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Original Article

Benefits of opposite screw insertion technique in medial open-wedge high tibial osteotomy: A virtual biomechanical study

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ABSTRACT

Background: Alignment correction of the lower limb by medial open-wedge high tibial osteotomy (HTO) is an efficient technique, but loss of correction and hardware failure can occur owing to inadequate fixation. A surgical technique using opposite screw insertion was previously applied for salvage of the lateral hinge fracture, but evidence for its utility as a protective strategy was unclear.
Methods: Finite element models were reconstructed using artificial bone models, commercial bone plate, and locking screws in the HTO model. The 6.5-mm cancellous or 6.5/8.0-mm pretensioned lag screw was virtually inserted from the opposite cortex to the medial tibial plateau. Testing loads were applied for simulating standing and initial sit-to-stand postures. The axial displacement of the posteromedial tibial plateau, which represents the loss of the posteromedial tibial plateau in clinical observation, and stresses on the bone plate, locking screws, and opposite screws were evaluated.
Results: Pretensioned lag screw insertion effectively reduced the loss of posteromedial reduction compared with the HTO model without opposite screw insertion [6.5-mm lag screw, by 50.8% (standing)/56.3% (sit-to-stand); 8.0-mm lag screws, by 51.9% (standing)/57.5% (sit-to-stand); normalised by the performance in the intact model]. The noncompressed opposite cancellous screw slightly reduced the stresses on the bone plate and screws, but did not contribute to the control of reduction loss at the posteromedial tibial plateau. Stresses on screws were lower than those on the corresponding bone plates, so the risk of screw breakage may be low.
Conclusion: The present study revealed that pretensioned opposite lag screw insertion is a simple and effective technique to improve the structural stability in medial open-wedge HTO. Further biomechanical and clinical verification will be required to enhance user confidence in this technique.
The translational potential of this article: The efficacy and advantages of additional opposite lag screw insertion in medial wedge high tibial osteotomy surgery have been described in this current study by a virtual biomechanical evaluation. Basing on this observation, it would worth further clinical trials for clarification and verification in reality.

Introduction

Medial open-wedge high tibial osteotomy (HTO) is recognised as a surgical option in dealing with medial osteoarthritis or varus malalignment of the knee joint. Previously, this technique was used to correct knee disease with inadequate varus deformity [1,2], and several studies with statements on postponing the necessity of total knee arthroplasty were conducted [3–5]. Using the medial open-wedge HTO technique, the mechanical alignment of the lower limb in the coronal plane is restored to achieve a redistributed loading on the tibial plateau. Basically, the potentially altered posterior slope on the tibial plateau in the sagittal plane after medial open-wedge HTO is well known and has been reported in many studies [6–9]. Sometimes, surgeons may adjust an adequate tibial posterior slope for patients during HTO according to the function of the anterior cruciate ligament.

However, owing to structural deficiency after medial open-wedge HTO, complications such as the lateral hinge fracture, loss of reduction, and hardware failure are common [10–12]. As a salvage procedure, Paccola and Fogagnolo [13] introduced a surgical method in which a supplement percutaneous lag screw is inserted from the lateral cortex to the medial

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tibial plateau, restoring adequate angular correction. This technique has been further verified by the biomechanical test with the lateral hinge fracture model and demonstrated significant improvement in structural stiffness compared with the HTO model with an unrepaired lateral hinge fracture [14].

Sufficient stability and safety after medial open-wedge HTO are essential to achieve the goal of enhanced recovery after surgery (ERAS), especially when encouraging early weight-bearing for patients to gain mechanical stimulation at the fracture site, which is beneficial to bone healing after surgery. Therefore, it is important to prevent the aforementioned complications after medial open-wedge HTO. Concerning possible hardware failure and loss of reduction after surgery, it is unknown if the screw technique from the opposite (lateral) cortex to the medial tibial plateau can be used as a precaution, such that safety of HTO can be further enhanced before the lateral hinge fracture has occurred. The purpose of the present study was to analyse the efficacy of opposite screw insertion in consideration of loss of posterior reduction and hardware safety in medial open-wedge HTO in a virtual biomechanical perspective.

Materials and methods

Model preparation

The reconstructed continuum-based tibial and fibular models from the computerised tomographic image (Light Speed VCT; GE Medical System, General Electric Company, USA; slice thickness: 1.25 mm; image resolution: 512 × 512 pixels) of surrogate tibial and fibular sawbones (#3401 and #3427-1; Sawbones, WA, United States) were used in the present study as the intact model. The tibial shaft is perpendicular to the ground in the sagittal plane, with a 3° varus tilting according to the general concept of the lower limb anatomy in the standing posture. Biplanar tibial tubercle–preserving osteotomy was simulated for approximately 15-mm expansion at the medial osteotomy site (Figure 1) as the designated correction in open-wedge HTO, referring to the instruction on the surgical technique of the TomoFix Medial High Tibial Plate (DePuy Synthes; Synthes GmbH, Oberdorf, Switzerland). The bone plate was reconstructed using the released parameters from a commercially available product (TomoFix standard, DePuy Synthes). The plate was placed at the anteroposterior region of the medial tibial model, referring to the instruction of the experienced surgeon. A total of 8 locking screws (diameter, 5 mm) were inserted in all locking holes on the plate with adequate screw length (Figure 2), whereas the threads on locking screws were removed for simplification.

To simulate the technique of opposite screw insertion, a 6.5-mm cancellous screw (core diameter, 4.5 mm; solid), 6.5-mm lag screw (core diameter, 4.5 mm; cannulated tunnel diameter, 2.8 mm), and 8-mm cannulated lag screw (shaft diameter, 5.5 mm; cannulated tunnel

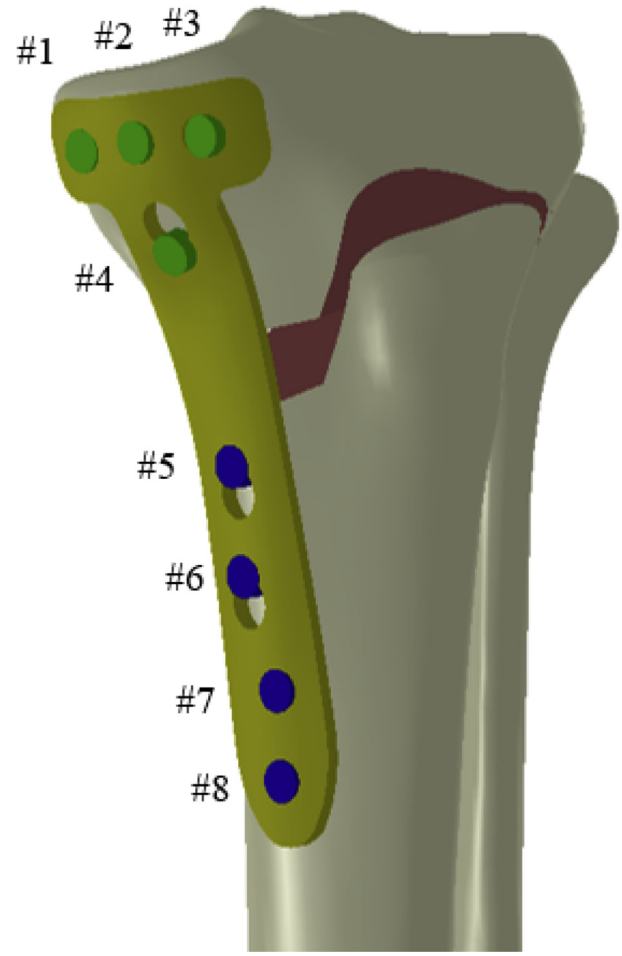

Figure 2. The model assembly of the high tibial osteotomy model with a commercial bone plate and locking screws. Numbers represent the order of screws in the simulation results.

diameter, 3.5 mm) were reconstructed according to published dimensions of commercial products (Zimmer Biomet, Inc., Warsaw, IN, United States; Stryker Corporation, Kalamazoo, MI, United States). One of the aforementioned three screws was used as the opposite screw in each of the three models. The opposite screw was inserted from the lateral cortex to the region beneath the medial lateral plateau, in an orientation of approximately 50° oblique in the coronal plane and 38.5°

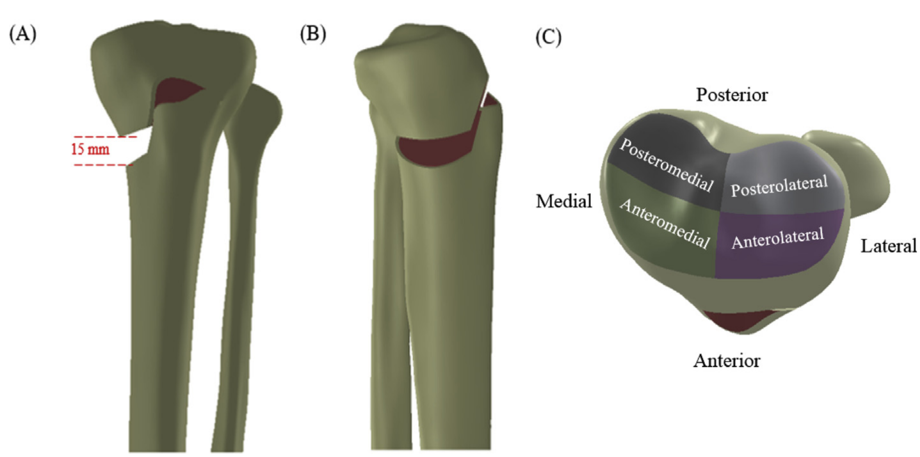

Figure 1. (A) The solid model representing a biplanar high tibial osteotomy in the coronal view. (B) The solid model representing a biplanar high tibial osteotomy in the sagittal view. (C) Orientation definition.

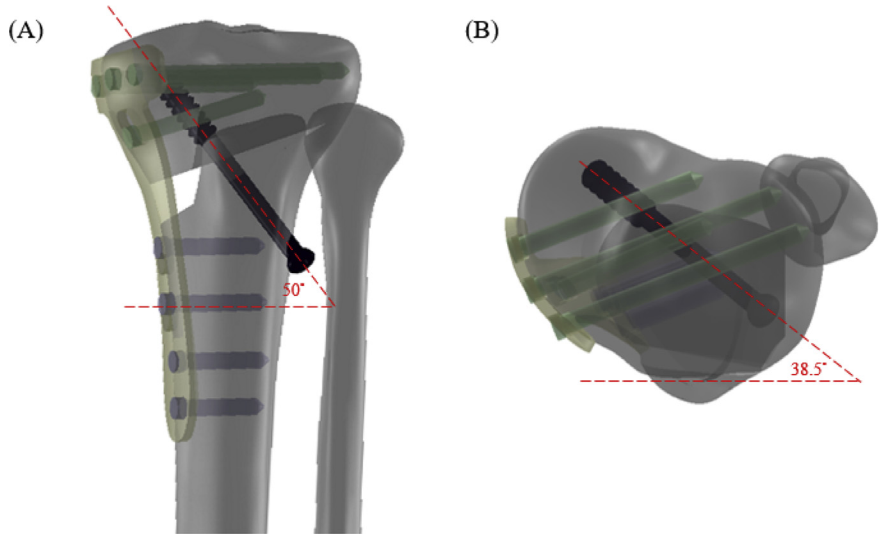

Figure 3. (A) The orientation of opposite lag screw insertion (black) in the coronal view. (B) The orientation of opposite lag screw insertion (black) in the transverse view.

oblique in the transverse plane (Figure 3).

All five models were meshed using tetrahedral elements in ANSYS Workbench 18.0 (ANSYS Inc., Canonsburg, PA, United States). Interfaces between bone and locking screws were bonded, and those between bone plate holes and the corresponding locking screw heads were also bonded to simulate ideal fixation. In opposite screw insertion, threads on the screws were preserved. The cancellous screw was bonded to the corresponding bony structure. The threaded region of the lag screw was bonded to the corresponding bony structure, while the shaft region was frictionless against the bony tunnel for screw insertion. The bone–plate interface was also frictionless. Material properties for the bony structure (cortical bone, Young's modulus: 15.1 GPa, Poisson's ratio: 0.3; cancellous bone, Young's modulus: 100 MPa, Poisson's ratio: 0.3) and metallic implants (titanium, Young's modulus: 110 GPa, Poisson's ratio: 0.3) were assigned accordingly. For simplification of the finite element analysis, the lower half of the surrogate bones were removed, and the bottom was fully fixed. Referring to the results of the convergence test, element numbers for the intact model, conventional HTO model (without opposite screw insertion), and HTO model with opposite 6.5-mm cancellous screw insertion, 6.5-mm lag screw insertion, and 8.0-mm lag screw insertion, respectively, were 152474, 160113, 159945, 160899, and 161142.

Loading conditions

Two different loading conditions were simulated in all five models. For the general loading condition, referring to the literature, the exertion of a 600-N axial compressive load was distributed on the full tibial plateau (simulating the load in the standing posture) [15]; to simulate the loading at the initial sit-to-stand movement; the other loading condition with exertion of a 600-N axial compressive load was distributed on the posterior half of the tibial plateau only. A pretension force of 100 N was assigned on the 6.5-mm and 8.0-mm lag screws, whereas there was no pretension force on the 6.5-mm cancellous screw.

Evaluating parameters

To determine the effect of the opposite screws on stabilisation, the axial displacement of the posteromedial tibial plateau was analysed (similar to the observation in a previous biomechanical study by Schröter et al. [16]) and compared with the intact model. In view of hardware safety, the maximal von Mises stresses on the bone plate, locking screw, and lag screw were compared. The representing order of locking screws is shown in Figure 2.

Results

Loss of posteromedial reduction

From the pattern of displacement on the tibial plateau in the transverse view, obvious loss of posterior reduction after loading was found at the posteromedial region of the tibial plateau. Values of the axial displacement were normalised in the intact model (without HTO) for the two different loading conditions. In the conventional HTO model without opposite screw insertion in two loading conditions, axial displacement at posteromedial region of the tibial plateau was increased by 61.0% (standing)/87.0% (sit-to-stand) compared with that in the intact model (Figure 4). Insertion of the 6.5-mm cancellous screw has slightly reduced the magnitude of reduction loss compared with the conventional HTO model (increase by 47.7–73.3%). Insertion of pretensioned 6.5-mm and 8.0-mm lag screws has significantly maintained the structural stability, with only 4.7% (standing)/36.3% (sit-to-stand) and 3.5% (standing)/35.2% (sit-to-stand) increases in reduction loss at the posteromedial tibial plateau.

Stress on the bone plate

Figure 5 presents the stress patterns and values on the bone plates in all models. With 600-N compressive force on the full tibial plateau, stress patterns are similar among all simulated models. Using the 6.5-mm cancellous screw slightly reduced the plate stress (52.4 MPa) compared with the conventional HTO model (54.1 MPa), whereas both lag screw models slightly increased the plate stresses (59.6 and 60.0 MPa with 6.5-mm and 8.0-mm pretensioned lag screw insertions, respectively). With a 600-N compressive load on the posterior half of the tibial plateau, using the 6.5-mm cancellous screw and pretensioned 6.5-mm and 8.0-mm lag screws for opposite screw insertions reduced the plate stresses (82.0 MPa, 78.8 MPa, and 79.0 MPa, respectively) compared with the conventional HTO model (91.9 MPa).

Stress on locking screws

The maximal von Mises stresses on all 8 locking screws in all models are presented in Table 1. For better realisation of the differences between models, the results were normalised to the 600-N load on the full tibial plateau without the opposite screw for loading condition (Table 2-A) and to the 600-N load on the posterior half of the tibial plateau without the opposite screw for loading condition (Table 2-B). Using the opposite 6.5-

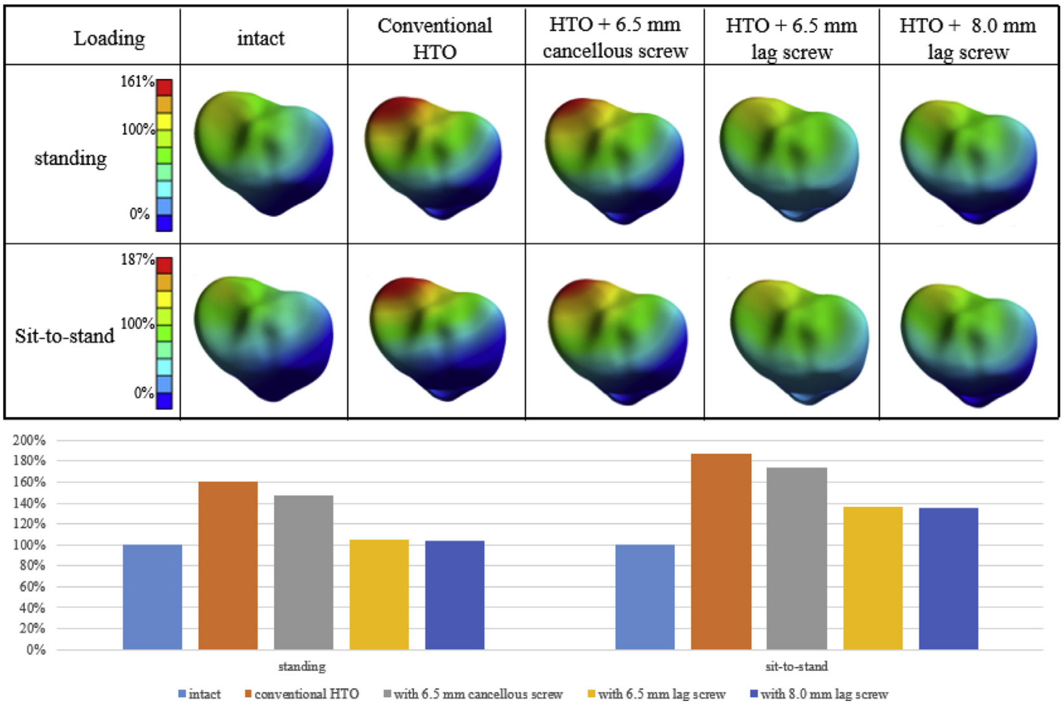

Figure 4. Loss of posteromedial reduction on the tibial plateau under simulated standing and initial sit-to-stand loading conditions. HTO = high tibial osteotomy.

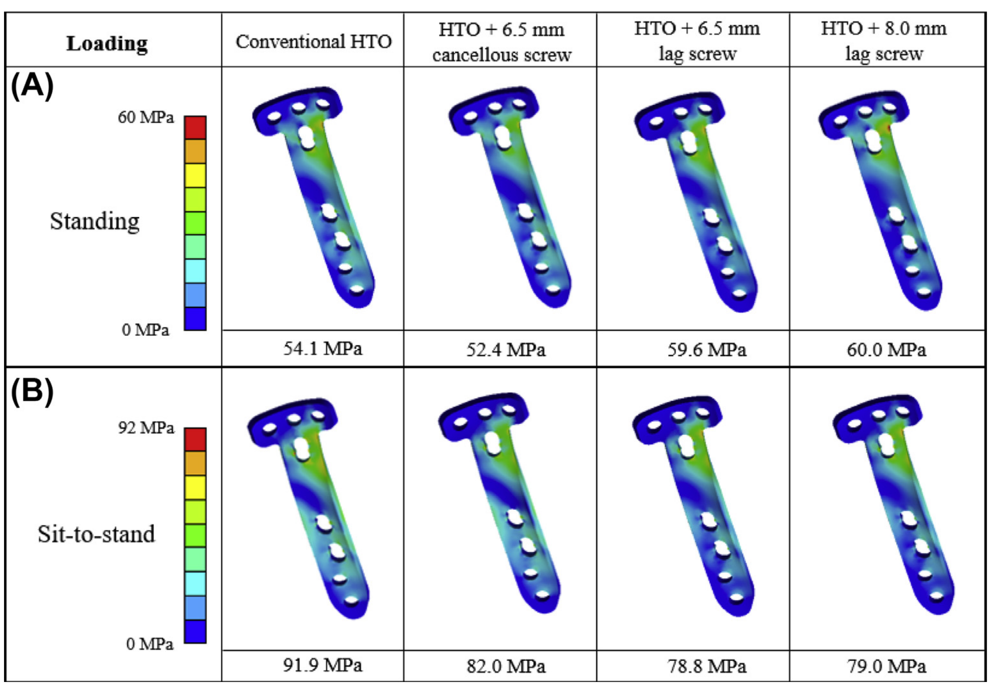

Figure 5. (A) Stress pattern and values of the bone plate in the high tibial osteotomy model with load on the full tibial plateau (standing); (B) stress pattern and values of the bone plate in the high tibial osteotomy model with load on the posterior half of the tibial plateau (initial sit-to-stand). HTO = high tibial osteotomy.

mm cancellous screw reduced all stresses on screws compared with the conventional HTO model. When using the pretensioned lag screws, stresses on Screws 1 to 4 increased. Changes in Screws 1, 2, and 4 were comparatively significant than changes in other screws.

Stress on oppositely inserted screws

With a 600-N compressive load on the full tibial plateau, the max von Mises stresses on the 6.5-mm cancellous screw, 6.5-mm lag screw, and 8.0-mm lag screw were 26.1 MPa, 42.1 MPa, and 40.3 MPa, respectively. With a 600-N compressive load on the posterior half of the tibial plateau, stresses on the 6.5-mm cancellous screw, 6.5-mm lag screw, and 8.0-mm lag screw were 46.2 MPa, 71.1 MPa, and 70.6 MPa, respectively. The magnitude of the stress was lower than that in the bone plate in the corresponding model.

Table 1
Maximal von Mises stress on the locking screw: (A) 600-N load on the full tibial plateau without the opposite screw and (B) 600-N load on the posterior half of the tibial plateau without the opposite screw (unit: MPa).

(A)	Conventional HTO	6.5-mm cancellous screw	6.5-mm lag screw	8.0-mm lag screw
Screw 1	24.3	19.1	29.4	30.1
Screw 2	19.6	16.8	22.8	22.2
Screw 3	20.4	19.1	21.6	21.3
Screw 4	41.4	37.3	47.5	46.2
Screw 5	15.7	12.7	13.4	13.4
Screw 6	16.3	14.6	17.6	17.6
Screw 7	12.1	11.3	12	12.1
Screw 8	20.2	19.1	19.9	19.8
(B)	**Conventional HTO**	**6.5-mm cancellous screw**	**6.5-mm lag screw**	**8.0-mm lag screw**
Screw 1	37.9	30.4	40.9	43.9
Screw 2	22.1	18.6	24.9	24.2
Screw 3	16.5	15.1	17.2	17
Screw 4	42.1	37.3	51.8	50.9
Screw 5	24.7	24.3	20.5	20.4
Screw 6	18.9	16	17.4	17.3
Screw 7	10.3	8.9	10.4	10.4
Screw 8	22.3	21.2	20.5	20.3

HTO = high tibial osteotomy.

Table 2
Normalised maximal von Mises stress on the locking screws: (A) 600-N load on the full tibial plateau without the opposite screw and (B) 600-N load on the posterior half of the tibial plateau without the opposite screw (unit: %).

(A)	Conventional HTO	6.5-mm cancellous screw	6.5-mm lag screw	8.0-mm lag screw
Screw 1	100.0	78.5	120.7	123.4
Screw 2	100.0	85.8	116.3	113.3
Screw 3	100.0	94.0	105.8	104.6
Screw 4	100.0	90.9	115.7	112.4
Screw 5	100.0	80.6	85.3	85.2
Screw 6	100.0	90.0	108.2	108.3
Screw 7	100.0	93.0	99.1	99.5
Screw 8	100.0	95.0	98.7	98.2
(B)	**Conventional HTO**	**6.5-mm cancellous screw**	**6.5-mm lag screw**	**8.0-mm lag screw**
Screw 1	100.0	80.1	107.6	115.7
Screw 2	100.0	84.3	112.6	109.5
Screw 3	100.0	91.4	104.1	102.9
Screw 4	100.0	88.6	123.1	120.8
Screw 5	100.0	98.2	83.0	82.6
Screw 6	100.0	84.7	92.1	91.4
Screw 7	100.0	87.0	101.6	101.5
Screw 8	100.0	95.0	91.8	91.1

HTO = high tibial osteotomy.

Discussion

The goal of HTO is to relieve pain and restore knee function by correcting the alignment of the knee joint. This technique transfers the joint load from the arthritic side to the relatively healthier region, postponing the requirement of partial or total knee arthroplasty [3–5]. Following the concept of ERAS, sufficient structural stability and implant safety are essential for patients' return to their original lifestyle. The present study evaluated the efficacy of using opposite screw insertion in medial open-wedge HTO by finite element analyses. Quantified results for the capability of maintaining posteromedial reduction of the tibial plateau and implant safety after opposite lag screw insertion are encouraging.

The tibial posterior slope is a highly important factor that alters tibiofemoral contact force [17–19], represented by the resultant anterior translation of the tibia and force transmitted to the anterior cruciate ligaments [20]. Therefore, maintaining an adequate tibial posterior slope is essential for a successful HTO. In the retrospective study by Asada et al [21], the patient group using the spacer plate (VS Osteotomy Plate; Biomet, Parsippany, United States) had a greater increase in the tibial posterior slope, whereas the other patient group had a more stable behaviour using the bone plate and staple to fix both anterior and posterior gaps in HTO. Using the cadaveric model and surgical navigation system, Jacobi et al. [22] concluded that a high-risk situation, such as significant osteoarthritis accompanied by flexion contracture, cases with large correction (15°), and a damaged lateral cortical hinge, will lead to an increase in the tibial posterior slope. To solve the problem of the lateral hinge fracture, Paccola and Fogagnolo [13] introduced the repairing technique by inserting the percutaneous lag screw inserted from the lateral cortex to the medial tibial plateau. As a supplement device in HTO, the opposite screw may share a partial mechanical load from the conventional assignment of the bone plate and locking screws. This technique has even been applied in HTO using an ordinary dynamic compression plate and obtained satisfactory results such that ideal correction and consolidation of the osteotomy site were achieved [23]. In the present study, larger axial displacements on the tibial plateau were observed at the posteromedial region in all models; the load was exerted on either full (standing) or posterior half (sit-to-stand) of the tibial plateau. Simply inserting a cancellous screw did not provide sufficient support to the structure, whereas both models with pretensioned lag screw insertion presented a stable performance similar to that in the intact model in the standing condition. In a more difficult mechanical environment in which only the posterior half of the tibial plateau was loaded, models inserted with opposite lag screws still represented better stability compared with the conventional HTO model. It may be the result from a strengthened structure by providing extra pretension force from the lag screw, causing an internally stiffer support against the outer physiological loads. Therefore, it seems that the diameter of the lag screw does not significantly alter the posteromedial reduction because the pretension force played a more important role. This result implies that the mechanical support beneath the posteromedial region of the tibial plateau helps prevent loss of correction, which echoes the suggestion by Asada et al. [21]. However, a noncompressive cancellous screw may not be helpful to enhance the internal stability in the current osteotomy case.

Hardware failure, which is common in HTO, can also be a risk factor for loss of reduction. Owing to the challenge of the unfavourable mechanical conditions of open-wedge osteotomy, bone plate and screws will have to bear a large mechanical load to support the “artificially caused” fracture fixation. Hardware failure may place the structure in an even more difficult condition. Chae et al. [11] reported 6 cases of screw breakage in their case series, with only 60–65% alignment correction preserved. Another case report by Otsuki et al. [24] described 3 cases with locking pin backout 2–8 weeks after HTO with a lateral hinge fracture. Hardware failure may also be associated with nonunion or delayed union after surgery, similar to that in trauma devices. For severe cases, conversion to total knee arthroplasty would be necessary with additional care in the surgical approach, level of deformity, soft tissue balance, and adequate implant selection [25]. In our results, lower stress compared with that in the corresponding plate in all models may indicate that the risk of screw breakage was not increased by changing the strategy of the treatment in HTO simulations. Using an opposite 6.5-mm cancellous screw in the present study reduced the stresses on the corresponding plate and locking screws, indicating that it may provide hardware safety. When using the lag screws, it has been found that the stresses on the first 4 screws (Screws 1 to 4) increased, especially for Screws 1, 2, and 4. This phenomenon may be because the fixation region of the lag screw is close to these screws, and the pretension force has generated extra pulling force around the Locking Screws 1, 2, and 4. The plate stresses increased in both models with opposite lag screw insertion owing to the extra pretension force provided in the simulated standing posture with loading exerted on the full tibial plateau but decreased in the initial sit-to-stand simulation, which is a more difficult mechanical environment for the hardware. It is also encouraging to note that the reinforced internal stability of the HTO model with pretensioned opposite lag screw insertion will be more stable and safer. However, to be conservative, it is not yet known if the different securing levels (pretension) will influence the stability and safety of the hardware, and this is an area of concern. In addition, initial loss of posteromedial reduction may occur during tightening the lag screw. Safety concern should also be noted that the lag screw may only be purchased at the cancellous bone region, which may be risky of the lag screw cut-out owing to the bending force on the screw shaft when the tibial plateau is loaded. Further verification would be required in clinical practice to provide stronger evidence for the usage of opposite screw insertion technique.

Some limitations of the present study were noted. First, this is a preliminary finite element study to evaluate the efficacy of opposite screw insertion in medial open-wedge HTO. The representativeness of the reconstructed model is of concern, and further mechanical validation will be required. Second, the setting of bonded behaviour between the objects in the present study would eliminate possible separation due to tensile force at the interface, which may be influential to the simulated results. Third, the opposite screw insertion technique has not been quantified and standardised yet. Owing to differences in the bone plate design, bone plate location, securing torque (pretensioning level of the lag screw) of the opposite screw, screw diameter, and anatomy of patients, further study to evaluate the optimal usage of the opposite screw should be considered. Fourth, the stress values represented in the present study were applied only for comparison and risk evaluation among models. The correlation between stress values and practical failure needs to be validated by a mechanical test. Finally, modelling of commercial products may not represent their efficacy and risk in actual clinical practice. Only partial parameters of the designs were extracted for modelling in the present study.

Conclusion

The present study evaluated the potential advantage of opposite screw insertion in medial open-wedge HTO. Oppositely inserted cancellous or lag screws may alter the stresses on the bone plate and locking screws, and the pretensioned lag screw can be more beneficial in avoiding loss of posteromedial reduction after HTO. With the help of early clinical experience and the biomechanical information provided in the present study, this technique may be worth considering for a more stable medial open-wedge HTO to achieve the goal of ERAS with great stability and safety.

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Conflicts of Interest

The authors have no conflicts of interest to disclose in relation to this article.

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