), gap distance (mm), correction angle (°), cortical-cancellous bone stresses (MPa), and stiffness (N/mm) of the hinge were used as outputs to compare the models. The effect of the position of the K-wire in the lateral hinge on the hinge stress and opening angle was also examined.

Results: The K-wires applied to the lateral hinge to prevent lateral cortex fracture reduced the hinge stress and increased the hinge stiffness. Higher force values were required to open the same amount of osteotomy compared to osteotomies without K-wires, which was a direct effect of increased hinge stiffness. Getting closer to the hinge for the K-wire position decreased the maximum stress value at the hinge and caused lower opening angles.

Conclusion: The higher force requirement for opening the osteotomy with K-wire application may reduce the risk of lateral hinge fracture by providing a more controlled and safer osteotomy opening, particularly for less experienced surgeons. Additionally, getting closer to the hinge for the K-wire position plays a positive role in preventing lateral hinge fractures. However, the opening angle decreases as the K-wire gets closer to the hinge.

Keywords: Finite element analysis, Kirschner wire, lateral cortical fracture, lateral hinge, lateral hinge fracture, medial opening wedge high tibial osteotomy.

Arthrosis of the medial compartment of the knee joint is 10 times more common than lateral arthrosis.[1] Medial compartment arthrosis is typically observed in varus knees and the load axis passes through the medial compartment of the joint. High tibial osteotomy (HTO) technique is applied to distribute this load from the medial compartment to the lateral compartment.[2]

The group of patients that this technique can benefit includes patients who can adapt to the treatment, are physically active, aged <65 years, have no ligament instability, and have localized medial compartment pain accompanied by varus malalignment of 5° to 15°.[3] Choosing the right patient is of utmost importance for treatment success.

Received: March 08, 2025
Accepted: June 14, 2025
Published online: July 21, 2025

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Doi: 10.52312/jdrs.2025.2252

Citation: Erdem TE, Ozkaya M, Kırılmaz A, Saray A, Yaka H, Turkmen F. Evaluation of the effectiveness of Kirschner wires in preventing lateral hinge fractures in high tibial osteotomy: A finite element analysis. Jt Dis Relat Surg 2025;36(3):683-695. doi: 10.52312/jdrs.2025.2252.

The following three techniques which are preferred to correct the deformity and realign the lower extremity: lateral closing-wedge HTO, dome osteotomy, and medial opening wedge HTO (MOWHTO).[2,3] Historically, HTO was first applied as lateral closing-wedge HTO. Over time, the MOWHTO has become more widely used owing to its advantages, i.e., it is a relatively easy-to-perform technique, preserves the bone stock, and does not place the fibular nerve and proximal tibiofibular joint at risk.[4,5]

In addition to preoperative planning and correction in accordance with the planning, achieving complete stability is of paramount importance for surgical success. Ensuring that the lateral cortical hinge is intact bears significant importance in achieving stability. This is attributable to the fact that in fractures of lateral cortical hinge, poor clinical outcomes such as loss of correction, delayed union, and nonunion are inevitable.[6-9]

Several studies have examined the effects of lateral cortical fracture during HTO and have investigated its long-term results. Different techniques have been attempted to prevent such fractures.[10-12] In the present study, we aimed to investigate the effect of Kirschner wires (K-wires) placed in the lateral hinge on lateral cortical fractures which may occur during MOWHTO technique. In this study, the finite element analysis (FEA) and a simple mathematical model simulating the wedge opening mechanics for the K-wire added osteotomies were conducted. To the best of our knowledge, this simple mathematical model is the first model in the literature to describe the hinge opening mechanics in detail. Additionally, by using mathematical model, another objective of this study was to investigate the effect of the K-wire position in the lateral hinge on the mechanics of the wedge opening.

PATIENTS AND METHODS

This biomechanical study using the FEA was conducted between August 2022 and January 2023 in the research laboratories of Department of Orthopedics and Traumatology, Necmettin Erbakan University, Faculty of Medicine, and Department of Mechanical Engineering, Karatay University, Faculty of Engineering and Natural Sciences. The study protocol was approved by the Necmettin Erbakan University Non-Drug and Non-Medical Device Research Ethics Committee (Date: 04.11.2022, IRB No: 2022-4025).

Generation of the models

Computed tomography (CT) images of the tibia of a 47-year-old man with varus deformity of the knee joint were acquired in Digital Imagining and Communications in Medicine (DiCOM) format. The CT sections starting from the proximal tibial joint were saved in the ".jpeg" format. These images were imported to SolidWorks (Dassault Systems SolidWorksCorp., Waltham, MA, USA) on a layer-by-layer basis, and the distances between them being identical to those in the CT images (Figure 1a). Images were captured with a distance of 2 mm proximally, increasing to 4 mm and gradually to 10 mm in the more distal regions. A total of 65 images were captured. Cortical and trabecular parts of the bone were included in the study. The outer and inner borders of the cortical bone were drawn as shown in the second image of Figure 1a. Therefore, the borders of cortical and trabecular bones were determined for each layer (the third panel of Figure 1a). While creating the solid model, a solid filled geometry was first obtained for the cortical bone using the outer borders in the cross-sections. A filled geometry of the trabecular bone was, then, created using the internal borders. Next, the trabecular bone geometry was subtracted from the other filled geometry to obtain the cortical bone geometry (the fourth panel of Figure 1a).

The proximal articular surface of the tibia was recorded to be 82 mm on the lateral medial axis and 60 mm on the anterior posterior axis (Figure 2a). The bone model was imported to the SpaceClaim solid modeling program (Ansys Inc., Canonsburg, PA, USA). The incision was created in this program. A 1-mm thick saw with radius tip was modeled (Figure 1b). A monoplanar incision line was created approximately 4 cm distal to the medial aspect of the tibial joint, targeting the fibular head, ending 13.9 mm medial to the lateral cortex and 15.7 mm distal to the lateral plateau of the tibia (Figure 2a).

Three models were created in the study as follows: no K-wire, one K-wire, or two K-wires applied to the lateral hinge (Figure 2b). The K-wires were terminated approximately 9 mm medial to the lateral cortex and 8 mm from the lateral plateau (Figure 2c). The applied K-wire was determined as 1.8 mm in diameter, which we routinely prefer in surgical practice.

Finite element analysis

Tetrahedral and hexahedral elements were used to create the mesh. In the solution mesh, in

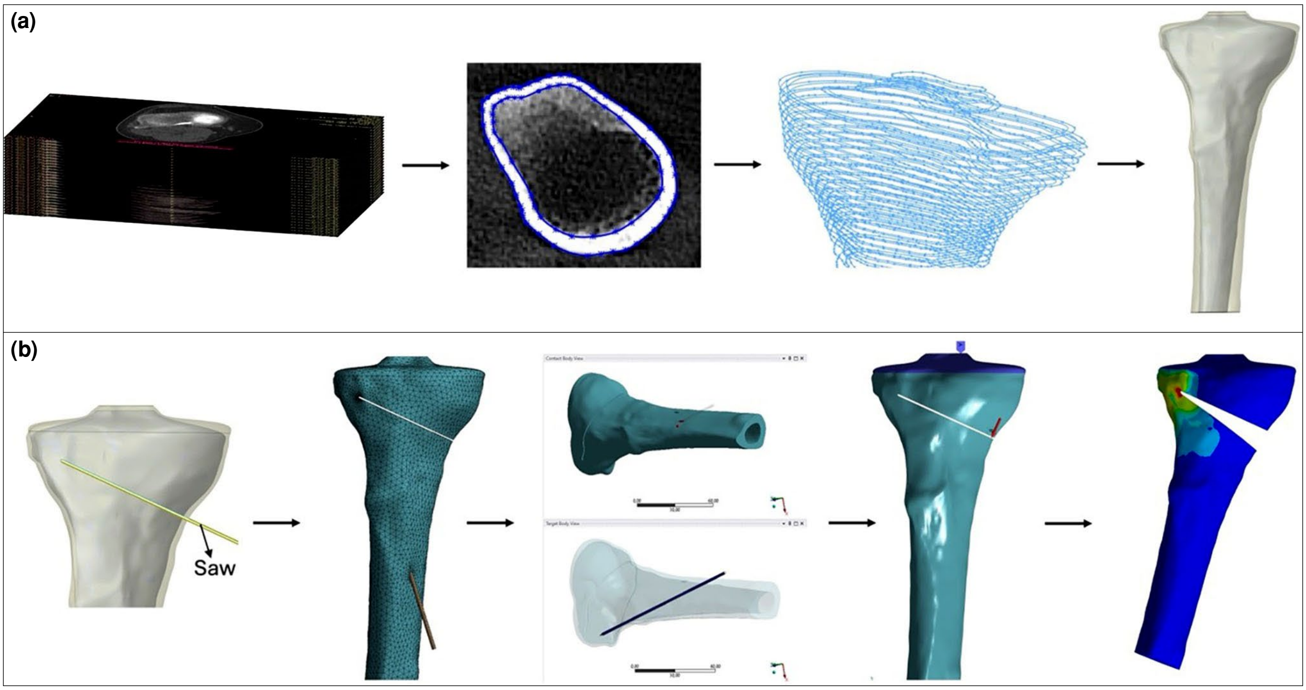

FIGURE 1. (a) Procedures in generation of the bone model, from left to right, aligning the computed tomography slices, drawing the cortical borders, generating solids for cortical and trabecular bone, final bone model, **(b)** procedures in finite element analysis, from left to right, creating the osteotomy, meshing the models, assigning materials, connections, and loading and boundary conditions, evaluating the results.

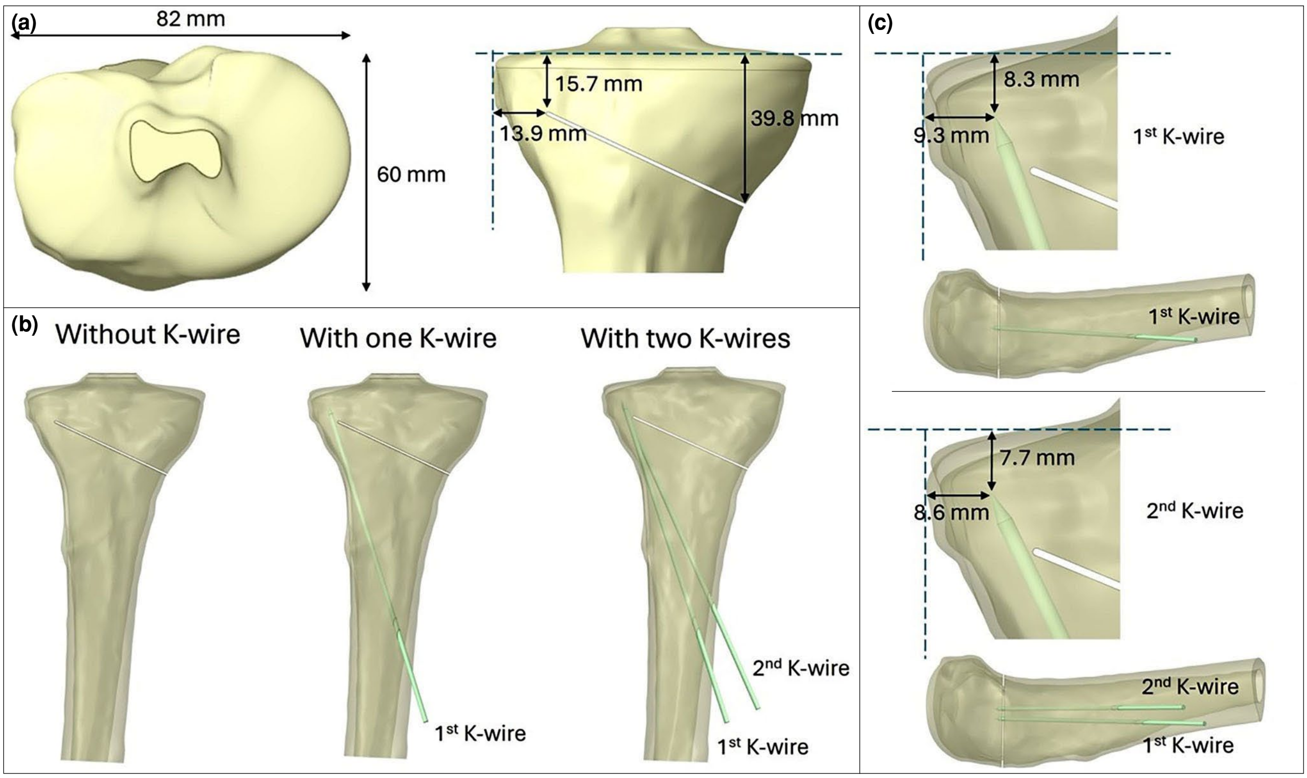

FIGURE 2. (a) Top view of the proximal articular surface of the tibia and view of the incision line, **(b)** models of without K-wire, one K-wire, and two K-wires, **(c)** distances of K-wires from lateral cortex and lateral tibial plateau.

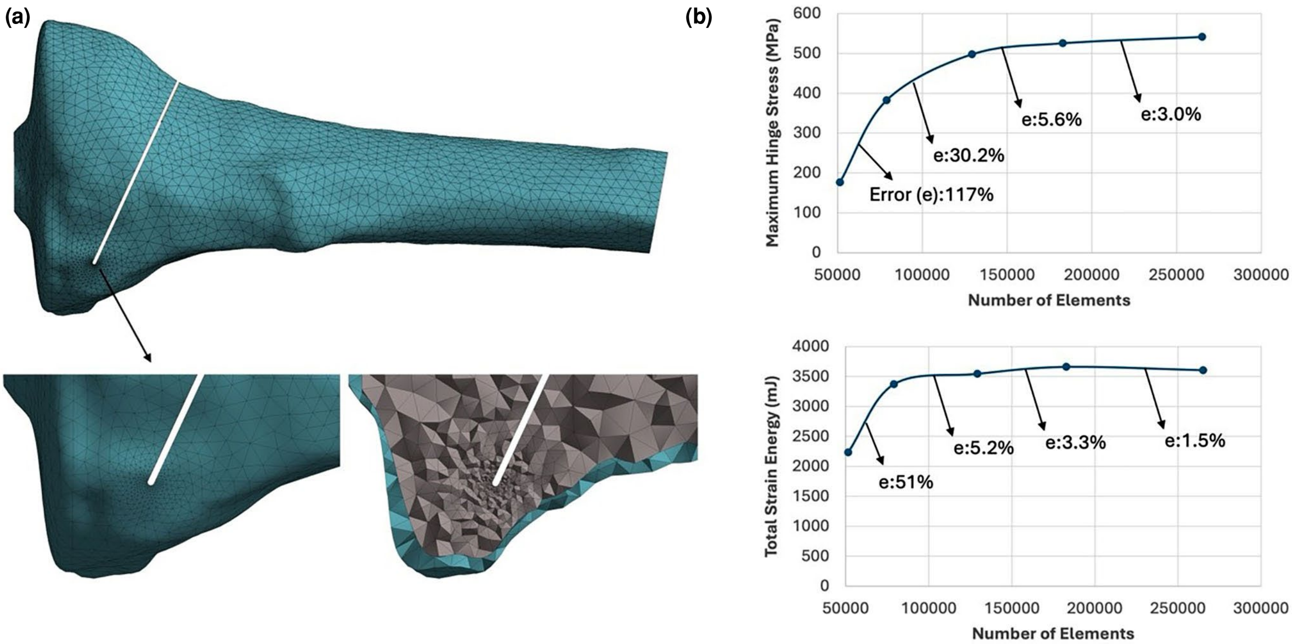

FIGURE 3. (a) Mesh model of the tibia, hinges and the section view, **(b)** results of the convergence analysis, maximum hinge stress *vs.* number of elements curve on top and total strain energy *vs.* number of elements curve at the bottom.

the regions where high stresses are expected to occur, the element sizes were reduced, and the elements were densified to refine the solution mesh (Figure 3a). To determine the sufficient numbers of element in the solution mesh, a mesh convergence analysis was conducted. The criteria in the determination were the percentage error. If the percentage error in maximum hinge stress (MPa) or total strain energy (mJ) was below 5% between two consecutive analyses, it was accepted that the mesh model converges to accurate result.

Literature review was carried out to assign material characteristics to the models. A model of bilinear isotropic hardening material was assigned for cortical and trabecular bone, whereas a model of multilinear isotropic hardening material was assigned for K-wires.[8-10] The mechanical properties shown in Table I were obtained from the data in these referenced studies. In both models, the modulus of elasticity and Poisson's ratio were used for the elastic part. The plastic part of the bilinear isotropic hardening model in the cortical and trabecular bones is defined by yield strength and tangent modulus. However, in the multilinear isotropic hardening model used for K-wires, the true stress-plastic strain curve generated using a large number of values for the plastic part was used. A bonded connection model was used to assign the connections between the cortical and trabecular bones and K-wires in the models (the third panel of Figure 1b).

The proximal articular surface of the tibia was completely immobilized in all directions (the fourth panel of Figure 1b). A load of 500 N was applied perpendicular to the distal aspect of the osteotomy line, increasing linearly over time (Figure 4). This final load value was applied in 50 equal intervals, starting at 0 and increasing

TABLE I
Mechanical properties of materials

	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Tangent modulus (MPa)
Cortical bone	18.2	0.26	84.5	685.4
Trabecular bone	0.372	0.3	2.19	61.0
K-wire (316L stainless steel)	190	0.31	-	-

by 10 N at each interval. This loading condition was created to appropriately reflect the loading and boundary conditions of the tibia during the operation.

Simultaneously with the applied force (N) for all three models, the gap distances (mm), displacement at gap distances (mm), correction angles (°), von-Mises stresses (MPa) at cortical and cancellous bones in hinge regions were recorded as outputs. Application of the force causes an instantaneous displacement occurs in the gap distance in the direction of the applied force. Using these data, the applied force-displacement in the gap distance curve for each model was generated. From the slope of the linear part of this curve, the stiffness (N/mm) value of the model was determined for each model. This stiffness value is a numerical measure of the resistance of the object to displacement under force. Therefore, the stiffness values calculated within the scope of the study were evaluated as the resistance of the models against the force. The slopes of the linear parts of the applied force-displacement in the gap distance curves were determined by applying regression analysis on the linear part. Regression analysis generates a mathematical formulation between force and displacement in the form of "y = mx," where the coefficient of the term "x" is the slope of the line; i.e., the stiffness.

Mathematical model of wedge opening with K-wire

In the present study, different from the studies in the literature, we generated a simplified mathematical model of wedge opening mechanics in a K-wire inserted osteotomy. Although the lateral hinge fractures in osteotomy are a fracture analysis problem, it would be useful to investigate the opening mechanics of a hinge with a K-wire. As it has been well documented, during the opening of the osteotomy, a force (F) is applied to the distal part of the osteotomy in the medial cortex (Figure 5a). Since this applied force results in mainly bending loads on the hinge, the hinge is simply subjected to the bending deformations during the opening as in the beam bending.

The force applied to open the osteotomy creates a resultant moment (M) at the hinge as can be seen on Figure 5a, and the distal osteotomy tends to rotate about the hinge. Due to this tendency, a certain amount of bending occurs at the hinge. The resultant moment in Figure 5.a acts around the hinge, and the most critical and damage-prone section is simply

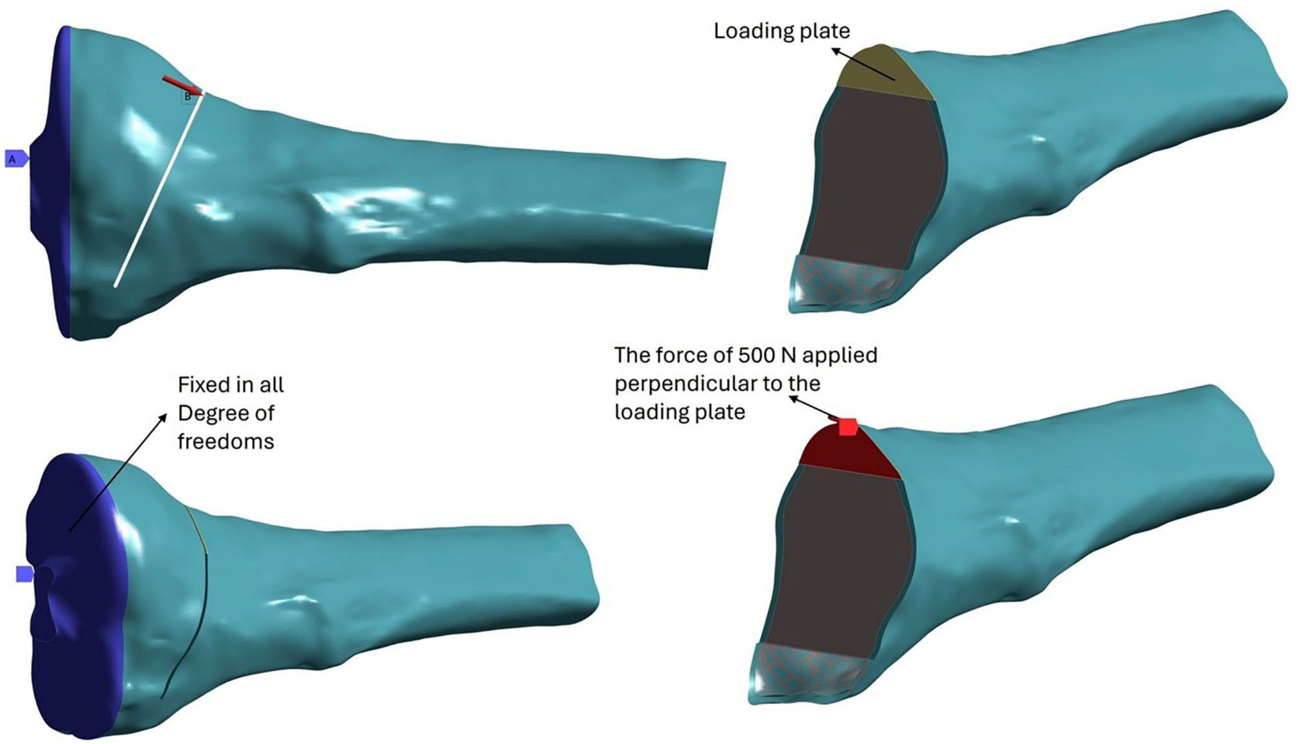

FIGURE 4. Loading and boundary conditions.

the one with the smallest cross-sectional area, since the applied loads produce more stress in a small area. When the measurement was made on the solid model used in this study, the weakest section with the smallest cross-sectional area in the hinge region was found to be the section B positioned at an angle of approximately 125° to the osteotomy line (Figure 5a). The section B is shown in Figure 5b, where A_{cr}, A_{tr}, and A_{kw} are the cross-sectional area of the cortical bone, trabecular bone, and K-wire, respectively, while y_{cr}, y_{tr}, and y_{kw} are the distances between the area centers of the structures and the coordinate system in the Y direction. If we consider an undeformed differential section at hinge with a thickness of *dl* in section B (Figure 5c, left figure), this differential section tends to distort with bending moment (Figure 5c, right figure). The bending moment causes an extension in the top portion and a compression in the bottom portion of the material. Therefore, there is an axis between these two regions in which there is no deformation in theory. This axis is called as the neutral axis (NA).

From the first moment of the cross-sectional area, we can calculate the location ($\bar{y}$) of NA from the top using Equation (1). In this formulation, Atotal is the total area of the cross section. However, when using this formula, a transformation must be made between the areas, considering the effect of the Young's modulus of the materials, as there is more than one structure with different material properties in the section. We converted the areas of the trabecular bone and K-wire to the cortical bone. To do this, A_{tr} was multiplied by E_{tr}/E_{cr} (the ratio between the Young's modulus) and A_{kw} was multiplied by E_{kw}/E_{cr} before using the Equation (1). After finding the location of the NA, the maximum

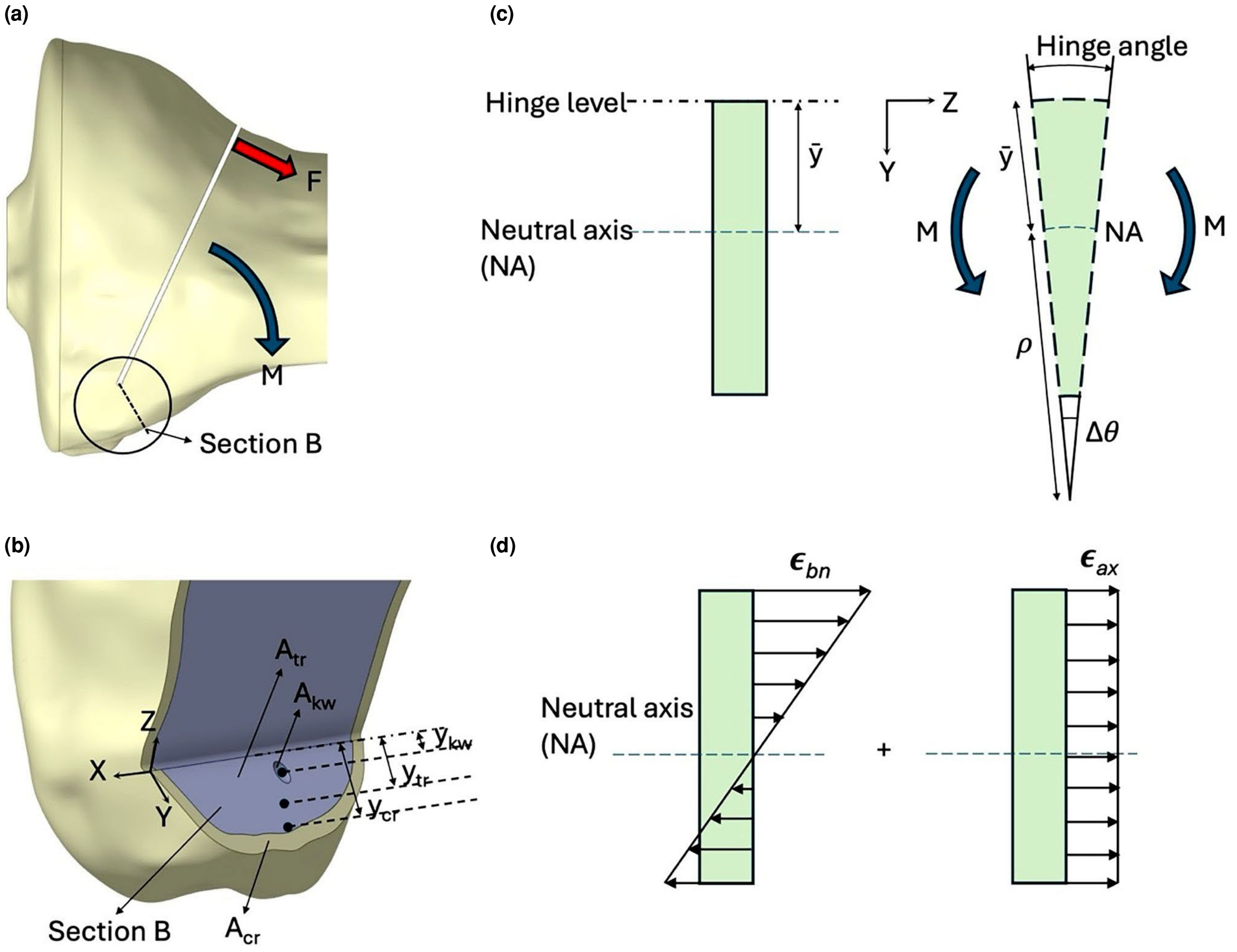

FIGURE 5. Mathematical model of the osteotomy opening, **(a)** the loading condition, **(b)** details of critical section B, **(c)** a differential part of the critical section at under hinge, and **(d)** the strain distribution on the critical section.

strain at hinge can be calculated by Equation (2) as the combination of bending strain (ε_{bn}) and axial strain (ε_{ax}) (Figure 5d). In this formulation ρ is the radius of the section (Figure 5c). While evaluating the stress values on hinge, there is also a combination of bending stresses and axial stresses as in the strains (Figure 5d). The hinge stress is calculated by Equation (3). The *I* is the area moment of inertia of the cross-section, and while calculating it, the area of materials should be also converted to the cortical bone area as in the location of the NA. The angular deformation ($\Delta\theta$) of the section, which we assumed that it is equal to the opening angle at the same time, can be calculated easily from Equation (4). For the maximum stress at the hinge, the stress value that was obtained from the Equation (4) was multiplied by the stress concentration factor, as the hinge at the osteotomy plane behaved like a stress concentrator.

$$\bar{y} = \frac{(A_{cr}\, y_{cr} + A_{tr}\, y_{tr} + A_{kw}\, y_{kw})}{A_{total}} \tag{1}$$

$$\varepsilon = \frac{\bar{y}}{\rho} + \frac{F\sin 35}{A_{total}} \tag{2}$$

$$\sigma = \frac{M\bar{y}}{I} + \frac{F\sin 35}{A_{total}} \tag{3}$$

$$\Delta\theta = \frac{dl}{\varrho} \tag{4}$$

By using these equations, we calculated the wedge opening angle and maximum stress at the hinge and compared them with the results of FEAs. Additionally, we utilized these equations to evaluate the effect of the K-wire location on the wedge opening mechanics, which was the first time carried out in this field.

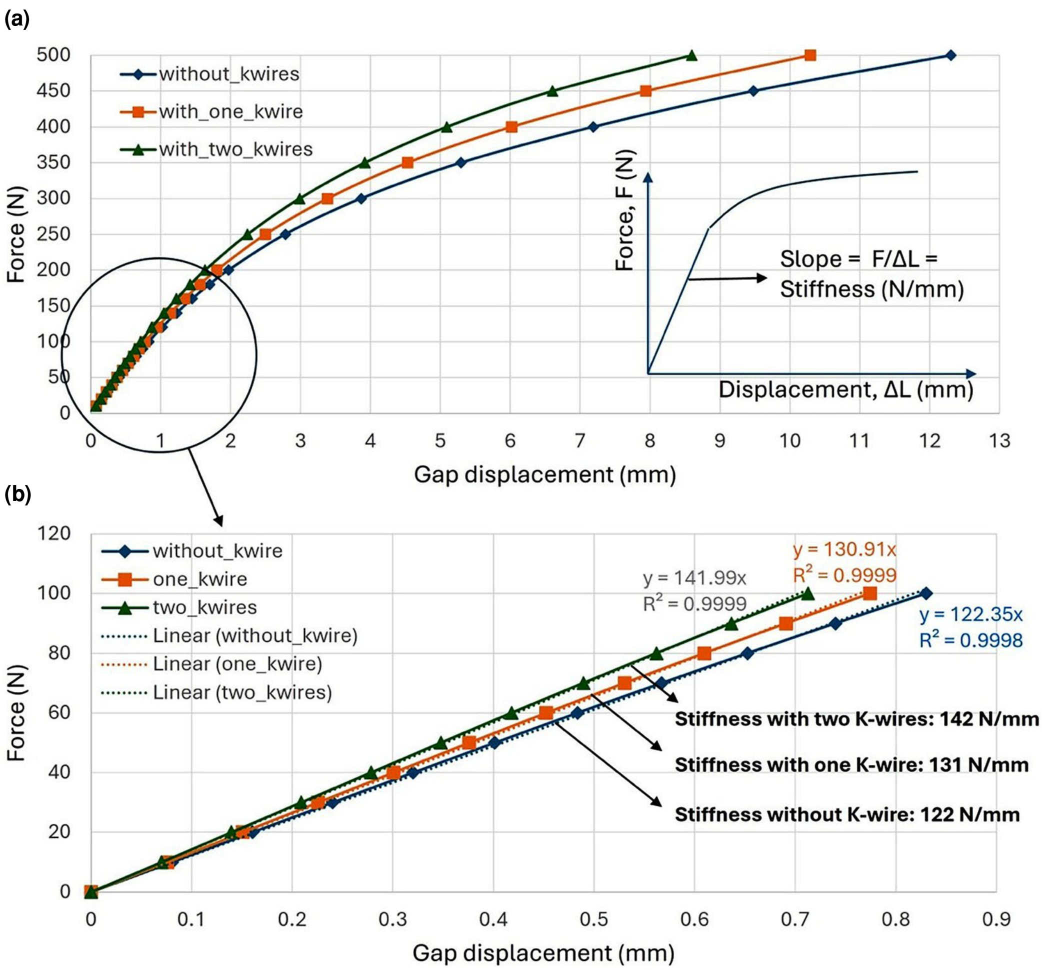

FIGURE 6. (a) Force-displacement curves of the models and calculation method of the stiffness, and **(b)** stiffness values of the models.

RESULTS

Results of the convergence analysis

The results of the convergence analysis are shown in Figure 3b. In this figure, the five points on each curve show the consecutive analyses performed with different number of elements. For the maximum hinge stress (MPa), the percentage error (e) between the fourth and fifth model was approximately 3% which is below of accepted convergence limit. For the total strain energy (mJ), the percentage errors between the third and fourth model of the fourth and fifth model were below the convergence limit. This means that the fourth and fifth mesh model can be used as converged mesh models, and they give the accurate stress and displacement results. As a result, we selected the fourth mesh model and used it in the rest of the analyses. Exceeding the number of elements beyond the fourth model increases the workload and the simulation time without any advantages.

Load-displacement behaviors

According to the FEA results, at 500 N of applied force, the control model (no K-wire) had 12.6° of opening and 13.3 mm of gap distance, the model with one K-wire had 10.5° of opening and 11.2 mm of gap distance, and the model with two K-wires had 8.8° of opening and 9.6 mm of gap distance. These results showed that mounting K-wires onto the lateral hinge reduced the opening angle and gap distance compared to the case of not mounting the K-wire under the same force value.

Examination of the applied force-displacement in the gap distance (Figure 6a) revealed that there was an almost linear relationship between the force and the displacement for the first 10 values. For this reason, the curves covering the first 10 values were redrawn to find the stiffness values and the regression analysis was applied to these data (Figure 6b).

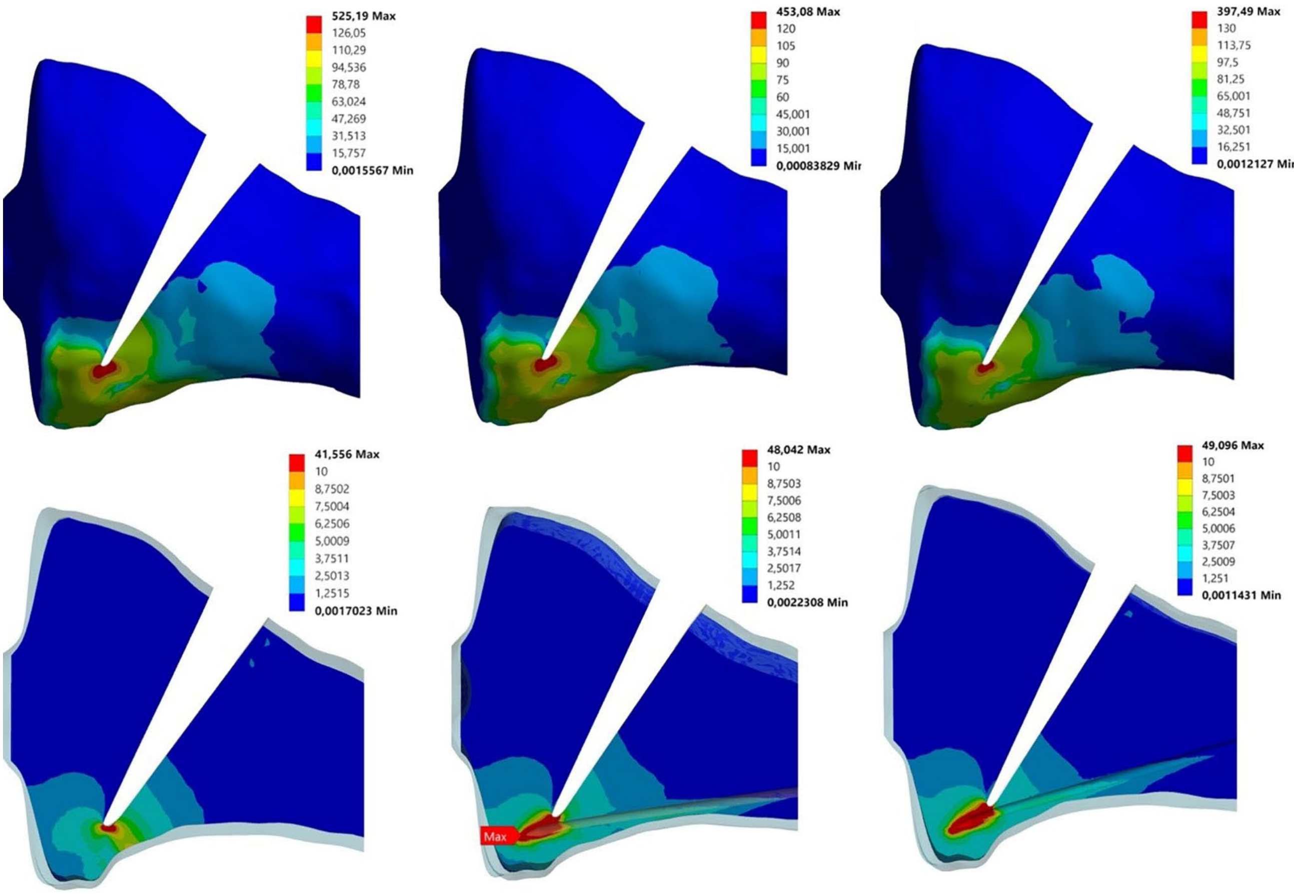

FIGURE 7. von-Mises stress (MPa) stress distribution on cortical and trabecular bones for each model, **(a)** no K-wire, **(b)** with one K-wire, and **(c)** with two K-wires.

TABLE II
Stress values on the cortical and trabecular bone at different correction angles (°) with FEA and mathematical model

	Without K-wire			One K-wire			Two K-wires		
	FEA		Math model	FEA		Math model	FEA		Math model
Correction angle	Cortical stress	Cancellous stress	Cortical stress	Cortical stress	Cancellous stress	Cortical stress	Cortical stress	Cancellous stress	Cortical stress
1	103.2	5.0	42.7	103.1	6.5	32.4	103.1	8.1	27.5
2	143.2	10.6	85.4	144.6	12.4	66.1	145.8	15.8	55.0
3	181.6	15.7	128.1	181.7	18.4	98.8	185.3	22.1	82.5
4	221.2	19.5	170.7	218.4	22.9	132.1	222.9	27.6	110.0
5	261.3	23.1	187.9	256.8	27.7	164.5	266	33.2	137.7

FEA: Finite element analysis.

According to the regression analysis, the stiffness was calculated as approximately 122 N/mm in the model without K-wire, approximately 132 N/mm in the model with one K-wire, and approximately 142 N/mm in the model with two K-wires. As a result, the K-wires applied onto the lateral hinge acted as an element resisting the applied force in the hinge and increased the stiffness of the lateral hinge.

Cortical and cancellous bone stress at hinges

The FEA results showed that the maximum stress over the lateral cortex occurred on the hinge for all models (Figure 7). While comparing the hinge stresses of the models under the same force value, K-wires attached to the lateral hinge decreased the stresses in the cortical bone and increased the stresses in the cancellous bone. The mathematical model showed the same trend with adding the K-wires.

In terms of the cortical bone stresses at the same angular opening of the wedge, the maximum stress values at the hinge were similar for all three models according to the FEAs (Table II). As a result, we could not make a correlation between maximum cortical hinge stresses and adding the K-wires with FEA results. On the other hand, the results obtained from the mathematical model revealed that adding K-wire to the lateral hinge decreased the maximum stress on the cortical bone at the same angular opening of the wedge (Table II). Additionally, from the FEA, the maximum stress on the cancellous bone increased with addition of the K-wires at the same opening angle. We did not compute the stress on cancellous bone by using mathematical model.

The effect of the K-wire location in the lateral hinge on the stress and wedge angle could be investigated with the help of the mathematical model. According to these results (Figure 8), moving the K-wire away from the hinge first increased the hinge stress up to a certain distance and, then,

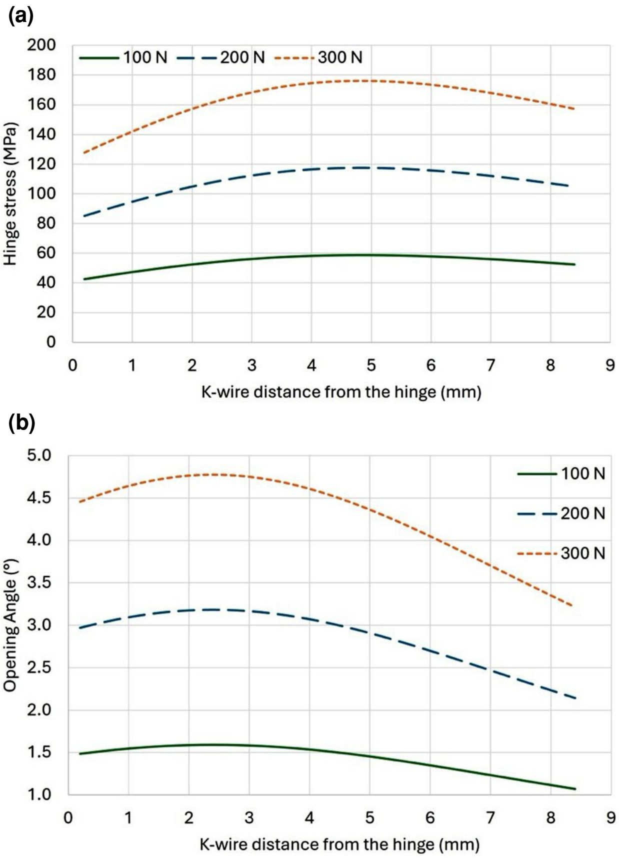

FIGURE 8. Effects of the K-wire distance from the hinge on **(a)** the stress and **(b)** opening angle.

decreased it after this distance. Similarly, the wedge angle increased with increasing distance up to a certain value and, then, decreased.

DISCUSSION

In the present study, we performed FEAs and generated a simple mathematical model to investigate the effect of the additional K-wire to the lateral hinge on the wedge opening mechanics in MOWHTO. The presented mathematical model has been the first model which explains the mechanics of the wedge opening not only in the K-wire added osteotomies, but also in the standard osteotomies. To the best of our knowledge, the effects of the position of the K-wire in the lateral hinge has been investigated for the first time in literature by this mathematical model.

Before evaluating the results of this study, it would be useful to explain the importance of the subject. It is of utmost importance to preserve the lateral cortex during correction. Fracture of the lateral cortex causes increased micro-movement and instability in this region. As a result, complications such as recurrent varus deformity, delayed union and nonunion may develop with loss of correction. Implant failure is also an important complication after lateral cortex fracture.[7] The occurrence of lateral cortex fracture during MOWHTO is not a complication that can be completely prevented.[13] Miller et al.[14] reported that they encountered 8.7% lateral cortex fracture in patients who underwent MOWHTO. Hernigou et al.[15] reported that they encountered lateral hinge fracture in 12% of patients who underwent MOWHTO and delayed union and loss of correction in this group. Kang et al.[16] investigated the biomechanics of fixation after lateral cortex fracture by FEA. They formed three groups as type 1 (fracture lateral to osteotomy), type 2 (fracture proximal to osteotomy), type 3 (fracture distal to osteotomy) according to Takeuchi classification and recorded plate and bone stresses and micro-movements under axial loading. Plate stress increased significantly, and bone stress decreased in type 2 and 3 fractures and micro-movements occurred in type 2 and 3 fractures and, therefore, union may be delayed. Significant complications such as loss of correction, nonunion, delayed union seen after lateral hinge fracture have led researchers to carry out studies to prevent this condition.

Various strategies have been developed to prevent lateral hinge fracture, which still maintains its importance in terms of complications.[11,12,17,18] One of them is adding a K-wire to the lateral hinge before the wedge opening. In a retrospective study of 120 patients, Gulagaci et al.[19] opened the osteotomy line by adding a K-wire to the lateral hinge in 60 patients. They reported that 72% of the fractures encountered were in the group without a K-wire. While 43% of the lateral hinge fractures were observed in the group without a K-wire, 16% of the lateral hinge fractures were observed in the group with a K-wire. The authors concluded that K-wires sent to the lateral hinge prevented fracture formation. However, in their study, the amount of osteotomy opening and the amount of applied force between the groups was not considered. In the retrospective study conducted by Mahmoud et al.,[20] the relationship between lateral hinge fracture and the use of two K-wires inserted parallel to the joint line and lateral to the osteotomy hinge was investigated. According to their results, the group in which K-wires were applied experienced a lower incidence of lateral hinge fracture. However, their study did not report any data regarding the osteotomy gap in patients who sustained a fracture, which is a critical factor influencing mechanical stress distribution. Moreover, the procedures were performed by two different surgeons, introducing potential variability related to surgical technique.

To the best of our knowledge, the only experimental study about adding the K-wire to the lateral hinge was performed by Dessyn et al.[10] They compared the maximum load applied and the maximum permissible displacements until the lateral hinge fracture between the groups in which a K-wire was added to the lateral hinge in one of each pair in a study performed in five pairs of cadavers. They showed that they were able to apply 880% more load and obtained 220% more displacement in the K-wire group than in the non-added group without breaking the lateral cortex. In another biomechanical study investigating the effect of the K-wire to the lateral hinge fractures were conducted by Ozmen et al.[21] In their numerical study, they evaluated the effectiveness of different protective techniques to decrease the risk of lateral cortex fractures during HTO. They used three-dimensional (3D) models with different sizes of K-wires with 1.6 mm, 2 mm, and 2.5 mm in diameter. Their results revealed that the forces required to open the osteotomy at the same degree were higher in K-wire added model when compared to non-added model, and this force value increased with increased size of K-wires.

We acknowledge that it looks like the topic has been extensively explored in the literature. However, we believe that our study provides a novel contribution by generating a mathematical model for wedge opening mechanics and investigating the effect of the K-wire position in the lateral hinge on the wedge opening mechanics. From the mechanical perspective, it can be speculated that techniques similar to inserting K-wire into the lateral hinge have already been used in the construction field for years. Steel wires are inserted into columns and beams in constructions. While concrete is quite resistant to compression loads, it is not resistant to tensile loads. To prevent tension in the concrete and make it resistant to tensional loads, thick steel wires are added into the concrete. This limits the amount of displacement under load and reduces the tensile stresses. We believe that adding K-wire into the lateral hinge has two effects, as in this example, and our mathematical calculations confirm these two mechanisms.

In this perspective, one of most important findings of the present study was that the single and double K-wires crossing the lateral hinge before opening the osteotomy increased the force which was required during wedge opening. This result was supported by both FEAs and the mathematical model. To open the osteotomy line at the same angular opening value or at the same gap distance, the greater force was required in K-wires added models. This is clear evidence of that adding a K-wire to the lateral hinge increases the stiffness of the hinge (Figure 6). This result is supported by the other studies in the literature.[10,21] The fact that the higher force required for the same amount of opening in the osteotomy line may be beneficial in terms of preventing lateral hinge fractures by providing a safer and more controlled opening of the osteotomy. Previous studies have shown that complications such as over correction, excessive posterior tibial slope change and lateral hinge fracture in MOWHTO can be improved with surgical experience.[22] Achieving the same amount of opening with higher forces in cases with K-wire application compared to cases without K-wire application during opening of the osteotomy may provide a protective effect for complications such as lateral hinge fracture and over correction for surgeons with less surgical experience, but further studies are needed.

The idea mentioned in the previous paragraph can also be interpreted in terms of surgical operation as follows. The lateral hinge fracture is essentially a fracture mechanics problem, and the fracture occurs as an initiation from the hinge or propagation of the crack in the hinge during the surgical operation. If the physician opens the osteotomy slowly and in a controlled way with the K-wires he added, intentionally or unintentionally, this can delay initiation or propagation of the crack. Otherwise, a sudden load without K-wire can increase the risk of the fracture. There is evidence in the literature to support this. It is a well-known concept that bone behaves as ductile under slow loading and deforms more before fracture, whereas it responds brittle under fast loading and may break even at low deformation values.[23,24]

When the stresses occurring in the hinge are evaluated, the FEA results in our study are not consistent with the results obtained from the mathematical model (Table II). According to the mathematical model, the maximum stress at the cortical hinge decreases at the same opening angle by adding one or two K-wires, which may be a positive effect in preventing the occurrence of the lateral hinge fractures. On the other hand, from the FEA results, we could not make a correlation between maximum cortical hinge stresses and adding the K-wires. We believe that the mathematical model was more reliable and FEA could not be able to predict the maximum stresses correctly. This is most probably due to the large deformations at the hinge. We used a static structural analysis in modeling the wedge opening, but at high opening angles hinges undergo too much deformation which may result in incorrect results. From this point, we suggest the researchers, who use FEA in their studies to evaluate the mechanics of wedge opening, that the results of the FEA should be interpreted cautiously. The results of the mathematical model are also consistent with the numerical study of Ozmen et al.[21] who showed that adding a K-wire to the lateral hinge decreased the hinge stresses at the same gap distance. For the cancellous bone, we did not simulate the hinge stresses with the mathematical model. However, the FEA results showed that the hinge stresses increased with addition of K-wires (Figure 7). This is because the K-wires are in a direct contact with cancellous bone, and if they bend during opening, they deform the cancellous bone and increase its stress value.

In addition, with the help of the mathematical model, we were able to easily examine how the position of the K-wire in the lateral hinge changes the stress value in the hinge or wedge angle. This has not been done before and it is one of the novel contributions of the present study to the literature. Figure 8 illustrates the effects of the K-wire position. According to this, moving the K-wire away from the hinge first increased the hinge stress up to a certain distance and, then, decreased it after this distance. In a similar manner, the wedge angle increased with increasing distance up to a certain value and then decreased. To illustrate, when a 300 N force is applied to open the wedge, positioning the K-wire 1 mm away from the hinge causes a stress of around 140 MPa at the hinge, while positioning it 5 mm away can increase this stress up to 180 MPa, indicating a significant difference. In other words, getting closer to the hinge for the K-wire position plays a positive role in preventing lateral hinge fractures. However, we can comment that the opening angle decreases, as it gets closer to the hinge (Figure 8b).

The stress and angle values in the Figure 8 are a result of the formulas given in the method section, and the factors that are effective in these values are essentially the area moment of inertia of the hinge section, the Young's modulus of the materials in the section, and the distance of the K-wire from the hinge. In our study, we used a simple model to present a novel and useful perspective. However, we did not conduct a detailed examination on which distance value was the most ideal or how it was determined. We believe that a detailed examination of this in future studies may be useful in reducing lateral hinge fractures.

Since we used the same bone model for all three models in our study, limiting factors such as age, bone quality, environmental factors were eliminated, and more objective results were obtained. We conducted a simple mathematical model by using the strength of the materials to examine mechanics of the wedge opening. On the other hand, lateral hinge fracture is a problem of fracture mechanics. The most satisfactory results can be predicted by using fracture mechanics analyses or models, which can be regarded as a limitation to our study.

In conclusion, K-wires applied to the lateral hinge to prevent lateral cortex fracture reduced the hinge stress and increased the hinge stiffness. Higher force values were required to open the same amount of osteotomy compared to osteotomies without K-wires, which was a direct effect of increased hinge stiffness. Based on these results, the higher force requirement for opening the osteotomy with K-wire application to the lateral hinge may reduce the risk of lateral hinge fracture by providing a more controlled and safer osteotomy opening, particularly for less experienced surgeons. Additionally, getting closer to the hinge for the K-wire position plays a positive role in preventing lateral hinge fractures. However, the opening angle decreases as the K-wire gets closer to the hinge.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Idea, concept: T.E.E., M.Ö., F.T.; Data collection: T.E.E., M.Ö. A.K.; Analysis: M.Ö., A.S., H.Y.; Control and critical review: H.Y., A.K., A.S., F.T.; Writing the article: T.E.E., M.Ö.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding: The authors received no financial support for the research and/or authorship of this article.

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