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ORIGINAL ARTICLE

Reduced lateral hinge stress and fracture risk in double-hinge medial open-wedge high tibial osteotomy: A finite element study

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ABSTRACT

Objectives: This study aims to describe the double-hinge medial open wedge high tibial osteotomy (DH-MOWHTO) with two lateral hinges and to investigate its feasibility and its utility in prevention of lateral hinge fractures (LHFs) using a finite element analysis (FEA) model.

Materials and methods: Three osteotomies were modeled. Model 1 (DH-MOWHTO) involved two monoplanar osteotomies from the same starting point, while Models 2 and 3 were standard monoplanar osteotomies using one osteotomy line from Model 1. They were compared in terms of maximum von-Mises stress value (MPa) in the hinges at 10° correction angle, gap distance at 10° correction angle (mm), force required to achieve a 10° correction angle (N), and total surface area (mm^2) of osteotomy surfaces contacting the saw.

Results: In DH-MOWHTO, the maximum anterior hinge stress at 10º correction angle was reduced by 28.1 to 39.6% and the maximum posterior hinge stress was reduced by 19.2 to 60.1% compared to single monoplanar osteotomies. The average stress reduction in the hinges was 36%. The force required for a 10° correction was approximately 78 N, 114 N and 85 N for Models 1, 2 and 3, respectively. The model with two monoplanar osteotomies had approximately 1.8 and 2 times more osteotomy surface area than Models 2 and 3, respectively.

Conclusion: In this FEA study, two lateral hinges can be created in MOWHTO and lower hinge stresses can be obtained by applying lower forces with this osteotomy. In the light of these findings, DH-MOWHTO may be a novel osteotomy technique to avoid LHF.

Keywords: Finite element analysis, fracture, double hinge, high tibial osteotomy, lateral hinge.

In younger patients with medial compartment osteoarthritis (OA) and varus malalignment, medial open-wedge high tibial osteotomy (MOWHTO) continues to be an effective surgical procedure by restoring the load bearing axis of the knee to normal alignment.[1] Gkekas et al.[2] demonstrated a 91.5% survival rate in patients with severe medial OA (Kellgren Lawrence III-IV) at a follow-up of 13.6 years. Although it is well documented that MOWHTO redirects the mechanical axis by laterally shifting it and, thus, transfers the load from the medial compartment to the lateral side, the surgical technique is complex and involves risks such as neurovascular injury, delayed union, and fracture formation.[3] Lateral hinge fracture (LHF) is one of the most common complications of MOWHTO and is the leading cause of loss of stability, displacement,

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nonunion, and recurrence of varus deformity.[4-6] The realization of the clinical and radiological consequences of LHF has led to the search for technical strategies to prevent LFH.[1] Nakamura et al.[7] classified osteotomies according to the level and depth of the proximal tibiofibular joint and demonstrated a safe hinge zone with a relative risk of 0.24 for type II and III LHF. Lobenhoffer and Agneskirchner[8] recommended maintaining a 10-mm distance between the osteotomy and the lateral cortex. Takeuchi et al.[9] showed that a distance of 5 mm between the osteotomy and the lateral cortex was sufficient. Although biplanar osteotomies have been shown to reduce the risk of LHF compared to uniplanar osteotomies, it was later shown that biplanar osteotomy has a higher LHF rate than monoplanar osteotomy.[10,11] A Kirschner wire (K-wire) positioned to intersect the osteotomy plane prior to opening the osteotomy has been shown to reduce the risk of LHF by acting as a mechanical restraint.[12,13] Although many techniques have been proposed to prevent LHF, LHF remains important due to its feared complications such as delayed union, nonunion and loss of correction.

The uniplanar and biplanar osteotomies described in the literature related to MOWHTO have a single hinge on the lateral side regardless of the number of osteotomies made, and studies on how the load and stress distribution would behave only examine the single hinge. In the literature, it has not been previously investigated whether it is possible to spread the stress distribution during the opening of the osteotomy over a wider area with two hinges and to distribute the load on one hinge to two hinges.

In the present study, we aimed to define the double-hinge MOWHTO (DH-MOWHTO) in a finite element analysis (FEA) model.

MATERIALS AND METHODS

This FEA study was conducted at Necmettin Erbakan University Faculty of Medicine, Department of Orthopedics and Traumatology between March 2024 and April 2024. The study protocol was approved by the Necmettin Erbakan University Ethics Committee (Date: 06.12.2024, No: 2024/5363). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Generations of the osteotomy models

In this study, three-dimensional (3D) computer-aided design (CAD) model of the human proximal tibia was used (Figure 1). This model was obtained from the authors previous study.[14] The 65-mm section of the proximal tibia measured from the articular surface was included in the analyses. Utilizing the distal tibia is ineffective, as it does not influence the mechanics of the osteotomy's opening and merely prolongs the computational time. The cortical and trabecular bones were included in the tibia model (Figure 1).

In the generation of the osteotomies, SpaceClaim version 2021 R2 software (Ansys Inc., Canonsburg, PA, USA) was used. The osteotomies were created from the frontal plane by using a flat plate which simulated the hand saw. This saw was 1 mm in thickness and one end of it was rounded to create a rounded hinge on the bone. To create osteotomy, the saw was placed at the appropriate position and then subtracted from both cortical and trabecular bones. In the present study, three different osteotomies were modeled. The first model was a novel approach in DH-MOWHTO. In the first model, two monoplanar osteotomies from the same starting point were made to create two hinges. The first and second osteotomy lines were inclined 27° and 22°, respectively from the articular surface. The starting point and the end points of the osteotomies are illustrated in Figure 1. The second and third models were the models with the standard monoplanar osteotomies in which created by using only one of the osteotomy lines in Model 1. Model 2 was created by using first osteotomy line of Model 1, while Model 3 by using second osteotomy line.

Finite element analysis

In this study, hexahedral (20 nodes) elements were dominantly used, but tetrahedral (10 nodes) and pentahedral (15 nodes) elements were also used when needed. Although the element sizes are regular throughout the model, the element sizes were further reduced in the hinge areas, and a fine mesh was created. The hinges are the possible stress risers and are critical for this case, therefore, many data points should be acquired with higher numbers of elements in these regions. In the present study, Model 1 had 86227 elements and 286479 nodes, Model 2 had 76632 elements and 255818 nodes, and Model 3 had 71866 elements and 240103 nodes. To determine these adequate numbers of elements in the solution mesh, a mesh convergence analysis was conducted in Model 3. The percentage errors in the maximum hinge stress (MPa) or total strain energy (mJ) were considered while determining adequate numbers of elements. If the percentage error was below 3% between two consecutive analyses, it was

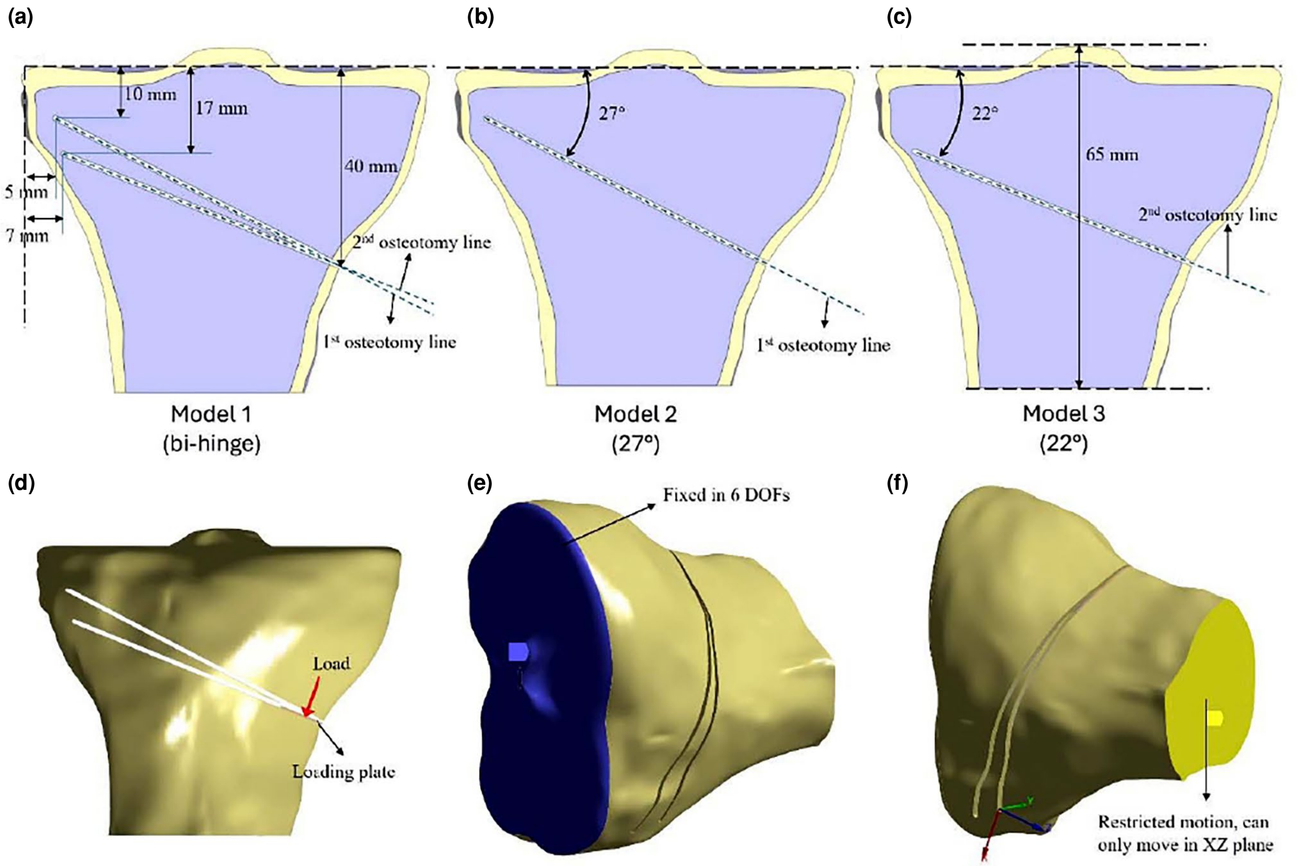

FIGURE 1. Osteotomy models are shown above. **(a)** Model 1 with two monoplanar cuts, **(b)** Model 2 with 27° monoplanar cut, and **(c)** Model 3 with 22° monoplanar cut. The loading and boundary conditions are shown below. **(d)** Loading condition, **(e)** superior boundary condition and **(f)** distal boundary condition.

accepted that the mesh model converges to accurate result.

There were three structures: cortical bone, trabecular bone, and a thin loading plate, in each one of the models. If a quick literature survey was done, linear isotropic and homogenous material model has been usually used for bone structures. This material behavior predicts the biomechanical response of the bone structure up to the yield limit and also under elastic small deformations. In the context of the opening wedge procedure, excessive deformation is observed in the hinge regions. Therefore, opening wedge procedure is better simulated by using an elastoplastic material model that takes into the consideration of plastic deformation in bone. Bilinear isotropic hardening material model or multilinear isotropic hardening model may be preferred. As the multilinear isotropic hardening model costs too much computational efforts and time, the bilinear isotropic hardening material model were selected for both cortical and trabecular bone. For the structural steel loading plate, linear isotropic and homogenous material model was used. Table I lists the material properties of the bones and loading plate. The reason behind the using the loading plate was to eliminate locally higher stresses caused by application of direct force to the bone.

During opening the wedge in the MOWHTO, while the bone fragment superior to the osteotomy line remains relatively immobile, the bone fragment distal to the osteotomy line is displaced. To simulate this, the tibia was fixed in six degrees of freedoms through the blue area in its joint surface (Figure 1) and a compressive force up to 125 N was perpendicularly applied to the loading surface which was placed to the distal bone surface at the osteotomy line. The load value in this context was assigned arbitrarily and does not hold critical significance. The primary focus was on the initiation of the gap and the relationship between the load value and the gap distance or angle.

TABLE I
Material properties for the bones and loading plate[15]

Bone structures	Young modulus (MPa)	Poisson's ratio	Yield strength (MPa)	Tangent modulus (MPa)
Cortical bone	18200	0.26	84.52	685.37
Trabecular bone	372	0.3	2.19	61.03
Loading plate	200000	0.25	-	-

Additionally, the motion of the distal end of the tibia was restricted and it had capability to move in only XZ plane (Figure 1f). In all models, the contacts between the cortical and trabecular bones and also contacts between the plate and bones were assigned as "bonded" contact, referring that the contact pairs show the same amount of deformation at the same node.

Outputs of the study

The models were evaluated in terms of different outputs, such as maximum von-Mises stress value (MPa) on the hinges at 10° correction angle, the gap distance (mm) at 10° correction angle, the force value (N) required to obtain 10° correction angle, and the total surface area (mm^2) of the osteotomy surfaces contacted with the saw.

The gap distance and correction angle were measured from the deformed tibia model after analysis. While the measurement of the correction angle is straightforward for monoplanar osteotomies, a specific measurement approach should be developed for Model 1, which involves

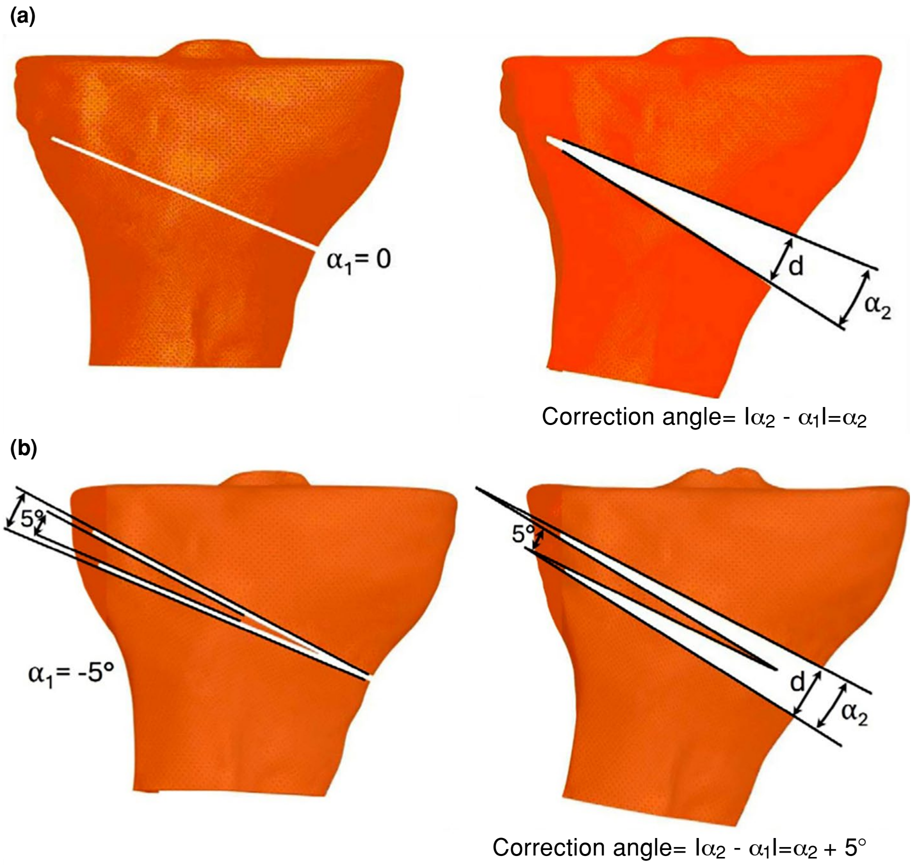

FIGURE 2. Calculation of the correction angle. **(a)** One monoplanar osteotomy for Model 2 and Model 3, and **(b)** two monoplanar osteotomies for Model 1. Here d is gap distance, α_1 and α_2 are the angles between the opposing surfaces before and after the opening, respectively.

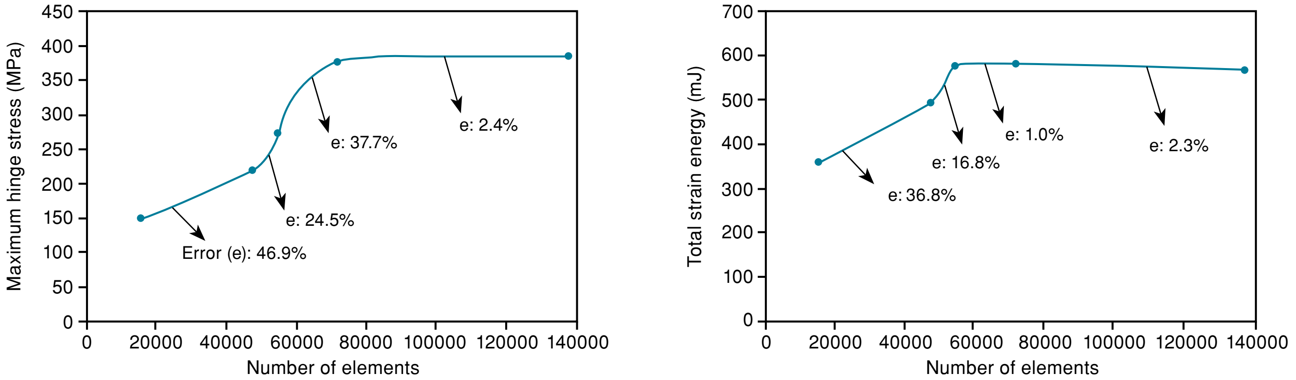

FIGURE 3. The results of the mesh convergence analysis. Maximum hinge stress (MPa) *vs.* number of elements in left and total strain energy (mJ) *vs.* number of elements in right.

two monoplanar osteotomies. Figure 2 shows the methods used in the measurement of the correction angles of models. As shown in Figure 2a, in the monoplanar osteotomy, opposing bone surfaces in the osteotomy line are parallel, with a 0° angle before analysis. After analysis, the angular displacement of these surfaces gives the correction angle. The difference in angles between opposing bone surfaces before and after analysis equals the correction angle. In model 1, with two monoplanar osteotomies, there is a 5° angle between opposing bone surfaces initially (Figure 2b). This angle between osteotomy lines can be considered negative. As the osteotomy opens, this negative angle decreases until opposing surfaces become parallel at a 5° correction angle. If opening continues, a positive osteotomy angle forms and increases. To calculate the correction angle, the change in angles between opposing surfaces must be calculated by subtracting the initial negative angle from the positive angle after opening. If a correction angle of 10° is desired, the positive 5° opening should be acquired at the osteotomy.

Statistical analysis

The differences between the obtained values, their arithmetic means, and various ratios were calculated. Since one model was used in each of the three groups, no comparative statistical analysis was performed.

RESULTS

The results of the convergence analysis are shown in Figure 3. The five points on the curves in this figure indicated the consecutive analyses performed with different number of elements. The percentage error between the last two models was below 3% for MPa, while errors between the third-fourth and fourth-fifth models were below 3% for total strain energy. Using the fourth and fifth mesh models provides accurate, converged results. We used the fourth mesh model for subsequent analyses, as additional elements only increase workload and simulation time.

The results of the study are the values occurred at a correction angle of 10° and are given in

TABLE II
Results of the analyses

Models	Osteotomies	Anterior hinge stress	Posterior hinge stress	Gap distance (mm)	Force value	Total surface area
Model 1 (bi-hinge)	1st	223.84	132.62	12.06	77.65	8825
	2nd	229.59	303.68			
Model 2 (27°)	1st	370.65	332	12.62	113.64	4910
Model 3 (22°)	2nd	317.26	375.99	12.42	84.60	4364

Maximum von-Mises stress (MPa) values on the hinges and gap distances (mm) are the values at 10° correction angle. The force (N) value shows the value required to get 10° correction angle. The total surface area (mm2) is the total area of osteotomy surfaces that contacts with the saw.

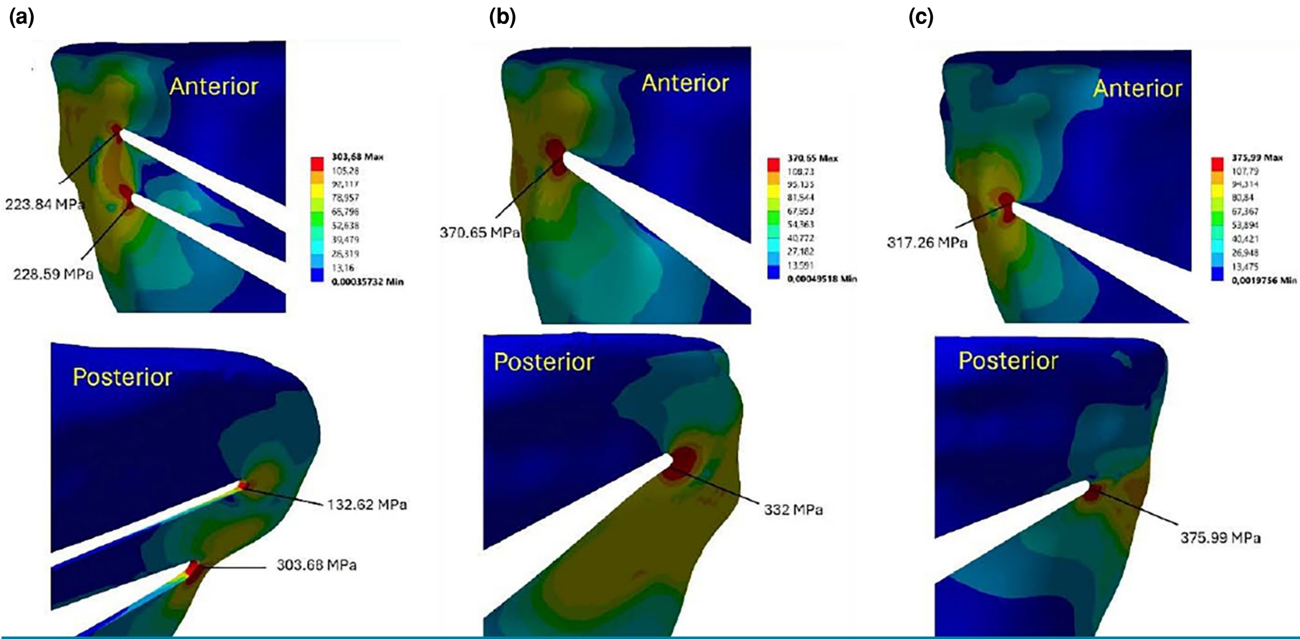

FIGURE 4. Stress distribution on the hinge region of **(a)** Model 1, **(b)** Model 2, and **(c)** Model 3 at 10° correction angle.

Table II and in Figures 4 and 5. In Model 1, the stress value anterior to the superior osteotomy was 223.84 MPa, anterior to the inferior osteotomy was 228.59 MPa, posterior to the superior osteotomy was 132.62 MPa, and posterior to the inferior osteotomy was 303.68 MPa. In Model 2, the anterior stress value was 370.65 MPa and the posterior stress value was 332 MPa. In Model 3, the anterior stress value was 317.26 MPa and the posterior stress value was 375.99 MPa (Table II, Figures 4 and 5). In DH-MOWHTO, the maximum anterior hinge stress at 10° correction angle was reduced by 28.1 to 39.6% and the maximum posterior hinge stress was reduced by 19.2 to 60.1% compared to single monoplanar osteotomies. The average stress reduction in the hinges was 36%.

The gap distance at a 10° correction angle was 12.06 mm in Model 1, 12.62 mm in Model 2, and 12.42 mm in Model 3. The difference in the gap distances between Model 1 and the other models were less than 5%. Contrary to this, using two monoplanar osteotomies changed the force value which is required to obtain 10° correction angle. According to the results of the analyses, the force values required to obtain 10° correction angle were approximately 78 N, 114 N and 85 N for Model 1,

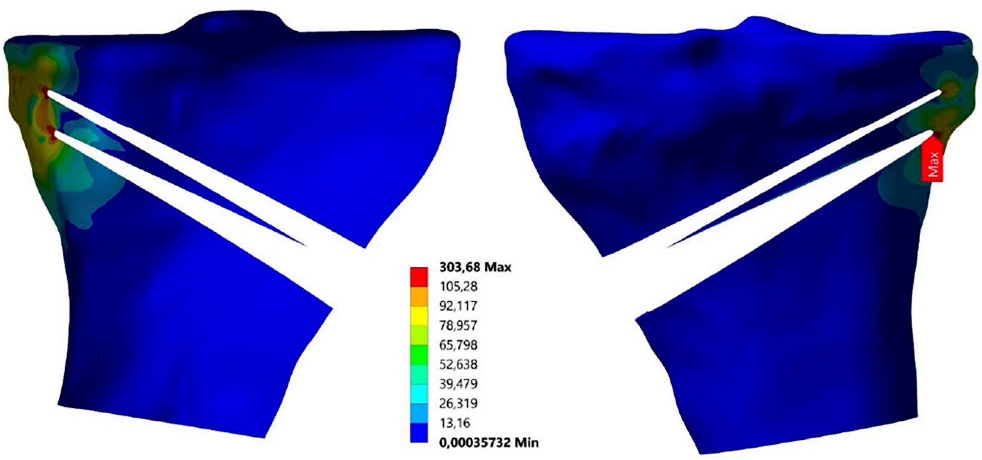

FIGURE 5. Stress distribution on the hinge region of Model 1.

Model 2, and Model 3, respectively (Model 1 <Model 3 <Model 2) (Table 2).

The total surface area of the osteotomy surfaces contacted with the saw is critical parameter that should be evaluated in the comparison of different osteotomy techniques. According to the results of the present study, the model with two monoplanar osteotomies had approximately 1.8 times and 2 times higher osteotomy surface area than Model 2 and Model 3, respectively (Table II).

DISCUSSION

In the present study, we attempted to define the DH-MOWHTO in a FEA model. The main finding of this study is that it is possible to create lower stress in the lateral hinges by distributing the stress that would occur in a single lateral hinge to two hinges with a lower force application and, therefore, defines DH-MOWHTO, which has a low-risk potential for LHF.

Lee et al.[15] demonstrated that the incidence of LHF after MOWHTO was higher on computed tomography (CT) than on plain radiographs and showed that the amount of medial opening was the only predictor of LHF in their study. The importance of the lateral hinge in high tibial osteotomies is known to be critical for bone consolidation and completion of an effective correction, and to date few studies have examined strategies to improve the fracture resistance of the lateral hinge.[12,16,17] Dessyn et al.[12] investigated whether a K-wire that crossed the osteotomy plane at the level of the lateral hinge had a protective effect on the lateral hinge in their study on fresh-frozen tibias. They showed that the maximum load and maximum displacement against fracture were 880% and 260% higher in tibias with K-wire, respectively. However, their study does not mention the stress change that occurs in the lateral hinge when the K-wire is removed after osteotomy fixation. The reason why a K-wire crossing the plane of the osteotomy increases the maximum force before the fracture occurs during osteotomy can be thought to be that the K-wire absorbs the force on the lateral hinge, and after the K-wire is removed, it can be thought that the stress caused by the total force required for deformity correction would be collected in the lateral hinge again. Considering that the strategies employed in MOWHTO to prevent single lateral hinge fracture may offer limited benefits due to the inherent characteristics of the technique, we attempted to evaluate the feasibility of adopting a "double-hinge" concept through a FEA-based study. The mean stress in DH-MOWHTO was 222.43 MPa, while the mean stress in isolated inferior osteotomy was 351.32 MPa and the mean stress in isolated superior osteotomy was 346.62 MPa, and the mean stress was approximately 36% lower in DH-MOWHTO. Considering the stress averages, we found that DH-MOWHTO significantly reduced the amount of stress occurring in the lateral hinge and spread the stress over a wider area. The results of this study indicate that utilizing a double-hinge high tibial osteotomy may be an alternative method to decrease stress seen at the lateral hinge, but further cadaveric and *in vivo* validation is necessary to vet this strategy.

Diffo Kaze et al.[16] showed in their FEA study that a drill hole extending anterior-posteriorly to the end of the osteotomy line reduced the stress on the lateral hinge and increased the correction angle by 1.5 times. Another important finding they obtained in their study was that the angles before crack formation in the lateral hinge were less than 5º and indirectly, they reached the assumption that fracture may occur in all corrections above 5º. Based on this finding, it can be speculated that DH-MOWHTO, which provides two corrections of 5° each, can provide more correction with a lower risk of LHF, and if the osteotomy planes are optimally adjusted, the formation of fissures or fractures can be prevented by preventing more than 5º of angulation in each hinge. One of the differences between DH-MOWHTO and the technique described by Diffo Kaze et al.[16] in their study may be related to bone defect formation. In DH-MOWHTO, there is no procedure that causes any bone loss, but in the Diffo Kaze et al.[16] study, the drill at the osteotomy apex has the effect of causing bone loss. On the other hand, one of the issues that should be mentioned about the DH-MOWHTO technique, although it is still early, is its possible effects on union. In our study, the osteotomy-related bone surface areas were 4910 mm^2 and 4364 mm^2 in isolated single osteotomy analyses, respectively, while they were 8825 mm^2 in DH-MOWHTO, and the increase in osteotomy-related bone area may have certain advantages related to ease of union. In addition, in a field with an osteotomy opening of approximately 12 mm, this triangular-shaped bone, which continues its connection with the lateral aspect of the proximal tibia in the middle of the osteotomy, may act as a bone flap and facilitate union. These opinions regarding ease of union are speculative, and further studies are needed to better understand whether increasing the area extends the healing time.

In relation to whether two hinges in MOWHTO would be possible and useful in avoiding LHF, although this FEA study shows that DH-MOWHTO is possible, the technique has a number of concerns that need to be addressed. The first of these is that the technique can be challenging to perform. After two osteotomies are made and osteotomy opening is started, it may be possible that one of the osteotomies opens and the other one does not. However, when the distance of the superior osteotomy apex to the lateral cortex was set to 5 mm and the distance of the inferior osteotomy apex to the lateral cortex was set to 7 mm, as the lateral cortex was inclined to approach medially, we saw in the FEA that both osteotomies opened almost equally. Since the obvious inequality of the stress distribution between the two hinges would cause inequality of hinge opening in the FEA, it seems that making two similar osteotomies for the time being will prevent such a problem. In order to observe the behavior during osteotomy opening in DH-MOWHTO, osteotomy should be performed on models and biomechanical tests should be performed. Another difficulty is to perform osteotomies in appropriate planes. In this regard, the feasibility of osteotomy on model bones should be investigated, but our opinion and planning on this subject is that two separate osteotomies can be performed under the guidance of appropriately placed K-wires, such as single-plan osteotomies, or it would be useful to perform the second osteotomy through a guide of the same size as the saw placed on the osteotomy line after the first osteotomy is performed. Biomechanical and model studies are needed and the next step would probably be the development of the DH-MOWHTO incision guide.

This study compared different osteotomy models; however, the lack of a biomechanical analysis specifically addressing hinge fractures represents a limitation. Another limitation is that the possibility that a fracture that may occur after DH-MOWHTO application may be a more complex fracture than a fracture that may occur in classical MOWHTO is not known and further studies such as biomechanical studies related to this issue are needed.

In conclusion, in this FEA study, two lateral hinges can be created in MOWHTO and lower hinge stresses can be obtained by applying lower forces with this osteotomy. In the light of these findings, DH-MOWHTO may be a novel osteotomy technique to avoid LHF, but further studies are still needed to demonstrate its feasibility.

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: H.Y., M.Ö., F.T.; DESIGN: H.Y., M.Ö., M.Ö., F.T.; Control/supervision: M.Ö., F.T.; Data collection and/or processing, analysis and/or interpretation: A.K., T.E.E., M.Ö.; Literature review: H.Y., A.K., T.E.E., M.Ö.; Writing the article: H.Y., A.K., T.E.E.; Critical review: M.Ö., F.T.;

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