Mechanical stability of the proximal tibia with different bone formations after plate removal in medial opening-wedge high tibial osteotomy: A finite element analysis

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ABSTRACT

Mechanical stability of the proximal tibia with different bone formations after plate removal in medial opening-wedge high tibial osteotomy: A finite element analysis

No clear agreement exists on the degree of bone formation required to remove a metal plate without correction loss after medial opening-wedge high tibial osteotomy (MOWHTO). We aimed to investigate the mechanical stability of the proximal tibia with different bone formations after plate removal in MOWHTO using finite element models and determine the extent of bone formation when the plate can be removed without correction loss. The mechanical stability of proximal tibial models with different extents of bone formation after plate removal was analyzed using finite element analysis. Bone stress and strain and micromotion were evaluated to investigate fracture risk and bone stability, respectively, in various types of tibial models. Peak von Mises stress was lower than yield strength when bone formation reached zone 3.5 (70%) or more in 5- and 10-mm osteotomy gap models, and zone 4 (80%) or more in a 15-mm gap model. Maximal principal strains were lower than 6,130 microstrain when bone formation reaches zone 3.5 (70%) or more in models with osteotomy gaps of 5, 10, and 15 mm. This indicates that plate removal without correction loss after MOWHTO may be possible when bone formation reaches zone 3.5 (>70%) or more during 5- and 10-mm osteotomy gap corrections, and zone 4 (>80%) or more.

Key words : high tibial osteotomy, plate removal, optimal timing, finite element analysis

1. INTRODUCTION

Medial opening-wedge high tibial osteotomy (MOWHTO) is a surgical intervention used to treat varus malalignment associated with medial osteoarthritis in middle or early old age [1, 2]. This procedure shifts the weight-bearing axis of the lower extremity laterally in the coronal plane, increases the width of the medial joint space, and reduces the medial compartment load to postpone transition to total joint surgery [3-7]. Compared with lateral closing-wedge osteotomy, MOWHTO has the advantage of easy adjustment of correction degree and a low risk of peroneal nerve damage [8]. However, lateral hinge fractures, implant breakage, and correction loss occur more frequently after MOWHTO due to the relatively unstable structure generated by the opening gap [1, 9]. Therefore, long and bulky metal plates with locking screws have traditionally been preferred for fixation in MOWHTO. A rigid and bulky metal plate improves stability around the osteotomy site; however, many patients complain of discomfort at the fixation site. Niemeyer et al. [10] reported that after MOWHTO, 40.6% of patients complained of local discomfort and irritation associated with the implant. Darees et al. [11] reported that 41.6% of patients treated with MOWHTO removed the plate because of the discomfort. Most Asian or lean patients with a thin subcutaneous layer visit an outpatient clinic to remove the metal plate before achieving complete bone union because of discomfort.

No clear agreement exists on the degree of bone formation required for plate removal without correction loss after MOWHTO. Staubli et al. [12] reported that approximately 90% of patients gained full consolidation of osteotomy site on simple radiography, computed tomography (CT), and magnetic resonance imaging in 1 year. Brinkman et al. [13] did not suggest hardware removal 1.5 years after corrective osteotomy. However, Kobayashi et al. [14] reported that the extent of posterior cortical bone union that reached zone 3 (40–60%) was enough for metal removal. Goshima et al. [15] suggested that hardware removal was possible without correction loss after MOWHTO when posterior cortical bone union reached the midpoint (>50%) of osteotomy gap. However, studies to determine the point where correction loss occurs after plate removal in MOWHTO with various degrees of correction are still insufficient, and finding this point using only clinical studies is challenging. Furthermore, to the best of our knowledge, no study has evaluated the mechanical stability of proximal tibial models with metal plates removed after MOWHTO.

We aimed to investigate the mechanical stability of the proximal tibia with different bone formations after plate removal in MOWHTO using finite element (FE) models, and to determine the degree of bone formation where the plate can be removed without correction loss. The present study hypothesized that a possible point for plate removal without the risk of correction loss would exist in the <50% progression zone of bone formation on anterior-posterior (AP) radiographs.

2. METHODS

2.1. Development of a normal proximal tibia FE model

2.1.1 Development of the normal proximal tibia model

The present study was approved by the institutional review board of Yonsei University Gangnam Severance Hospital (approval No. 3-2024-0263). Cross-sectional images of the lower extremities of a 62-year-old Asian female were obtained using 64-channel CT with a slice interval of 0.1 mm. Three-dimensional geometric contour of the tibia was created by stacking the CT cross-sectional images using Mimics (version 17.021.0; Materialize Inc., Belgium). Bone surfaces were modified into more sophisticated solid models using computer-aided design (CAD) software and Unigraphics NX (version 2021; Siemens PLM Software, Torrance, CA). An FE mesh was generated using HyperMesh (version 8.0; Altair Engineering, MI, USA). A "tie" contact condition was applied assuming full constraints between bone and bone. The distal end of the tibial bone was assumed to be fully constrained in all tests [16, 17]. An FE analysis was conducted using ABAQUS (version 6.1411; Dassault Systems, France).

2.1.2 Material property

As for the tibia, cortical bone was considered linear elastic, isotropic, and homogeneous material with an assumed Young's modulus (E), E = 17,000 MPa and Poisson ratio (ν), ν = 0.33 [18, 19]. Cancellous bone was simulated as a linear isotropic material with E = 910 MPa and ν = 0.2 [20].

2.1.3 Mesh convergence

Convergence of the FE model was also investigated. Mesh convergence was defined as the maximum displacement of trabecular bone, which is within 95% of the pressure of the next two smaller mesh sizes [21]. The average FE size was 0.8 mm for the cortical and cancellous bone. The numbers of elements were as follows: cortical bone, 77,576 and cancellous bone, 178,726.

2.1.4 Intact model validation

The finite element model was validated by comparing it with data from a previous study that experimentally validated an FE model of a human cadaveric tibia [22]. The FE model is validated under axial loading conditions. The minimum and maximum principal strains were investigated. The largest values of the minimum principal strain on the tibia bone and reference model were −542 and −569 microstrain, respectively. The largest values of the maximum principal strain on the tibia and reference model were 403 and 426 microstrain, respectively. The difference was set at 10%. Therefore, the FE model in this study was validated by comparing the differences in the largest values of the minimum and maximum principal strains on the tibia between the FE model and literature data.

2.2. Development of proximal tibia FE model with plate removal after MOWHTO

2.2.1 Development of the MOWHTO model

The constructed FE model was used to simulate MOWHTO with rotation of the distal part of the tibia in the coronal plane to create a valgus correction angle. The MOWHTO models with 5, 10, and 15 mm gaps were generated by removing a single-plane wedge-shaped osteotomy bone at the proximal tibia while leaving a 10 mm hinge from the lateral cortex (Fig. 1a). The MOWHTO was simulated such that the mechanical loading axis was located at 62.5% from medial to lateral, as suggested by Fujisawa et al. [23].

2.2.2 Development of proximal tibia model with different extents of bone formation after plate removal

A commercially used fixation plate, TomoFix (DePuy Synthes, Warsaw, IN, USA), was assumed to be bulky using MOWHTO simulation and modeled three-dimensionally using the CAD program, Unigraphics NX (version 7.0; Siemens PLM Software, Torrance, CA, USA). The plate model was virtually fixated into the proximal tibia to simulate MOWHTO fixation and then removed to create a proximal tibia model with bony deficiency at the opening wedge and screw holes. To create proximal tibial models with different degrees of bone formation at the time of hardware removal, we further subdivided the osteotomy filling index proposed by Brosset et al. [24]. The tibia models with different union progressions at the time of plate removal were generated by artificially forming bone formation from the lateral cortex of the osteotomy wedge to 20% (zone 1), 40% (zone 2), 50% (zone 2.5), 60% (zone 3), 70% (zone 3.5), 80% (zone 4), and 100% medially (Fig. 1b).

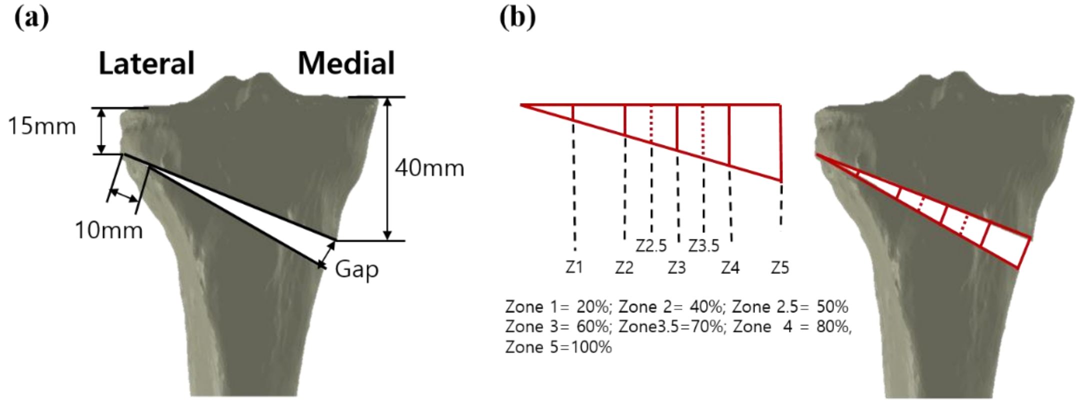

Figure 1. Specifications of the MOWHTO used in this study (a) and osteotomy filling index with seven identified zones (b).

2.3. Stability analysis of the proximal tibia models with different extent of bone formation after plate removal

Physiological loading and intervention-induced compression were applied to the MOWHTO models; the 200N intervention induced a compressive load that was uniformly exerted on the tibial osteotomy site in a distracted cortex [18, 19, 25]. According to the results from a previous study, restoration of physiological transfer of a knee load was assumed in the present study, which led to load repartitions of 60% and 40% on the medial and lateral tibial plateaus, respectively (Fig. 2a and 2b) [26].

Three parameters were used to compare the differences in stress, strain, and micromotion with variations in bone formation. First, peak stress (peak von Mises stress, PVMS) was investigated in the cortical bone and lateral hinge area in the FE models, and the stress values were compared to the yield strength to verify stability. The yield strength of the tibial cortical bone (177.2 MPa for axial compression) was obtained from a previous publication [27]. Next, the maximum principal strain in the bones was evaluated. Third, change in height at the medial edges of the opening gap was evaluated to compare bony stability (Fig. 2c). The FE analysis was conducted using ABAQUS (version 6.14; Dassault Systems, France).

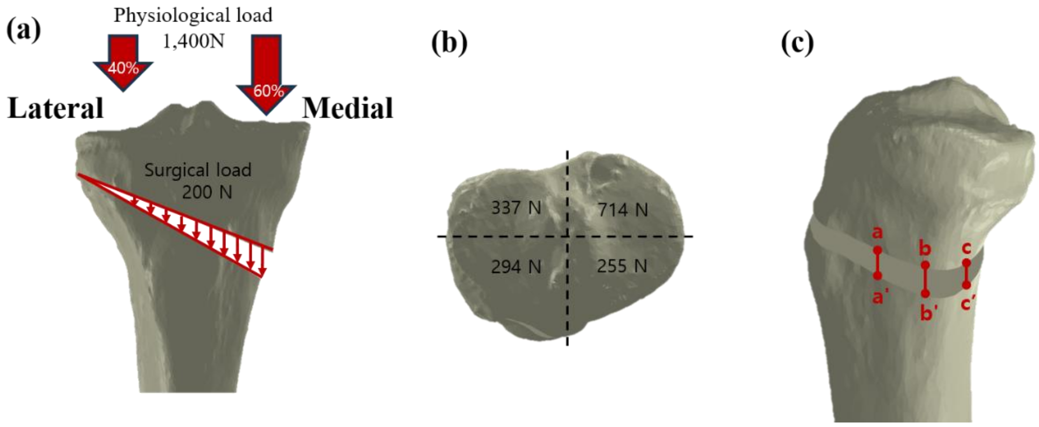

Figure 2. Loading conditions used in the present study; physiological and surgical loads (a), and loads on the four regions of the tibial plateau (b). Three edges a-a', b-b', and c-c' along the medial cortex were defined to evaluate the height changes in loading condition (c).

3. RESULTS

3.1. Stress distribution on the bone

Peak von Mises stress was greatest around the posterolateral end of the osteotomy wedge in all the models, and tended to decrease with progressive gap filling (Fig. 3).

In models with osteotomy gaps of 5 and 10 mm, PVMS was greater than yield strength (177.2 MPa) when bone formation reached zone 3 (60%) or less; however, PVMS was lower than yield strength when bone formation reached zone 3.5 (70%) or more (Fig. 4a and 4b).

In models with 15mm gaps, PVMS was greater than yield strength when bone formation reached zone 3.5 (70%) or less (Fig. 4c); however, PVMS was lower than yield strength when bone formation reached zone 4 (80%) or more (Table 1).

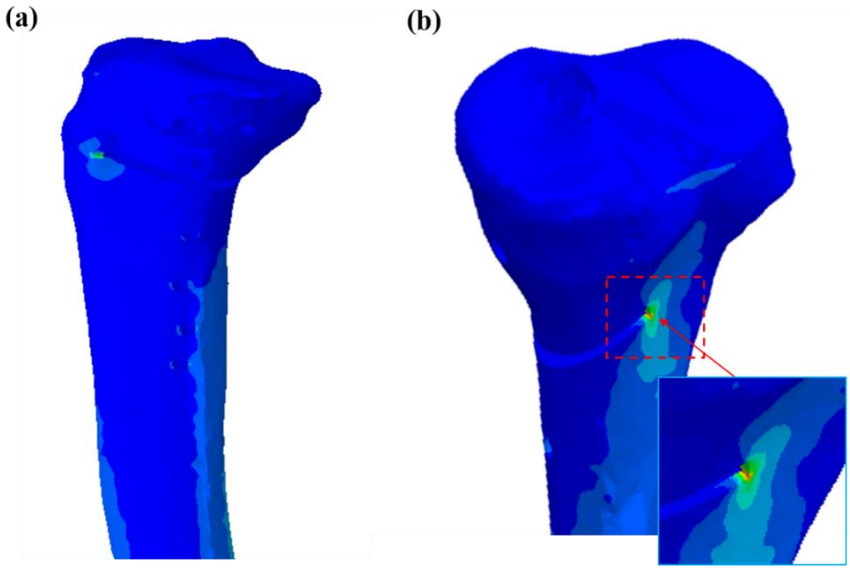

Figure 3. Stress distribution around the proximal tibia with opening gap of 5 mm filled with zone 3.5 (70%) bone formation after plate removal; medial view (a) and posterior view (b). The arrow indicates that the peak stress was observed at the posterolateral osteotomy wedge site.

Table 1. Peak von Mises stress at cortical bone

Opening Gap (mm)	Peak Von Mises Stress (MPa)						
	Zone 1	Zone 2	Zone 2.5	Zone 3	Zone 3.5	Zone 4	Zone 5
Gap 5	4230	1009	769	286	**159***	**101***	**39***
Gap 10	2707	794	455	285	**171***	**128***	**39***
Gap 15	1954	855	589	336	231	**127***	**39***

* Lower than the yield strength: axial compression 177.2 MPa

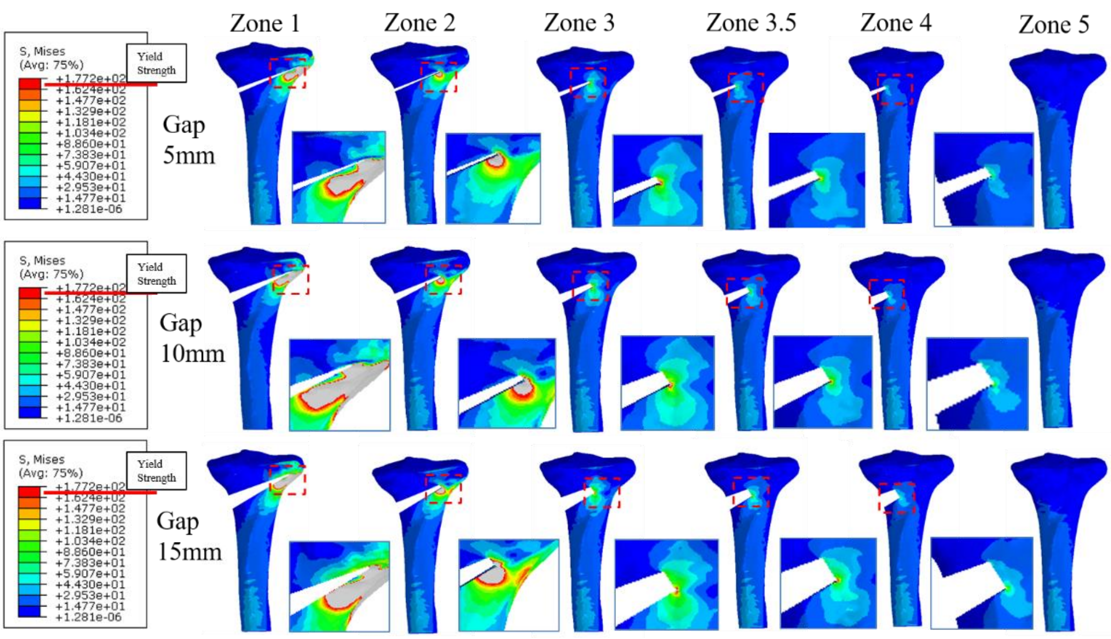

Figure 4. Stress distribution around the proximal tibia with opening gaps of 5 mm (top), 10 mm (middle), and 15 mm (bottom) filled with bone formations each (posterior view). The enlarged image portion represents the point at which the peak stress was observed.

3.2. Strain distribution on the bone

Strain was also greatest around the posterolateral end of the osteotomy wedge in all the models and tended to decrease with gap-filling progression.

Maximal principal strain was greater than 10,000 microstrain when bone formation reached zone 3 (60%) or less in models with osteotomy gaps of 5, 10, and 15 mm; however, it was lower than 6,130 microstrain when bone union reached zone 3.5 (70%) or more in all the models (Fig. 5) (Table 2).

Table 2. The maximum principal strain

Opening Gap (mm)	Maximum principal strain ($\times 10^{-6}$)						
	Zone 1	Zone 2	Zone 2.5	Zone 3	Zone 3.5	Zone 4	Zone 5
Gap 5	170000	90700	44900	10100	5920	3470	1580
Gap 10	107300	76400	31400	11100	5470	3850	1580
Gap 15	96500	88000	34800	10500	6130	3030	1580

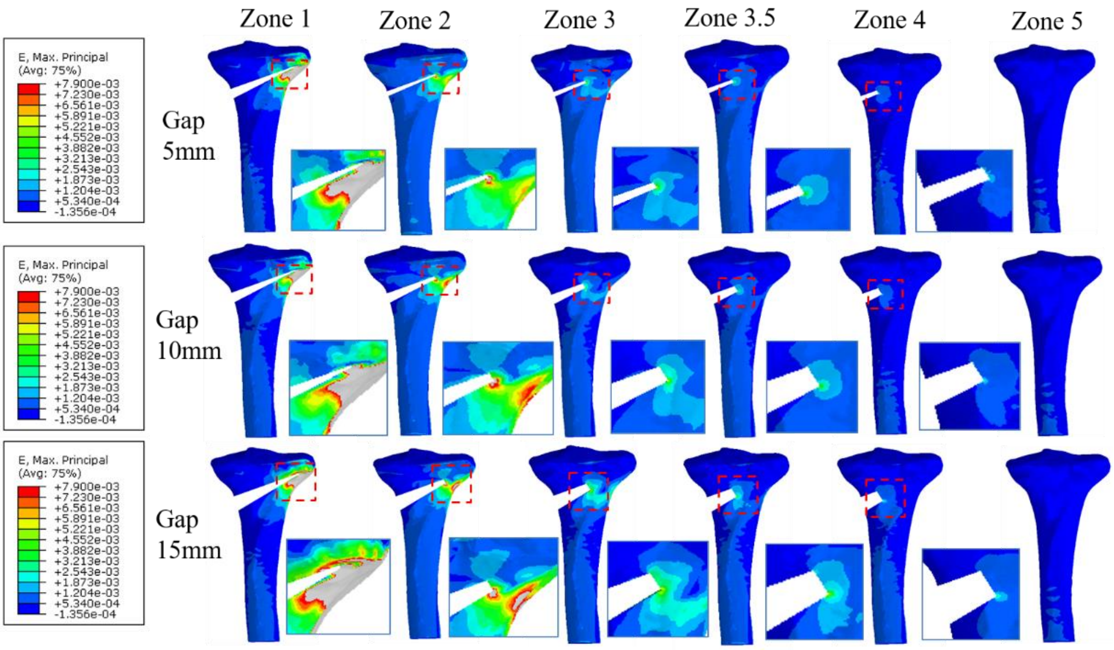

Figure 5. Strain distribution arournd the proximal tibia with opening gaps of 5 mm (top), 10 mm (middle), and 15 mm (bottom) filled with bone formations each (posterior view). The enlarged image portion represents the point at which the maximal strain was observed.

3.3. Micromotion at the edges of the opening gap

As the osteotomy correction gap increased, change in height at the edges of the opening gap tended to increase. Change in height at the edges of the osteotomy gap tended to increase from anterior to posterior (aa’<bb’<cc’) (Table 3).

Table 3. Change in height at the medial edges of the opening gap

Gap (mm)	Change in the height at medial edges (mm)															
	Zone1	Zone 2			Zone 2.5			Zone 3			Zone 3.5			Zone 4		
	aa', bb′, cc'	aa'	bb'	cc'	aa'	bb'	cc'	aa'	bb'	cc'	aa'	bb'	cc'	aa'	bb'	cc'
Gap 5	>5	1.61	1.83	1.86	1.02	1.12	1.14	0.34	0.37	0.37	0.18	0.19	0.19	0.10	0.11	0.11
Gap10	>10	2.12	2.31	2.38	0.98	1.00	1.01	0.43	0.46	0.47	0.24	0.25	0.26	0.15	0.16	0.17
Gap15	>15	2.78	2.99	3.05	1.53	1.65	1.69	0.56	0.60	0.61	0.32	0.34	0.35	0.21	0.22	0.22

4. DISCUSSION

The most critical finding of the present study is that PVMS was lower than yield strength when bone formation reached zone 3.5 (70%) or more in the 5- and 10-mm gap models, and zone 4 (80%) or more in the 15-mm gap model. However, PVMS was greater than yield strength when bone formation reached zone 3 (60%) or less in the 5- and 10-mm gap models, and zone 3.5 (70%) or less in the 15-mm gap model, which could lead to bone fracture or correction loss after metal removal.

The maximum stress and strain in zones 1–4 were measured at the posterolateral end of the wedge, which is thought to be due to the loading that was more concentrated in the posterior direction than the anterior. The maximal principal strain was lower than 6,130 microstrain when bone union reached zone 3.5 (70%) or more in all the models; these were lower than 7,900 microstrain, which was previously reported to cause low cycle (<10,000 cycles) fatigue microcracking [28]. Micromotion at the medial edge of the opening gap tended to increase from anterior to posterior, which was thought to be due to the higher load on the posterior part than the anterior part.

When considering metal plate removal to relieve discomfort and obtain clinical benefits, no clear agreement exists on the degree of bone formation that allows hardware removal without correction loss after MOWHTO. Brinkman et al. [13] reported that complete union was achieved in 90% 1 year after the surgery and recommended that the metal plate should not be removed before 1.5 years after MOWHTO. However, there is no consensus that plate removal is possible only when complete union is achieved, and many surgeons attempt to remove the plate before complete union. Goshima et al. [29] reported that metal removal without correction loss is possible if gap filling arrives at zone 2 (25–50%) on simple AP X-ray radiographs; however, in another follow-up study, they experienced loss of correction in 6 (5.9%) of 101 patients who underwent plate removal according to these criteria [15].

In a follow-up study, Goshima et al. [15] reported in their follow-up study that posterior cortical-bone union rate was the only predictor of correction loss. They suggested using receiver operating characteristic curve analysis cut-off value that posterior cortical bone union rate of <43.3% caused an increase in posterior tibial slope and decrease in medial proximal tibial angle [15]. They finally concluded that when the posterior cortical bone union reached the gap center (50%), the plate could be removed without loss of correction. However, statistical analysis using data from the 6 (5.9%) of

101 correction loss cases seems to have limitations in representativeness; therefore, biomechanical analysis using an FE model to determine the degree of bone formation extent where the plate can be removed without correction loss seems to be meaningful. According to the present study, PVMS was lower than yield strength when bone formation reached zone 3.5 (70%) or more in 5- and 10-mm osteotomy gap models, and zone 4 (80%) or more in a 15-mm gap model. Our study results suggest that it would be safer to perform plate removal after obtaining sufficient bone formation rather than performing it near the osteotomy gap center (50%) to avoid correction loss despite continued patient discomfort.

The present study has several limitations. Firstly, the present study was conducted under static conditions because dynamic knee joint motion is too complicated in terms of computing resources and time. In future studies, a more suitable representation of the mobile joint and study of the models under cyclic loading should be conducted. Secondly, only the tibia was simulated in this study. Expanding the scope of the cartilage may be required to investigate the pressing biomechanics of MOWHTO. Third, our results cannot be applied to patients with osteoporosis.

However, to the best of our knowledge, this is the first FE analysis to demonstrate the appropriate timing of metal removal without correction loss after MOWHTO. The results of this study will be helpful in decision-making regarding the timing of metal removal after MOWHTO.

5. CONCLUSION

The present study demonstrated that plate removal seems to be possible without correction loss after MOWHTO when bone formation reached zone 3.5 (>70%) or more during 5- and 10-mm osteotomy gap corrections, and zone 4 (>80%) or more during 15-mm gap correction.

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ABSTRACT IN KOREAN

내측 개방형 근위 경골 절골술 후 금속판을 제거한 근위 경골 모형에서 골 형성 정도에 따른 근위 경골의 기계적 안정성: 유한 요소 분석

개방형 근위 경골 절골술 후 교정 손실 없이 금속판을 제거하는 데 필요한 골 형성 정도에 대한 명백한 합의는 없다. 본 연구의 목적은 내측 개방형 근위 경골 절골술 후 금속판을 제거한 서로 다른 골 형성을 가진 근위 경골 모형의 기계적 안정성을 유한 요소 모델을 이용하여 분석하고, 교정 손실 없이 금속판 제거가 가능한 골 형성 정도를 결정하고자 하였다. 유한 요소 분석을 이용해 금속판 제거 후 골 형성 정도가 다른 근위 경골 모형들의 기계적 안정성을 분석하였다. 다양한 유형의 골형성을 가진 근위 경골 모형에서 뼈의 응력과 변형률, 미세움직임을 평가하여 골절 위험성과 골 안정성을 조사하였다. 5mm 및 10mm 내측 개방형 근위 경골 절골 모형에서는 골 형성이 구역 3.5 (70%) 이상에 도달했을 때, 15mm 내측 개방형 근위 경골 절골 모형에서는 골 형성이 구역 4 (80%) 이상에 도달했을 때 최대 응력은 항복 강도보다 낮았다. 5, 10, 15mm 내측 개방형 근위 경골 절골 모형에서 골 형성이 구역 3.5 (70%) 이상에 도달했을 때 최대 변형률은 6,130 마이크로-변형률보다 낮았다. 이는 5mm 및 10mm 내측 개방형 교정 절골술에서는 골 형성이 구역 3.5 (>70%) 이상에 도달하였을 때, 15mm 내측 개방형 교정 절골술에서는 골 형성이 구역 4 (>80%) 이상에 도달할 경우 내측 개방형 근위 경골 절골술 후 교정 손실 없이 금속판 제거가 가능할 수 있음을 나타낸다.

핵심되는 말 : 근위 경골 절골술, 금속판 제거, 적절한 시기, 유한 요소 분석