

Optimal Plate Position for Biomechanical Stability in Medial Opening-Wedge High Tibial Osteotomy: A Finite Element Analysis

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Background: Research on the ideal fixation position for plates in medial opening-wedge high tibial osteotomy (MOWHTO) directly applicable in clinical settings is scarce. Therefore, this study aimed to evaluate the biomechanical effects of different plate positions in MOWHTO through finite element analysis (FEA) to explore a potentially optimal plate position.

Methods: Utilizing the computed tomography images of a 67-year-old man, a 3-dimensional model of the knee, along with an implant (TomoFix standard plate and screws), was created to simulate a virtual MOWHTO with a 10° medial opening gap. Biomechanical stability analysis of the bone-implant construct was conducted through FEA under physiologic loading simulating a 1-legged stance, with varying plate positions. Configurations for plate fixation, determined by anterior-posterior depth and height, resulted in a total of 9 fixation positions (anterior, center, and posterior in terms of depth; proximal, middle, and distal in terms of height). Criteria for assessment included inter-fragmentary micromotion at the medial opening gap, mean stress on the lateral hinge, the entire tibial bone, and the implant, stress shielding effect, and peak von Mises stress (PVMS).

Results: The inter-fragmentary micromotion at the medial opening gap exhibited a tendency to decrease as the fixation position of the plate moved posteriorly and proximally, observed in both axial and shear micromotion. The mean stress on the lateral hinge of the tibia progressively decreased with more posterior or proximal plate placement, reaching its minimum in the most posterior and proximal position. In terms of the mean stress imposed on both the entire bone and implant, it decreased when the plate was positioned posteriorly and proximally, and this position was deemed favorable from the perspective of the stress shielding effect. PVMS predominantly occurred at hole 1 of the plate and its corresponding screw, and it was lower than the yield strength of the titanium alloy regardless of the plate's position.

Conclusions: Placing the plate more posteriorly and proximally in MOWHTO could minimize inter-fragmentary micromotion, reduce stress on the lateral hinge and bone-implant construct, and enhance stress shielding, all without increasing the risk of implant breakage, suggesting it as a potentially optimal plate position.

Keywords: High tibial osteotomy, Plate position, Micromotion, Stress, Stability

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High tibial osteotomy (HTO) is a well-established surgical procedure for addressing medial compartment knee osteoarthritis accompanied by varus deformity.¹⁾ By redistributing the load, it alleviates pressure on the medial compartment of the knee, thereby leading to clinical improvement.¹⁾

Notably, among various HTO procedures, the medial opening-wedge HTO (MOWHTO) is the most widely used in current clinical practice.^{1,2)} This preference is attributed not only to its avoidance of potential drawbacks associated with other types of HTO (lateral closing wedge HTO and dome HTO) but also to its relative ease in achieving the desired correction of lower limb alignment.²⁻⁴⁾ However, various complications may also arise in relation to MOWHTO, including implant failure, hinge fracture, correction loss, malunion, and nonunion, all of which can directly impact clinical outcomes.⁵⁻⁷⁾

Aforementioned complications can arise due to the instability of the medial opening gap resulting from osteotomy.^{7,8)} Although the introduction of the locking plate system has reportedly reduced associated side effects,¹⁾ complications are still known to occur. Consequently, numerous studies have explored ways to enhance the mechanical stability of the medial opening gap in MOWHTO through implant utilization.⁸⁻¹²⁾ Nevertheless, research on the ideal position for plates directly applicable in clinical settings is scarce. Despite some related studies,^{8-10,12)} their limited settings for plate positioning and evaluation criteria hinder the generalization of findings. Therefore, well-designed studies that overcome the aforementioned limitations are required. With the increasing emphasis on rapid rehabilitation after MOWHTO,¹³⁾ addressing this issue could provide insights into achieving optimal surgical outcomes.

Therefore, this study aimed to evaluate the biomechanical effects of different plate positions in MOWHTO through finite element analysis (FEA) to explore a potentially optimal plate position. It was hypothesized that there would be a specific biomechanically optimal plate posi-

tion for the bone-implant construct, including the medial opening gap, in MOWHTO.

METHODS

This study was conducted using FEA with de-identified patient imaging data and was deemed exempt from ethical approval and informed consent.

Reconstruction of the 3-Dimensional Knee Model and Implants

Prior to conducting FEA, a 3-dimensional (3D) model of the knee and the implants (plate and screws) were constructed. For the creation of the 3D model, computed tomography (CT) images of the right lower limb of a 67-year-old man without lower limb malalignment, anatomical abnormalities, osteoarthritis, or a history of previous surgery were employed. The CT images datasets were acquired using a 256-slice dual-source CT scanner (SOMATOM Definition Flash 256, Siemens Healthcare) with tube parameters set at 80–140 kVp and 140–280 mA. The specifications included a 0.75-mm slice thickness, a 512 × 512-pixel acquisition matrix, and a field of view ranging from 140 to 350 mm. Digital Imaging and Communications in Medicine files obtained through CT scans were imported into Mimics software (version 25, Materialise) to create the 3D knee model.¹⁴⁾ Using this software, the tibia and fibula were meticulously reconstructed and then transferred to 3-Matic software (version 18, Materialize) for implementing the osteotomy. In this study, a biplanar osteotomy, consisting of a transverse and ascending osteotomy, was adopted and simulated to produce a 10-mm opening wedge gap (Fig. 1).¹¹⁾ Additionally, bone grafting was excluded to exclusively analyze the loading conditions of bone and implant. The computer-aided design model of the TomoFix standard plate and screws (TomoFix Osteotomy System, DePuy Synthes), a locking fixation system widely employed in recent MOWHTO procedures for stabilizing the medial opening gap, was utilized (Fig. 2).^{11,15)}

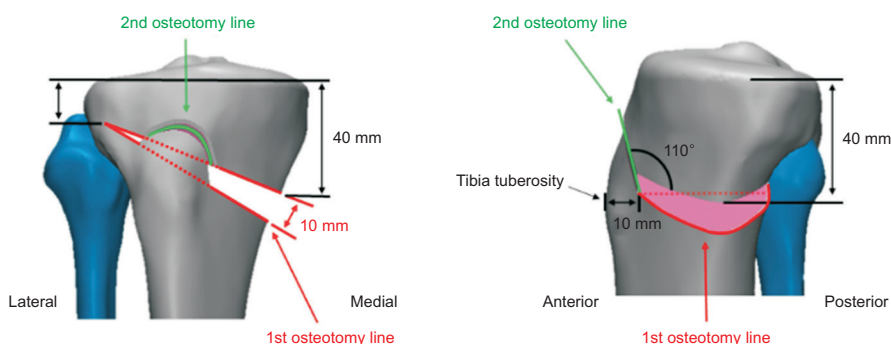


Fig. 1. The transverse osteotomy (first osteotomy) in the sagittal plane was initiated 40 mm below the medial joint surface and ended 15 mm below the lateral joint surface, ensuring a parallel cut to the joint surface. The ascending osteotomy (second osteotomy) in the coronal plane was set 10 mm posterior to the tibia tuberosity, forming a 110° angle with the transverse osteotomy cut.

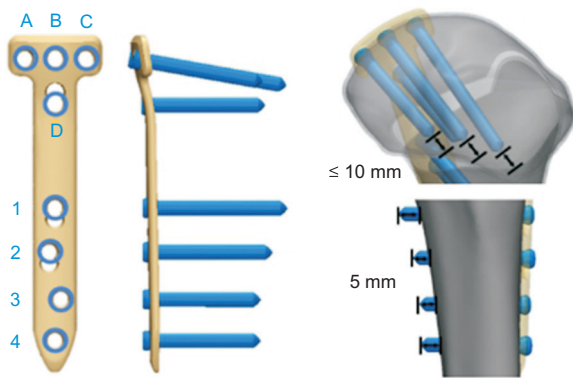


Fig. 2. The dimensions of the plate length, width, and thickness were 115 mm, 16 mm, and 3 mm, respectively. The locking screws had a diameter of 5 mm. For holes A, B, C, and D, the screw lengths were designed to reach within approximately 10 mm of the far cortex. Conversely, for holes 1, 2, 3, and 4, the screws were configured to protrude about 5 mm beyond the far cortex to achieve bicortical fixation.

The locking screws were set to securely fasten to the plate, and the screw threads were omitted for a streamlined analysis.

Development and Verification of Finite Element Model

The reconstructed 3D models were loaded into the Abaqus software (version 2022, Dassault Systems) for finite element modeling and analysis. The tibia, due to its anatomical features, was set to be divided into 3 regions (epiphysis, metaphysis, and diaphysis) and consisted of the outer cortical bone, inner cancellous bone, and medullary cavity, each exhibiting distinct mechanical properties.¹⁶⁾ The mechanical characteristics of each region and layer were determined by referencing data from previous studies.^{17,18)} Specifically, the epiphysis of the cortical bone tissue was defined as 20 mm below the articular surface, the metaphysis was identified as 20 mm to 60 mm from the articular surface, and the region below was designated as the diaphysis. The elastic moduli for these regions were set at 7,500, 10,500, and 15,000 MPa, respectively, with a consistent Poisson's ratio of 0.33 applied universally to the cortical bone.¹⁷⁾ For the interior of the cortical bone, from the articular surface to 60 mm downward, the elastic modulus of the cancellous bone tissue was applied (400 MPa), and the region below corresponding to the medullary cavity was assigned the elastic modulus of bone marrow (300 MPa).¹⁸⁾ Poisson's ratios for cancellous bone and bone marrow were set at 0.3 and 0.45, respectively (Fig. 3).¹⁸⁾

The mechanical properties of the plate and screws were derived from Titanium alloy, with Young's modulus and Poisson's ratio set at 113,000 MPa and 0.33, respective-

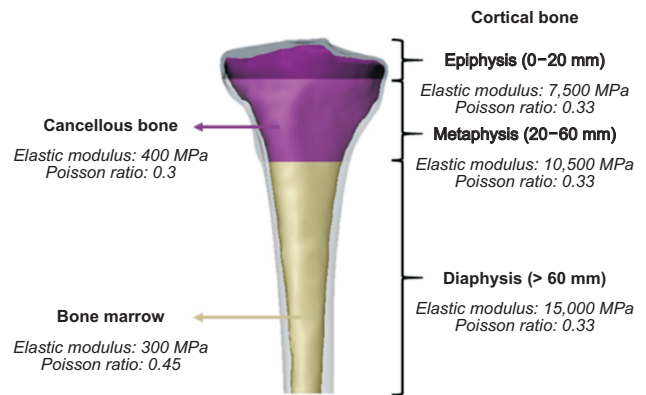


Fig. 3. Mechanical properties of each region and layer of the tibia model.

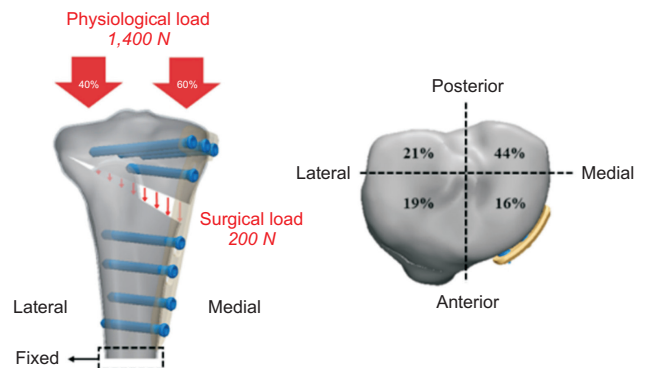


Fig. 4. Physiological and surgical load applied on the tibia model.

ly.¹⁹⁾ The plate and locking screws were assumed to be fully bonded, and a friction coefficient of 0.3 was applied at the interface between the bone and screws.²⁰⁾ The components of each region of cortical and cancellous bone, as well as plates and screws, were assumed to possess linear elastic properties, homogeneity, and isotropy for their respective parts.

To impose physiological loading on the knee joint, all degrees of freedom of the distal tibia were constrained, simulating a 1-legged stance. The applied load on the knee joint was 1,400 N, representing 200% of the body weight, distributed with 60% on the medial and 40% on the lateral tibial plateau.²¹⁾ Additionally, a uniform force of 200 N was applied to the upper portion of the osteotomy site to simulate the compressive load resulting from the medial opening (Fig. 4).¹¹⁾ To ensure the reliability of the FEA results, the tibia model used in this study underwent validation, referencing a 4-point bending test from prior research.²²⁾

Analysis of Mechanical Stability of Bone-Implant Construct

Subsequently, an assessment of the mechanical stability of the bone-implant construct was conducted according to the position of the implant. The 3D model of the tibia was manipulated to position the complete overlap of the medial and lateral condyles in the sagittal plane. At this position, the implant was set to be fixed on the medial side of the tibia. Initially, with the upper edge of the plate aligned parallel to the articular surface, the implant was placed 4 mm, 8 mm, and 12 mm below the articular surface (proximal, middle, and distal in height, respectively). At each height, the implant was aligned to match the longitudinal axis of the tibia (center in depth). Subsequently, while the distal portion of the plate was kept stationary, the upper part was moved forward and backward by 10 mm each to specify the anterior and posterior positions (anterior and posterior in depth, respectively). This resulted in the implementation of plate fixation at a total of 9 locations (Fig. 5).

The assessment of the biomechanical stability of the bone-implant construct, encompassing the medial opening gap, included the following evaluations: (1) inter-fragmentary micromotion at the medial opening gap, (2) mean stress applied to the lateral hinge area of the tibia, (3) mean stress on the bone and implant and the stress shielding effect, and (4) the peak von Mises stress (PVMS) occurring on the plate and each screw. The magnitude of inter-fragmentary micromotion at the medial opening gap was quantified between 2 points representing the widest gap of the osteotomy site. Under load, inter-fragmentary micromotion was measured in the vertical and anteroposterior directions, denoted as axial and shear micromotion. In addition, the sum of micromotion in each direction was considered as total micromotion. The region of interest for assessing the mean stress on the lateral hinge was specifically confined to the tip of the osteotomy according to the

previous studies,^{19,23)} as this area encompasses the hinge axis and is subjected to the highest stress during distraction, making it the most susceptible site for hinge fractures (Supplementary Fig. 1). Subsequently, mean stresses applied to each bone and implant under load were analyzed, and using these measurements, the stress shielding effect was estimated with the following formula: (mean stress at bone / mean stress at implant construct) x 100%. Finally, the PVMS generated on the plate and each screw were assessed, and the risk of implant failure was evaluated by comparing it to the yield strength of the titanium alloy (880 MPa).²⁴⁾

RESULTS

Inter-fragmentary Micromotion at the Medial Opening Gap

Micromotion at the medial opening gap was generally smaller as the plate was placed posteriorly, and the effect of its height was relatively minor (Fig. 6). Specifically, inter-fragmentary axial micromotion was observed to be the smallest when the plate was located at the most posterior position, particularly at the mid and proximal heights. Similarly, shear micromotion decreased as the plate positioned posteriorly, with the smallest observed when placed at the proximal height. Considering both axial and shear micromotion together, it was evident that inter-fragmentary micromotion was most pronounced when the plate was placed anteriorly and distally, whereas minimized when the plate was positioned at the most posterior and proximal location.

Mean Stress Applied to the Lateral Hinge Area of the Tibia

The mean stress on the cortical and cancellous bone within the lateral hinge area of the tibia, encompassing the hinge axis, was evaluated. It was observed that the mean

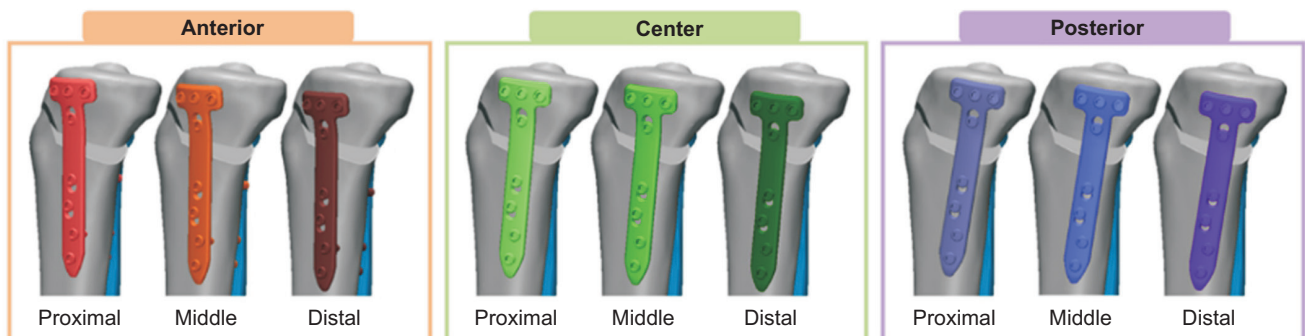


Fig. 5. Simulation of plate fixation in 9 positions according to anterior-to-posterior and proximal-to-distal positions.

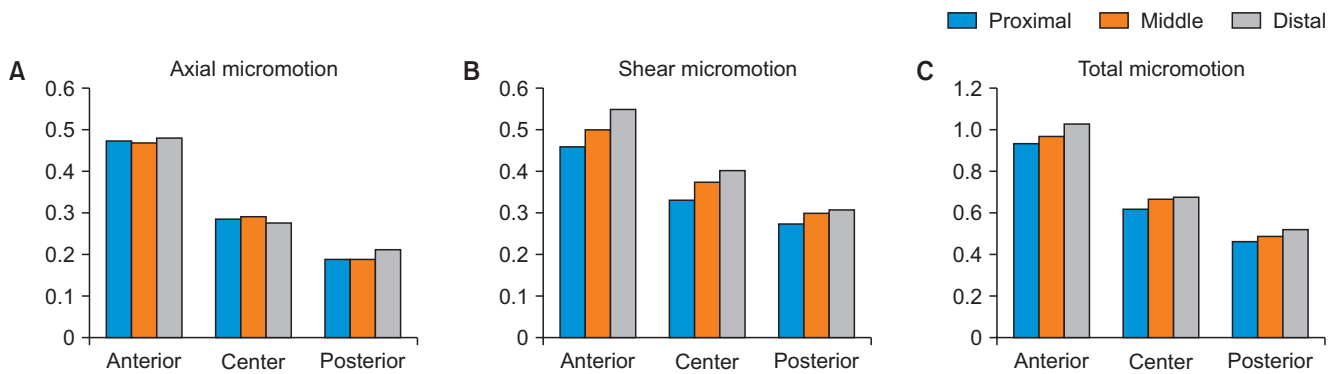


Fig. 6. (A) Inter-fracture micromotion in the axial direction. (B) Inter-fracture micromotion in the shear direction. (C) The sum of micromotion in the axial and shear directions.

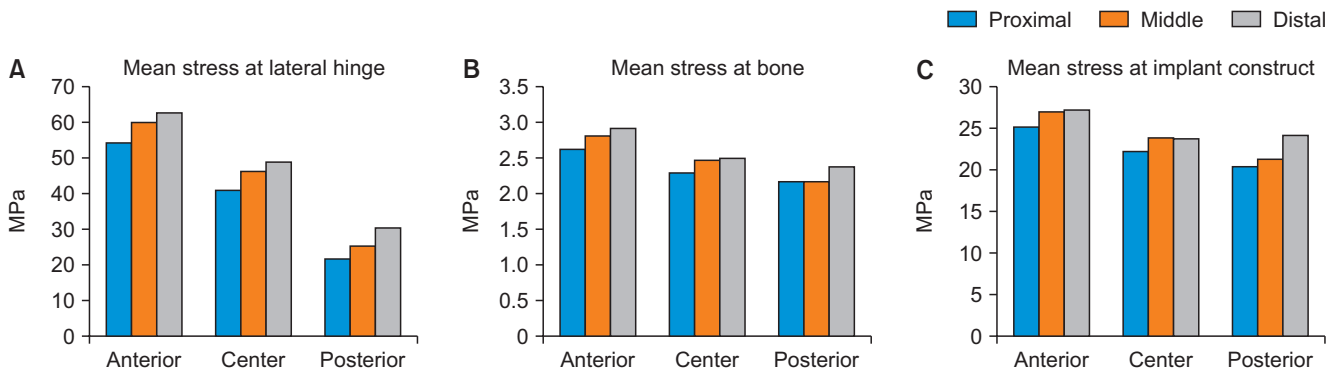


Fig. 7. Mean stress applied to the lateral hinge (A), bone (B), and implant construct (C).

stress was minimized when the plate was placed in the most posterior and proximal position, while it increased progressively as the plate was moved to a more anterior or distal position (Fig. 7A).

Mean Stress Applied to the Bone and Implant and the Stress Shielding Effect

The mean stress applied to the tibia was derived from the entire cortical and cancellous bone tissue, while that of the implant was calculated based on the full configuration of the plate and screws. Notably, a decrease in mean stress was observed in both the tibia and the implant as the plate was positioned more posteriorly and proximally (Fig. 7B and C). When estimating the stress shielding effect based on the obtained results, the most favorable outcome was observed when the plate was located at both the most anterior and distal position and the most posterior and proximal position (Table 1).

PVMS Occurring on the Plate and Each Screw

In the implant, PVMS predominantly occurred at around hole 1 of the plate and the corresponding screw, and this

Table 1. Estimated Stress Shielding Effect* According to the Plate Position

Plate position	Anterior	Center	Posterior
Proximal	10.4	10.4	10.7
Middle	10.4	10.4	10.2
Distal	10.7	10.5	9.8

*The estimation of the stress shielding effect was conducted by applying the formula: (mean stress at bone / mean stress at implant construct) x 100%.

remained consistent regardless of the implant's position. PVMS decreased as the implant was positioned more posteriorly and distally. Importantly, PVMS was found to be lower than the yield strength of the titanium alloy in all implant positions (Fig. 8).

DISCUSSION

The principal finding of this study is that placing the plate more posteriorly and proximally proves advantageous

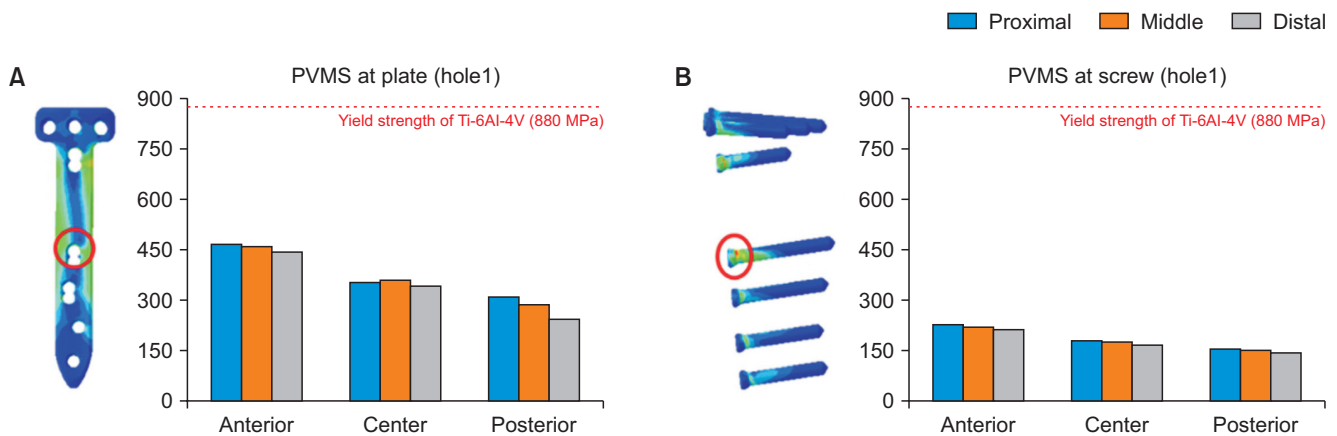


Fig. 8. Peak von Mises stress (PVMS) occurring on the plate (A) and screw (B).

in minimizing micromotion at the medial opening gap, reducing stress on the lateral hinge of the tibia, the entire tibial bone, and the implant, while enhancing the stress shielding effect, all without introducing the risk of implant breakage. The findings of this study can offer strategies to improve the clinical outcomes of MOWHTO by reducing the potential risk of complications associated with the surgical technique.

Despite the development and introduction of locking plates specifically designed for MOWHTO, complications arising from insufficient mechanical stability of bone-implant construct are still known to occur. Although these occurrences are not that frequent, unstable maintenance of the medial opening gap following MOWHTO can lead to critical issues such as implant failure, correction loss, malunion, and nonunion.⁵⁻⁷⁾ Consequently, research has been conducted on the utilization of implants to enhance the mechanical stability of the bone-implant construct during MOWHTO, with a particular focus on determining the optimal fixation position.^{8-10,12)} However, prior studies, while providing clinically important insights, may possess certain limitations. Firstly, some studies conducted analyses without excluding the influence of bone substitutes.^{8,9)} Since bone substitutes can independently contribute to mechanical stability, this might have unintentionally impacted the analysis of the implant's effects. Given that MOWHTO is frequently performed without bone substitutes,²⁵⁾ an analysis excluding their influence becomes imperative. Additionally, the analysis of plate positions was not well-structured, and the variables for validation were comparatively restricted. Most studies concentrated solely on the anterior-to-posterior positions of the plate,^{8-10,12)} and the evaluation methods for biomechanical stability were likewise limited. Due to these outlined limitations, additional research is deemed necessary

to validate the clinical applicability of the findings. Hence, in this study, a quantitative analysis of the biomechanically optimal plate position during MOWHTO was conducted using FEA, allowing for the assessment of not only the micromotion at the medial opening gap but also the detailed stress distribution in the lateral hinge and bone-implant construct.

This study demonstrated that micromotion at the medial opening gap of the tibia increased when the plate was positioned anteriorly and distally, while micromotion decreased with the plate placed posteriorly and proximally. Similarly, a diminishing tendency in stress applied to the lateral hinge of the tibia was observed when the plate was positioned posteriorly and proximally, and this pattern was equally evident in both the entire bone and the implant. These findings are believed to be attributable to the following reasons. First, the vertical load exerted on the articular surface of the knee was uneven, being more pronounced posteriorly than anteriorly.²¹⁾ Indeed, the findings of this study revealed that the magnitude of shear micromotion at the medial opening gap was generally larger than axial micromotion. Furthermore, from a biomechanical perspective, the placement of the implant posteriorly may induce more effective load transmission, as it allows for the reduction of the moment arm. Consequently, placing the plate posteriorly, where the load is relatively substantial, not only alleviates micromotion but also mitigates stress on the lateral hinge of the tibia, the entire tibial bone, and the implant. Second, the medial opening gap created by MOWHTO is generally larger posteriorly than anteriorly. This asymmetry in the medial opening gap may occur during surgery as an attempt to maintain a posterior tibial slope.²⁶⁾ Accordingly, the region with a relatively larger opening gap could be mechanically unstable, and placing the plate in proximity to this region enhances mechanical

stability. Third, positioning the plate posteriorly could extend the available length of screws, thereby enhancing fixation strength.¹⁰⁾ Furthermore, posterior plate placement may improve stability by directing the screws toward the lateral hinge rather than the posterolateral side. Fourth, consistent with the previously mentioned third reason, as the plate is positioned superiorly, mechanical stability increases with the corresponding increase in screw length. Indeed, it was observed that the screws applied when the plate was superiorly positioned were relatively longer compared to those used with the inferiorly placed plate in this study (Supplementary Table 1). Additionally, proximal plate placement may reduce the likelihood of a D-hole screw protruding through the medial opening gap. Therefore, positioning the plate proximally contributes to increased bone purchase, thereby enhancing mechanical stability. For the aforementioned reasons, in order to enhance the biomechanical stability of the bone-implant construct during MOWHTO, it is advisable to position the plate as posterior and proximal as possible. Specifically, consistent with findings in previous studies, greater emphasis should be placed on the posterior placement of the plate.^{8-10,12)}

The assessment of the risk of implant breakage revealed that PVMS predominantly occurred in Hole 1 of the implant and its corresponding screw. This area is presumed to experience relatively concentrated stress, as it corresponds directly beneath the medial opening gap.²⁷⁾ In the same context, the observed increase in PVMS as the plate was positioned superiorly could be interpreted as Hole 1 getting closer to the medial opening gap due to the proximal placement of the plate. However, akin to other measurement parameters, PVMS significantly decreased when the plate was positioned posteriorly, demonstrating notable distinctions between anterior and posterior placements, while the impact of plate height was relatively minimal. Importantly, irrespective of the implant's placement, PVMS in both the plate and screw did not surpass the yield strength of the titanium alloy, indicating a low risk of implant breakage. Therefore, positioning the plate posteriorly and proximally during MOWHTO could not only be biomechanically ideal but also be associated with a low risk of implant breakage.

Several limitations may exist in this study. First, the analysis was conducted using only 1 subject, implying that the tibia model employed in this study may not represent all anatomical variations and diverse bone densities, and statistical validation was not feasible. Second, this study was conducted with the medial-opening wedge gap set at 10 mm. In actual clinical practice, however, the opening gap may vary depending on the patient's condition and

limb alignment, and the analysis results might differ with varying opening gaps. Third, among the numerous anatomical structures comprising the knee joint, only the tibia bone was utilized for analysis. Although the effect might be marginal, consideration of the load imposed by the fibula and soft tissues around the knee was not performed during the analysis. Fourth, although the implant used in this study is among the most widely utilized, considering that various fixation devices can be employed in MOWHTO, the findings of this study may not be applicable when implants other than the one used in this research are employed.²⁸⁾ Fifth, as this study is a descriptive laboratory study through FEA, there may be discrepancies from actual clinical situations. As the surgical process is influenced by various factors, including the soft tissues around the osteotomy site and the surgical instruments used to maintain the medial opening gap—factors not considered during the analysis—there may be some limitations in applying the results of this study to an actual surgical procedure. Finally, as this study was conducted under a static load condition, the influence of dynamic conditions such as walking or squatting was not analyzed.

This is not the first study to report an optimal plate fixation position during MOWHTO. Indeed, some previous studies have suggested the posterior placement of the plate during this surgical procedure.^{8-10,12)} Nevertheless, this study can serve to solidify the findings of previous research by employing various assessment parameters not analyzed in prior studies, and it also holds clinical significance as it provides information on the ideal height of plate placement for the first time. By offering evidence-based strategies to minimize complications associated with MOWHTO, this study could contribute to improving clinical outcomes.

Placing the plate more posteriorly and proximally in MOWHTO could minimize inter-fragmentary micromotion, reduce stress on the lateral hinge and bone-implant construct, and enhance stress shielding, all without increasing the risk of implant breakage, suggesting it as a potentially optimal plate position.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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SUPPLEMENTARY MATERIAL

Supplementary material is available in the electronic version of this paper at the CiOS website, www.ecios.org.

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